PREFACE

This report is the result of the graduation research of J.R. van Rutten in which the mechanical behaviour of unbound granular materials used in the base course in pavement structures has been analysed. The research has been accomplished at the Road and Railroad Research Laboratory of Delft University of Technology, in order to obtain a Master of Science Degree at the Delft University of Technology, Faculty of Civil Engineering and Geosciences.

The report gives a review of the unbound granular materials tested at the Delft Road and Railroad Research Laboratory during the past 20 years. Many material parameters as well as stiffness and strength parameters of these materials have been collected and analysed in order to establish some relationships between these mechanical parameters and easy to obtain material parameters. Therefore, regression techniques have been applied on the data set of unbound granular materials.

I wish to thank the graduation committee for their support, patience, guidance, and open attitude during the research. I also would like to thank the people and students working at the Delft Road and Railroad Research Laboratory for their commitment and assistance. Much appreciation is expressed to Karel Karsen and Eugene van der Heijden for their intense coaching during the last years. Flip Wauters helped me writing technical English and gave useful comments on the granular and statistical part of this study frequently.
Once again my heartfelt thanks go to my parents, my brothers, and my girlfriend whose gracious support, assistance, understanding, and patience as always have been one hundred per cent.

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ABSTRACT

In this study, relationships have been established between mechanical properties and easy to obtain (physical) material characteristics of unbound granular materials (used or available in The Netherlands). Avoiding complex laboratory tests to retrieve the mechanical properties then, non-linear models, characterising the resilient behaviour of unbound base materials, instead of linear models (rules of thumb) can be used during the design of pavement structures. This will result in better predictions for pavement life.

The search for these relationships between mechanical properties and (physical) material characteristics has been focussed mainly on relationships for the cohesion, and the resilient modulus (M_r-θ model) parameters. Furthermore, it has been decided to relate the k_2 parameter to the k_1 parameter of the same resilient model.

The data set composed in this study contains 53 different material samples with approximately 30 material and mechanistic parameters collected from different sources, adapted where necessary. The search for density parameters has been emphasised. The influence of cementation and carbonatation in time has been avoided.
The data set consisted of a poor material data set; the grading curve properties resemble each other or differ barely. Other material parameters could not be used because of their 'measurement' error.

The relationships have been obtained using linear and log-linear regression analysis, resulting in different regression functions. The reliability of a model has been determined by the ratio of the number of data points to the number of explaining (independent) variables in the model (degrees of freedom), the correlation coefficient (r^2) and the standard error of the estimator.

All combinations of material properties as being expected of any influence have been used in the regression analysis. Material filters have been set as well, using mixed granulates materials only or involving materials with the degree of compaction. These filters did not improve the results of the regression.
3 regression models have been proposed for the mechanical properties:

- **cohesion** (failure characteristics/strength);
- **k_1 relation** (stiffness/resilient modulus)
- **relationship between k_2 and k_1** (stiffness/resilient modulus).

However observing a good correlation coefficient for the k_1 relationship, the fit of the regression line appeared reasonable. The other models found in SPSS showed a fairly good fit.

CONTENTS

1 INTRODUCTION AND SCOPE OF THIS STUDY

1.1 Introduction

In this chapter a brief description of the development of pavement engineering using unbound granular materials is discussed, leading to the objective of the study. The boundaries of this study have been defined as well. This chapter ends with a flow chart of the study, which shows both the procedures carried out and the structure of this report.

1.2 Change in focus on pavement engineering

Nowadays, an international trend to build roads with a longer life span can be observed. Economic prosperity, especially in the developed countries, has resulted in a sharp increase in traffic both in volume and in weight. This high traffic growth leads to traffic congestion, not only due to lack of capacity but also due to pavement maintenance and reparation works. The increase in vehicle weight, axle loads, etc., results in faster deterioration of the road network. The combination of the lack of capacity and the faster deterioration results in a situation where traffic flows should be obstructed as less as possible. Hence, obstruction due to maintenance works should be limited. Thus, a longer life is required.

As mentioned, road construction is subjected to changes more than ever. These changes concern amongst others:

1. The increase in number and magnitude of wheel loads, change in kind of wheel loads and wheel configuration. Transport vehicles are increasing in number as well as magnitude, and the use of super single tires and different axle configurations is increasing too.
2. The materials used for pavement construction, their properties, and their constitution in the pavement structure. In addition to marginally modified materials, new and stronger materials are being introduced where thorough studies of the materials before introduction are desirable.
3. The budget as well as time available for maintenance and renewal of pavement structures, which forces administrators, engineers, and contractors to introduce efficient maintenance activities, implying the use of new techniques as well as materials.

Because of these changes, pavement engineering should be practised on a scientific rather than an empirical basis. There is a lack of theoretical knowledge in practise. For a scientific approach to pavement engineering, a thorough understanding and knowledge of the mechanical behaviour of, amongst others, the unbound granular materials used in pavement structures, is necessary [MOLENAAR 1997].

1.2.1 Lack of knowledge on the behaviour of unbound granular materials

A good pavement design procedure should use the correct strength and stiffness characteristics of all applied materials. For the unbound granular materials applied in the base and sub-base of a pavement structure, the knowledge concerning the material characteristics is relatively limited.
Research has shown that the mechanical behaviour of unbound granular materials is stress dependent. Moreover, the material quality and the quality of construction (e.g. the degree of compaction of the materials used in the pavement structure) influence largely the performance of such base courses and thus of the pavement structure as a whole.

The traditional test methods used to determine the engineering characteristics of unbound granular materials are mostly empirically based. The parameters obtained from these tests cannot be used as inputs to the mechanistic pavement design procedures used nowadays. Therefore, these procedures either do not use the unbound granular materials to their full structural capacity and attribute only a limited structural role to the granular layers, or overestimate the structural capacity of rather marginal materials [SWEERE 1990, p. 17]. Hence, in many of the mechanistic pavement design procedures, unbound granular materials do not feature strongly. These design procedures focus on designing the asphalt layer, given the subgrade conditions and predicted traffic loading. The main structural element of the pavement is the asphalt layer and the significance of the unbound granular base is virtually reduced to that of a working platform.

The reason why granular materials do not feature strongly in mechanistic (asphalt layer focussed) design procedures is twofold [SWEERE 1990, pp. 107-108]:

4. Granular materials show a marked moisture-dependent mechanical behaviour. The phenomena governing this dependency are not yet fully understood and the mechanical parameters needed for pavement engineering are, therefore, determined in the worst possible condition. Clearly, this may lead to a conservative design underestimating the structural role of the granular layer.
5. Granular materials show a complex stress-dependent behaviour. Determination of fundamental stress-strain parameters requires complicated, elaborate testing techniques. Complex material and pavement models are required to incorporate stress-dependency in the design. Since these requirements are often not met, pavement-engineering practice again leads to a conservative design by attributing only a limited structural role to the granular layers in the pavement.

1.2.2 Retrieving material characteristics for unbound granular materials

The widespread use of the cyclic load triaxial test nowadays allows for a direct measurement of the resilient stress-strain properties of unbound granular materials. These properties are considered as indispensable for a sound analytical mechanical engineering of pavement structures.
However, triaxial testing of sub-base but especially coarser base materials is complex, costly, and time-consuming with respect to the required equipment, sample preparation, sample testing and data analysis and interpretation. For this, triaxial testing and thus fundamental pavement engineering based on stress dependent behaviour of unbound layers is by no means common practice.

It is common practice to characterise unbound granular materials with a range of less complex standard and non-standard tests to establish material properties just like simple material behaviour, in order to exploit these test results further. These material properties are, amongst others, proctor density, optimum moisture content, Californian Bearing Ratio (CBR), etc. General relationships between these material properties and resilient stress-strain properties of unbound granular materials are desirable.

During the last two decades the Laboratory for Road and Railway Research of the Delft University of Technology has obtained many data with respect to the material characteristics of unbound granular materials available in The Netherlands. These data are related to both standard tests and repeated load triaxial tests and can be used perfectly to relate results of simple tests to characteristics needed as input for mechanistic design of pavement structures.

1.2.3 Recipe based specifications of granular materials

The lack of knowledge described above as well as the lack of general relationships between material properties and failure, resilient deformation and permanent deformation behaviour of unbound granular materials has resulted in limited and recipe based specifications.

These specifications for unbound granular materials in the base and sub-base of pavement structures currently concern:

- the particle size distribution;
- hardness of the granular materials;
- composition of the granular materials;
- degree of compaction;
- CBR-value and the increase of CBR-value in time. In the Netherlands, some unbound granular materials applied in base courses or in the sub-base of a road structure, e.g. crushed concrete mixed together with slag, will have a CBR-value increasing in time. (See section 2.2.2, Figure 2.2)

1.2.4 Towards practical specifications for a pavement structure

In pavement construction engineering, however, the mechanical material characteristics mentioned below are of importance:

- strength: cohesion (c) and angle of internal fraction (φ);
- stiffness: resilient modulus (M_r);
- permanent deformation behaviour (ε_p).

These characteristics are discussed in Appendix E, sections E.4.2 and E.4.3

The physical material characteristics determined with less complex standard tests and non-standard tests are sometimes related to the mechanical material characteristics of the unbound granular materials, but these relationships are limited or expressed in a qualitative way. There is certainly a need for improved relationships. Then, the introduction of practical specifications given by commissioner for the construction of a pavement structure is achievable instead of the recipe based specifications ruling nowadays.

1.3 Scope of the study

The aim of this study is to establish a correlation between mechanical properties of unbound granular materials and (physical) material characteristics.

The search for these relationships is mainly focussed on relationships for the cohesion, angle of internal friction, and the resilient modulus (M_r-θ model). This will be analysed in chapter 2 (section 2.3) and chapter 4 (section 4.2.1)

After establishing this correlation, mechanistic engineering of pavement structures could become more sound, profound, and should allow, amongst others, designing and engineering pavement structures from the desk without the necessary laboratory tests but rather based on these correlations.
Development and introduction of practical specifications for unbound granular materials might be feasible as well.

The limitations of the study are:

- Due to strongly varying material properties, only *unbound* granular materials have been analysed. The focus is mainly on unbound granular materials used or available in The Netherlands. Furthermore, all except one material (limestone) did not contain particles smaller than 2 µm.
  See appendix A for the description of unbound granular materials.
- Established relationships have been based on data obtained at the Laboratory for Road and Railway Research of the Delft University of Technology.
  This will be explained in chapter 4 section 4.3.

1.4 Thesis structure

This study consists of four parts:

1. After an analysis of the components of a pavement structure together with the design principles for pavement design, the relevance of incorporating non-linear models to characterise the resilient behaviour of unbound base materials is illustrated. By this, it will be established that improved relationships between mechanical properties of unbound granular materials and their material characteristics are recommendable.
2. A literature review has been made to review shortly the relevant relationships for the mechanical behaviour of unbound granular materials.
3. The method of the study is discussed together with the parameters to be retrieved. The data have been collected, adjusted and analysed, followed by various regression analyses to reveal the correlations between mechanistic properties of unbound granular materials and easily obtainable material characteristics.

Each chapter in this report will treat a main activity of the study (literature review, analysis, findings, results, case study and conclusions), while background information (calculations, data set, explanations of parameters, diagrams, and graphics) has been placed in the appendices. *Figure 1.1* shows the procedures carried out to accomplish the study as well as the structure of this report.

Gewijzigde veldcode

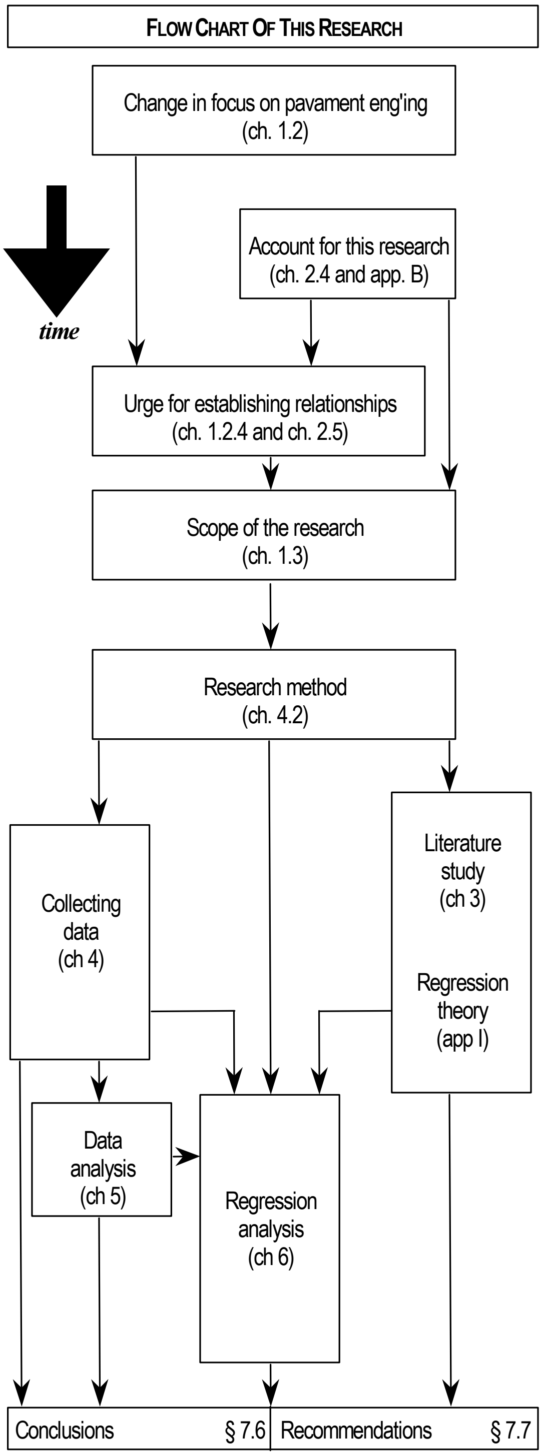


Figure 1.1 Bookmarker of this report and flow chart of the study

2 SIGNIFICANCE OF THE BASE COURSE: ACCOUNT FOR THE STUDY

2.1 Introduction

This chapter is started with an analysis of the components of a pavement structure with their functions, followed by the design principles for pavement design.
To conclude, the relevance of incorporating non-linear models instead of linear models to characterise the resilient behaviour of unbound base materials is illustrated. For that, some calculations with KENLAYER have been made. It will demonstrate that improved relationships between mechanical properties of unbound granular materials and their material characteristics are recommendable.

2.2 Flexible pavement structures; general description

2.2.1 Regular Dutch flexible pavement structures

Figure 2.1 shows typical asphalt pavement structures for both secondary roads and motorways in The Netherlands. In this section as well as in the figure the Dutch terminology to denote the various layers of a pavement structure is clarified.

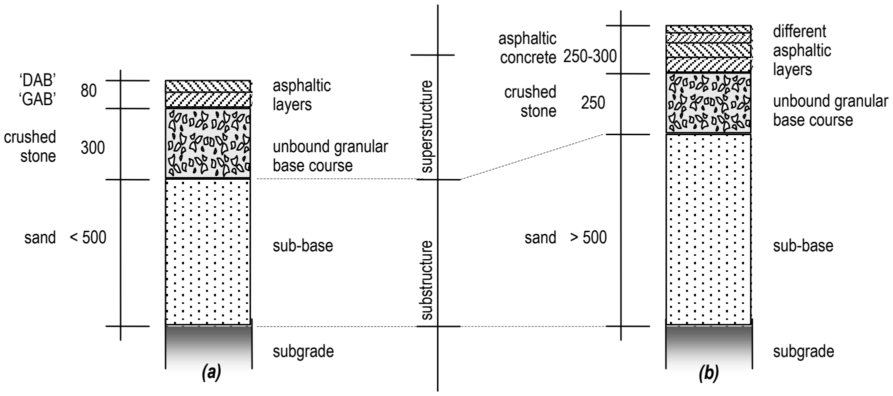


Figure 2.1 Pavement structure of a secondary road (a) and a motorway (b)

Going from top to bottom in Figure 2.1, the following layers can be distinguished [SWEERE 1990, pp. 26-27]:

- The wearing course consisting of dense asphaltic concrete. This layer provides the skid resistance required by traffic and it serves as an impermeable layer protecting the lower pavement layers from the ingress of water. On motorways (Figure 2.1 b), another kind of wearing course is widely used: the application of a porous wearing course providing horizontal drainage through the wearing course and reducing traffic noise, in Dutch called 'ZOAB' ('Zeer Open Asfalt Beton').

- The binder course, consisting of coarse graded asphaltic concrete. The main function is levelling of the lower layers. In case of a porous wearing coarse a dense bituminous binder course is applied.

- The bituminous base, consisting of one or more layers of gravel or stone asphaltic concrete.
  As the asphalt layers in motorway road structures (Figure 2.1 b) result in a high bending stiffness because of its resulting thickness, it may behave essentially as a rigid pavement. It distributes the load over a relatively wide area of soil. The asphalt package itself supplies the major portion of the structural capacity of the pavement structure. For this reason, minor variations in subgrade strength have little influence upon the structural capacity of the pavement structure.

- The unbound granular base, consisting of gravel, slag or recycled materials (see Appendix A), has a structural role and serves as a working platform for the construction of the upper layers:
  - to the superimposing layers it provides the bearing capacity by adding stiffness to the pavement which reduces the tensile strain at the bottom of the asphalt layer which increases the pavement life;
  - to the underlaying layers it spreads the traffic loads by distributing the load through a finite thickness of pavement. It therefore reduces the vertical compressive stress induced by traffic in the subbase and subgrade to a level at which unacceptable deformation will not occur in these layers [KISIMBI 1999, p. 5].
  - Hence, it provides resistance to shear failure as well as resistance to permanent deformation.

  For a further focus on the unbound granular base, see section 2.2.2.
  Another option than a bituminous and an unbound granular base as shown in Figure 2.1 is a full-depth asphalt concrete structure, where a gravel asphaltic concrete layer replaces the unbound base course.

- The sub-base, consisting of sand. It provides extra stiffness, drainage facilities and gives added protection against frost action where necessary.
  Applying sand of substantial thickness in the sub-base of major roads is a typical aspect about Dutch pavement structures, for reason of its availability.
  In other countries, the sub-base often consists of granular materials with a higher CBR-value such as locally available gravel-clay mixtures. Where the CBR of these granular materials is lower than 25 or 30%, an extra capping layer is applied.
  In case of weak sub-grades, the sub-base replaces the upper part of the sub-grade, thereby providing a smooth transition in stiffness from the stiff upper layers to the weak sub-grade.

- The subgrade.

2.2.2 Focus on the unbound granular base

Both the unbound base as well as the sub-base has a stress dependent behaviour. Static and cyclic load triaxial testing is required to determine the stress dependent resilient and permanent deformation behaviour.

Compaction of the base course is a very important factor influencing the performance of the base and of the pavement structure as a whole. Moreover, good compaction of the base is believed to be the most cost-effective measure to increase pavement life, as compared to e.g. increasing asphalt thickness.
This implies that compaction should be given a priority at design stage by giving concise specification on relative compaction and that quality control should ensure that the specified compaction level is indeed delivered during construction [KISIMBI 1999, p. 126].

In Figure 2.1 a, the role of the base course is of especial importance, where the thinner asphalt layers behave as a truly flexible slab. Flexible pavements consist of series of layers with the highest-quality materials at or near the surface. Hence, the strength of such a pavement is the result of building up layers, thereby distributing the load over the subgrade rather than by the bending action of the slab [KISIMBI 1999, p. 4].

As mentioned in section 1.2.3, some unbound granular materials applied in base courses or in the sub-base of a road structure will have a CBR-value increasing in time. Limiting stress levels in a mix granulate base course after compaction under both construction and in-service traffic will increase its strength and stiffness as a result of cementation and carbonisation. This reflects on pavement performance by a reduction of the asphalt strains and thus an increase of the pavement life [KISIMBI 1999, p. 126].
This is a typical aspect of Dutch road structures. Therefore, the minimum required increase of the CBR-value of some unbound granular materials has been prescribed in the Dutch RAW 2000 [CROW 2000, pp. 446-450], i.e. The Dutch Specifications for Road Construction. These materials are mixed granulate, crushed concrete, and mixed granulate with slag. See Figure 2.2 for some of these typical CBR-values.

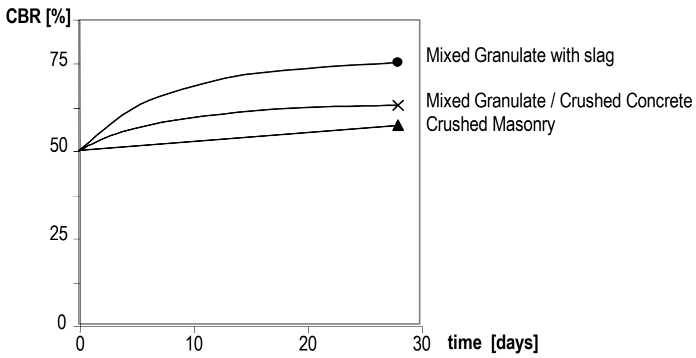


Figure 2.2 Minimum CBR-value and minimum increase in time, based on prescribed values by the Dutch RAW, during the first 28 days immediate after construction

2.2.3 Use of recycled materials

In the Netherlands, increasing attention has been paid for a number of years to recycling of waste products to obtain road construction materials of sufficient quality. Regarding unbound granular bases, recycling of construction and demolition waste into granulates is by now becoming quite standard. Stony materials are processed in crusher plants to obtain granulates with the required particle size distribution. Crushed masonry, crushed concrete and mixtures of these materials are commercially available, with and without cementing additives [SWEERE 1990, p. 33]. Yearly, about 10-15 million metrics ton of mixed granulate is used for road construction. The Dutch Government aims for the highest sustainable re-use possible.

Apart from the wearing course, recycled asphaltic materials are re-used in all asphaltic layers. Rates of around half recycled asphalt granulate and half new aggregates in asphaltic layers are regular. About 1.5-2 million metrics ton of asphaltic materials out of 7.5 million metrics ton yearly produced is recycled asphaltic material.

For a more elaborate description of recycled granular materials, the reader is referred to appendix A.

2.3 Structural Pavement Design

Examples of empirical design methods are:

- The TRRL method. (British Transport and Road Research Laboratory)
- The ROAD NOTE 3I-method.
- The AASHTO Method. (American Association of State Highway and Transportation Officials)
- The Shell Pavement Design Manual. (SPDM)

It is not in the scope of this study to discuss all these design methods. In the paragraphs below, a short abstract of the design approach in general will be discussed.

2.3.1 Design approach

In the structural design of pavements two failure criteria are generally considered (Figure 2.3):

1. The horizontal flexural tensile strain at the bottom of the asphalt layer to minimise fatigue cracking;
2. The vertical compressive strain at the top of the subgrade to reduce the permanent deformation (ε_p, known as rut development).

Normally, the strength of the base is not taken into consideration. Quite often, it is stated that e.g. the resistance to deformation is controlled via the specifications.

The introduction of the concept of design life is particularly important in pavements, since they do not fail suddenly but gradually deteriorate over a long period. This is essentially a fatigue phenomenon, in the sense that the deterioration, which is caused by the stresses and strains in the structure, results from both the magnitude and the number of load applications that the pavement experiences [MEDANI 1999, p. 2].

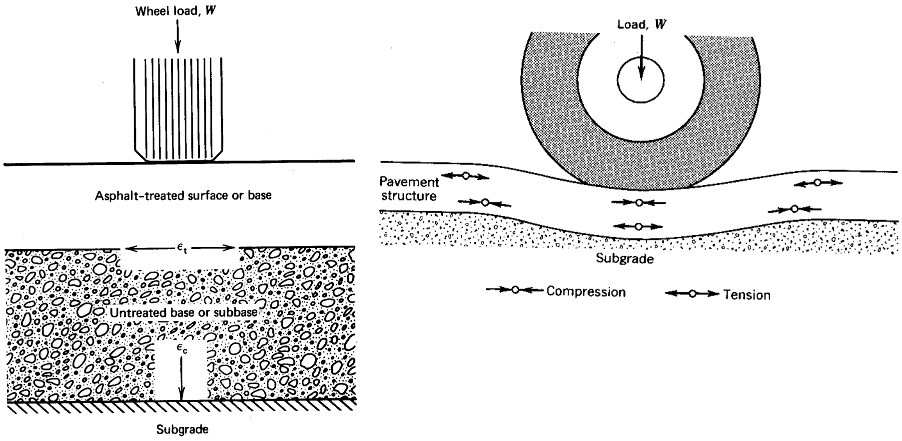


Figure 2.3 Tensile and compressive strains in flexible pavements [WRIGHT 1996, p. 462]

2.3.2 Stresses induced in a pavement

The development of the stresses by a moving wheel on an element in the pavement and their change with time is shown in Figure 2.4. The time of loading depends on the vehicle speed, depth below the pavement surface and wheel, axle and suspension configuration [COLLOP & CEBON, 1995].

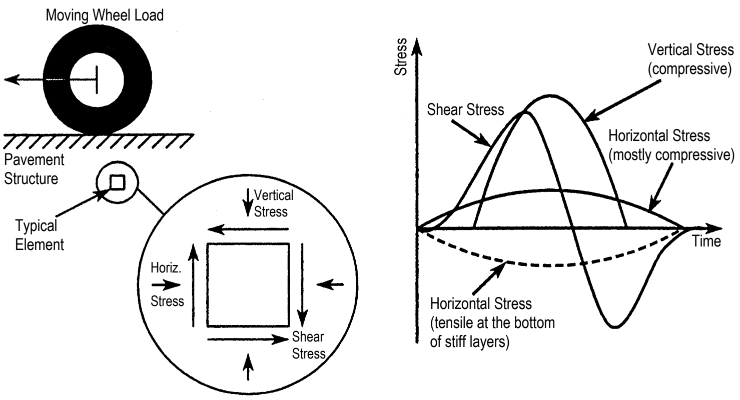


Figure 2.4 Stresses induced by a moving wheel load on a pavement element [BROWN,1978]

The pavement as a whole system is subjected to a stress controlled loading. Those layers, which have considerable structural significance (thick and stiff, so a great bending stiffness), will also be subjected to stress controlled condition. However, thin surfacing layers essentially follow the movement of the lower structure layers which results in strain controlled situation [BROWN 1978].

2.3.3 Failure of the pavement structure

Generally, two modes of structural failure are considered, being permanent deformation and cracking.

Rutting or permanent deformation is the accumulation of tiny irrecoverable strains in a material under repeated loading which eventually cause a measurable rut to be developed. These small strains are due to the visco-plastic response of materials when subjected to dynamic loading, and they accumulate over millions of traffic load applications to form a large deformation. These permanent deformations can occur in the asphalt layers, the unbound granular base and sub-base, and in the subgrade as well.
Most design methods do not take into account the permanent deformation of the asphalt layer or unbound granular base. However, there are a few exceptions like e.g. the method of the Belgian Road Research Centre. In this method permanent deformation is described by equation 2.1

$$u_p = u_{el} \cdot a \cdot N^b \qquad 2.1$$

where:

- u_p : permanent deformation
- u_{el} : elastic deformation
- N : number of load repetitions
- a : material parameter

The weakness of all methods, however, is that they are based on linear elastic material behaviour which is certainly not the case for unbound granular materials, as has been stated in section 2.2.2.

Cracking or fatigue of the asphalt layer arises from repeated tensile strains due to traffic loading. The maximum tensile strain is found, according to structural analysis, at the bottom of the bituminous layer. The crack, once initiated, propagates upward causing gradual weakening of the structure.

The Wöhler Approach

In order to determine the resistance to cracking of the pavement, the tensile strain calculated at the bottom of the asphalt layer is used as input in a Wöhler type fatigue relation.
Similarly to the tensile strain, the vertical compressive strain at the top of the subgrade is calculated and used in a Wöhler type fatigue relation to calculate the numbers of load repetitions until excessive deformation of the subgrade occurs.
This approach is simple in use and generally provides sufficient accurate predictions.

Shear failures

Failures that occur in soil masses as a result of the action of highway loads are principally shear failures: the shear stress then has reached its maximum, resulting in shear failure of the base course or subgrade. Shear failure of the base course may appear equivalent to permanent deformation, but the mechanism of appearance is different. The failure behaviour of a road base material is described by the failure stress ($\sigma_{1,f}$).

Parameters of influence for the maximum allowable shear stress are the cohesion (c) and the angle of internal friction (φ) of the unbound granular materials in the base course.

The value of the angle of internal fraction (φ) is assumed to include the factors of resistance to sliding (or rolling) of the soil particles over one another and any interlocking that may have to be overcome before a slip can occur. In a simple explanation, cohesion is supposed to include both 'true' cohesion, due to intermolecular attraction, and 'apparent' cohesion, due to surface tension effects in the water contained in the clay mass.

As stated, for the large majority of soils shearing resistance is made up of both cohesion and internal friction. For these soils the shearing resistance on any plane is frequently, though somewhat empirically, given by Coulomb's law.

For an elaborate description of failure mechanisms in base courses, the reader is referred to appendix E section E.4.2, where has been dealt with the angle of internal friction (φ) and cohesion (c). These material properties are related to the principal failure stress ($\sigma_{1,f}$) and the confining stress (σ_3) according to the Mohr Coulomb model.

2.3.4 Design life of a road structure

From the previous sections it is clear that analyses on the stress-strength conditions of the pavement layers and materials is necessary, in order to be able to make pavement life predictions. The accuracy of the predictions depends of course on the models used to characterise materials and pavement response when subjected to loads.
It has also been mentioned that unbound granular base courses show a stress dependent resilient behaviour and that they will show excessive permanent deformation when subjected to too high stresses. Until now, however, it is common practice to assume the granular base to behave like an elastic material. In the current design systems, no attention is paid to the behaviour of unbound base courses.

The objective of this chapter is therefore to show that the stress conditions in the road structure are indeed being influenced when taking into account the stress dependency in the unbound granular base course. Hence, this will result in different analyses for pavement life predictions.

2.4 Sensitivity analysis for different base course modelling

With the use of KENLAYER, a sensitivity analysis has been made on both linear and non-linear elastic three-layer systems to illustrate the effects of the way of modelling the stiffness of the unbound granular base course. Therefore, a road structure with varying asphalt layer thickness as well as varying subgrade stiffness has been evaluated.

Based on the KENLAYER output the relative design life has been calculated and evaluated. In addition, the maximum shear stress in the unbound base as calculated by using the various approaches to describe the stiffness of the unbound granular base has been evaluated.

As will be seen, these results will vary with the model used for the stiffness of the unbound granular base-layer, whereas the variation in relative design life might differ significantly.

The three ways of modelling the stiffness of the unbound granular base-layers are:
1. dependent on the stiffness of the subgrade (Shell-approach, equation 3.2 ch. 3);
2. dependent on the stiffness of the subgrade, while subdividing the unbound granular base into two sub-layers;
3. stress dependent, while using the resilient modulus (M_r) for the unbound granular base.

See the appendix B for a precise description of the three models.

With KENLAYER several values have been calculated for the centre of a 50 kN wheel load:
- the horizontal tensile strain at the bottom of the asphalt layer;
- the vertical compressive strain at the top of the subgrade;
- horizontal and vertical stresses at several interesting depths of the structure, i.e. at the border or in the middle of a certain base sub-layer, to obtain the shear stress (τ) in these points;
- the layer stiffness.

2.4.1 Specifications of the road structure and input for KENLAYER

Consider Figure 2.5, where the pavement structure with its characteristics and varying base and subgrade stiffness and asphalt layer thickness is given.

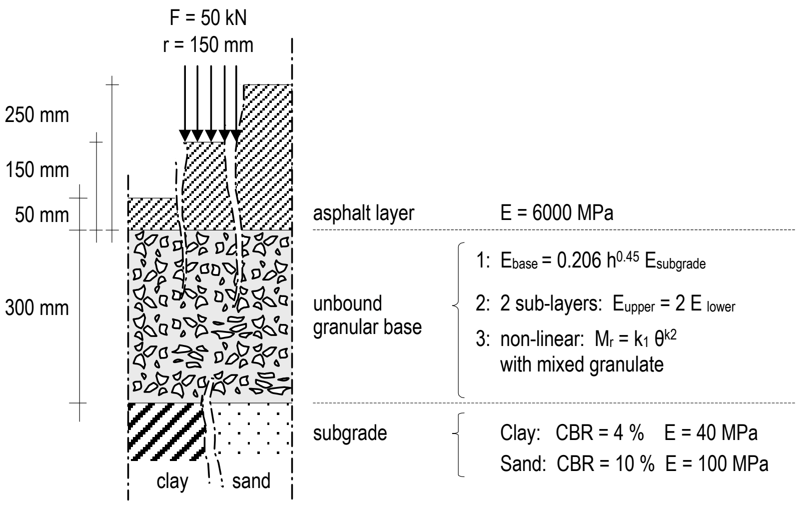


Figure 2.5 Pavement structures as evaluated with KENLAYER.

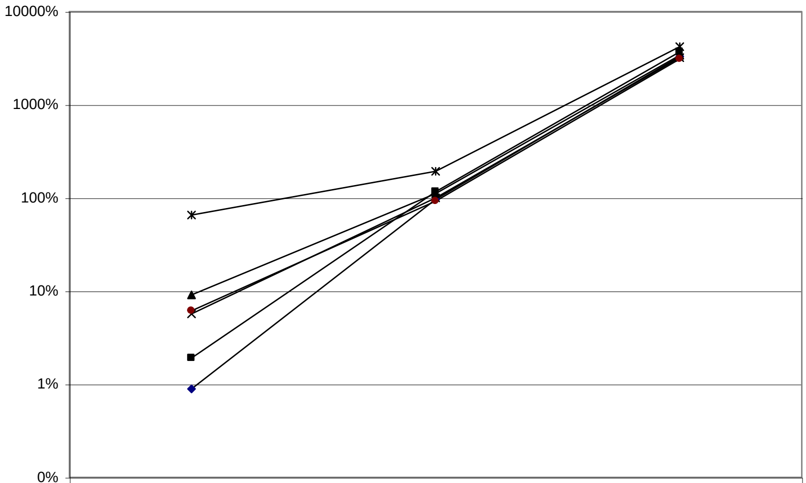
For calculations with non-linear elastic three-layer systems, material properties of the unbound granular base are required. In this case mixed granulate with three different densities and crushed masonry have been evaluated:

1. commercially graded mix granulate of crusher plant at Zestienhoven, The Netherlands, with density 95% of Maximum of Proctor Density, MPD (MG16H 95);
2. commercially graded mix granulate with density 100% MPD (MG16H 100);
3. commercially graded mix granulate with density 105% MPD (MG16H 105);
4. crushed masonry with density 100% MPD (CM 100)

The commercially graded mix granulates with varying density have been analysed by KISIMBI (1999, pp. 84-88) at the Road and Railroad Research Laboratory of Delft University of Technology. Note that, as found by KISIMBI, the resilient modulus of MG 16H 100 is substantially lower than both MG 16H 95 and MG 16H 105, which is remarkable and unexpected. This will result in deviant results calculated by KENLAYER.

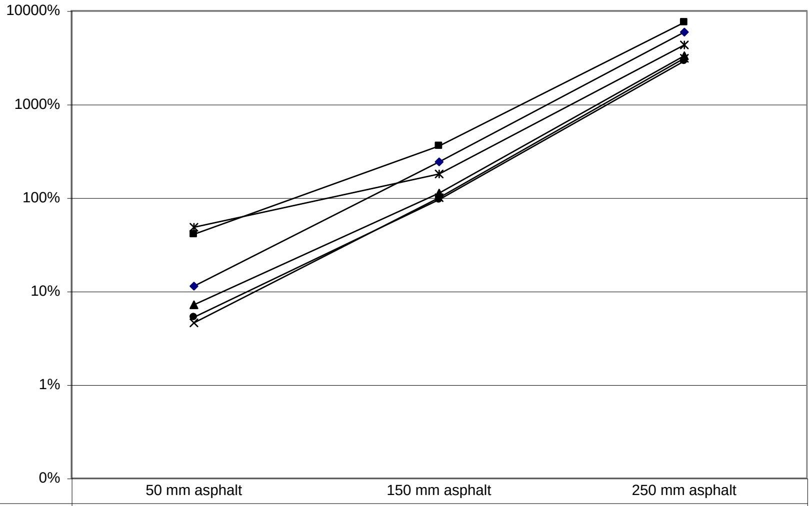
2.4.2 Results: relative design life

In the figures below (Figure 2.6 - Figure 2.9), the resulting relative design life of the pavement structure is compared using different models for characterising the stiffness of the base-layer. The relative design life is calculated depending upon both horizontal tensile strain at the bottom of the asphalt layer and vertical compressive strain at the top of the subgrade.



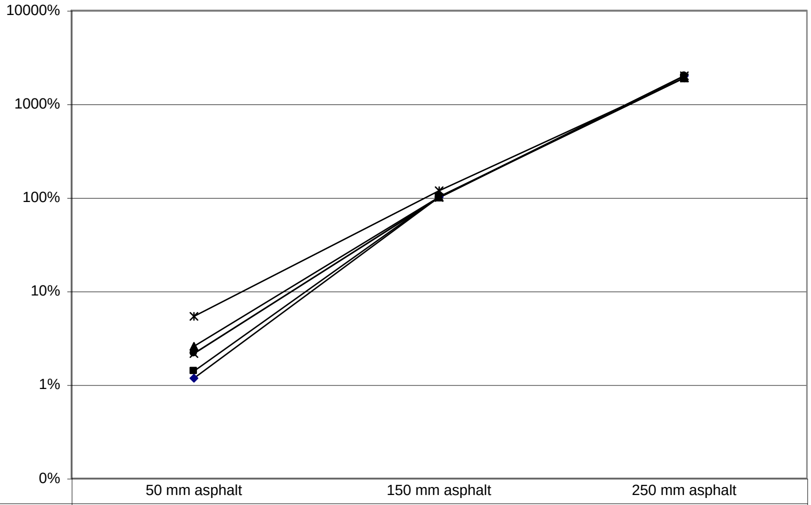
	50 mm asphalt	150 mm asphalt	250 mm asphalt
method 1 Mixed Gran.	1%	96%	3300%
method 2 Mixed Gran.	2%	117%	3700%
method 3 Mixed Gran. 95	9%	111%	3400%
method 3 Mixed Gran. 100	6%	100%	3200%
method 3 Mixed Gran. 105	65%	193%	4200%
method 3 Cr.Masonr.	6%	92%	3100%

Figure 2.6 Relative pavement life based on the radial strain at the bottom of the asphalt layer.(subgrade = 4 CBR)



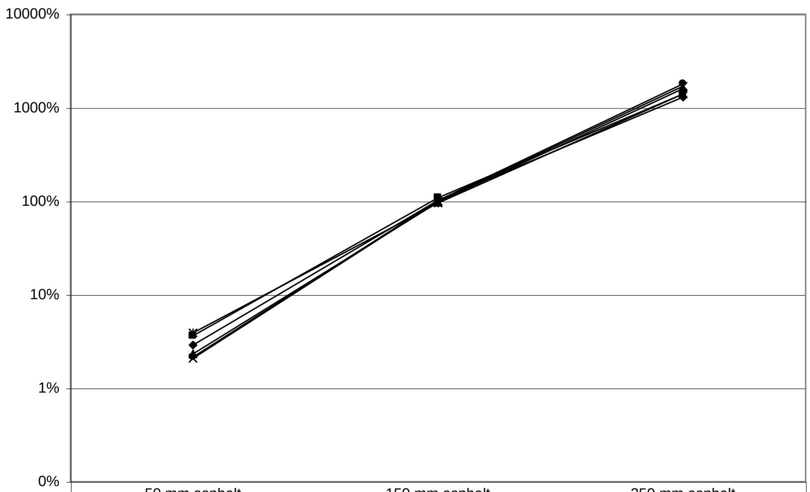
	50 mm asphalt	150 mm asphalt	250 mm asphalt
method 1 Mixed Gran.	11%	242%	5900%
method 2 Mixed Gran.	41%	357%	7500%
method 3 Mixed Gran. 95	7%	112%	3300%
method 3 Mixed Gran. 100	5%	100%	3100%
method 3 Mixed Gran. 105	48%	179%	4300%
method 3 Cr.Masonr.	5%	95%	2900%

Figure 2.7 Relative pavement life based on the radial strain at the bottom of the asphalt layer.(subgrade = 10 CBR)



	50 mm asphalt	150 mm asphalt	250 mm asphalt
method 1 Mixed Gran.	1%	101%	2000%
method 2 Mixed Gran.	1%	102%	1900%
method 3 Mixed Gran. 95	3%	101%	1900%
method 3 Mixed Gran. 100	2%	100%	2000%
method 3 Mixed Gran. 105	5%	118%	1900%
method 3 Cr.Masonr.	2%	100%	2000%

Figure 2.8 Relative pavement life based on the compressive strain at the top of the subgrade. (subgrade = 4 CBR)



	50 mm asphalt	150 mm asphalt	250 mm asphalt
method 1 Mixed Gran.	3%	102%	1300%
method 2 Mixed Gran.	4%	109%	1400%
method 3 Mixed Gran. 95	2%	97%	1600%
method 3 Mixed Gran. 100	2%	100%	1700%
method 3 Mixed Gran. 105	4%	96%	1400%
method 3 Cr.Masonr.	2%	102%	1800%

Figure 2.9 Relative pavement life based on the compressive strain at the top of the subgrade. (subgrade = 10 CBR)

2.5 Observations and conclusions

By means of KENLAYER, several road structures with varying asphalt layer thickness as well as varying subgrade stiffness have been evaluated.
Special emphasis was placed on the modelling of the base layer for which both linear and non-linear elastic three-layer systems have been used. From the analysis, the following conclusions can be drawn:

- Especially for pavement structures with a thin asphalt layer as well as for pavement structures with a weak subgrade, the relative design life strongly depends upon the model used for the mechanical properties of the base course.
- Where the subgrade has a higher stiffness, the relative design life may differ from each model used for the stiffness of the base course. This is mainly the situation for the horizontal strain at the bottom of the asphalt layer.
- When the subgrade has a lower stiffness and thick asphalt layers are used, the influence of the modelling of the base course is of less importance for the design life of a pavement structure.

It has been shown that when taking into account the stress dependency in the unbound granular base course indeed the stress conditions in the road structure are being influenced, resulting in different predictions for pavement life.

Therefore, it can be concluded that use of simplified models to characterise the stiffness of the base should be discouraged. The reason for this is that such models do not allow taking into account the effect of the type of material, the stress conditions, and the degree of compaction. All the influences are reflected in the values for k_1 and k_2 of the Mr-θ model.
Since the compaction parameters that control the stress dependent behaviour are difficult to obtain, the relationships between k_1 and k_2 on mechanical and physical characteristics like grading, grain shape and density are certainly welcome.

3 LITERATURE REVIEW: MECHANICAL BEHAVIOUR OF UGM

3.1 Introduction

By nature, unbound granular materials are rather difficult materials to deal with, in respect of engineering properties. This is particularly due to inherent diverse behaviour of parent material because of geological history that influenced the mineralogical composition, particle shape and particle size distribution of unbound granular base materials. Moreover, the actual degree of compaction and moisture content are of great importance.

In this chapter a short survey of relevant relationships for the mechanical behaviour of unbound granular materials is given. As stated in chapter 1 section 1.3, mainly results originated from the Laboratory of Railroad and Road Engineering have been taken into consideration. These results have been established mainly by SWEERE (1990), VAN NIEKERK (1995), HUURMAN (1997), Lefevre (1998), KISIMBI (1999), and MURAYA (2000). Some of these studies have been summarised in appendix C.

3.2 Resilient modulus / Stiffness

The stress-strain characteristic of base course materials is very important in a pavement analysis since it will determine the resilient modulus variation and the stress-strain distribution in a pavement. This is why it is necessary to measure the resilient response correctly and accurately in the laboratory.
According to VAN NIEKERK (1995, p. 151) and validated by tests performed by MURAYA (2000), the resilient modulus (M_r) for granular base course materials can best be related to the sum of the principal stresses (θ). This model is known as the M_r-θ model as described in appendix E. Despite being used widely, the M_r-θ model is theoretically incorrect, for it can not discriminate between the influence that the different stress invariants (σ_1 and σ_3) have on the stress dependency of M_r. The model, however, describes the behaviour of the resilient modulus for granular base course materials very well as long as loading conditions (σ_1/σ_3) remain mild [MURAYA 2000, p. 164].

3.2.1 Correlating the resilient modulus to easy to measure properties

Resilient modulus testing at the level of sophistication needed to obtain satisfactory results is for most laboratories more suitable for a research project rather than for routine production type testing. A very attractive approach for obtaining resilient moduli for use in design is to calculate values using generalised empirical relationships. Such relationships give resilient modulus as a function of statistically relevant, easy-to-measure physical properties of the material. These relationships for resilient modulus can be established through carefully designed and conducted research projects for each class of material [BARKSDALE & KHOSLA 1997, p. 271].

BARKSDALE & KHOSLA (1997, p. 271) point out several factors where or by which the coefficient of variation (CV) of the mean resilient modulus, either experimentally determined or calculated, fluctuates. Because of all these factors, empirical correlations between resilient modulus and easy to measure properties can be used in pavement design considering the large expected overall variation in resilient modulus as material properties and environmental conditions change with both time and location.

Some qualitative relationships for the k_1 and k_2 values of the M_r-θ model are given in Table 3.1. The table originates from Maree (1977). It gives an impression of the ambiguous influence of compaction on the k_1 and k_2 parameters, while the influence of compaction on the resilient modulus is evident. The fine particles as well as the moisture content seem to be of great importance as well.

Factor	Δ factor	Influence on k_1	Influence on k_2	Influence on M_R
Density	Increase	ambiguous	Ambiguous	slight increase
Grading: max. part. size	Increase	no influence	no influence	no influence
$Z_{fines,\ 75\mu m}$	Increase	slight increase	slight decrease	optimum at 9%
Particle shape	More angular	not established	not established	slight increase
Particle surface	Rougher	not established	not established	slight increase
Degree of saturation	Higher	decrease to 47%	hardly/not affecting	decrease to 50%

Table 3.1 Infuence of some secondary factors on elastic parameters [after Maree]

For the wide range of materials tested by SWEERE, the resilient modulus M_r shows no correlation with the California Bearing Ratio CBR. Apparently, the widely applied rule $E = 10 \cdot CBR$ [MPA] has proven to be invalid for granular materials and sands, as stated by SWEERE (1990, p. 365). Additional data from literature show E-CBR relationships to be invalid for soils as well.

Cohesive subgrades

BARKSDALE & KHOSLA (1997, p. 271) state that the *reliability* of subgrade resilient modulus evaluation has less effect on pavement thickness than the *reliability* of M_r measurement for the asphalt concrete and for the M_r of thick aggregate bases. A modest variation of up to 10% or 15% of the true resilient modulus has, for most conditions, only a small effect on the overall design thickness. Moreover, the large variation in resilient moduli due to the environmental moisture cycle should be taken into account.

These findings suggest that as a practical alternative the subgrade resilient modulus could be evaluated from empirical relations (as a function of easy to measure properties) A number of states in the USA have already developed generalised resilient modulus relationships for use in design, particularly for cohesive subgrade soils [BARKSDALE & KHOSLA 1997, p. 284].

A well-known example of estimating the resilient modulus for subgrade soils is given in Figure 3.1 from which equation 3.1 as developed by McLeod can be derived. Equation 3.1 is a better approach for unbound granular materials, where equation 3.2 represents the stiffness relationship for sands and clayey materials. Equation

3.2 originates from the Shell Pavement Design Manual (SPDM) and has been established by means of vibration measurements, being suitable for the road conditions in The Netherlands. See Figure 3.2.

$$E_{subgrade} = 24 \cdot CBR^{0.62} \qquad 3.1$$

$$E_{subgrade} = 10 \cdot CBR \qquad 3.2$$

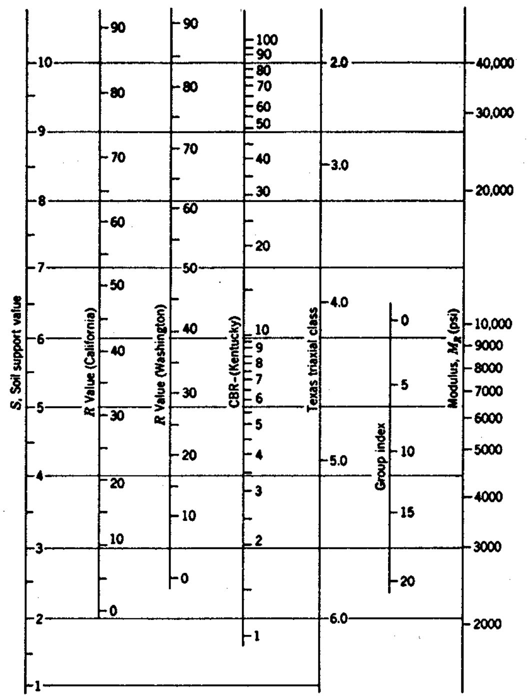


Figure 3.1 Correlation chart for estimating resilient modulus of subgrade soils (1 psi = 6.9 kPa) [Van Til, 1972]

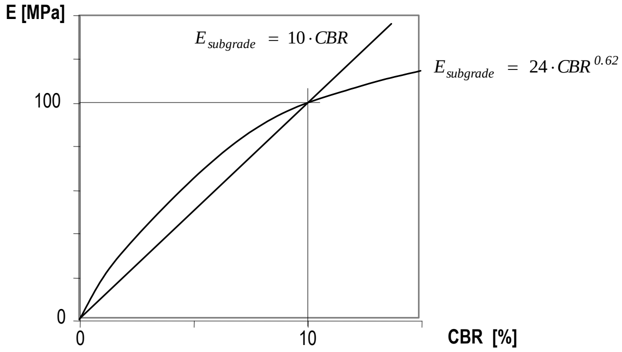


Figure 3.2 McLeod versus SPDM function for the $E_{subgrade}$

Aggregate base

The reliability of the aggregate base resilient modulus evaluation conversely is more important than for the subgrade when:

- the base is thick;
- for thin to moderately thick asphalt concrete surfacing and strong, deep bases on a weak subgrade;
- for thin to moderately thick asphalt concrete surfacing and weak, deep bases on either strong or weak subgrades.

Both cases occur in The Netherlands. Resilient modulus evaluation of base materials should be carried out on a routine basis.

The resilient modulus of an aggregate is strongly dependent upon the state of stress to which an element of material is subjected. The resilient modulus is also affected to a much lesser degree by the following additional factors given in approximately decreasing order of importance [BARKSDALE & KHOSLA 1997, p. 273]:

1. degree of saturation;
2. aggregate size;
3. angularity;
4. density;
5. surface roughness.

While applying triaxial tests on mix granulates, differing only in particle size distribution, Lefevre (1998, p. 140) found that continuously graded materials showed better resilient deformation behaviour than uniformly graded materials. Hence, besides the list of BARKSDALE given above, the shape of the particle size distribution is of influence as well.

There is a clear relationship between the k_1 and k_2 factor of the M_r-θ model. This will be discussed in chapter 5. VAN NIEKERK found that k_2 correlated strongly with the grading, by means of the extension coefficient (C_{ext}; explained in appendix D). This relationship is depicted in Figure 3.3. For the four base materials in consideration a correlation coefficient of r^2=0.997 was determined [VAN NIEKERK 1995, pp. 100-102]. Correlating k_2 to e.g. grading appeared to be more complex for the materials investigated by SWEERE. VAN NIEKERK found that for these materials k_2 is much more dependent on the type of material involved.

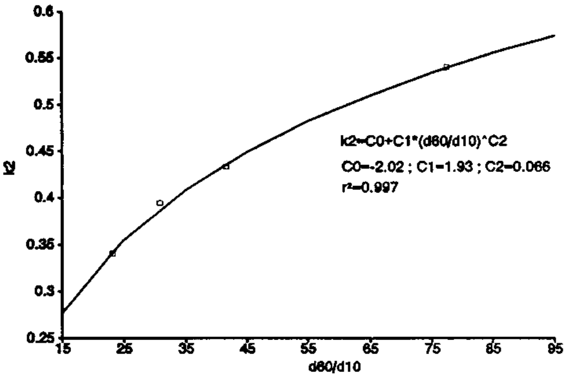


Figure 3.3 Relation between the coefficient k_2 (M_r-θ model) and the extension coefficient (C_{ext}) for the crushed base materials, as established by VAN NIEKERK

3.2.2 Moisture sensitivity

Moisture sensitivity is the change in resilient modulus (or permanent deformation) caused by a change in moisture content of the material. Repeated load triaxial tests can be performed to evaluate this moisture sensitivity.
In his study, SWEERE (1990, p. 367) states that the grading and the nature of the fine fraction are the factors that dominate the suction dependent-behaviour of granular materials.
Granular materials with a grading on the Fuller curve nevertheless show a distinct suction dependent stiffness, explained by the presence of clay in the fine fraction.

3.2.3 Triaxial tests

The popular K-θ resilient modulus model introduced by BROWN & PELL (1967, pp. 487-504)– in this report known as the M_r-θ model – cannot always distinguish one material from another at the 95% confidence level. The more accurate Uzan, U.T.-Austin or FHWA models are recommended to characterise resilient modulus behaviour [BARKSDALE & KHOSLA 1997, p. 283].
In Table 3.2 a brief excerpt of the models mentioned above is shown. For a thorough survey of granular material resilient modulus models (advanced models included) as well as cohesive subgrade soil resilient modulus models, it is referred to BARKSDALE & KHOSLA (1997, pp. 105-112).

MODEL	MODEL EXPRESSION	LINEAR REGRESSION MODEL USED	PLOT
K-θ	$M_R = K_1\theta^{K2}$	$\text{Log } M_R = \text{Log}K_1 + K_2\text{Log}\theta$	Log M_R vs Log θ
UZAN	$M_R = K_3\,\theta^{K4}(\sigma_d)^{K5}$	$\text{Log } M_R = \text{Log}K_3 + K_4\text{Log}\theta + K_5\text{Log}\sigma_d$	Log M_R vs Log θ
UT-AUSTIN	$M_R = N_6\sigma_d^{N7}\sigma_3^{N8}$ $N_6 = K_6 = 10^a$ $N_7 = 1 - K_7$ $N_8 = -K_8$	$\text{Log}\varepsilon_a = a + K_7\text{Log}\sigma_d + K_8\text{Log}\sigma_3$	Log M_R vs Log σ_d or Log M_R vs Log ε_a
UTEP	$M_R = K_9\,\theta^{K10}\varepsilon_a^{K11}$	$\text{Log } M_R = \text{Log}K_9 + K_{10}\text{Log}\theta + K_{11}\text{Log}\varepsilon_a$	Log M_R vs Log θ

Table 3.2 Basic granular material resilient modulus models [BARKSDALE & KHOSLA, 1997]

Concerning triaxial tests the following observations have been made:

- In the search for simplified test procedures for determination to resilient properties, the repeated static load triaxial test yields the same results as the far more complicated cyclic load triaxial test [SWEERE 1990, p. 366].
- The time-consuming "static triaxial creep test" procedure suggested in the literature can be replaced by the repeated static load test procedure presented by SWEERE (1990, p. 366) without loss of accuracy.

- It has been established that similar M_r values may be found if the constant σ_3 in the constant confining pressure (CCP) triaxial test is equal to the mean of the cyclic value in the variable confining pressure (VCP) triaxial test [VAN NIEKERK 1996].
- According to SWEERE the resilient characteristics of unbound granular materials are not affected by loading history. This implies that a large number of tests for determination of resilient parameters can be carried out on the same specimen.

In this research, results obtained from different kind of (triaxial) tests in different studies have been used, but all data originate from the Delft Road and Railroad Research Laboratory.

3.2.4 Stress state

In many empirical as well as mechanistic design methods it is current to assume that unbound granular base materials behave linear elastic as proposed by Young's relation. Often, the elastic or resilient behaviour of unbound granular materials is estimated using empirically based relationships, for instance the relationship between CBR and E. However, the cyclic load triaxial tests, enabling direct measurement of resilient strain under actual applied stresses, established a non-linear behaviour of unbound granular base materials.
Different models have been developed to describe the non-linear behaviour of the material. See appendices B and E for a brief description of some of these models.

Research by KISIMBI (1999, p. 125) has learned that a considerable gain in pavement performance will be achieved when types of self-cementing base materials are loaded at a mild stress level. An average increase factor of 2.5 with respect to the allowable number of load repetitions for all mixes is observed if the material is not too severely loaded during construction of the road. These mix granulates clearly show cementation and carbonisation in early life which increases the strength and the stiffness.

3.3 Permanent deformation behaviour

The permanent deformation characteristics of base and subgrade can readily determined as an extension of the resilient modulus test using a repeated load triaxial test apparatus. It can be performed to establish the development of this type of deformation because of a number of load repetitions at different stress ratio's.

If the load application on pavement materials is small compared to the strength of the material and if it is repeated for a large number of times, the deformation under each load repetition is nearly completely recovered. The deformation is proportional to the load then and may be considered as elastic.

3.3.1 Factors of influence

The permanent deformation behaviour is related to the number of load repetitions and the applied stress level in the layers of the pavement structure.

According to SWEERE (1990, p. 366), the resistance to permanent deformation is affected by grading. For materials with the same maximum particle size, those with a coarse grading show a lower resistance than those with a fine grading. Furthermore, he found that the resistance to permanent deformation of granular materials in general is much larger than that of sands.

Amongst others, the grading of the granular materials in the base and sub-base affects the potential of grains to rearrange themselves upon loading and unloading. If a material has been compacted to its Maximum Proctor Density, a uniformly graded material will not have as much the potential to rearrange its grains as a well-graded material upon loading (and unloading).
MURAYA (2000, p.166) observed that the grading corresponding to the – well graded – upper limit (UL) of the Dutch specification for granular base course materials has developed less permanent deformation than gradings corresponding to the lower limit (LL) or average grading (AL).

A well-graded material can withstand higher stress levels than a uniformly graded material before it fails or deforms for its higher shearing resistance. However, because of its higher shearing resistance rearranging the grains in a well-graded material will occur at higher stress levels than in uniformly graded materials.

3.3.2 Validity of permanent deformation is limited

The methods found in literature that predict permanent strain from the stress ratio at failure or from resilient properties are inapplicable for the wide range of materials tested in cyclic load triaxial tests with large numbers of load applications, as done by SWEERE (1990, p. 366). Apparently, the latter type of testing is required to establish permanent strain properties of granular materials.

3.3.3 Deformation model established by Huurman

See Figure 3.4. With respect to permanent deformation (ε_p), HUURMAN and VAN NIEKERK found that the base materials:

- either show a linear increase of ε_p with N on a log(ε_p)-log(N) scale for all stress ratios (AN^B);
- or show an increase of ε_p with N which is linear for low values of N but then exponential (accelerated) for higher values of N for higher stress ratios (also on a log(ε_p)-log(N) scale). This accelerated increase of ε_p for higher values of N (>50000) is observed most clearly for the tests, which are performed at the higher stress ratios.

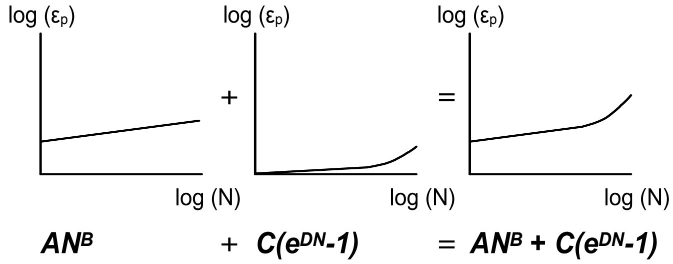


Figure 3.4 Permanent deformation model for base materials [HUURMAN 1997]

The permanent deformation (ε_p) for the base materials can best be related to the number of applied load repetitions (N) and to the failure ratio ($\sigma_1/\sigma_{1,f}$). HUURMAN (1997, pp.122-123) has expanded the model as applied for the sands to be capable of dealing with the observed behaviour. This is illustrated in the schematically in Figure 3.4. The model is described in equation 3.3.

$$\varepsilon_p = A\left(\frac{N}{1000}\right)^B + C\left(e^{D\frac{N}{1000}} - 1\right) \qquad 3.3$$

Where
ε_p permanent strain
N number of load repetitions
A, B, C, D were found to be dependent on the failure ratio $\sigma_1/\sigma_{1,f}$ according to equations 3.4 to 3.7.

$$A = a_1\left(\frac{\sigma_1}{\sigma_{1,f}}\right)^{a_2} \qquad 3.4$$

$$B = b_1\left(\frac{\sigma_1}{\sigma_{1,f}}\right)^{b_2} \qquad 3.5$$

$$C = c_1\left(\frac{\sigma_1}{\sigma_{1,f}}\right)^{c_2} \qquad 3.6$$

$$D = d_1\left(\frac{\sigma_1}{\sigma_{1,f}}\right)^{d_2} \qquad 3.7$$

Where
a_1 .. d_2 are material parameters.

The parameter A in equations 3.3 and 3.4 describes the offset, i.e. the permanent deformation at N=1000. The parameter B in equations 3.3 and 3.5 describes the way in which ε_p changes when N increases.

VAN NIEKERK (1995, pp. 69-71) has retrieved these material parameters for some base materials, observing that some base materials indeed show the described linear increase of ε_p with N, also for high values of N and for higher stress ratios as well. This phenomenon applies to both the axial strain as to the radial strain. There seems to be a dependency of the coefficients in c_1 versus c_2 and d_1 versus d_2.

Correlating the coefficients of the model to material properties seemed impossible, probably due to the fact that the model is relatively complex while the data set VAN NIEKERK worked with was limited (4 materials). It is believed that the second term of equation 3.3 can be explained from the crushing resistance of the material [VAN NIEKERK 1995, p.117].

3.4 Failure behaviour

3.4.1 Angle of internal friction

The granular base course materials analysed by VAN NIEKERK (1995, pp. 83, 84) showed a satisfactory correlation between the angle of internal friction (φ) and:

1. the grading: The quality of the grading can be expressed by the parameter $A_{psdc\text{-}FC}$, estimating the deviation of the particle size distribution curve of the analysed material from the fuller curve, by subtracting their areas, see appendix D section D.3.5.

~~8.~~2. the sharpness of the grains, which can be expressed by the Volders Verhoeven Sharpness (VVS_{rinsed}), relating the shape of the grains to the shape of two reference materials. See appendix D section D.7.

Met opmaak: opsommingstekens en nummering

This correlation has been explained as follows:

- In a well-graded material (lower $A_{psdc\text{-}FC}$ -value) the presence of grains of all sizes will result in a dense packing with a very high amount of inter granular contact areas and thus a high level of friction between the grains.
- In a material with angular grains (higher VVS_{rinsed}-value) interlocking between the grains will result in an increase of φ.

Furthermore, a good grading and consequent packing lead to a large amount of inter granular contact areas and thus to a higher shearing resistance (τ) of the material.

3.4.2 Failure stress

VAN NIEKERK found for both the sands and the materials that if the failure stress is calculated for several levels of confining stress (σ_3), these values of $\sigma_{1,f}$ can very well be correlated directly to material properties. For the granular base course base materials the failure stress can very well be correlated to the grading ($A_{psdc\text{-}FC}$) and the sharpness (VVS_{rinsed}). See Figure 3.5. For the four base materials in consideration a correlation coefficient of r^2=0.997 has been achieved [VAN NIEKERK 1995, pp. 85-86].

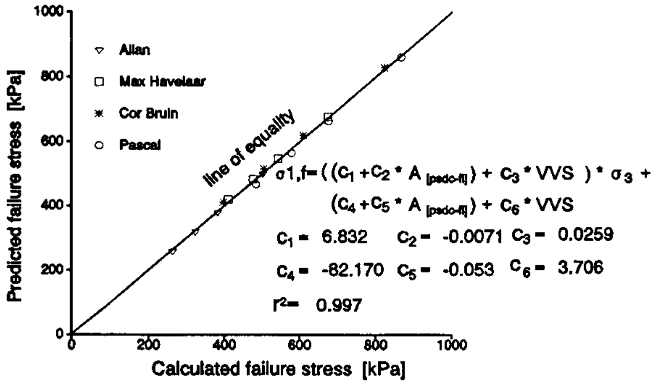


Figure 3.5 Correlation model and predicted and calculated values of failure stress ($\sigma_{1,f}$) for the base materials found by VAN NIEKERK

3.5 Compaction

Abundant previous research has learned that the mechanical behaviour of granular materials is very much influenced by the degree of compaction of specimens. This relates to e.g. CBR values but also to more fundamental failure behaviour, resilient and permanent deformation behaviour.
KISIMBI (1999, p. 123) found that the CBR value increases exponentially with the increase of relative compaction. The resilient modulus of mix granulates is very much dependent on the relative compaction. As the relative compaction increases with 2.5%, an exponential upward shift of the resilient modulus will be found.

With respect to c and φ there is a small increase of the angle of internal friction with relative compaction whereas the cohesion value increases exponentially with relative compaction.

Hence, compaction of the base material is a very important factor influencing the performance of the base and of the pavement structure as a whole. It is believed to be the most cost-effective measure to increase pavement life, as compared to e.g. increasing asphalt thickness.
Heavy compaction of the unbound base material results in a stiffer base resulting in a reduction of the asphalt strain and accordingly in an increase in the allowable number of load repetitions. Furthermore, a stronger base limits the risk of shear failure and permanent deformation of the base.

Based on a thorough literature review and a numerical simulation for his research, LEFEVRE (1998, p.p. 30, 123) has determined the main parameters influencing the compactibility, in decreasing order of influence:

- **Particle size distribution**: This comprises the most important parameter of influence. See section 3.5.1 as well as section 3.6. Uniformity and coarseness are of importance.
- **Composition**: (% of concrete granulate) The composition influences the density by means of the specific density of the components of the material. This kind of increase in specific density at an equal void ratio does not necessarily result in an improvement in mechanical behaviour.
- **Particle shape**: Expressed in the roundness and the texture of the particles (angularity). Round particles compact easier than angular particles. In the latter, the same void ratio can be achieved only by increasing the compactive effort.

3.5.1 Maximum proctor density for base materials

Both the maximum proctor density and the dry density might be considered as a function of the grading of a base course material and its specific gravity.

Parameters of relevance influencing the (proctor) density are:

- the slope of the particle size distribution curve;
- the coarseness of the mixture;
- the dry density of a single sized fraction of the material;
- the gap in the particle size distribution curve, indicating either uniformity either missing fractions in the of the particle size distribution curve.

The factors summarised above have been established by the measurement of data by LEFEVRE (1998, p.123).

The density of an unbound granular material increases with increasing coefficient of uniformity (C_u). In other words, uniformly graded mixtures compact worse than more continuously graded mixtures. Nevertheless, when comparing material samples from several researches graphically, a reasonable correlation coefficient could not be found [LEFEVRE 1998, p. 13]. FLOSS (1970) found a relation between C_u and MPD, but the base materials tested by SWEERE (1990) does not show a relation between the proctor density and the coefficient of uniformity. The completely different base materials with respect to mineralogy and the two gradings used by SWEERE might be the explanation for the lack of relationship.

HUURMAN & VAN NIEKERK (1995, p. 76) found that there seems to be a correlation between the maximum proctor density and the coefficient of extension (C_{ext}; see appendix D). According to VAN NIEKERK (1995, pp. 77, 78) it was found that for the materials taken from SWEERE's research the MPD could much better be correlated to Crushing Factor (CF).
The influence of the average grain-size (D_{50}) however proved to be minor: The coarseness of materials, with an equally shaped particle size distribution does not influence the compaction [LEFEVRE 1998, p. 11].
Floss (1970) found there is a distinct relationship between the maximum proctor density and the percentage of grains larger than 2 mm.
LEFEVRE (1998, pp. 122-123) managed to establish again that the results of the Proctor compaction test is well related to the results of the vibrating compaction test. The latter compaction method uses a compaction apparatus, which has been developed to compact large-scale triaxial specimens, and is considered to approach the compactive mechanisms and the achievable densities of the unbound construction layers in situ better than the Proctor test.

3.5.2 Maximum proctor density for sands

VAN NIEKERK (1995, pp. 73-74) found a very good correlation between the Maximum Proctor Density (MPD) and the grading of the sand, by means of the coefficient of the curvature (C_{curv}) and the percentage passing the 63 μ_{sieve} (Z_{fine}).
As well for the sands an inverse relationship between the Optimum Moisture Content and the MPD has been observed.

Considering sands in general, the MPD will mainly be a resultant of the packing of the grains and thus of the grading. In this case the MPD does not depend upon the density of the grains (specific gravity) as well, as the specific gravities for sands are all close to each other.
A well-graded material achieves a high MPD because the presence of grains of all sizes results in filling the pores and thus a low void content and high a MPD.

3.5.3 Optimum Moisture Content inversely related

It has also been found that the Optimum Moisture Content (OMC) is inversely related to the maximum proctor density. Both VAN NIEKERK (1995, pp. 74-75) and SWEERE (1990, appendix 2) have observed this phenomenon. See Figure 3.6 for the relations for sands examined by VAN NIEKERK.

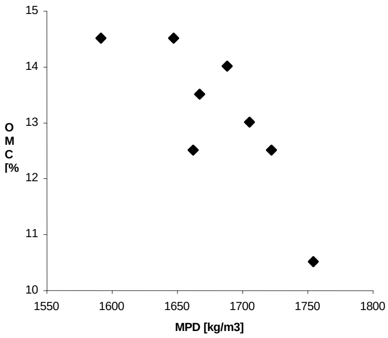


Figure 3.6 Relation between OMC and MPD for sands examined by VAN NIEKERK

3.5.4 Degradation and its influence on compaction

It should be taken into consideration that due to the degradation (crushing) of unbound granular materials during compaction tests (tamping of the Proctor hammer) or during compaction in situ, the particle size distribution changes, causing a change in density. Herewith a higher particle percentage can be obtained. In an exceptional occasion, even the Fuller curve might be attained.
Related to the mechanism described above, VAN NIEKERK found a relationship between the maximum proctor density and the average crushing factor ($CF_{average}$).

The degradation of the material is dependent on the resistance of a material to degradation (composition) and the amount of contact points in the sample, which in turn is dependent on the particle size distribution (uniform or well-graded) [LEFEVRE 1998, p. 51].

3.6 Particle size distribution

VAN NIEKERK (1995) and HUURMAN (1997) found that the shear strength of sands and mixed granulates described by the cohesion (c) and the angle of internal friction (φ) were clearly related to the grading of the material. In a well-graded material, the presence of diverse sized grain particles results in a dense packing with a very high amount of inter-granular contact areas and thus a high level of friction between the grains.
Manteaw (1996) found that both the resilient and failure behaviour of laterite material is strongly influenced by particle size distribution. He demonstrated that laterites with 50% and 60% fines content have very high cohesion values as compared to laterites with 30% and 40% fines content hence increasing the resistance to shear failure especially at low level of confinement. The same was observed on the resilient behaviour.
Lefevre (1998) showed that the resilient deformation behaviour of recycled mixed granulate from masonry and concrete rubbles depends on the grading. Based on five different particle size distribution curves, five mixes have been composed, all originating from the same granular materials. A variation of up to a factor of 1.5 on the resilient modulus has been found. Additionally, a continuously graded mix showed better resilient deformation behaviour than a uniformly graded mix.

It has been found that well graded unbound granular material with $C_u \geq 5$ gives higher density than poorly graded material. This arises from the continuously graded material in such a way the following fractions fill up the pores, left by the previous fraction to produce a densely packed matrix.
When a material consists of a large amount of fines, these fines influence the compaction mechanism of the coarser fractions.

Resilient modulus and grading

- The resilient modulus of granular materials is affected by the grading [SWEERE 1990, p. 366]. For materials with the same maximum particle size, those with a coarse are more stress-dependent than those with a fine grading.
- The difference in resilient stiffness between granular materials and sands is less pronounced than the difference in resistance to permanent deformation.
- When the percentage of fine particles (Z_{fines}) is increasing, the cohesion will increase as well. This will increase the bending stiffness as well by sticking the

larger grains together, hence a reduction of the resilient modulus while an increase in bending stiffness. This results in an increase of the k_1 factor. See appendix D, section D.3 for the influence of fine particles (Z_{fine}) on the resilient modulus. A maximum for Z_{fine} has been established for optimal M_r performance.

3.7 Sharpness

VAN NIEKERK (1995, p. 37) states that it has been found that the Volders Verhoeven Sharpness parameter (VVS; cf. appendix D section D.7.) explains the Poisson's ratio whereas VVS_{rinsed} explains the failure behaviour of the base materials. No correlation seems to be found between VVS and VVS_{rinsed} for the base materials. It therefore might be advisable to investigate how well VVS_{rinsed} can be reproduced in the test.
The particle shape of mixed granulate is angular, since these granulates results from the crushing of masonry and concrete waste.

3.8 Mix composition

The composition of a granular material has a great influence on the overall material behaviour. Material composed of particles originating from different types of parent rock will perform differently when subjected to the equal loading and other conditions. For instance, a material consisting of granite as parent rock will have a greater resistance to mechanical degradation and bearing capacity than laterites. In case of recycled materials, granulates constituting from concrete demolition will again have a greater resistance to mechanical degradation and bearing capacity than granulates consisting of masonry rubble.

3.8.1 Curing time

KISIMIBI (1999, p. 123) found that the CBR of the mix granulates investigated increases clearly with the increase of both the curing time and the amount of concrete granulates in the mix. The curing time on its turn is very much dependent on mix composition.

3.8.2 Resilient modulus

An upward shift in M_r-θ relation will occur when increasing the percentage of concrete mix. This is due to the fact that the strength of the bonds is more influenced by the percentage of concrete.
Irrespective of the mix composition in use, the resilient modulus seems to exhibit higher values under mild loading than under severe loading conditions, where beginning of permanent deformation is observed.

For a profound elaboration of the characteristics and properties of the resilient modulus, it is referred to appendix E, section E.4.3.

4 RESEARCH METHOD

4.1 Introduction

In this chapter, the method used to develop the relations between physical parameters and mechanistic properties is discussed. Also the data that have been used in this study are presented together with their sources from which they have been retrieved. The collected data are described together with the assumptions and the remarks. Appendix F comprises the full data range, whereas an extract of the complete data set has been placed in appendix G. This data set has been used as input during the search for correlations in SPSS.

4.2 Research approach for establishing mechanistic correlations

The purpose of this study is to establish correlations between mechanical properties of unbound granular materials and their (physical) material characteristics. It is preferred that these physical material characteristics can be obtained quite easily by means of e.g. simple tests which are commonly used in practice.

4.2.1 The parameters to retrieve correlations for

The relationships to be found should lead to a prediction of mechanistic layer properties of the unbound granular base course. These properties comprise:

- stiffness: resilient modulus (M_r);
- strength: angle of internal friction (φ) and cohesion (c).

The most commonly used model to describe the resilient modulus (M_r) is the M_r-θ model (see appendix E section E.4.3). Although theoretically not correct, this M_r-θ model can best describe the resilient modulus for granular unbound materials at stress levels which are significantly lower than the stress levels at which shear failure occurs. The latter is usually the case for pavement structures with relatively thick asphalt layers.

4.2.2 Qualification of the data

The correlations as described above have to be established through regression techniques. Therefore, the data of different material samples require being collected under the same circumstances according to similar test conditions and specifications. By this, the data will be similarly and can be compared equivalently. Furthermore, it is preferable that the data set is as complete as possible, since reliable regression analysis needs a minimum amount of samples (degrees of freedom). Moreover, regression analysis based on a large data set can increase the reliability of the established relationship.

Therefore, only data from the Road and Railroad Research Laboratory of Delft University of Technology have been collected, where sufficient data of current granular base course materials are available. For an elaborate account see section 4.3.

4.2.3 Point of departure for establishing correlations

Initially, the search for correlations for stiffness (k_1, k_2) and strength (φ and c) is based on:

1. relationships found in literature as discussed in chapter 3 (Literature Survey);
2. correlations found by VAN NIEKERK, who tried to establish relationships for eight sands and four base materials available in the Netherlands; these have been mentioned in chapter 3. At first, the validity of VAN NIEKERK's relationships found for the four base materials will be investigated for the unbound granular base materials used in this study;
3. rational determination of qualitative relationships between different material parameters. These correlations between parameters have been analysed statistically, too, using computer software (chapter 5);
4. trial-and-error, mainly based on statistical analyses. However, while applying trial-and-error methods, the right statistical techniques should be applied. For instance, in regression analysis multicollinearity might occur which has to be avoided. This phenomenon will be described in appendix I.

4.3 Sources

For the following reasons only data established at the Road and Railroad Research Laboratory of Delft University of Technology have been used:

- the provision to use data which have been collected by means of tests done according to the same specifications (refer section 4.2.2);
- the availability of data concerning current and useful base course materials in The Netherlands.

Consequently, data have been used from studies done by SWEERE, HUURMAN and VAN NIEKERK, LEFEVRE, MURAYA and KISIMBI. Most of these studies have been summarised in appendix C.

4.3.1 Huurman and Van Niekerk

Besides testing and establishing relationships of eight sands, VAN NIEKERK and HUURMAN also analysed four mix granulate base materials. The base materials investigated are:

- Allan
- Max Havelaar
- Cor Bruin
- Pascal

These samples have been named after the streets in the cities of Rotterdam and Zaandam, the Netherlands, from which the material sample has been taken. The origin of the granular materials is sometimes unknown.

4.3.2 Sources provided by SWEERE

The data of two out of four groups of materials investigated by SWEERE have been incorporated in this study, known as group C and group R. See description below.

SWEERE (1990, p.124) has investigated these two groups because of the structural importance of these materials in pavement engineering.

Group C

Group C consists of conventional unbound granular base course materials. See Table 4.1 for the materials together with their origin.

Name	Origin
Lava	quarry in the Eifel-area, Germany
Stol (natural gravel/loam mixture)	natural deposits in Limburg, The Netherlands
Porphyry	quarry in Belgium
Limestone	quarry in Belgium
Crushed gravel	produced from gravel from the river Meuse, The Netherlands
Silicon-manganese slag	by-product from the manganese production in Belgium

Table 4.1 Unbound granular base course materials from SWEERE's study

"Of these materials, only lava has been used widely in the Netherlands in granular base courses. Stol has been applied occasionally. Porphyry, limestone and crushed gravel were included in this study to expand the number of crushed stone materials to obtain a reference with foreign road base practice. The industrial by-product silicon-manganese slag was included to investigate its potential as an unbound road base material." (SWEERE 1990, p.125)

To study the influence of grading and composition, part of the unbound base course materials have been tested at different laboratory-made grading envelopes and compositions. In addition, materials as produced by crusher plants were tested as such. All have been incorporated in this study.
One grading curve was made in conformity with the upper limit of the Dutch specifications for unbound granular base course materials (0/40 mm; indicated as “B”-grading); the other grading was made in conformity with the lower limit of these specifications (indicated as “O”-grading). Each material was sieved into a number of fractions and subsequently recombined to obtain the desired grading envelope. The materials stol and silicon-manganese slag were tested at their as-received grading (natural).
For more details about the composition of the materials the reader is referred to SWEERE [1990, pp. 124-127].

Group R

Group R consists of recycled unbound granular base course materials. See Table 4.2.

Name	
crushed masonry	two lots
crushed concrete	two lots
crushed clinker	
mixture of 50% crushed bricks and 50% crushed concrete	(Volume percent, approx.)
crushed rubble	three lots
waste incineration slag	

Table 4.2 Recycled unbound granular base course materials from group R of SWEERE's study

All materials given in Table 4.2 were obtained from crusher plants that recycle construction and demolition waste into granular road building materials. Part of the materials was tested at commercial compositions and grading envelopes. For these materials again, the composition, and grading curve has been determined by laboratory analysis. For more details, it is referred to SWEERE [1990, pp. 127-128].

4.3.3 Data from Lefevre

From the study of LEFEVRE (1998), complementary data have been retrieved in order to complete the sample data of MURAYA and KISIMBI. These data mostly regard information about density and specific gravity parameters of the recycled granular materials.
Furthermore, LEFEVRE predetermined the composition and grading envelope of these unbound granular materials, analysing the influence of the crusher type used on both compaction and mechanical properties. Subsequently, both MURAYA and KISIMBI have applied these materials with identical composition and grading.

To obtain these granulates with predetermined composition and grading envelope, one lot of concrete and one lot of masonry rubble have been split. Then, the lots were crushed by two different crushers, i.e. an impact and a jaw crusher to introduce a difference in particle shape related to the crusher type.
The four lots of crushed material (granulates) so obtained were then sieved to obtain the following 10 fractions: 0 – 0.125 mm, 0.125 – 0.25 mm, 0.25 – 0.5 mm, 0.5 – 1 mm, 1 – 2 mm, 2 – 4 mm, 4 – 8 mm, 8 – 16 mm, 16 – 31.5 mm, and 31.5 – 45 mm.
This resulted in 40 ‘basic’ fractions as given in Table 4.3 from which the mix granulates have been designed and composed according to any desired grading and composition, with a variation of particle shape.

Code	Granulate	Crusher-type
CI	**C**oncrete	**I**mpact crusher (Prahl)
CJ	**C**oncrete	**J**aw crusher (“Kaak”)
MI	**M**asonry	**I**mpact crusher (Prahl)
MJ	**M**asonry	**J**aw crusher (“Kaak”)

Table 4.3 Fractions generated by Lefevre to compose mix granulate

The influence of the crushing method with two different types of crushers could not be demonstrated in the analysis. Therefore, KISIMBI and MURAYA have used granular mix granulates obtained with a jaw crusher only.

4.3.4 Data provided by Muraya and Kisimbi

The recycled granular materials composed by LEFEVRE and subsequently analysed by KISIMBI (1999) and MURAYA (2000) differentiate between:

1. Composition
   (See appendix A for a complete description of recycled mix granulates)
   a. 50% crushed concrete to 50% crushed masonry [m/m], referred to as 50/50
   b. 65% crushed concrete to 35% crushed masonry [m/m], referred to as 65/35
   c. 80% crushed concrete to 20% crushed masonry [m/m], referred to as 80/20

2. Grading
   Both LEFEVRE, MURAYA and KISIMBI have tested materials according to certain predetermined particle size distribution curves. This set of gradings has partly been used in this study and is discussed in section 4.6.2.

3. Crusher type
   In the studies of KISIMBI and MURAYA only mix granulates produced with a jaw crusher have been tested. See section 4.3.3.

4. Compaction
   In the studies of MURAYA and KISIMBI, the CBR values, the failure behaviour, and the resilient deformation behaviour have been analysed in relation to the degree of compaction.
   To do so the Maximum Proctor Density (MPD) of a mix granulate has been determined and CBR and triaxial specimens have been compacted and tested to respectively 95%, 97.5%, 100%, 102.5% and 105% of the Maximum Proctor Density.

Incorporation of commercially graded mix granulate by KISIMBI

For the investigation of mechanical behaviour in relation to the degree of compaction KISIMBI used an “as produced (commercially)” graded mix granulate rather than composing granulates to a determined grading and composition. This commercially graded mix granulate, originating from a crusher plant nearby Rotterdam (The Netherlands), conforms to the R.A.W. [CROW, 2000] specifications with respect to grading and composition.

Sample data of this mix granulate at different compaction levels have been incorporated in this study. The records of this mix granulate have been named identically like KISIMBI did in his study (*MG 16H*) followed by the relative degree of compaction.

4.4 Selection of the parameters to be collected

From the sources discussed above, the parameters depicted in Table 4.4 have been retrieved. These parameters were chosen because of their availability and apparent relationship with k_1, k_2, c, and φ.
Most of the parameters have already been described or defined in appendices D and E. They will not be discussed again. Other current or easy to understand parameters will be described briefly in the table.

Clarification of Table 4.4

- Parameters where the ‘name/quantity’ is printed **bold** have been used for the regression analysis. These parameters were selected because it was believed that they could be useful explaining variables of the regression analysis.
- Parameters where the ‘name/quantity’ is printed *italic* have been retrieved as auxiliary parameters to calculate other essential parameters for useful regression analysis;
- Parameters with regular printed ‘name/quantity’ have been collected as well, but appeared to be incomplete hence not useful for regression analysis.

NAME / QUANTITY	SYMBOL	UNIT	REMARKS / EXPLICATION
Material description			General description of the record
Group code			Sweere's coding
Material code			Sweere's coding
Sequence number			Sweere's coding
Composition			Composition of the sample
Source			Original study
Age of sample	T_{sample}	days	Either 3, 7 or 28 days
Specimen Size		mm·mm	Size of the sample given as: ∅·h
Resilient parameter k_1	k_1	MPa	See appendix E section E.4.3 eq. E.26
Resilient parameter k_2	k_2	-	
Angle of internal friction	φ	- (°)	See appendix E section E.4.2
Cohesion	c	kPa	
Principal stress at failure	$\sigma_{1,\ failure}$	kPa	Auxiliary parameter to calculate $\tau_{failure,\ \sigma3=12\ kPa}$
Confining pressure / Principal stress	σ_3	kPa	Auxiliary parameter to calculate $\tau_{failure,\ \sigma3=12\ kPa}$
Shear stress at failure, σ_3=12 kPa	$\tau_{failure,\ \sigma3=12\ kPa}$	kPa	See app. E section E.4.2 eq. E.21
Moisture content	w	- (%)	See app. E section E.3.3
Dry density	ρ_{dry}	kg/m³	i.e. dry unit weight, see section E.3.5 eq. E.19
Specific Gravity Solids	SG_{solids}	kg/m³	See section D.5 equation D.18
Volume Density Grains	ρ_{grains}	kg/m³	Specific gravity grains with enclosed air voids
Relative Density	$\rho_{relative}$	-	Defined as ρ_{dry}/ρ_{grains}
Degree of Compaction		-	Defined as ρ_{dry}/MPD
Maximum Proctor Density	MPD	kg/m³	
Modified Maximum Proctor Density	MMPD	kg/m³	See appendix E section E.3.2
Optimum Moisture Content	OMC	- (%)	See appendix E section E.3.4
Volders Verhoeven Sharpness	VVS	- (%)	See appendix D section D.7
rinsed Volders Verh Sharpness	VVS_{rinsed}	- (%)	to loosen particles and omit larger fractions
Crushing Factor, average	$CF_{average}$	-	
Crushing Factor grading 4 - 5.6		-	
Crushing Factor grading 5.6 – 8		-	
Crushing Factor grading 8-11.2		-	
Crushing Factor grading 11.2–16		-	See appendix D section D.4
Crushing Factor grading 16-22.4		-	
Crushing Factor grading 22.4-31.5		-	
Crushing Factor grading 31.5–45		-	
Crushing Factor, weighted	$CF_{weighted}$	-	Weighted average CF, see section D.4.3
D_{85}-value	D_{85}	mm	
D_{60}-value	D_{60}	mm	
D_{50}-value, median	D_{50}	mm	D_l = Sieve aperture through which *l*% mass of the material passes
D_{30}-value	D_{30}	mm	
D_{15}-value	D_{15}	mm	
D_{10}-value	D_{10}	mm	
Fuller Curve Fitting parameter	$D_{PSDC\text{-}FC}$	m/m (%)	
Fuller Curve Fitting parameter	$A_{PSDC\text{-}FC}$	(m/m)·mm (%)	See appendix D section D.2.2
Fuller Curve Fitting parameter	$A_{PSDC\text{-}FC;middle}$	(m/m)·mm (%)	
Skeleton Coefficient (D_{85}, D_{15})	$SC_{85\text{-}15}$	-	See appendix D section D.3.4
Skeleton Coefficient (D_{60}, D_{10})	$SC_{60\text{-}10}$	-	
Coefficient of uniformity	C_{uni}	-	See appendix D section D.3.1
Coefficient of curvature (D_{30},D_{60},D_{10})	$C_{curv\ D30D60D10}$	-	See appendix D section D.3.2

NAME / QUANTITY	SYMBOL	UNIT	REMARKS / EXPLICATION
Coefficient of curvature (D_{50},D_{85},D_{15})	$C_{curv\ D50D85D15}$	-	See appendix D section D.3.2
Extension coefficient	C_{ext}	-	See appendix D section D.3.3
Z_{fines}	$Z_{fines,\ \varnothing=75\mu m}$	- (%)	Percentage passing the 75 μm sieve
Grading parameter	∅ 0,02	- (%)	Sieve analysis: percentage passing the sieve with given ∅ of the aperture in mm
Grading parameter	∅ 0,063	- (%)	
Grading parameter	∅ 0,125	- (%)	
Grading parameter	∅ 0,25	- (%)	
Grading parameter	∅ 0,5	- (%)	
Grading parameter	∅ 1	- (%)	
Grading parameter	∅ 2	- (%)	
Grading parameter	∅ 4	- (%)	
Grading parameter	∅ 8	- (%)	
Grading parameter	∅ 16	- (%)	
Grading parameter	∅ 22,4	- (%)	
Grading parameter	∅ 31,5	- (%)	
Grading parameter	∅ 45	- (%)	

Table 4.4 Parameters as retrieved in this study for regression analyses. For interpretation of the use of typefaces, please read the clarification above.

4.5 Data set in brief with abridged table of records

See Table 4.5 for the data set in brief with all records and some distinguishing fields (parameters). The complete data set, where the fields have been grouped by record (sample material), is placed in appendix F while in appendix G the extracted data set that has been used for regression analysis has been depicted.

As can be seen in the records originating from SWEERE, the angle of internal friction (φ) and the cohesion (c) is missing. However, for some statically tested material samples, where k_1 and k_2 are missing, the shear stress at failure (τ_f) appeared to be available. To give an indication about the failure criterion for *all* sample materials, the shear stress at failure for other materials has been calculated. This will be discussed more extensively in section 4.6.5.

4.6 Considerations and remarks about the data set

4.6.1 Specimen size

For the materials tested by SWEERE and VAN NIEKERK, a specimen size of 400·800 mm^2 ($Ø·h_{sample}$) has been used, being ten times the nominal particle size. The height of the specimen (800 mm) matches the ratio of specimen height to specimen diameter of two. KISIMBI and MURAYA tested their materials with a specimen size of 300·600 mm^2, the diameter measuring approximately 6 – 7 times the maximum grain size D_{max}. They used a smaller sample size to increase the ease of handling of the specimens.
These sample sizes have been chosen in order to be able to incorporate materials at their full grading and to avoid the specimen size effects. Since the 300·600 mm^2 specimen size appeared to be reliable as well. It is assumed that comparing these measurements is allowed without scaling transformation.

Description of sample sample codes and grading	Source	k_1 [MPa]	k_2 [-]	φ [˚]	c [kPa]	Dry d'y [kg/m^3]	Grading
Allan NIEKERK	V Niekerk	32,126	0,433	41,6	45,89	1929	
Max Havelaar NIEKERK	V Niekerk	61,456	0,34	43,7	73,69	1632	
Cor Bruin NIEKERK	V Niekerk	20,171	0,54	52,86	48,88	1885	
Pascal NIEKERK	V Niekerk	28,956	0,394	50,98	68,67	1679	
lava CO1 LAB05	Sweere	26,9	0,35			1778	fine
lava CO2 LAO07	Sweere	19,2	0,47			1640	coarse
lava CO2 LAOS05	Sweere					1681	coarse
porphyry CO3 POB03	Sweere	29,2	0,32			2113	fine
porphyry CO4 POO01	Sweere	22,9	0,43			2075	coarse
crushed gravel CO5 GGB01	Sweere	40,9	0,23			1968	fine
crushed gravel CO6 GGO01	Sweere	47,2	0,31			2042	coarse
limestone CO7 KAB02	Sweere	156,8	0,14			2129	fine
limestone CO8 KAO01	Sweere	37,7	0,45			2287	coarse
stol CO9 STN01	Sweere	157,8	0,05			2121	natural
silicon manganese slag C10 SMC01	Sweere	43,5	0,34			1809	commercial
crushed masonry 1 R01 MGB07	Sweere	6,3	0,49			1530	fine
crushed masonry 1 R01 MGBS03	Sweere					1485	fine
crushed masonry 1 R02 MGO10	Sweere	4	0,65			1523	coarse
crushed masonry 2 R03 M2B01	Sweere	27,5	0,3			1585	fine
crushed masonry 2 R04 M2O02	Sweere	18,3	0,43			1516	coarse
crushed concrete 1 R05 BGB01	Sweere	21,1	0,48			1863	fine
crushed concrete 1 R05 BGBS04	Sweere					1815	fine
crushed concrete 1 R06 BGO01	Sweere	11,2	0,59			1878	coarse
crushed concrete 1 R06 BGBS04	Sweere					1882	coarse
crushed clinker R07 KGB01	Sweere	41,8	0,28			1803	fine
crushed clinker R08 KGO01	Sweere	18,6	0,45			1695	coarse
crushd masnr/concr (65/35) R09 FFB01	Sweere	77,3	0,17			1660	fine
crushd masnr/concr (65/35) R10 FFO01	Sweere	22,6	0,44			1676	coarse
crushed concrete 2 R11 B2C01	Sweere	71,8	0,21			1858	commercial
crushed rubble 1 R12 K1C01	Sweere	34,8	0,35			1704	commercial
crushed rubble 2 R13 K2C01	Sweere	36,1	0,34			1712	commercial
crushed rubble 3 R14 K3C01	Sweere	30,1	0,36			1710	commercial
G4CJ/MJ50/50 AL	Kisimbi	7,308	0,555			1718	average
G4CJ/MJ65/35 AL	Kisimbi	13,637	0,51			1735	average
G4CJ/MJ80/20 AL	Kisimbi	41,615	0,332			1787	average
MG 16H 94.7% rel.comp.	Kisimbi	29,154	0,362	44,63	14,88	1684	commercial
MG 16H 98% rel.comp.	Kisimbi	25,571	0,358	43,25	37,82	1742	commercial
MG 16H 100.5% rel.comp.	Kisimbi	26,767	0,356	47,26	53,64	1787	commercial
MG 16H 102,3% rel.comp.	Kisimbi	30,726	0,353	44,48	48,62	1819	commercial
MG 16H 104.9% rel.comp.	Kisimbi	40,207	0,384	47,88	130,81	1865	commercial
G1CJ/MJ65/35 97% rel.comp. UL	Muraya	33,187	0,329	35,1	69,8	1702	finest content
G1CJ/MJ65/35 100% rel.comp. UL	Muraya	21,106	0,411	28,3	143,2	1755	finest content
G1CJ/MJ65/35 103% rel.comp. UL	Muraya	23,854	0,464	36	133,1	1807,65	finest content
G4CJ/MJ65/35 97% rel.comp. AL	Muraya	48,108	0,266	36,9	55,5	1683	average
G4CJ/MJ65/35 100% rel.comp. AL	Muraya	14,947	0,465	40,5	98	1735	average
G4CJ/MJ65/35 103% rel.comp. AL	Muraya	26,902	0,439	42,9	89,5	1787	average
G4CJ/MJ65/35 105% rel.comp. AL	Muraya	43,499	0,385	38,1	181,9	1821	average
G5CJ/MJ65/35 97% rel.comp. LL	Muraya	15,663	0,463	41,1	51,7	1615	coarse content
G5CJ/MJ65/35 100% rel.comp. LL	Muraya	15,663	0,463	35,5	77,1	1665	coarse content
G5CJ/MJ65/35 103% rel.comp. LL	Muraya	33,024	0,376	41,6	103	1715	coarse content
G5CJ/MJ65/35 105% rel.comp. LL	Muraya	20,015	0,451			1748	coarse content

G4CJ/MJ50/50 100% rel.comp. AL	Muraya	17,053	0,491	39,5	96,8	1718	average
G4CJ/MJ80/20 100% rel.comp. AL	Muraya	37,22	0,387	38,7	125,5	1787	average

Table 4.5 Abridged data set, including all records and some distinguishing parameters

4.6.2 Composition and grading of the recycled granular materials

LEFEVRE, KISIMBI, and MURAYA have tested materials according to certain predetermined particle size distribution curves. These curves are related to the grading limitations for unbound granular base course materials as given in the Dutch RAW and represent upper (**UL**) and lower (**LL**) limits of the grading envelope. Furthermore, materials with an average curve (AVERAGE: the average between the upper and the lower limits of the grading envelope), a uniformly graded curve (UNI) as well as a gap-graded curve (GAP) have been tested. The latter comprises some grading sizes dominantly, while missing others.
As stated in section 4.3.2, for the materials tested by SWEERE a similar distinction between upper and lower limits of the grading curve has been made.

In this study, it was not possible to involve the GAP and UNI grading test data, since most of the important material properties have not been determined for these gradings.
Additionally, some other grading envelopes have been used, namely natural (SWEERE), and commercial grading curves (SWEERE and KISIMBI; section 4.3.4). These grading curves, as well as the VAN NIEKERK grading curves will be analysed in chapter 5.

4.6.3 Time factor (curing time) not incorporated

In the investigation of the CBR value and the resilient deformation behaviour in relation to composition performed by MURAYA, it was anticipated that curing time, defined as the time elapsed between specimen preparation and testing, would affect material behaviour. Previous studies [SWEERE 1990, VAN BEERS & VAN NIEKERK 1998] have demonstrated that strength and stiffness of mix granulates can increase in time due to a chemical process of cementation and carbonation. Specimens exhibit after already 3 to 7 days of curing a clear increase of stiffness, which is adversely affected by loading up to higher deviatoric stress levels. In practice, while applying the unbound granular base course in the pavement structure, this so-called initial curing effect will be abrogated by, for instance, the regular passing of heavily loaded construction traffic flows. In pavement structures with thicker asphalt layers (larger than 10 cm), it may be assumed that the lower stress levels in the base course will occur because of the break-up of the curing effect.
To exclude the curing effect or rather the factor time from this study, only specimen data after curing time of zero or up to maximum 3 days have been selected. SWEERE and VAN NIEKERK have not involved the curing time in their studies.

4.6.4 k_1 and k_2 given at mild stress levels

From previous analyses it was anticipated that the severity of ‘early life’ loading of a base course material after it has been compacted as well as ‘in-service’ loading affects the further development of strength and stiffness due to cementation and carbonatation. Moreover, in the research conducted by VAN BEERS and VAN NIEKERK (1998), it was observed that on a test pavement the stiffness of measuring points loaded at high load magnitudes remained lower than the stiffness of measuring points loaded to low load magnitudes (10 and 30 kN). Therefore, MURAYA and KISIMBI determined the resilient modulus (k_1 and k_2 values) at both severe and mild stress levels.

KISIMBI [1999, pp. 66-67] found that the M_r-θ model describes the measured resilient behaviour better for mild than for severe test loading conditions. This is due to the fact that under the mild loading condition the material is not loaded to the higher (σ_c/σ_3) ratios at which a decrease of M_r is observed at a given confining pressure (σ_3). See appendix E section E.4.3.

- Under mild loading conditions, the (σ_c/σ_3) ratios are limited to 6-8;
- Under severe loading conditions, the specimen is loaded up to (σ_c/σ_3) ratios at which beginning of permanent deformation after 100 loading cycles is observed.

In the (σ_c/σ_3) ratio, σ_c is the cyclic deviator stress, and σ_3 is the confining pressure, the latter in a range between 12–72 kPa.

In this study, only k_1 and k_2 given at 'mild' stress levels have been collected, because of the reasons below:
- The observations as done by KISIMBI;
- Compatibility with the SWEERE and VAN NIEKERK materials;
- Time factor (curing time) has been set aside. Hence, applying higher stress levels during testing to cancel out cementation, resulting in lower stiffness characteristics is not necessary;
- The (σ_c/σ_3) ratio occurring in granular base courses of pavement structures with a relatively thick overlaying asphalt package (motorways) is usually low. This study is trying to establish relationships for this type of pavement structures.

4.6.5 Introducing the shear stress at failure: replacing the phi and c

For the material samples tested by SWEERE, data for the angle of internal friction as well as for the cohesion were not available. For this, the shear stress at failure with confining pressure of σ_3=12 [kPa] has been calculated for all sample materials. The shear stress ($\tau_{failure;\sigma3=12kPa}$) gives an indication about the failure behaviour of the unbound granular material. It is related to the angle of internal friction (φ) and cohesion (c) according to equation 4.1, and so, part of the Mohr-Coulomb criterion. See appendix E section E.4.2.

$$\sigma_{1,f} = \frac{(1+\sin\varphi)\cdot\sigma_3 + 2\cdot c\cdot\cos\varphi}{1-\sin\varphi} \qquad 4.1$$

For all unbound granular materials tested by VAN NIEKERK, KISIMBI, and MURAYA, data about failure stress ($\sigma_{1,f}$) with confining pressure σ_3=12 [kPa] were available. For some statically tested material samples analysed by SWEERE, through lack of k_1 and k_2 values, the shear stress at failure (τ_f) appeared to be available. These measurements have been incorporated as well.

Estimation for c and φ of the 105% compacted sample Muraya

For the G5 Lower Limit mixed granulate sample at 105% relative compaction investigated by MURAYA, neither the cohesion nor the angle of internal friction for the 4 day old sample have been retrieved, since it was not possible to execute a permanent deformation test on a four days sample. For this, MURAYA equated the missing values for the cohesion and the angle of internal friction (of the 4 days

sample) to the cohesion and angle of internal fraction of the 28 days sample. See Table 4.6 from MURAYA.
In this study, to avoid an incorrect assumption for the values of the cohesion and the angle of internal friction, this sample material has not been incorporated in the regression analysis.

Gradation	Compaction [%]	Time [days]					
		4		14		28	
		c [kPa]	ϕ [°]	c [kPa]	ϕ [°]	c [kPa]	ϕ [°]
G1 K65	97	69.8	35.1	82.5	38.6	93.9	41.5
	100	143.2	28.3	97.8	35.5	64.4	40.6
	103	133.1	36.0	126.0	41.7	121.8	45.9
G4 K65	97	55.5	36.9	75.4	38.1	94.4	39.2
	100	98.0	40.5	88.2	39.3	77.9	38.0
	103	89.5	42.9	105.1	43.8	120.1	44.8
	105	181.9	38.1	160.4	41.2	142.3	43.8
G5 K65	97	51.7	41.1	44.7	42.0	38.0	42.9
	100	77.1	35.5	66.5	37.2	56.7	38.7
	103	103.0	41.6	93.6	43.2	85.0	44.7
	105	85.7	42.6	85.7	42.6	85.7	42.6

(shaded) no permanent deformation test at 4 days hence c and ϕ values obtained from the 28 days post resilient deformation test only. Hence the same values at 4, 14 and 28 days

Table 4.6 c and φ values of CJ/MJ65/35 samples at different compaction levels, gradings and sample age [MURAYA, 2000]

4.6.6 Density properties

Since compaction (grain skeleton) of unbound granular materials is believed to be of great influence on several mechanistic material characteristics, such as stiffness and rutting development, as much as parameters about density has been retrieved. These parameters are:

- Dry density (ρ_{dry}): i.e. dry unit weight of the material (sample). (section E.3.5 eq. E.19);
- Specific Gravity Solids (SG_{solids}): The specific gravity of the solid materials without air voids. (section D.5 equation D.18);
- Volume Density Grains (ρ_{grains}): Specific gravity grains with enclosed air voids;
- Relative Density ($\rho_{relative}$): Defined as ρ_{dry}/ρ_{grains};
- Degree of compaction: Defined as ρ_{dry}/MPD, giving an indication of the severity of compaction related to the Maximum Proctor Density;
- Maximum Proctor Density (MPD);
- Modified Maximum Proctor Density (MMPD): (appendix E section E.3.2);
- Optimum Moisture Content (OMC) (appendix E section E.3.4).

SPPD as equivalent for MPD

In the data set both the Maximum Proctor Density, used by VAN NIEKERK, LEFEVRE, KISIMBI, and MURAYA, as well as the Modified Maximum Proctor Density, as applied by SWEERE have been retrieved.

For the base materials analysed by SWEERE, the MPD was not available. However, Sweere determined the MMPD and the SPPD (Single Point Proctor Density). It is believed that for unbound granular materials the dry density - moisture content relationship is quite 'flat', which means that there is no unique moisture content for the maximum dry density. (Cf. Figure E.11 in appendix E.3.5). Therefore,

determining the Proctor Density at a single moisture content in the range of 6 to 10% by mass proved to be acceptable.
The SPPD has been determined by using a different diameter (∅) for the sample mould and a different number of compaction strokes, comparing to the MPD, t. Nevertheless, the total amount of compaction energy applied per unit of volume is identical to the compaction energy required for the determination of the MPD. For this reason, it may be assumed that the SPPD for the SWEERE materials may be compared to the MPD of other unbound granular materials collected in the data set.

For a few SWEERE base materials, the SPPD appeared to be higher than the MMPD. This will be discussed in chapter 5 section 5.7.1

Estimation of volume density grains
For the base materials tested by VAN NIEKERK, the volume density of the grains was not available. These densities have been estimated based on the two criteria below:

1. The densities correspond with densities of mixed granulates with similar material characteristics (MPD, k_1-value, cohesion).
   When comparing the MPD and cohesion, the "Max Havelaar" and "Pascal" base materials of VAN NIEKERK resemble in some way to the "G5CJ/MJ65/35 - MU-RAYA" at 100% compaction. However, when comparing the k_1-value and MPD the two materials of VAN NIEKERK resemble to "crushed rubble 1 R12 K1C01 - SWEERE." Concerning the MPD only "crushed masonry/concrete (65/35) R09 FF B01" seems to be a good equivalent.
2. A good fit on the trendline depicted in Figure 4.1 (see chapter 5 as well), where the dry density of the grains is compared with the MPD. When analysing the MPD - dry density ratio (MPD : ρ_{grains} [-]) for the materials as given above, a ratio of around 0.80-0.83 has been revealed.

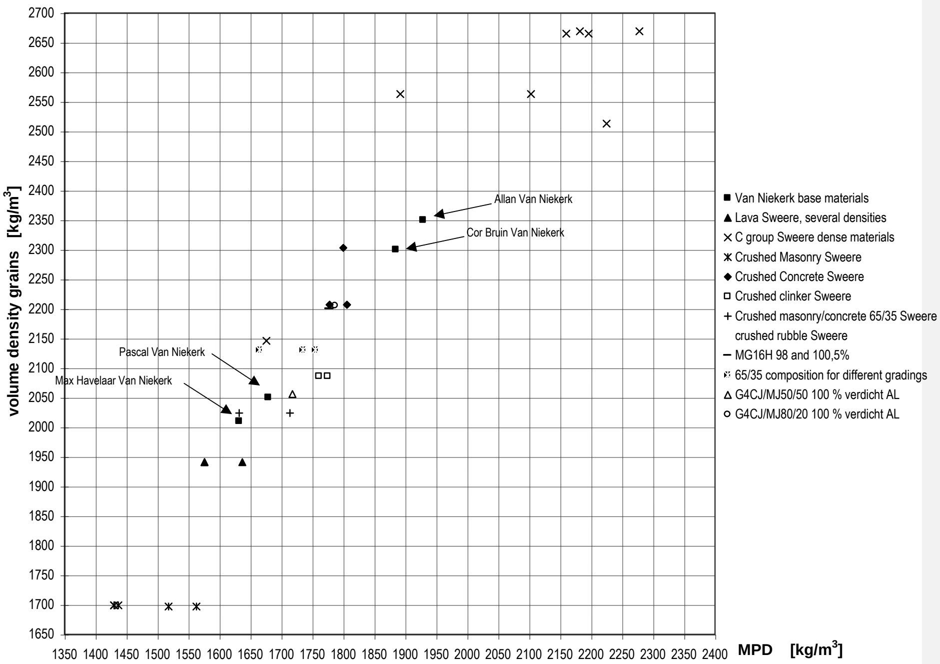


Figure 4.1 MPD-ρ_{grains} relationship estimating the ρ_{grains} of the Van Niekerk base materials

All comparable materials consist of recycled materials, having a volume density of the grains of around 2030 kg/m^3 (2130 kg/m^3 for G5CJ/MJ65/35). Therefore, the volume density of the grains for "Max Havelaar" and "Pascal" has been set to 2010 and 2050 kg/m^3 respectively, maintaining the MPD : ρ_{grains} ratio to 0.81-0.82.

The "Allan" and "Cor Bruin" base materials of VAN NIEKERK have relatively high MPD values. The base materials tend to have the properties of crushed gravel or crushed concrete. Maintaining a MPD : ρ_{grains} ratio of around 0.82 (like crushed concrete and crushed rubble materials of SWEERE) the volume density of the grains for "Allan" and "Cor Bruin" has been set to 2350 and 2300 kg/m^3 respectively.

The volume density of the MG16H base material as analysed by KISIMBI has been estimated by analysing the volume density versus the MPD as well. With an MPD of 1778 kg/m^3 for MG16H, one might conclude that the commercially mixed granular base material is composed of a larger portion crushed concrete. Therefore, the volume density of the grains has been set to 2200 kg/m^3.

Moisture content during testing not determined

Although collected for the materials tested by SWEERE, the moisture content of the specimens analysed by VAN NIEKERK, LEFEVRE, KISIMBI, and MURAYA was not available.
The Optimum Moisture Content for both MPD and MMPD has been incorporated.

4.6.7 Z_{fines} value calculated for percentage smaller than 75 µm instead of 63 µm

The Z_{fines} value, indicating the percentage of fine particles passing the 63 µm-sieve appeared to result in values of low variety. Therefore, the Z_{fines} value for fine particles passing the 75 µm-sieve has been calculated. The 75µm-sieve is being applied according to the AASHTO-standards and is therefore, a regular value as well.

4.7 Conclusions

The data set used in this study for establishing relationships between mechanistic material parameters can be found in appendix F. It contains 53 different material samples with approximately 30 material and mechanistic parameters collected from different sources, adapted where necessary.

The search for density parameters has been emphasised, resulting in different density/gravity parameters. Missing mechanistic parameters, such as φ and *c*, have been substituted by other representative values ($\tau_{failure;\sigma3=12kPa}$).
When substitution was not satisfactory because of the lack of too many parameters, the material samples have been omitted. For this reason, the mixed granulates with GAP-graded and UNIFORMLY-graded distribution curves tested by MURAYA could not be incorporated.
To make the data set complete for the materials tested by MURAYA and KISIMBI, many data have been retrieved and calculated from the study of LEFEVRE.

The influence of cementation and carbonatation in time, resulting in time dependent stiffness, is avoided by collecting only data of material samples of around 0 or 3 days old.

5 ANALYSIS OF THE DATA OBTAINED

5.1 Introduction

In this chapter, the data set as collected in this study will by analysed more thoroughly for characteristics of the data set, measurement errors, bi-variate correlations and outliers. Based on these analyses, some conclusions concerning the regression (method and focus) can be drawn. These conclusions are grouped together in section 5.8.
In chapter 6 it will be shown that the analyses executed in this chapter are indispensable for an appropriate regression analysis.

Only remarkable observations that will be discussed in this chapter are depicted. All the other graphics are presented in appendix H. Most of the analyses described in the next two chapters have been executed by means of the software module SPSS for Windows.

5.2 Significance of a thorough data analysis

A literature study emphasised that data analysis in general and analysis of measurement error of the data set should take place before starting regression analysis [BERRY & FELDMAN 1985, pp.26-37]: "When regression is applied based on material properties with great error or great uncertainty, the predicted regression model will contain this error, too."
Furthermore it is recommendable to have a thorough insight in the characteristics of the data set on which regression analysis takes place, since the absence of a good model fit by regression techniques, an expected correlation or relationship does not mean that such a fit or correlation does not exist at all. After all, regression analysis takes place for the materials collected in the data set. If the data set is not of enough variation, a regression will not succeed, while still being in existence.

5.3 Statistical characteristics of the data set

In appendix H section H.1 the output of the SPSS statistical analysis is given. Based on the complete data set some histograms, outliers, the mean value, the variance, etc have been calculated.

Knowing the outliers in the data set is essential, since these values can influence the correlation coefficient significantly or can result in a completely different regression model. Therefore, some boxplots have been generated during this study. It can be seen that mainly the SWEERE materials (Sillicon Manganese Slag and Stoll) result in outliers. The incorporation of these SWEERE materials has been discussed in chapter 4. Most of them are natural base course materials, which have been widely applied in pavement engineering in the past. These materials of natural origin do have (natural) gradings with a large fines fraction, resulting in distinctive grading coefficients or extreme values of k_1 and k_2 of the M_r-θ model.

5.4 Correlation between material and/or mechanistic parameters

5.4.1 Table with correlation coefficients obtained with SPSS

In search for relationships between two different material properties or between a material property and a mechanistic parameter, the Pearson correlations or bi-variate correlations have been determined. This is one of the conditions as stated in section 5.2.
The Pearson correlation only gives insight in linear relationship that may not be the only kind of relationship. Therefore, scatter plots have also been generated by means of SPSS. While analysing these scatter plots graphically, it is possible to get any notion of non-linear relationships such as exponential or logarithmic relationships. For the latter, the Pearson correlations have also been determined for the natural logarithmic values of the data set.

The Pearson correlation tables as well as a few significant scatter plots have been placed in appendix H section H.2 and section H.3. It appeared that combination of LN and natural values in scatter plots sometimes gave better results. These plots have been incorporated too.

5.4.2 Scatter plots of the material parameters

Generating scatter plots for the mechanistic material parameters did not give very hopeful results. Clear relationships can hardly be distinguished. Some scatter plots are depicted and described in appendix H section H.3. Some distinguishing scatter plots are placed in the sections below.

k_1-parameter

It appeared that the k_1 parameter could not be related to the density and relative density, or the grading parameters. This will be found again in the regression analysis discussed in chapter 6.
Figure 5.1 however shows that a slight relationship between k_1 and the Volders Verhoeven Sharpness, as found by VAN NIEKERK (1995, p. 37), can be seen. See section 3.7, The Volders Verhoeven Sharpness appears to be a material parameter that is complicated to determine. For a substantial part of the materials used in this data set the Volders Verhoeven Sharpness is missing. For both reasons it has been decided not to incorporate this material parameter in regression analysis.

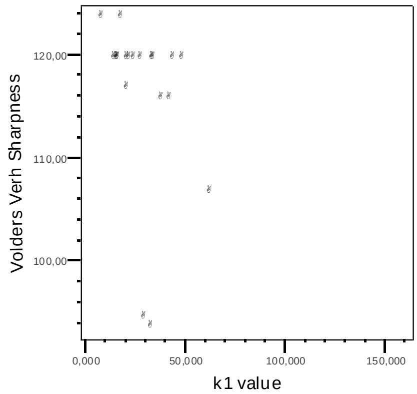


Figure 5.1 Checking the Volders Verhoeven relationship for the current data set

k_2-parameter

For the k_2 parameter no relationship with any other material parameter could be found while analysing the scatter plots graphically. As can be seen in appendix H section H.1 the range for k_2 (difference between maximum and minimum) is very low. This may be an explanation for the difficulties in finding an graphical relationship to any of the material parameters. The reader is referred to section 5.7.4 for other remarks about k_2 and for the decision not to search for regression equations.

Cohesion

It has been mentioned that no cohesion data were available for the SWEERE materials. Therefore, for the scatter plots below, only the mixed granulates with both different composition and grading have been depicted.
The cohesion appeared to correlate slightly with the dry density of the sample or the relative density. (See the scatter plots in Figure 5.2 below)

There might be a weak relationship for the cohesion with some grading coefficients and parameters. These have been depicted in appendix H section H.3.4.
However, an expected relationship between cohesion and Z_{fines} could not be found.

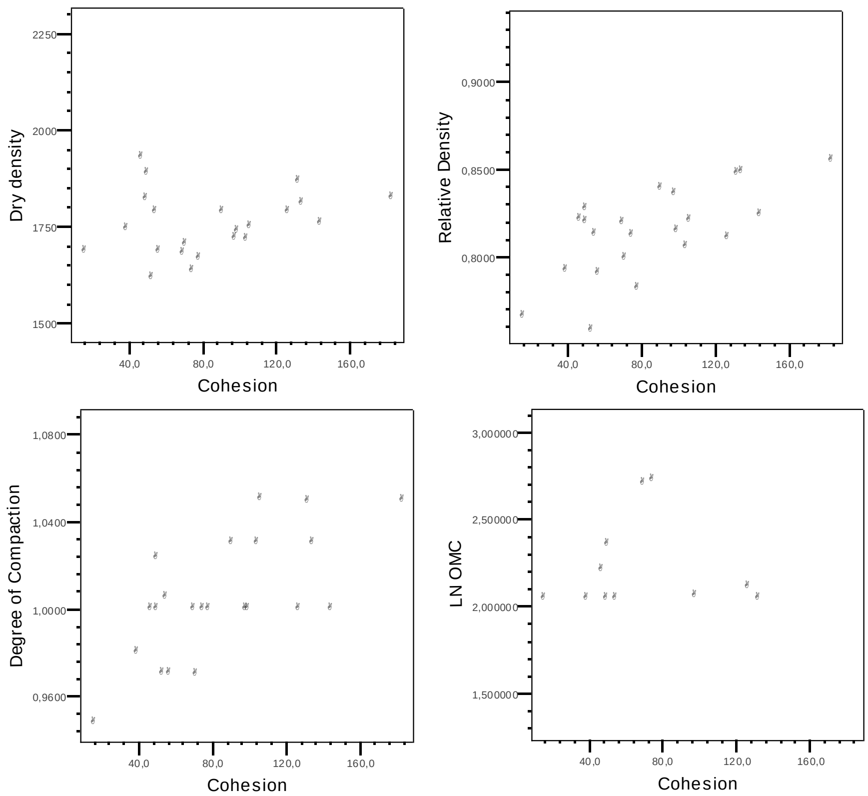


Figure 5.2 Scatterplots for mixed granulates where the cohesion is related to other material properties

Angle of internal friction

Due to the lack of data, the SWEERE materials could also not be used to search for correlations explaining the angle of internal friction (φ). For the smaller grain size fractions, some relationships might be distinguished, see Figure 5.3.

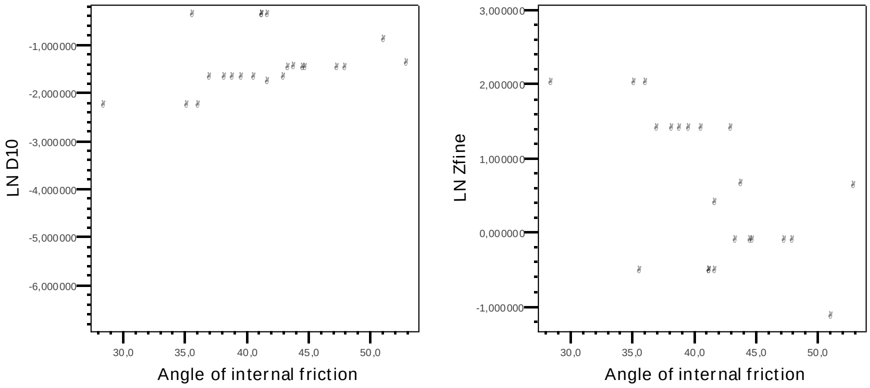


Figure 5.3 Scatterplots for the angle of internal friction

Analysing the values of the angle of internal friction in the data set, it can be seen that the value often is approximately 40˚. When determining the cohesion and angle of internal friction in the laboratory, the slope – being the angle of internal friction – will give less measurement errors than the intercept, representing the cohesion.

Therefore it can be stated:

> *Since the relationships found for the angle of internal friction appeared to be poor and since variation of the angle of internal friction is very small, it has been decided to assume the value for φ being 40˚, refraining from model fitting by means of regression techniques. See the data set as depicted in chapter 4 or appendix F.*

5.5 Misleading correlations in the data set

It appears that in the Pearson correlation tables (section 5.4.1) some misleading correlations might be found. This may induce the occurrence of multicollinearity during regression analysis as well (appendix I).

One reason for these misleading correlations is the direct relationship between parameters because of their mathematical or physical relationship, e.g. the cohesion, angle of internal friction and $\tau_{\sigma failure,\sigma conf\ press=12kPa}$ accoding to the Mohr Coulomb criterion.

Another significant reason is the limited variation in grading curves available in this data set (see figures in appendix H section H.4). For this, most of the grain size percentage parameters (D_i) as well as grading curve parameters (curvature coefficients) and other grading coefficients (sieve size parameters) show high Pearson correlations.

The reason for limited availability of different particle size distribution curves, is that the materials with their distribution curves as analysed in this study have to comply with the Upper Limit and Lower Limit in grading characteristics prescribed by the

Dutch RAW (CROW, 2000). See chapter 4 section 4.6.2 and appendix D sections D.2, D.3.
For some other available particle size distribution curves a complete data set of material properties is not available and so, these have been left out of this study.

When using a limited number of grading curves only, the grading curve can be fixed easily by means of, e.g., the D_{50} value and the coefficient of curvature C_{curv}.

Please, note that in practice there is no bi-variate correlation between several grading parameters. Still, the bi-variate correlations found in this data set should be taken into consideration while applying regression techniques, since these correlations may induce multicollinearity in regression equations. This is a mathematical problem: the mathematical algorithm used for the regression analyses will not be able to allocate the right constants to the right independent variables, resulting in misleading regression indicators like the (adjusted) correlation coefficient.

5.6 Particle size distribution curves

As stated before, there is limited variation in available grading curves, leading to misleading bi-variate correlations in the data set. The particle size distribution curves are depicted in appendix appendix H section H.4.

5.7 Outliers and measurement errors

5.7.1 MPD – OMC relationship

As was done by VAN NIEKERK (chapter 3 section 3.5.3) an Optimum Moisture Content - Maximum Proctor Density relationship has been established for the data set as collected in this study. See Figure 5.4

In this figure, the SPPD values (Single Point Proctor Density) for the SWEERE materials have been incorporated too. The SPPD is comparable with the Maximum Proctor Density of other unbound granular materials because of the equivalent total amount of compaction energy applied per cubic millimetre. (The reader is referred to chapter 4 section 4.6.6 and appendix E section E.3.4)

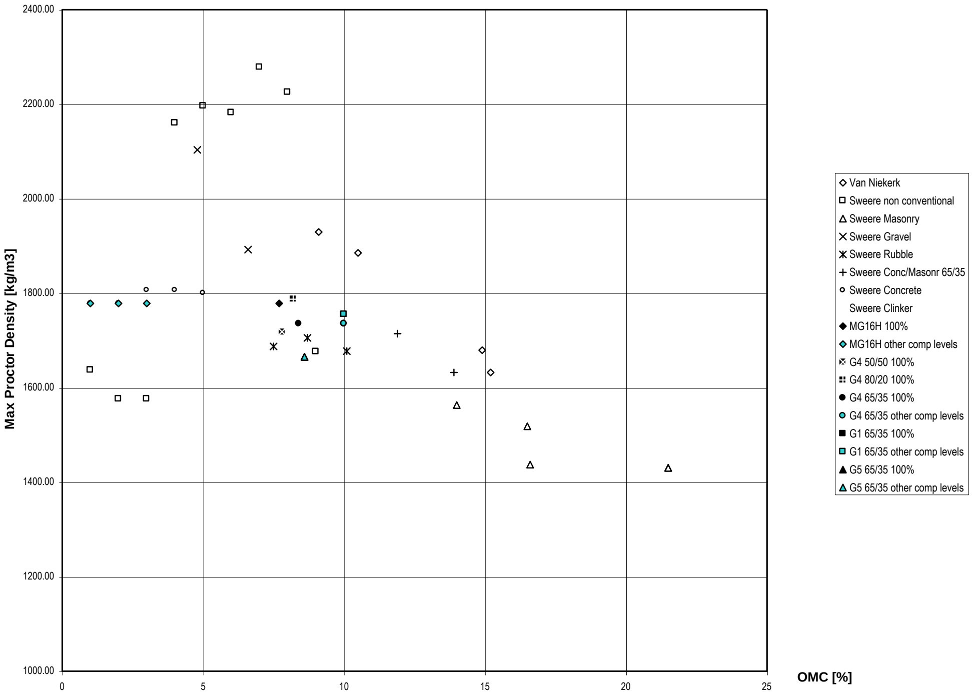


Figure 5.4 MPD-OMC relationship for all base course materials used in the data set

While retrieving the optimum moisture content for the granular materials of MURAYA and KISIMBI, it was found that the dry density - moisture content relationship is quite 'flat', indicating that there is no unique moisture content for the maximum dry density. (Cf. Figure E.11 in appendix E.3.5). Determining the Proctor Density at a single moisture content in the range of 6 to 10% by mass proved to be acceptable but ambiguous. Hence, it is safe to assume that for the Optimum Moisture Content in the data set a significant possibility for substantial measurement errors and so data errors are omnipresent.

Although being of great influence for the cohesion and the k_1 properties, the optimum moisture content has not been incorporated in the regression analysis.

5.7.2 Outliers in MPD and SPPD values

For a few SWEERE base materials, the SPPD appeared to be higher than the MMPD. These materials are listed in Table 5.1. Generally, it is assumed that the SPPD is comparable with the MPD, hence, a SPPD higher than the MMPD (with a higher level of compaction effort) is not logical. One explanation might be that SWEERE performed the MMPD-test on a scaled-down 0-22.4 mm material, whereas he performed the SPPD-test on effectively the full 0/40 mm grading. However, SWEERE states that the influence of scaling down the grading on the dry density obtained appears to be small, which proved to be a conclusion consistent with results found at Nottingham University [SWEERE 1990, pp. 145-146].

Material description	SPPD [kg/m³]	MMPD [kg/m³]
porphyry CO4 POO01	2196	2038
crushed gravel CO6 GGO01	2103	2029
stol CO9 STN01	2225	2174
crushed clinker R08 KGO01	1761	1699
crushed mas'onry/concrete (65/35) R10 FFO01	1714	1713

Table 5.1 List of SWEERE base materials with SPPD higher than MMPD

The first four materials listed in Table 5.1 have not been used for regression analyses with the MPD involved, since the MPD-values of these materials could distort the dependency of the regression.

5.7.3 Analysis of volume density grains - MPD relationship

Figure 5.5 shows a clear relationship between the volume density of the grains and the MPD. The conventional materials tested by SWEERE induce a curve in the top of the scatter plot. Furthermore, some outliers can be pinpointed.
As can be seen, the crushed gravel discussed in section 5.7.2 can be considered as an outlier.

Figure 5.5 has also been used for the determination of the missing volume density-grains values of the VAN NIEKERK materials.

5.7.4 k_1 - k_2 relationship

Placing the k_1 and k_2 coefficients of the M_r-θ resilient modulus model in a graph, a distinctive relation between both coefficients can be distinguished. See figures Figure 5.6 and Figure 5.7. The LN (k_2) – k_1 relationship has been depicted too for showing the linear relationship. Apparently, the k_1-k_2 relationship may consist of an exponential function.

Granular materials with a certain ability to develop to a bound base course (in time) will react less stress sensitive than granular materials without cementation characteristics. This means that the k_2 parameter of the M_r-θ model will remain low for these cementitious materials, while k_1 will be relatively high. The k_2 value represents the elastic modulus. This mechanism can be observed in Figure 5.6 and Figure 5.7 below as well:
Hence, the stiffer the material, the higher the k_1 and the lower its k_2. When k_2 is low, stress dependency of the material is less pronounced.
It has been decided to relate the k_2 parameter to the k_1 parameter for the reasons below:

- For the M_r-θ model the elastic modulus is mainly determined by the k_1 parameter;
- The mean value for k_2 is fairly low, additionally having a small range;
- Difficulties in finding an graphical relationship for the k_2 parameter to any of the simple material parameters (section 5.4.2);
- A clear relationship between k_2 and k_1. (Figure 5.6 and Figure 5.7)

Outliers in the k_1 - k_2 relationship

In the LN (k_2) – k_1 relationship in Figure 5.6 it is plausible to presume that the *limestone CO7 KAB02* may be an outlier (see arrow) since this will not fit the virtual straight line. When analysing the data set it can be found that this sample material is of the Sweere Upper Limit grading materials, containing a considerable amount of fine particles. This material has been left in the regression data set but will appear as an outlier many times.

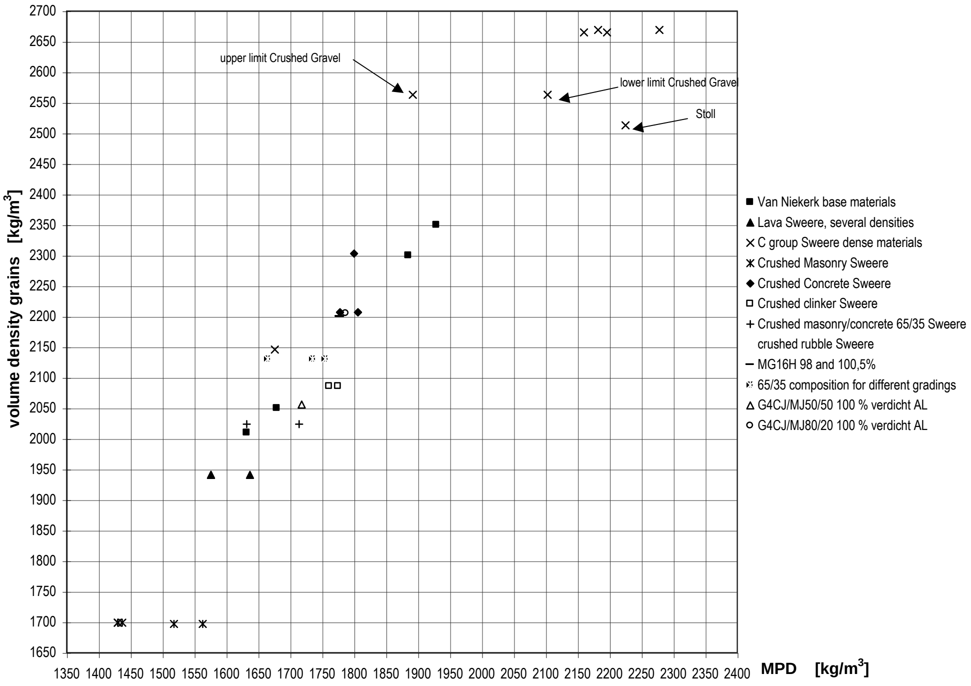


Figure 5.5 Volume density grains versus MPD of all materials

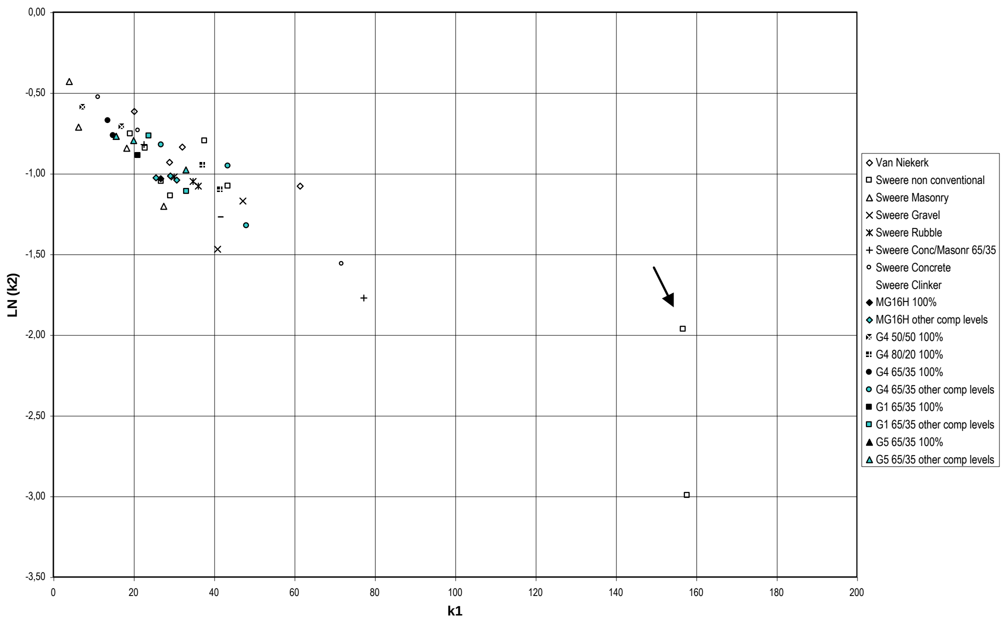


Figure 5.6 $LN(k_2) – k_1$ relationship where a distinction between the different material groups has been made

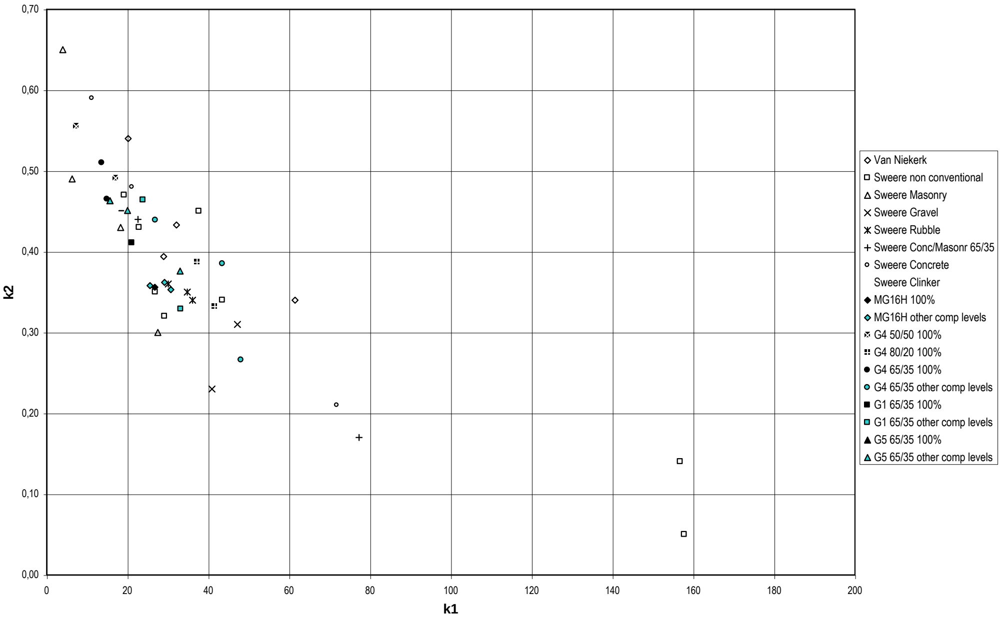


Figure 5.7 $k_2 - k_1$ relationship with a distinction between different material samples

5.7.5 Measurement error during the composing and testing fase

Specimens prepared in laboratory always show variation in, for instance, density, compaction, specimen size, and grading composition. These variations will even increase when the specifications for preparing the specimen are not described accurately or when the process of preparation is not considered conscientiously. These differences sometimes make it difficult to compare laboratory test measurements executed by various researchers.

Literature (KISIMBI, 1999, p.p. 51) shows that, for instance, the specimens prepared by KISIMBI with compaction levels of 95% and 97.5% were compacted by hand tamping as with vibrating compaction these compaction levels were exceeded. The specimens with compaction levels of 100%, 102.5%, and 105% were compacted by vibration compaction. Moreover, the specimen with compaction level of 95% and 97.5% were compacted in six layers instead of 3 layers to distribute the compactive effort better over the specimen.
MURAYA, (2000, p.p. 63) however, compacted his specimens in three layers only, whereas Sweere did not use this procedure.

5.8 Conclusions

- It should be noted that, although a large data set is available, the variation in certain parameters is relatively small. This makes the data set less useful for the purpose of this study
- The tested gradings, for instance, all complied with to the specifications. This implies that the grading parameters show bivariate correlations and therefore are not used together in regression analysis.
- Therefore, it can be concluded that the tests, which have been executed in previous studies, are suitable for the analysis as aimed in this study.

- The Pearson correlation only gives insight in linear relationship that may not be the only kind of relationship. Therefore, generating scatter plots is recommendable, to get any notion of non-linear relationships. It appeared that combination of LN and natural values in scatter plots sometimes gave better results.

- When the executed regression is based on material properties with great error or great uncertainty, the predicted regression model will contain this error, too.
- Because of this, the optimum moisture content has not been involved in the regression analysis, although it has a great influence on the cohesion and the k_1 properties

- It has been decided to relate the k_2 parameter to the k_1 parameter for the reasons below:
    - ♦ In the M_r-θ model the elastic modulus is mainly determined by the k_1 parameter.
    - ♦ The mean value for k_2 is fairly low, additionally having a low range.
    - ♦ It was difficult to find a graphical relationship between the k_2 parameter and any of the material parameters.
    - ♦ A clear relationship exists between k_2 and k_1.

- Since the relationships found for the angle of internal friction appeared to be poor and since variation of the angle of internal friction is very small, it has been decided to assume a fixed value for φ being 40˚. No attempts have been made to develop a regression equation for φ..

- Although the Volders Verhoeven Sharpness could be a fairly successful explaining variable , it is a material parameter being too complicated to determine. Furthermore, the Volders Verhoeven Sharpness is not available for many material samples. For both reasons it has been decided not to incorporate this material parameter in regression analysis.

6 REGRESSION ANALYSIS

6.1 Introduction

Based on the bi-variate correlation or Pearson coefficients and the scatter plots, which have been discussed in chapter 5, relationships for k_1, k_1-k_2, and cohesion are determined by means of regression analysis. In this chapter, the results obtained with linear and log-linear regression analysis will be discussed.
In the output of regression analysis, the parameters and coefficients of importance have been pointed out. The value of r^2 describes how good the fit is between the model and the data. However, it does not describe how reliable the model is.
The reliability of a model is determined by the ratio of the number of data points to the number of explaining (independent) variables in the model (degrees of freedom). A good model therefore has a high value of r^2 (good fit) together with a high number of degrees of freedom (reliability).
In appendix I a more thorough explanation for regression analysis is described. Most regression output can be found in appendix J.

6.2 Conditions for an appropriate regression analysis

The reader is referred to appendix I for a general description of the theory of (log-) linear regression techniques and their points of attention. In addition to that appendix, several statistic basic assumptions must be met in order to be able to appropriately estimate the coefficients of the dependent variables and to conduct tests of statistical significance. These essential conditions borrowed from BERRY & FELDMAN (1985, p. 10; quoted in italics) are listed below:

1. *All variables must be measured at the interval level and without error.*
2. *For each set of values for the k independent variables, the mean value of the error is 0.* These *k* independent variables are the material parameters (as discussed in chapter 4) integrated in the proposed regression model.
3. *For each set of values for the k independent variables, the variance of the error term is constant.*
4. *For any of two sets of values for the k independent variables, the error terms are uncorrelated, thus there is no autocorrelation.* This has been analysed in chapter 5 section 5.4.1 and section 5.4.2.
5. *For each independent variable in the regression model, each independent variable is uncorrelated with the error term.*
6. *There is no perfect collinearity, i.e. no independent variable is perfectly linearly related to one or more of the other independent variables in the model.* More about collinearity and multicollinearity is explained in appendix I section I.5.
7. *For each set of values for the k independent variables, the error of the variable is normally distributed. Because of the reasonably large data set (amount of materials involved) obtained in this study, the Central Limit Theorem will be effective, implying a normal distribution for the error of the predicted variable.*

Most of the conditions above have been analysed in chapter 5. Not all conditions have been studied since some conditions can be reasoned based on practical insights. Other conditions are irrelevant or do not occur in this study.

It should always be taken into consideration that in a regression analysis the absence of a good model fit for an expected correlation or relationship does not mean that such a fit or correlation does not exist at all: The regression analysis or search for correlations has been applied on the materials collected in the data set. If the data set shows too little variation (the range of values of a particular variable is too small), a regression will not succeed, while a relationship is still being present.

6.3 Regression procedure

First, it has been determined which material properties influence the particular mechanical property. This has been done by rationalising and is further based on the findings in the literature review (chapter 3).
When inserting these material properties as independent variables in the regression models, the results appeared to be very poor. However, it should be noted that in that phase of the study, only one proposed regression model has been evaluated.

In addition to these poor results, it has been listed which material properties could exert influence on the mechanical characteristic for which a relationship had to be found. Material properties not easily to obtain or barely available, such as the Volders Verhoeven Sharpness (VVS) or Crushing Factor (CF), or having a certain error (OMC; chapter 5 section 5.7.1) have been left out of consideration.
All different combinations of the material properties as described above have been inserted in the regression algorithms to search for relationships in SPSS. These combinations consisted of 3 or 4 material parameters. As discussed in chapter 5, in these compiled combinations no correlations between the independent material properties must occur because of multicollinearity. The reader is referred to app. I.

Based on the combinations of independent material properties the regression analysis has been executed according to different regression models.

6.3.1 Generating algorithms: different regression models

In SPSS, both linear and log-linear regressions have been executed because of the availability of both natural values as logarithmic values of the various material properties.

- Linear regressions sometimes do not always appear mathematically or physically correct. However, these models gave reasonable results.
- By means of a log-linear regression, it is possible to generate a non-linear model for the dependent mechanical characteristic.
- When the combination of the independent variables consisted of both natural and logarithmic values, a third regression can be obtained, containing an exponential function.

Based on the approach above, the following models have been inserted in the SPSS regression analysis.

$z = a \ln x + b \ln y + d$

$\ln z = a \ln x + b \ln y + d$ becomes $z = x^a \cdot y^b$

$\ln z = a \cdot x + b \cdot y + d$ becomes $z = e^{ax} \cdot e^{by}$

$\ln z = a \ln x + b \cdot y + d$ becomes $z = x^a \cdot e^{by}$

6.3.2 Regression techniques used in SPSS

The different combinations of independent variables together with the different regression models have been used in SPSS. In SPSS, regression analysis took place according to an 'ENTER' technique or a 'STEPWISE' technique. In the latter SPSS calculates which independent variables should be included in the proposed regression function based on the degrees of freedom and the change in adjusted correlation coefficient. See appendix I.

6.3.3 Filtering the data set

Finally, the data set has been filtered; it could be possible that a better fit may be obtained while using a logical part of the total data set. Therefore, the same regressions have been applied for a selection of the total data set:

1. Materials with a relative compaction of 100% MPD only;
2. mixed granulates only;
3. a sequence of mixed granulates with increasing hardness

The regression did not improve at all. Therefore, the results of this filtering technique have been left out.

6.4 Results of the regression analysis

While executing the regression analyses, there has been a focus on the adjusted correlation coefficient and the standard error of the estimate, giving an indication for the goodness of fit of the regression model. These coefficients are discussed in appendix I.
Furthermore, it has been verified whether there was no Pearson correlation between the independent variables in order to avoid multicollinearity in the regression.

In some cases, the correlation coefficient appeared to have almost the same value while trying to fit the data for different models as described above. Therefore, the models determined by loglinear regression have been preferred for the fit of the data set, in order to introduce a non-linear function of the dependent variable.

It appeared for the regression of the k_1-value that the contribution of the OMC or LN (OMC) to the predicted value was very low. This may be explained by the very low variety of the optimum moisture content.

6.4.1 Excluding two outliers

In search for a relationship between the k_1 and k_2 value as well as for a relationship for the cohesion, the Pascal VAN NIEKERK material appeared to be an outlier and therefore it has been excluded from the data set.

Furthermore, it has been found that in the search for a relationship for the cohesion, the MG 16H 94.7%rel. comp. of KISIMBI appeared to be an outlier as well. This may be explained by the very low degree of compaction, having no practical significance. In addition, this data point was removed from this data set.

6.4.2 Cohesion

For the relationship for the cohesion, it has been found that the cohesion can best be fitted with the following material properties:

- degree of compaction.
- Z_{fines}.

The independent material properties can be reasoned and have been discussed in the literature survey (chapter 3). On other studies, these properties have been found being of influence on the cohesion as well.

The proposed relationship consists of an exponential function. Additionally, a second regression has been made with a similar correlation coefficient, resulting in the same predictors but having a logarithmic value instead of a natural value, or vice versa. In appendix J all regression output is given.

The established parameters with its coefficients and final proposed formula for the cohesion are shown in Table 6.1. Figure 6.1 depicts the predicted value versus the measured value of the cohesion.

dependent variable:	**LN cohesion**				
				95% confidence interval	
		coefficient	std. error	lower bound	upper bound
predictors:	**constant**	3.909	0.087	3.725	4.093
	LN degr. of comp.	9.602	1.782	5.825	13.379
	Z_{fines}	$8.558 * 10^{-2}$	0.018	0.047	0.124
r^2	0.737				
$r^2_{adjusted}$	0.705				
Std. error of the estimate	0.2477				

$$LN\,c = 3.909 + 9.602 \cdot LN(DegrComp) + 8.558 \cdot 10^{-2} \cdot Z_{fines}$$

Relationship

$$c = 49.85 \cdot e^{\frac{Z_{fines}}{11.7}} \cdot DegrComp^{9.602} \qquad \textit{Eq 6.1}$$

Table 6.1 Regression output as found for the relationship for the cohesion

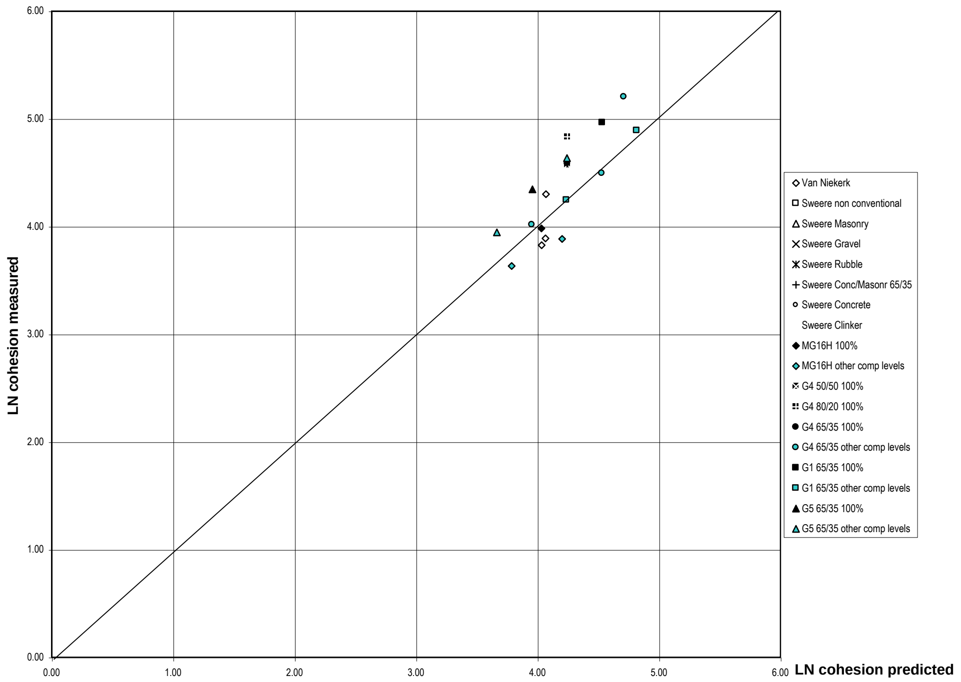


Figure 6.1 Predicted versus measured value for the cohesion.

6.4.3 k_1 relationship

It appeared that the k_1-value can best be related to the following material properties:

- Volume density of the grains.
- D_{85} value.
- Coefficient of uniformity.

In the final relationship for the k_1-value, the volume density of the grains can be considered as an indicator for the composition of the material, influencing the k_1-value as well. Furthermore, the D_{85} value is an indication of the coarseness of the material. The coefficient of uniformity gives an indication of the characteristic of the grading curve.
By incorporating the volume density of the grains, the composition of the granular material is taken into consideration.
It is remarkable that the regression technique did not opt for the degree of compaction. Involving this parameter has been analysed as well, but did not result in better predictions.

Analysing the output of SPSS, it has been found that the residual of the predicted value of the crushed masonry/crushed concrete (k_1=77.3) of SWEERE is very high. In the second regression step, this SWEERE material has been omitted. This resulted in a better model fit.

When analysing the statistical parameters, it can be observed that the standard errors of the coefficients of the predictors are fairly high, being an indication of the goodness-of-fit for the proposed model. The rather high correlation coefficient can be explained by the position of both some extreme values and the outliers. See Figure 6.2.

In appendix J all regression output is given.

The determined parameters with its coefficients and final proposed formula for the k_1-value are shown in Table 6.2. Figure 6.2 depicts the predicted value versus the measured value of the k_1-value.

dependent variable:	**k_1**				
				95% confidence interval	
		coefficient	std. error	lower bound	upper bound
predictors:	**constant**	- 357.839	136.282	-633.066	-82.611
	D_{85}	- 0.431	0.192	- 0.819	- 0.043
	LN vol dens grains	51.778	17.839	15.752	87.805
	$C_{uniformity}$	$3.627 * 10^{-2}$	0.004	0.027	0.045
r^2	0.734				
$r^2_{adjusted}$	0.714				
Std.err of the estimate	12.61				*Eq 6.2*

Relationship
$$k_1 = -357.9 + 51.8 \cdot LN(Vol\,Dens\,Grains) - 0.431 \cdot D_{85} + 3.627 \cdot 10^{-2} \cdot C_{uniformity} \qquad \text{Eq 6.2}$$

Table 6.2 Regression output as found for the relationship for the k_1-value

When leaving the greatest outlier of Figure 6.2 out of the dataset, it can be observed that the goodness-of-fit will be better. The correlation coefficient will increase up to r^2=0.782, decreasing the standard error to 11.15. However, the outlier is a commercially graded Crushed Concrete sample (SWEERE) showing no irregularities at all.

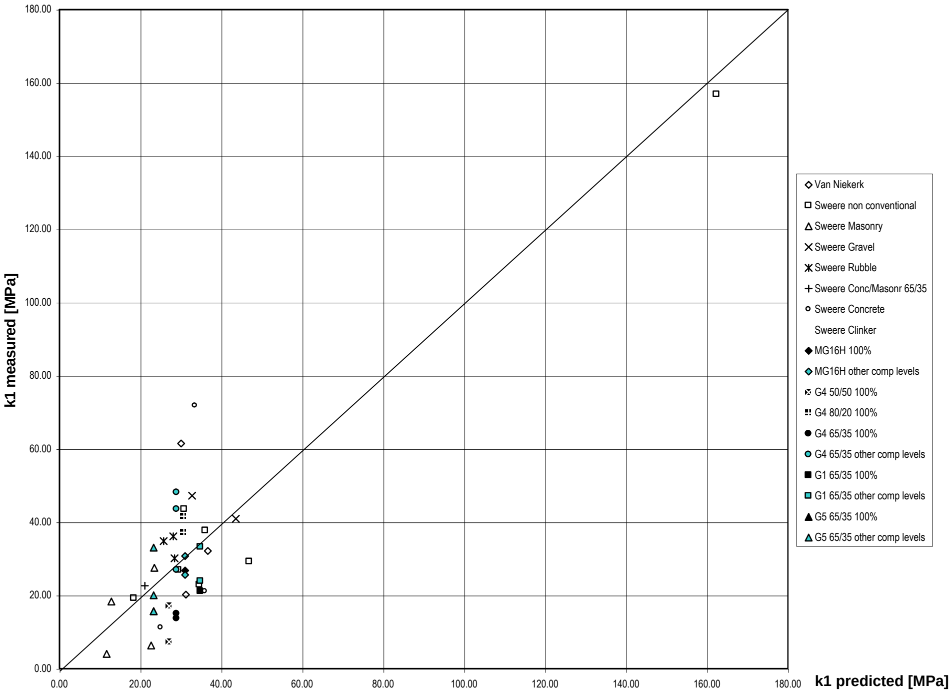


Figure 6.2 Predicted versus measured value for the k_1-value.

6.4.4 Relationship between k_2 and k_1

For the determination of the k_2-k_1 relationship the following predicting material properties could be ound:

- k_1-value.
- Distance from the grading curve (Particle Size Distribution Curve) to the Fuller Curve.
- Coefficient of uniformity.

In the final relationship the $D_{(PSDC\text{-}FC)}$ can be considered as an indication of the capability to develop a very dense material skeleton, whereas the coefficient of uniformity gives the variation in coarseness of the grains.

In appendix J all regression output is given.

The established parameters with its coefficients and final proposed formula for the k_2 relationship are shown in Table 6.3. Figure 6.3 depicts the predicted value versus the measured value of the k_2-value.

dependent variable:	**LN k_2**				
				95% confidence interval	
		coefficient	std. error	lower bound	upper bound
predictors:	**constant**	- 0.432	0.041	- 0.515	- 0.349
	k_1	- 1.542 * 10^{-2}	0.001	- 0.017	- 0.014
	$D_{(PSDC\text{-}FC)}$	- 7.619 * 10^{-4}	0.000	- 0.001	0.000
	$C_{uniformity}$	3.402 * 10^{-4}	0.000	0.000	0.000
r^2	0.913				
$r^2_{adjusted}$	0.907				
Std. error of the estimate	0.127836				
Relationship:					

$$LN\,k_2 = -4.432 - 1.542\cdot 10^{-2}\cdot k_1 - 7.619\cdot 10^{-4}\cdot D_{(PSDC-FC)} + 3.402\cdot 10^{-4}\cdot C_{uniformity}$$

$$k_2 = 0.65\cdot e^{\left(\frac{C_{uniformity}}{34020} - \frac{k_1}{1542} - \frac{D_{PSDC-FC}}{76190}\right)} \qquad \text{Eq 6.3}$$

Table 6.3 Regression output as found for the relationship for the k_2-k_1 relationship value

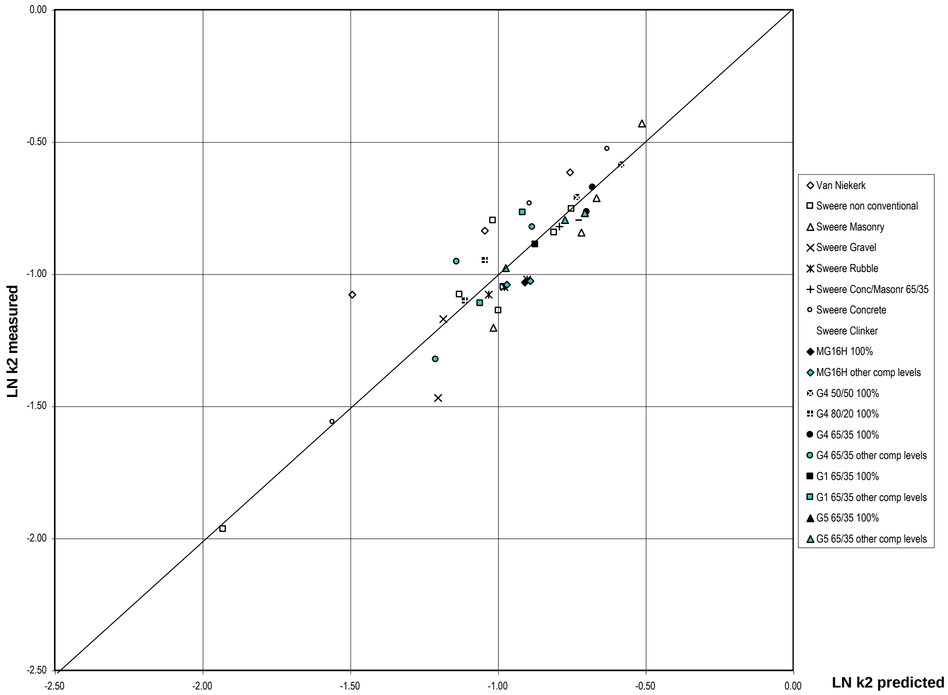


Figure 6.3 Predicted versus measured value for the k_2 -value.

6.5 Conclusions

In this chapter, 3 regression models have been proposed for the mechanical properties:

- cohesion for the failure characteristics (strength) of unbound granular materials;
- both a k_1 relation and a relationship between k_2 and k_1, taking part of the stiffness (resilient modulus) characteristics.

The regression models found in SPSS showed a reasonable fit. For this, several statistical coefficients have been taken into consideration to get a better insight in the goodness-of-fit of the proposed regression model. The outliers, who revealed in the graphics have been analysed as well. However observing a good correlation coefficient for the k_1 relationship, the fit of the regression line appeared quite insufficient.

While executing regressions comprising all combinations of material properties to be expected of any influence, some filters have been set as well. These filters consist of a sub-selection of materials with the same material characteristics (composition; mixed granulates) or degree of compaction. The introduction of these filters did not improve the results of the models to obtain. For this, the output has not been discussed in this study.

More elaborated conclusions will be drawn in chapter 7 (Conclusions and recommendations).

7 CONCLUSIONS AND RECOMMENDATIONS

7.1 Introduction

In this chapter, a summary of the research will be given, followed by an evaluation of the original scope of the study with the final results. Furthermore, the method of research is discussed, followed by observed limitations, observations, remarks, conclusions and recommendations.

7.2 Aim of this study

The original scope of this study is to establish a correlation between mechanical properties of unbound granular materials and (physical) material characteristics. The search for these relationships has been focussed mainly on relationships for the cohesion, and the resilient modulus (M_r-θ model) parameters k_1 and k_2.

7.3 Limitations as found during this study

1. Due to strongly varying material properties, only *unbound* granular materials have been analysed.

2. The focus is mainly on unbound granular materials used or available in The Netherlands.

3. Since the relationships found for the angle of internal friction appeared to be poor and since variation of the angle of internal friction is very small (φ being 40˚), it has been decided to set φ at a fixed value of 40˚.

4. It appeared difficult to estimate the OMC. The reason for this was that for a granular material, the relation between moisture content and dry density was almost a horizontal line. Therefore it has been decided not to incorporate the moisture content in regression analysis.

5. It has be decided to establish only relationships applicable for pavement structures with a relatively thick top (asphalt) layer than thin ones. In the latter structures, the (σ_c/σ_3) ratio occurring in granular base course will attain higher levels, resulting in different resilient modulus characteristics.

7.4 Research method

After determining which material properties influence the particular mechanical property, the results appeared to be very poor. In addition it has been listed which material properties could exert influence on the mechanical characteristic for which a relationship had to be found. Material properties that are (a) not easily to obtain, (b) barely available, and (c) have a certain error have been left out of consideration. All different combinations of the material properties have been inserted in the regression algorithms, consisting of 3 or 4 material parameters.

In SPSS, both linear as log-linear regressions have been executed because of the availability of both natural values as logarithmic values of the various material properties.
The models depicted below have been inserted in the SPSS regression analysis.

$$z = a \ln x + b \ln y + d$$
$$\ln z = a \ln x + b \ln y + d \quad \text{becomes} \quad z = x^a \cdot y^b$$
$$\ln z = a \cdot x + b \cdot y + d \quad \text{becomes} \quad z = e^{ax} \cdot e^{by}$$
$$\ln z = a \ln x + b \cdot y + d \quad \text{becomes} \quad z = x^a \cdot e^{by}$$

In SPSS, regression analysis took place according to an 'ENTER' technique or a 'STEPWISE' technique.
Moreover, the data set has been filtered: (a) materials with a relative compaction of 100% MPD only, (b) mixed granulates only, (c) a sequence of mixed granulates with increasing hardness. The regression did not improve at all. Therefore, the results of this filtering technique have been left out.

7.5 Results: predicted regression models

Relationship found for the cohesion
For the cohesion, the formula in equation 7.1 is proposed.

$$c = 49.85 \cdot e^{\frac{Z_{fines}}{11.7}} \cdot DegrComp^{9.602} \qquad 7.1$$

The material properties can be reasoned well and have been found in literature as well.

Relationship for the k_1-value
For the k_1-value, the formula in equation 7.2 is proposed.

$$k_1 = -358 + 51.8 \cdot LN(Vol\,Dens\,Grains) - 0.431 \cdot D_{85} + 3.627 \cdot 10^{-2} \cdot C_{uniformity} \qquad 7.2$$

In equation 7.2, the volume density of the grains can be considered as an indicator for the composition of the material, influencing the k_1-value. The D_{85} value is an indication of the coarseness of the material. The coefficient of uniformity gives an indication of the characteristic of the grading curve.
It has not been expected that the regression technique opts for the volume density of the grains rather than the degree of compaction.

It can be observed that the standard errors of the coefficients of the predictors are fairly high, being an indication of the goodness-of-fit for the proposed model. The good correlation coefficient can be explained by the position of both some extreme values and the outliers. In the regression, the crushed masonry/crushed concrete of SWEERE has been left out of the dataset.

Applying the regression analysis on a reduced group of materials (mix granulates at several degrees of compaction only) did not improve the results.

Relationship between k_2 and k_1

For the cohesion, the formula in equation 7.3 is proposed.

$$k_2 = 0.65 \cdot e^{\left(\frac{C_{uniformity}}{34020} - \frac{k_1}{1542} - \frac{D_{PSDC-FC}}{76190}\right)} \quad 7.3$$

The $D_{(PSDC-FC)}$ can be considered as an indication of the capability to develop a very dense material skeleton, whereas the coefficient of uniformity gives the variation in coarseness of the grains.

Remarks

- It should always be taken into consideration that the absence of a good model fit by regression techniques, an expected correlation or relationship does not mean that such a fit or correlation does not exist at all. The regression analysis is or search for correlations has been applied on materials collected in the data set.
- One should take notice of the fact that many of the predictors (independent material variables) do contain a certain (measurement or determination) error. This influences the goodness of fit of the proposed regression models.

7.6 Conclusions

1. By means of KENLAYER, several road structures with varying asphalt layer thickness as well as varying subgrade stiffness have been evaluated. Special emphasis was placed on the modelling of the base layer for which both linear and non-linear elastic three-layer systems have been used. It has been demonstrated when taking into account the stress dependency in the unbound granular base course indeed the stress conditions in the road structure are being influenced, resulting in different predictions for pavement life.
   It can be concluded that use of simplified 'rules of thumb' to characterise the stiffness of the base should be discouraged. Such models do not allow taking into account the effect of the type of material, the stress conditions, and the degree of compaction.
   Since the compaction parameters that control the stress dependent behaviour are difficult to obtain, the relationships between k_1 and k_2 on mechanical and physical characteristics are welcome.

2. Relationships found in literature helped determining which parameters to involve in the regression in this study, but some of these relationships could not be found again in this data set.

3. Considering the data set as used in this study:
   The data set contains 53 different material samples with approximately 30 material and mechanistic parameters collected from different sources, adapted where necessary. Much attention has been paid to the collection of parameters of similar tendency (testing conditions and testing protocol). The search for density parameters has been emphasised. Missing mechanistic parameters, such as φ and c, have been substituted by other representative values ($\tau_{failure;\sigma 3=12kPa}$), but have not been involved in the regression procedures.
   The influence of cementation and carbonatation in time, resulting in time dependent stiffness, is avoided by collecting only data of material samples with an age of 0 or 3 days.

4. The data set contains some poor material properties. Many material properties show autocorrelation because of limited variation in grading curve properties.

5. For the cohesion as well as for the k_2-k_1 relationship, two fairly good fitting models have been proposed. See section 7.5.
   For the relationship found for the k_1-value, the statistical parameters indicate that the goodness-of-fit for the proposed model is not so good. The explanation for the good correlation coefficient found may be the position of both the extreme values and the outliers.

6. Filtering of the data set in order to do the regression analysis for a smaller selection of unbound granular materials did not give better results for all analysed mechanical parameters.

7. When using the relationships found for the mechanical properties, one should bear in mind the range of materials for which the proposed relationships are valid. Especially the grading curve of the material to be used should preferably be between the Upper Limit and Lower Limit of the grading curve.

7.7 Recommendations

- It is advised to consider other regression techniques, too. The introduction of dummy variables or a step by step regression technique might give different points of view on the data set or relationships to be found.

- Before applying regression analysis on a large data set, it is recommendable to start with a statistical experimental design program, in order to avoid obtaining a data set with low variation for some material properties.

- When executing laboratory tests in order to obtain material or mechanical parameters, it is advised to repeat the same test several times. By obtaining several observations, variation in measurement and measurement error can be reduced.

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APPENDICES

A UNBOUND GRANULAR MATERIALS: INVENTARISATION

A.1 Introduction

According to WRIGHT (1996, p. 410), soil might be defined as all the earth material, both organic and inorganic, that blankets the rock crust of the earth.
One of the most important facts regarding soils and soil deposits is their normal lack of homogeneity. Due to the more or less random process of their formation, soils vary greatly in their physical and chemical composition. However, soils derived from the same parent material under similar factors of geographic location, climate and topography will be very similar wherever they are found [WRIGHT 1996, p. 411].

In this appendix, several soil types will be explained concisely. Subsequently, the soil types to be analysed in this study, thus used in the base and sub-base of pavement constructions, will be described more elaborate.

A.2 General soil types

The theory presented in this section has been borrowed from WRIGHT (1996, pp. 411-412) and MOLENAAR (1991, pp. 6.4-6.6).

Sand and gravel

Sand and gravel are coarse-grained soil types possessing little or no cohesion and with the particle size ranging from 80 mm (in The Netherlands: 40mm) for coarse gravel to 0.08 mm (in The Netherlands: 0.063 mm) for fine sand (Figure A.1). They are readily identified by visual inspection and are distinguished by their relative stability under wheel loads when confined, by their high permeability, and by their low shrinkage and expansion in detrimental amounts with change in moisture content.
The term ‘gravel’ is usually applied to natural pit, river, or bank gravels consisting largely of rounded particles; ‘crushed gravel’ or ‘crushed stone’ is the term applied to the products of crushing larger rocks into gravel sizes.

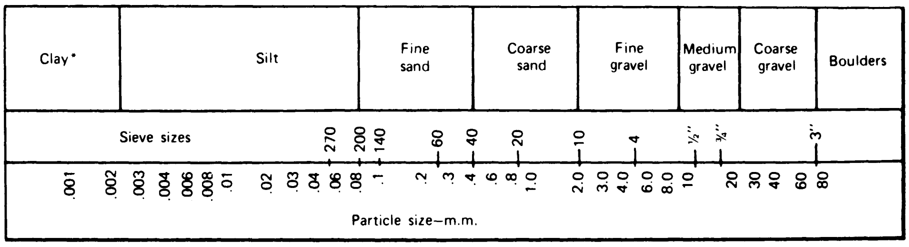


Figure A.1 Grain-size classification (AASHTO Specification M146.)

Silt

Silt is the term applied to fine-grained soils of low to medium plasticity, intermediate in size between sand and clay. Silt generally possess little cohesion, undergo considerable shrinkage and expansion with change in moisture content, and possess a variable amount of stability under wheel loads. If they contain large percentages of flat scalelike particles, such as mica flakes, they are likely to be highly compressible and somewhat elastic in nature.
Organic silts contain appreciable amounts of decomposed organic matter and are generally highly compressible and unstable.

Clay

Clays are distinguished by the occurrence of very fine grains of 0.002 mm or finer. Clays generally possess medium to high plasticity, have considerable strength when dry, undergo extreme changes in volume with change in moisture content, and are practically impervious to the flow of water.
'Lean clay' is the term given to silty clays or clayey silts, while fine, colloidal clays of high plasticity are called 'fat clays'.
Clays may be further distinguished by the fact that, although they may possess considerable strength in their natural state, this strength is sharply reduced and sometimes completely destroyed when their natural structure is disturbed, that is, when they are remoulded.

Loam

Loam is an agricultural term used to describe a soil that is generally fairly well graded from coarse to fine (Table A.1), that is easily worked, and that is productive of plant life.

Fraction	Range
Clay	< 2 μm
Fine silt	2 – 20 μm
Coarse silt	20 – 63 μm
Sand	63 μm – 2 mm

Table A.1 Equally graded fraction portions for loam [after Molenaar, 1991]

In engineering this name frequently appears in combination with other terms: a soil may be called 'sandy loam', a 'silty loam', or a 'clay loam', depending on the size of the predominating soil fraction. The bearing capacity of loam when wet is high, however decreasing strongly when the moisture content is increasing.

Loess

Loess is a fine-grained aeolian soil characterised by its nearly uniform grain size, predominantly silt, and by its low density. 50% of the particle sizes is between 10 and 50 μm. Loam mainly consists of the minerals given in Table A.2.

Mineral	Percentage [%]
Quartz	50 – 75
Veldspaat	10 – 25
Chalk	10 – 30
Clay particles	0 – 5

Table A.2 Equally graded fraction portions for loam [after Molenaar, 1991]

Muck

Muck is soft or silt clay, very high in organic content, which is usually found in swampy areas and river or lake bottoms.

Peat

Peat is a soil composed principally of partially decomposed vegetable matter. Its extremely high water content, woody nature, and high compressibility make it an extremely undesirable foundation material.

A.3 Conventional base course material

Graded crushed rock/stone

Graded crushed rock/stone is a typical base course material in both temperate and tropical areas. One method of producing this material is by quarrying the parent rock and processing consisting of crushing and sometimes screening by crusher plants. The material usually termed as 'crusher-run' may be separated in different particle fractions by sieving, and recombined to produce a desired particle size distribution. Another method is by crushing and screening natural granular material, rocks, or boulders [KISIMBE 1999, p. 13].

Experience has shown that there is a large variability of quality of material from place to place, rock to rock and within the same quarry, or borrow pit. To ensure that the materials are durable, apart from meeting the required grading, some empirical tests are performed to determine their resistance to mechanical degradation.

Blast furnace slag

Slag is a residue in the process of pig iron and other furnace processes. Depending on the way in which the hot residue from the blast furnace process is cooled down, different types of slag are obtained. Slow cooling produces a high-density coarse slag, which is processed in a crusher plant to obtain the desired grading [SWEERE 1990, p. 32].

Although blast furnace slag is in fact a recycled material, some countries like the Netherlands are considering it as a conventional base course material.

A.4 Recycled material

Increasing attention has been paid in a number of developed countries to the recycling of waste products to obtain road construction material.

In most cases, it is supported by governmental policies, which give high priority to recycling of waste product instead of dumping them as landfill. This is born out of the fact that

- the waste products still have a certain quality that can be used;
- dumping fees are high;
- natural resources are getting more scarce;
- concern for the environmental sustainable development.

Regarding unbound granular road bases, recycled materials originate from demolition waste from roads, buildings and engineering structures. During the demolition process, care is taken to separate stony material from wood, paper, plastic etc [SWEERE 1990, p. 33]. Further separation is undertaken in the course of

crushing process, by a number of separation technology [LEVEFRE & VAN NIEKERK 1998, annexes].
The stony materials are processed in a crusher plant to obtain granulates with the required particles size distribution. Depending on the origin of the demolished structure, masonry, concrete or mixed granulates can be obtained after processing.

Crushed concrete
Crushed concrete is produced from demolished concrete structures, and should consist of at least 80% by mass of gravel concrete or crushed stone concrete.
In the Dutch RAW, i.e. Dutch Specifications for Road Construction [CROW 2000, pp. 446-450], maximum amounts for impurities like other broken stony material, asphalt, wood and plastic are given as well as a maximum for the amount of flaky particles. The particles should have a dry unit weight of at least 2100 kg/m^3.

The material shows a high stability and a fairly high stiffness and strength which can increase in time, due to a cementing carbonation process. It is applied in road construction as a base course material and in concrete industry as an aggregate for concrete. In road construction a 0/40 mm grading is mostly used [VAN BEERS & VAN NIEKERK 1998].

Crushed masonry
A much weaker material than crushed concrete is crushed masonry, produced by crushing masonry rubble (bricks plus mortar). It should consist of at least 85% by mass of broken masonry and other crushed stone or stony material.
The particles should have a dry unit weight of at least 1600 kg/m^3. Limiting values are specified for impurities like plastic, wood and asphalt concrete as well as for the amount of flaky particles.

In its pure form this material is only used in minor roads. The material has a low stiffness, comparable to that of sand, and shows a low resistance to abrasion and impact. Because of the relative large quantities available and the need to apply it in a useful way, it is often upgraded by mixing with an equal amount of crushed concrete to get mixed granulate [VAN BEERS & VAN NIEKERK 1998].

Mix granulate
Mixed granulate is produced by mixing at least 50% and at most 80% [m/m] crushed concrete with crushed masonry. It may contain at most 10% of other sorts of crushed stone or stony material.
Again limiting values are specified for all kind of impurities and amount of flaky particles.

The engineering properties of this material are in between those of crushed concrete and crushed masonry.

Nowadays it is also quite common to add hydraulically active materials, which as a consequence of their cementing activity can result in materials with higher strength and stiffness. Hydraulically active additives are typically several types of slag, which result from the production of steel and phosphor. The mixture of mix granulate and hydraulic slag gives a so-called hydraulic mix granulate.

According to VAN BEERS & VAN NIEKERK (1998), mix granulates and hydraulic mix granulates at present constitute about 80% of the unbound and lightly bound granular base courses applied in the Netherlands.

B CALCULATIONS WITH KENLAYER

B.1 Theory

B.1.1 Determination of the Young's modulus of unbound materials

To obtain the (stress dependent) resilient modulus for an unbound granular base, instead of static and cyclic load triaxial testing, three other empirical approaches for determination of the Young's modulus are very common.

In two of these approaches material characteristics are not of any influence on the modulus of the substructure. Both the thickness of the base course and the modulus of the subgrade are of importance.
In the third approach however, the material properties, e.g. degree of compaction and moisture content, are incorporated by means of the introduction of the stress dependent resilient modulus.

In equation B.4 a well-known relationship for the Young's modulus of the subgrade or sub-base is given:

$$E_{subgrade} = 10 \cdot CBR \qquad B.4$$

Where:
$E_{subgrade}$: Dynamic modulus of elasticity of the subgrade [N/mm^2]
CBR : Californian Bearing Ratio [%]

B.1.2 Material independent, focussed on E modulus subgrade: one formula

In the first material independent approach, the Young's modulus of an unbound layer is directly based on the Young's modulus of the underlying layer.

According to the Shell Pavement Design Manual, the Young's modulus of unbound layers can be obtained by equations B.5 and B.6.

$$E_{base} = 0.206\, h_{base}^{0.45}\, E_{sub\text{-}base} \qquad B.5$$

$$E_{sub\text{-}base} = 0.206\, h_{sub\text{-}base}^{0.45}\, E_{subgrade} \qquad B.6$$

Where:
$2 < 0.206\, h^{0.45} < 4$
h Thicknes of the layer [mm]
E Dynamic modulus of elasticity of the underlying layer [N/mm^2]

B.1.3 Material independent, focussed on E modulus subgrade: differentiation

In the second material independent approach, the Young's modulus of the substructure is directly derived from the Young's modulus of the subgrade. The thickness of the (sub-)base is not contributing to the Young's modulus of the layer.

The unbound layer under consideration (either sub-base or base) is divided in an equally thick upper and lower part, to give a differentiation to the Young's modulus, decreasing with the depth. See equations B.7 and B.8.

$$E_{lower\ part\ sub\text{-}base} = 2 \cdot E_{subgrade} \tag{B.7}$$

$$E_{upper\ part\ sub\text{-}base} = 2 \cdot E_{lower\ part\ sub\text{-}base} \tag{B.8}$$

The same kind of equations (B.7 and B.8) can be used for the base course versus the sub-base.

B.1.4 Material and stress dependent: Multi-layered linear elastic theory

Based on the original work done by Burmister on two layered systems, rapid developments have been made for a method that allow stresses and strains to be calculated throughout the entire layered pavement system [MOLENAAR 1993 p. 6].

To obtain the stress dependent resilient modulus of unbound materials, the M_r-θ equation B.9 is of importance:

$$M_r = k_1\left(\frac{\theta}{\theta_0}\right)^{k_2} \tag{B.9}$$

Where

- M_r resilient modulus [MPa]
- θ sum of the principal stresses [kPa]
- θ_0 reference stress of 1 kPa [kPa]
- k_1 material parameter [MPa]
- k_2 material parameter [-]

See appendix E as well.

B.2 KENLAYER multi-layer Program

The KENLAYER program has been developed by HUANG (1993) and can be applied only to flexible pavements with infinite layers in the horizontal direction. The backbone of KENLAYER is the solution for an elastic multilayer system under a circular loaded area. The solutions are superimposed for multiple wheels, applied iteratively for non-linear layers, and collocated at various times for visco-elastic layers. As a result, KENLAYER can be applied to layered systems under different wheel configurations with each layer behaving differently, linear elastic, non-linear elastic, or visco-elastic. Moreover several sets of material properties can be run one after the other. Both U.S. customary units and SI units can be used, as long as it is consistent. [HUANG 1993, pp. 100-115]

B.3 Sensitivity analysis

Consider Figure B.2, where the pavement structure with its characteristics and varying stiffnesses and asphalt layer thicknesses is given.

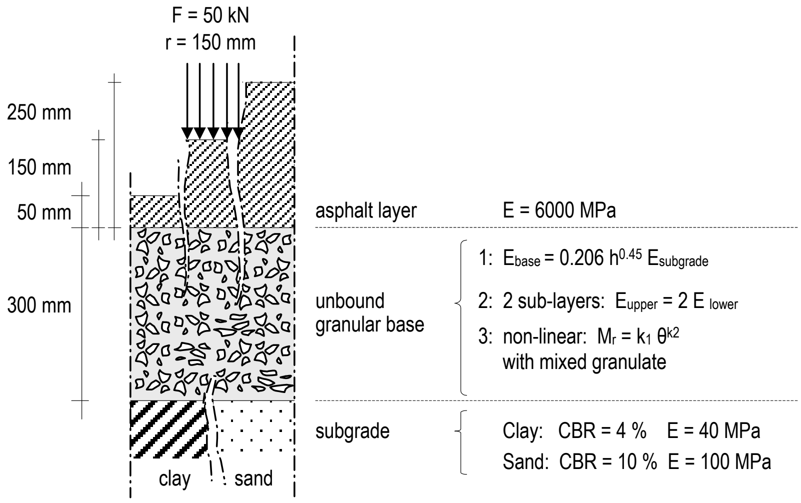


Figure B.2 Pavement structures as evaluated with Kenlayer.

For calculations with non-linear elastic three-layer systems, the material properties of the unbound granular base are required. In this case mixed granulate with three different densities and crushed masonry have been evaluated:

1. commercially graded mix granulate of crusher plant at Zestienhoven, The Netherlands, with density 95% of the Maximum Proctor Density, MPD (MG16H 95);
2. commercially graded mix granulate with density 100% MPD (MG16H 100);
3. commercially graded mix granulate with density 105% MPD (MG16H 105);
4. crushed masonry with density 100% MPD (CM 100)

See Table B.3 for k_1 and k_2 values as well as the specific gravity, Poisson's ratio and earth pressure at rest (k_0).

	Density [%]	Spec.Grav. [kN/m³]	k_1 [MPa]	k_2 -	v -	k_o -
MG16H 95	95	18.05	29.15	0.362	0.35	1.5
MG16H 100	100	19.00	26.77	0.356	0.35	1.5
MG16H 105	105	19.95	40.21	0.384	0.35	1.5
CM 100	100	19.00	18.3	0.43	0.35	1.5

Table B.3 Properties of unbound granular base materials

The commercially graded mix granulates with varying density have been analysed by KISIMBI (1999, pp. 84-88) at the Road and Railway Research Laboratory of Delft University of Technology. Note that, as found by KISIMBI, the resilient modulus of MG 16H 100 is substantially lower than both MG 16H 95 and MG 16H 105, which is remarkable and unexpected. This will result in deviant results calculated with

KENLAYER. See Figure B.3 for a graphical explanation of the results obtained by KISIMBI.

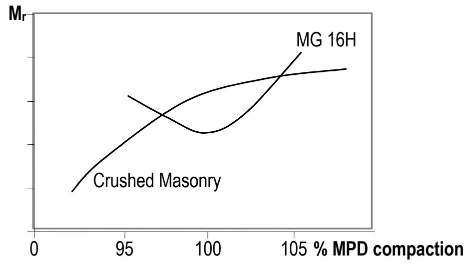
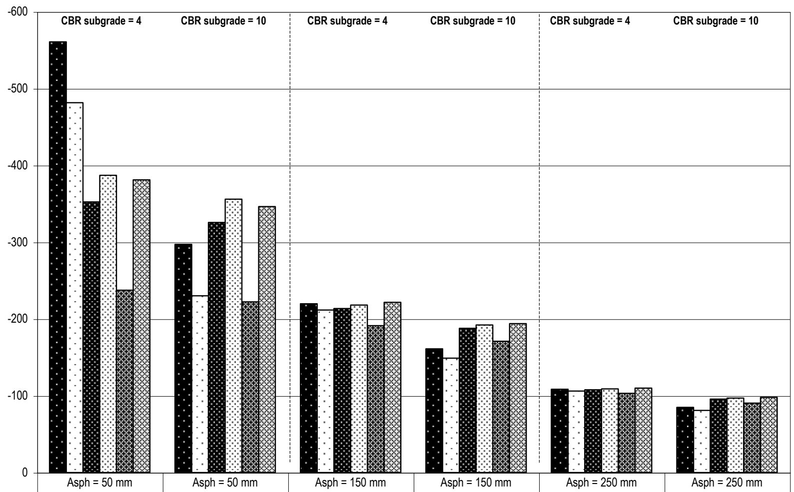


Figure B.3 Resilient modulus characteristics for mixed granulates found by KISIMBI.

The figures below are some graphical results of the KENLAYER calculations. These figures comprise:

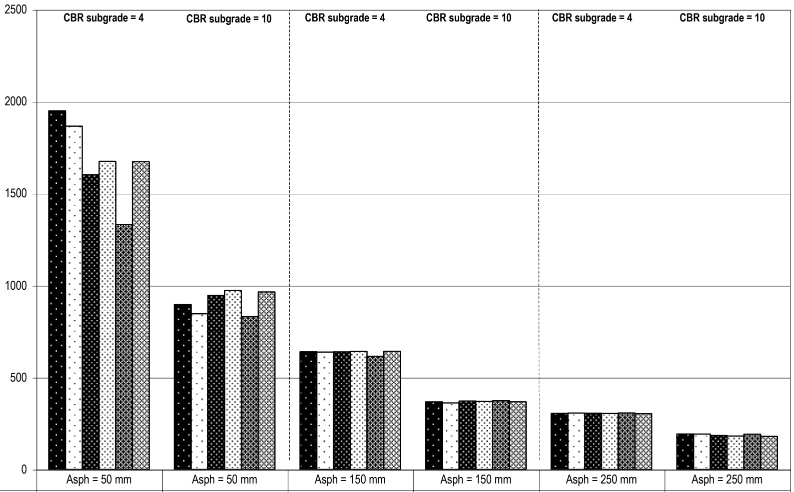
- the calculated horizontal strain at the bottom of the asphalt layer, where results with the same thickness for the asphalt layer are grouped together;
- the calculated vertical compressive strain at the top of the subgrade, where results with the same thickness for the asphalt layer are grouped together;
- the shear stress value for a road structure with a certain thickness of the asphalt layer calculated for several interesting depths. In these figures the results are grouped by stiffness of the subgrade.

All stress and strain values are valid for the centre of a 50 kN wheel load. A negative stress or strain value means a tensile stress or strain, while a positive value means a compressive stress or strain.



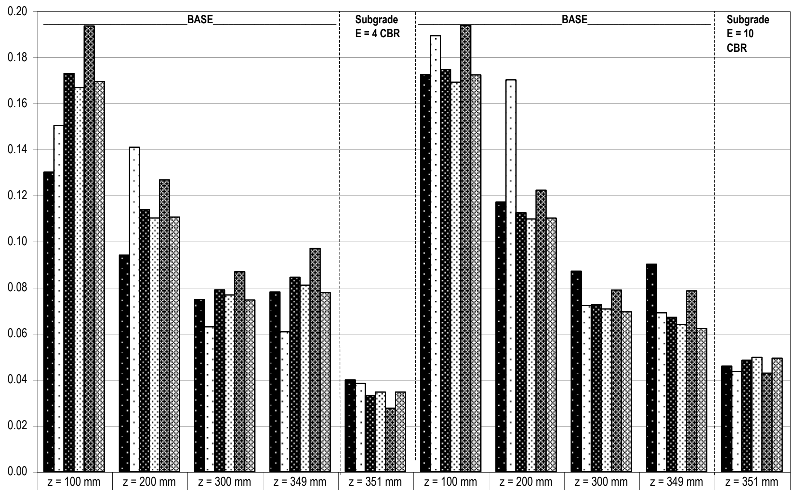
	Asph = 50 mm	Asph = 50 mm	Asph = 150 mm	Asph = 150 mm	Asph = 250 mm	Asph = 250 mm
method 1 Mixed Granulate 100%	-560.7	-297.1	-219.7	-161	-108.4	-84.9
method 2 Mixed Granulate 100%	-481.5	-230.1	-211.5	-148.9	-106.1	-80.93
method 3 Mixed Granulate 95%	-352.3	-325.6	-213.5	-187.8	-107.7	-95.65
method 3 Mixed Granulate 100%	-387	-355.9	-218.1	-192.1	-108.9	-96.94
method 3 Mixed Granulate 105%	-237.4	-222.2	-191.2	-170.9	-103.1	-90.39
method 3 Crushed Masonry 100%	-381.1	-346.2	-221.6	-193.9	-109.9	-97.83

Figure B.4 Horizontal strain [µm/m] at the bottom of the asphal layer



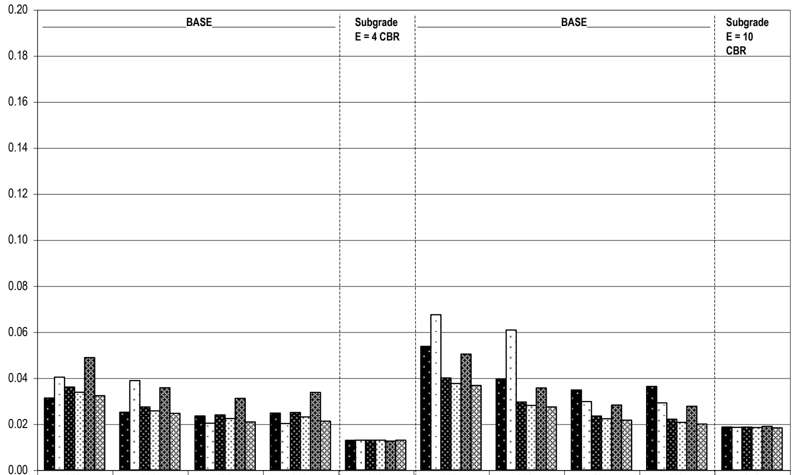
	Asph = 50 mm	Asph = 50 mm	Asph = 150 mm	Asph = 150 mm	Asph = 250 mm	Asph = 250 mm
method 1 Mixed Granulate 100%	1949	895.8	639.6	367.5	304.8	192.9
method 2 Mixed Granulate 100%	1866	846.1	637.9	361.6	306.5	192.4
method 3 Mixed Granulate 95%	1602	946.3	639.4	371.9	305.7	184.4
method 3 Mixed Granulate 100%	1675	972.8	641.4	369.4	304.4	181.8
method 3 Mixed Granulate 105%	1332	831	614.9	373.6	307.2	191.4
method 3 Crushed Masonry 100%	1673	964.8	642.1	367.8	302.8	179.6

Figure B.5 Vertical strain [μm/m] at the top of the subgrade



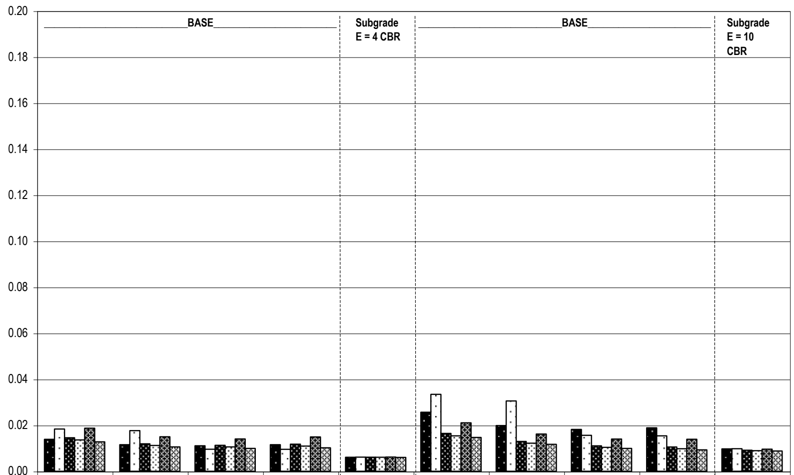
	z = 100 mm	z = 200 mm	z = 300 mm	z = 349 mm	z = 351 mm	z = 100 mm	z = 200 mm	z = 300 mm	z = 349 mm	z = 351 mm
method 1 Mixed Granulate 100%	0.1301	0.0940	0.0747	0.0780	0.0398	0.1725	0.1171	0.0870	0.0901	0.0458
method 2 Mixed Granulate 100%	0.1503	0.1409	0.0628	0.0607	0.0383	0.1893	0.1702	0.0721	0.0689	0.0435
method 3 Mixed Granulate 95%	0.1730	0.1137	0.0789	0.0844	0.0331	0.1747	0.1124	0.0725	0.0670	0.0484
method 3 Mixed Granulate 100%	0.1668	0.1101	0.0767	0.0810	0.0345	0.1692	0.1097	0.0706	0.0638	0.0496
method 3 Mixed Granulate 105%	0.1936	0.1267	0.0868	0.0970	0.0275	0.1938	0.1223	0.0788	0.0785	0.0428
method 3 Crushed Masonry 100%	0.1695	0.1106	0.0745	0.0778	0.0345	0.1723	0.1101	0.0694	0.0622	0.0493

Figure B.6 Shear stress (τ) at different depths (z) where $h_{asphalt}$ = 50 mm



	z = 200 mm	z = 300 mm	z = 400 mm	z = 449 mm	z = 451 mm	z = 200 mm	z = 300 mm	z = 400 mm	z = 449 mm	z = 451 mm
method 1 Mixed Granulate 100%	0.0312	0.0251	0.0235	0.0247	0.0129	0.0537	0.0395	0.0347	0.0363	0.0187
method 2 Mixed Granulate 100%	0.0403	0.0388	0.0203	0.0202	0.0129	0.0674	0.0608	0.0297	0.0291	0.0185
method 3 Mixed Granulate 95%	0.0360	0.0274	0.0239	0.0250	0.0129	0.0400	0.0295	0.0234	0.0220	0.0186
method 3 Mixed Granulate 100%	0.0337	0.0257	0.0223	0.0230	0.0129	0.0376	0.0280	0.0222	0.0207	0.0184
method 3 Mixed Granulate 105%	0.0488	0.0357	0.0311	0.0337	0.0125	0.0503	0.0356	0.0282	0.0277	0.0189
method 3 Crushed Masonry 100%	0.0323	0.0246	0.0209	0.0212	0.0129	0.0367	0.0274	0.0216	0.0199	0.0183

Figure B.7 Shear stress (τ) at different depths (z) where $h_{asphalt}$ = 150 mm



	z = 300 mm	z = 400 mm	z = 500 mm	z = 549 mm	z = 551 mm	z = 300 mm	z = 400 mm	z = 500 mm	z = 549 mm	z = 551 mm
method 1 Mixed Granulate 100%	0.0139	0.0115	0.0111	0.0116	0.0061	0.0256	0.0199	0.0182	0.0189	0.0098
method 2 Mixed Granulate 100%	0.0183	0.0177	0.0096	0.0095	0.0062	0.0334	0.0306	0.0156	0.0154	0.0098
method 3 Mixed Granulate 95%	0.0146	0.0120	0.0113	0.0118	0.0061	0.0164	0.0130	0.0111	0.0106	0.0091
method 3 Mixed Granulate 100%	0.0136	0.0112	0.0106	0.0109	0.0061	0.0154	0.0122	0.0104	0.0098	0.0090
method 3 Mixed Granulate 105%	0.0187	0.0150	0.0140	0.0149	0.0062	0.0210	0.0162	0.0140	0.0139	0.0096
method 3 Crushed Masonry 100%	0.0128	0.0106	0.0099	0.0102	0.0060	0.0147	0.0117	0.0099	0.0093	0.0088

Figure B.8 Shear stress (τ) at different depths (z) where $h_{asphalt}$ = 250 mm

In the tables below, the direct results of KENLAYER are given, revealing calculated strains, stresses, and shear stresses at several levels in the given road structure.

The data are grouped by stiffness of the subgrade and by the asphalt layer thickness.

Asphalt layer = 50 mm

Subgrade = 4 CBR			method 1 Mixed Granulate 100%	method 2 Mixed Granulate 100%	method 3 Mixed Granulate 95%	method 3 Mixed Granulate 100%	method 3 Mixed Granulate 105%	method 3 Crushed Masonry 100%
z = 49 mm	ε radial	[μm/m]	-560.7	-481.5	-352.3	-387	-237.4	-381.1
z = 49 mm	σ radial	[N/mm²]	-4.9680	-4.2200	-2.9950	-3.3230	-1.9050	-3.2680
z = 100 mm	σ vertical	[N/mm²]	0.3032	0.3094	0.3502	0.3406	0.3827	0.3394
z = 100 mm	σ radial	[N/mm²]	0.0430	0.0088	0.0042	0.0071	-0.0044	0.0004
z = 100 mm	τ	[N/mm²]	0.1301	0.1503	0.1730	0.1668	0.1936	0.1695
z = 200 mm	σ vertical	[N/mm²]	0.1733	0.1547	0.1691	0.1687	0.1699	0.1662
z = 200 mm	σ radial	[N/mm²]	-0.0147	-0.1271	-0.0584	-0.0516	-0.0835	-0.0549
z = 200 mm	τ	[N/mm²]	0.0940	0.1409	0.1137	0.1101	0.1267	0.1106
z = 300 mm	σ vertical	[N/mm²]	0.0953	0.0883	0.0796	0.0824	0.0695	0.0818
z = 300 mm	σ radial	[N/mm²]	-0.0540	-0.0374	-0.0782	-0.0710	-0.1041	-0.0673
z = 300 mm	τ	[N/mm²]	0.0747	0.0628	0.0789	0.0767	0.0868	0.0745
z = 349 mm	σ vertical	[N/mm²]	0.0748	0.0705	0.0597	0.0626	0.0495	0.0624
z = 349 mm	σ radial	[N/mm²]	-0.0813	-0.0509	-0.1091	-0.0993	-0.1444	-0.0931
z = 349 mm	τ	[N/mm²]	0.0780	0.0607	0.0844	0.0810	0.0970	0.0778
z = 351 mm	σ vertical	[N/mm²]	0.0742	0.0700	0.0593	0.0621	0.0491	0.0619
z = 351 mm	σ radial	[N/mm²]	-0.0054	-0.0067	-0.0069	-0.0069	-0.0059	-0.0071
z = 351 mm	τ	[N/mm²]	0.0398	0.0383	0.0331	0.0345	0.0275	0.0345
z = 351 mm	ε vertical	[μm/m]	1949	1866	1602	1675	1332	1673

Subgrade = 10 CBR			method 1 Mixed Granulate 100%	method 2 Mixed Granulate 100%	method 3 Mixed Granulate 95%	method 3 Mixed Granulate 100%	method 3 Mixed Granulate 105%	method 3 Crushed Masonry 100%
z = 49 mm	ε radial	[μm/m]	-297.1	-230.1	-325.6	-355.9	-222.2	-346.2
z = 49 mm	σ radial	[N/mm²]	-2.4650	-1.8320	-2.7390	-3.0270	-1.7580	-2.9360
z = 100 mm	σ vertical	[N/mm²]	0.3992	0.3975	0.3728	0.3636	0.4035	0.3637
z = 100 mm	σ radial	[N/mm²]	0.0542	0.0189	0.0234	0.0253	0.0159	0.0191
z = 100 mm	τ	[N/mm²]	0.1725	0.1893	0.1747	0.1692	0.1938	0.1723
z = 200 mm	σ vertical	[N/mm²]	0.2167	0.1881	0.2009	0.2003	0.2005	0.1980
z = 200 mm	σ radial	[N/mm²]	-0.0175	-0.1522	-0.0239	-0.0191	-0.0440	-0.0222
z = 200 mm	τ	[N/mm²]	0.1171	0.1702	0.1124	0.1097	0.1223	0.1101
z = 300 mm	σ vertical	[N/mm²]	0.1121	0.1021	0.1138	0.1167	0.1018	0.1154
z = 300 mm	σ radial	[N/mm²]	-0.0620	-0.0421	-0.0311	-0.0245	-0.0559	-0.0233
z = 300 mm	τ	[N/mm²]	0.0870	0.0721	0.0725	0.0706	0.0788	0.0694
z = 349 mm	σ vertical	[N/mm²]	0.0855	0.0798	0.0903	0.0934	0.0781	0.0925
	σ radial	[N/mm²]	-0.0946	-0.0580	-0.0437	-0.0343	-0.0788	-0.0319
z = 349 mm	τ	[N/mm²]	0.0901	0.0689	0.0670	0.0638	0.0785	0.0622
z = 351 mm	σ vertical	[N/mm²]	0.0848	0.0792	0.0896	0.0926	0.0775	0.0918
z = 351 mm	σ radial	[N/mm²]	-0.0068	-0.0078	-0.0072	-0.0066	-0.0080	-0.0067
z = 351 mm	τ	[N/mm²]	0.0458	0.0435	0.0484	0.0496	0.0428	0.0493
z = 351 mm	ε vertical	[μm/m]	895.8	846.1	946.3	972.8	831	964.8

Asphalt layer = 150 mm

Subgrade = 4 CBR			method 1 Mixed Granulate 100%	method 2 Mixed Granulate 100%	method 3 Mixed Granulate 95%	method 3 Mixed Granulate 100%	method 3 Mixed Granulate 105%	method 3 Crushed Masonry 100%
z = 149 mm	ε radial	[μm/m]	-219.7	-211.5	-213.5	-218.1	-191.2	-221.6
z = 149 mm	σ radial	[N/mm²]	-1.9860	-1.9060	-1.9260	-1.9710	-1.7080	-2.0050
z = 200 mm	σ vertical	[N/mm²]	0.0620	0.0648	0.0651	0.0623	0.0791	0.0601
z = 200 mm	σ radial	[N/mm²]	-0.0005	-0.0158	-0.0069	-0.0052	-0.0185	-0.0045
z = 200 mm	τ	[N/mm²]	0.0312	0.0403	0.0360	0.0337	0.0488	0.0323
z = 300 mm	σ vertical	[N/mm²]	0.0415	0.0398	0.0420	0.0411	0.0457	0.0403
z = 300 mm	σ radial	[N/mm²]	-0.0086	-0.0378	-0.0127	-0.0102	-0.0256	-0.0088
z = 300 mm	τ	[N/mm²]	0.0251	0.0388	0.0274	0.0257	0.0357	0.0246
z = 400 mm	σ vertical	[N/mm²]	0.0290	0.0283	0.0288	0.0289	0.0280	0.0288
z = 400 mm	σ radial	[N/mm²]	-0.0179	-0.0123	-0.0191	-0.0158	-0.0342	-0.0129
z = 400 mm	τ	[N/mm²]	0.0235	0.0203	0.0239	0.0223	0.0311	0.0209
z = 449 mm	σ vertical	[N/mm²]	0.0254	0.0249	0.0251	0.0253	0.0236	0.0254
z = 449 mm	σ radial	[N/mm²]	-0.0240	-0.0155	-0.0249	-0.0208	-0.0438	-0.0170
z = 449 mm	τ	[N/mm²]	0.0247	0.0202	0.0250	0.0230	0.0337	0.0212
z = 451 mm	σ vertical	[N/mm²]	0.0253	0.0247	0.0250	0.0252	0.0235	0.0253
z = 451 mm	σ radial	[N/mm²]	-0.0004	-0.0011	-0.0009	-0.0007	-0.0015	-0.0005
z = 451 mm	τ	[N/mm²]	0.0129	0.0129	0.0129	0.0129	0.0125	0.0129
z = 451 mm	ε vertical	[μm/m]	639.6	637.9	639.4	641.4	614.9	642.1

Subgrade = 10 CBR			method 1 Mixed Granulate 100%	method 2 Mixed Granulate 100%	method 3 Mixed Granulate 95%	method 3 Mixed Granulate 100%	method 3 Mixed Granulate 105%	method 3 Crushed Masonry 100%
z = 149 mm	ε radial	[μm/m]	-161	-148.9	-187.8	-192.1	-170.9	-193.9
z = 149 mm	σ radial	[N/mm²]	-1.4140	-1.2940	-1.6790	-1.7210	-1.5120	-1.7390
z = 200 mm	σ vertical	[N/mm²]	0.1045	0.1089	0.0821	0.0790	0.0946	0.0775
z = 200 mm	σ radial	[N/mm²]	-0.0028	-0.0260	0.0021	0.0038	-0.0061	0.0041
z = 200 mm	τ	[N/mm²]	0.0537	0.0674	0.0400	0.0376	0.0503	0.0367
z = 300 mm	σ vertical	[N/mm²]	0.0651	0.0610	0.0572	0.0562	0.0610	0.0556
z = 300 mm	σ radial	[N/mm²]	-0.0139	-0.0606	-0.0018	0.0001	-0.0102	0.0008
z = 300 mm	τ	[N/mm²]	0.0395	0.0608	0.0295	0.0280	0.0356	0.0274
z = 400 mm	σ vertical	[N/mm²]	0.0420	0.0403	0.0423	0.0422	0.0422	0.0421
z = 400 mm	σ radial	[N/mm²]	-0.0274	-0.0190	-0.0045	-0.0022	-0.0142	-0.0011
z = 400 mm	τ	[N/mm²]	0.0347	0.0297	0.0234	0.0222	0.0282	0.0216
z = 449 mm	σ vertical	[N/mm²]	0.0357	0.0344	0.0373	0.0374	0.0365	0.0374
z = 449 mm	σ radial	[N/mm²]	-0.0369	-0.0238	-0.0067	-0.0039	-0.0189	-0.0025
z = 449 mm	τ	[N/mm²]	0.0363	0.0291	0.0220	0.0207	0.0277	0.0199
z = 451 mm	σ vertical	[N/mm²]	0.0355	0.0343	0.0372	0.0372	0.0363	0.0372
z = 451 mm	σ radial	[N/mm²]	-0.0018	-0.0027	-0.0001	0.0004	-0.0015	0.0006
z = 451 mm	τ	[N/mm²]	0.0187	0.0185	0.0186	0.0184	0.0189	0.0183
z = 451 mm	ε vertical	[μm/m]	367.5	361.6	371.9	369.4	373.6	367.8

Asphalt layer = 250 mm

Subgrade = 4 CBR			method 1 Mixed Granulate 100%	method 2 Mixed Granulate 100%	method 3 Mixed Granulate 95%	method 3 Mixed Granulate 100%	method 3 Mixed Granulate 105%	method 3 Crushed Masonry 100%
z = 249 mm	ε radial	[μm/m]	-108.4	-106.1	-107.7	-108.9	-103.1	-109.9
z = 249 mm	σ radial	[N/mm²]	-0.9838	-0.9613	-0.9776	-0.9890	-0.9320	-0.9993
z = 300 mm	σ vertical	[N/mm²]	0.0250	0.0261	0.0255	0.0245	0.0292	0.0237
z = 300 mm	σ radial	[N/mm²]	-0.0028	-0.0106	-0.0037	-0.0027	-0.0083	-0.0019
z = 300 mm	τ	[N/mm²]	0.0139	0.0183	0.0146	0.0136	0.0187	0.0128
z = 400 mm	σ vertical	[N/mm²]	0.0179	0.0174	0.0180	0.0177	0.0192	0.0174
z = 400 mm	σ radial	[N/mm²]	-0.0052	-0.0179	-0.0059	-0.0048	-0.0108	-0.0038
z = 400 mm	τ	[N/mm²]	0.0115	0.0177	0.0120	0.0112	0.0150	0.0106
z = 500 mm	σ vertical	[N/mm²]	0.0136	0.0134	0.0136	0.0136	0.0136	0.0135
z = 500 mm	σ radial	[N/mm²]	-0.0086	-0.0058	-0.0090	-0.0076	-0.0145	-0.0064
z = 500 mm	τ	[N/mm²]	0.0111	0.0096	0.0113	0.0106	0.0140	0.0099
z = 549 mm	σ vertical	[N/mm²]	0.0123	0.0122	0.0123	0.0123	0.0121	0.0123
z = 549 mm	σ radial	[N/mm²]	-0.0108	-0.0069	-0.0112	-0.0096	-0.0178	-0.0081
z = 549 mm	τ	[N/mm²]	0.0116	0.0095	0.0118	0.0109	0.0149	0.0102
z = 551 mm	σ vertical	[N/mm²]	0.0123	0.0121	0.0122	0.0123	0.0121	0.0123
z = 551 mm	σ radial	[N/mm²]	0.0001	-0.0002	0.0000	0.0001	-0.0003	0.0002
z = 551 mm	τ	[N/mm²]	0.0061	0.0062	0.0061	0.0061	0.0062	0.0060
z = 551 mm	ε vertical	[μm/m]	304.8	306.5	305.7	304.4	307.2	302.8

Subgrade = 10 CBR			method 1 Mixed Granulate 100%	method 2 Mixed Granulate 100%	method 3 Mixed Granulate 95%	method 3 Mixed Granulate 100%	method 3 Mixed Granulate 105%	method 3 Crushed Masonry 100%
z = 249 mm	ε radial	[μm/m]	-84.9	-80.93	-95.65	-96.94	-90.39	-97.83
z = 249 mm	σ radial	[N/mm²]	-0.7531	-0.7131	-0.8613	-0.8741	-0.8086	-0.8831
z = 300 mm	σ vertical	[N/mm²]	0.0451	0.0471	0.0340	0.0328	0.0392	0.0319
z = 300 mm	σ radial	[N/mm²]	-0.0062	-0.0198	0.0012	0.0020	-0.0028	0.0025
z = 300 mm	τ	[N/mm²]	0.0256	0.0334	0.0164	0.0154	0.0210	0.0147
z = 400 mm	σ vertical	[N/mm²]	0.0302	0.0289	0.0260	0.0254	0.0280	0.0250
z = 400 mm	σ radial	[N/mm²]	-0.0095	-0.0322	0.0001	0.0010	-0.0044	0.0016
z = 400 mm	τ	[N/mm²]	0.0199	0.0306	0.0130	0.0122	0.0162	0.0117
z = 500 mm	σ vertical	[N/mm²]	0.0214	0.0208	0.0208	0.0206	0.0212	0.0205
z = 500 mm	σ radial	[N/mm²]	-0.0150	-0.0104	-0.0013	-0.0001	-0.0068	0.0006
z = 500 mm	τ	[N/mm²]	0.0182	0.0156	0.0111	0.0104	0.0140	0.0099
z = 549 mm	σ vertical	[N/mm²]	0.0189	0.0185	0.0190	0.0189	0.0191	0.0188
z = 549 mm	σ radial	[N/mm²]	-0.0189	-0.0123	-0.0022	-0.0007	-0.0088	0.0002
z = 549 mm	τ	[N/mm²]	0.0189	0.0154	0.0106	0.0098	0.0139	0.0093
z = 551 mm	σ vertical	[N/mm²]	0.0188	0.0184	0.0189	0.0188	0.0190	0.0187
z = 551 mm	σ radial	[N/mm²]	-0.0007	-0.0012	0.0006	0.0009	-0.0002	0.0011
z = 551 mm	τ	[N/mm²]	0.0098	0.0098	0.0091	0.0090	0.0096	0.0088
z = 551 mm	ε vertical	[μm/m]	192.9	192.4	184.4	181.8	191.4	179.6

C RESEARCH OVERVIEW

C.1 Research made by Van Niekerk

The study of VAN NIEKERK (1995) was part of the overall Ph.D. research program of HUURMAN (1997). In the study by VAN NIEKERK an attempt has been made to relate (complex) material behaviour to material properties determined from simple material testing, such as grading, grain shape (sharpness), hardness (crushing resistance), etc.
The aim of the study was to make it possible to establish the material behaviour required for a fundamental pavement design in a way accessible for road engineering practice.

The study has proven that it is very well possible to establish much more insight in material behaviour from mainly simple material tests, which are since long very common practice in road engineering.

VAN NIEKERK has tested sands and base materials with respect to:

- compactibility (MPD and OMC);
- strength (cohesion and angle of internal friction);
- elastic deformation behaviour (M_r and μ);
- permanent deformation behaviour (ε_p).

Various types of material behaviour can be explained from a limited number of material properties which can be determined by simple material tests. These properties are:

- particle size distribution;
- grain shape (angularity);
- crushing resistance;
- specific gravity;
- moisture-suction characteristics.

For the compactibility, the strength, and the elastic deformation behaviour, the found correlations cover well the full range of investigated sands and base materials. With respect to permanent deformation behaviour for the base materials, no correlation has been found. This might be attributed to the limited number of base materials tested and the complexity of the permanent deformation behaviour model which accompanies the base materials.

All relations found by VAN NIEKERK have been determined by means of (non) linear regression analysis. The correlations accurately predict the behaviour of the materials. The relations are only applicable on the materials under consideration. The number of materials however is restricted. These materials have been named after the street from which the sample material has been taken. See Table C. 4 below.

Sands:	Base materials
Allan	Allan
Weiver	Max Havelaar
Baars	Cor Bruin
Max Havelaar	Pascal
Zaan	
Cor Bruin	
Pascal	
Split	

Table C. 4 Materials investigated by VAN NIEKERK

The study of VAN NIEKERK has proven to be thoroughly but again, only applicable on the materials under consideration. Others tests have shown that when examining other base materials and sands, e.g. originating materials from South Africa, the models found by VAN NIEKERK could not easily be validated.

Findings by VAN NIEKERK of relevance for this study are described in chapter 3.

C.2 Research made by Kisimbi

The study of KISIMBI (1999) has been conducted as part of the Ph.D. research project of VAN NIEKERK. It has been attempted to correlate the mechanical behaviour of unbound and lightly bound granular road building materials to material condition (density, moisture content, etc.) and physical material properties (particle size distribution, composition, particle shape and texture) [KISIMBI 1999, pp. 122-124].
Therefore VAN NIEKERK conducted mechanical tests on materials varying with respect to influence factors which are perceived to affect the mechanical behaviour.

KISIMBI investigated the mechanical behaviour of mix granulates in relation to material quality (composition) an construction practice (degree of compaction, curing time and loading conditions).
The mechanical behaviour has been determined from both empirical and more fundamental material testing. The material testing involved the following tests:

1. CBR tests which relates to the strength and to a lesser degree to the bearing capacity of granular materials. Although the test is empirical and does not yield fundamental mechanical parameters it is still the most commonly applied test for UGMs and design procedures based upon it are thus validated from a vast amount of experience.
2. Cyclic load triaxial tests and monotonic loading triaxial tests from which fundamental mechanical behaviour, i.e. failure, resilient and permanent deformation behaviour of UGMs is established under conditions of loading, grading, density and moisture content much more closely simulating the actual conditions in a pavement.
3. Monotonic loading triaxial tests under single stage and multistage testing procedures to compare the results of the two different testing procedures and evaluate whether multistage testing can be an alternative to the “conventional” procedure of single stage testing.

For single stage testing (SST), a minimum of three specimens have to be tested to establish the failure behaviour, whereas for multistage tests (MST) the failure behaviour of an UGM can be determined from testing of one specimen

Both empirical and simple to perform tests have been used by KISIMBI. The major obstacle for general application of fundamental mechanical behaviour of unbound granular materials is the complexity and costs of the tests required establishing such stress dependent fundamental mechanical material behaviour.

The mix granulates have been composed to a grading providing an average within the Dutch grading envelop for granular base course material. The compositions and grading of the mix granulates were obtained from sieved fractions of concrete and masonry granulates crushed by a jaw crusher.

To investigate the influence of composition in relation to curing time and loading conditions on the resilient deformation behaviour:

- CBR and triaxial specimens have been composed to three mix compositions (50%-50%, 65%-35% and 80%-20% mass ratio of concrete to masonry granulates) similar to the lower, average and upper boundary of the Dutch specification for mix granulate composition.
- Tests have been performed on different curing times (0, 7, 14, and 28 days)
- Cyclic load triaxial tests have been performed on different specimens under mild (σ_c/σ_3-ratio limited to 6-8) and severe loading conditions. In the latter beginning of permanent deformation is observed.

To investigate the influence of relative compaction on the mechanical behaviour the specimens have been compacted to 95%, 97.5%, 100%, 102.5% and 105% of the maximum proctor density.

Observations made by KISIMBI of importance for this study are described in chapter 3 (Literature survey).

C.3 Research of Lefevre

This study (1998) too was part of VAN NIEKERKs Ph.D. research program “Establishing and modelling of fundamental behaviour of unbound road buildings materials and the correlation with material properties derived from simple material tests” (2002).

The objective of LEFEVRES study was to establish the influence of the compactibility of mix granulate in relation to physical material properties and to investigate the influence of the compaction method on the compactibility of mix granulates.

Therefore, the influence of the particle size distribution, affecting the compactibility enormously, has been investigated by means of numerical simulation. Furthermore the influence of the grading on compactibility of unbound granular materials has been numerically investigated.

Based on the literature survey and the numerical simulation the main parameters influencing the compactibility have been selected, being the particle size distribution, particle shape, and composition.

By using two different types of crushers (impact crusher and jaw crusher) LEFEVRE has obtained four basic granulates (two concrete and two masonry granulates) sieved in various sequential fractions in order to compose mix granulates of all desired particle size distributions, compositions and to introduce crusher type related differences in particle shape. The influence of the crushing method could not be demonstrated in the study.
The compactive behaviour has been analysed, based on different methods to determine the density of an unbound material. The influence of the particle size distribution and composition on the density has been established by means of regression analysis.
The execution of triaxial tests on mix granulates, (extremely) differing in particle size distribution only, showed that continuously graded materials show better resilient deformation behaviour than uniformly graded materials. Calculations with Kenlayer revealed that only extreme difference in grading, i.e. continuously graded and uniformly graded mix granulates, shows a difference in allowable number of load repetitions of a factor 2 for the normative horizontal asphalt strain design criterion.

C.4 Research performed by Muraya

The study of MURAYA (2000) was also part of the Ph.D. research of VAN NIEKERK. MURAYA's study deals with the permanent deformation behaviour of mix granulates applied as road base material in relation to specific material properties and compaction. To this end, a large amount of large scale triaxial tests have been performed on different mix granulates (grading and composition) at different degrees of compaction.
In addition, resilient deformation tests and failure tests have been performed to completely characterise the fundamental stress dependent mechanical behaviour of such base materials. By doing so, MURAYA succeeded in a sound mechanistic analysis of the performance of pavement structures with such base course materials.
The gradings used by MURAYA are:

- **UL**: finest allowable grading corresponding to the upper limit of the Dutch specification for granular base course materials;
- **LL**: coarsest allowable grading corresponding to the lower limit of the Dutch specification.
- **AL**: average of gradings UL and LL.

The elaborate study made by MURAYA is ended by many conclusions divided in accordance to the different types of mechanical behaviour tested, i.e. failure behaviour, resilient deformation and permanent deformation behaviour.
Where of relevance, conclusions of MURAYA have been placed in chapter 3.

D PROPERTIES OF AGGREGATES

D.1 Introduction

The term ‘aggregate’ refers to granular mineral particles that are widely used for highway bases, subbases, and backfill. Aggregates are also used in combination with a cementing material to form concretes for bases, subbases, and wearing surfaces. Sources of aggregates include natural deposits of sand and gravel, pulverised concrete and asphalt pavements, crushed stone, and blast-furnace slag [WRIGHT 1996, p. 430]. (See appendix A as well)

The most important properties of aggregates used for highway construction are:

- particle size and gradation;
- hardness or resistance to wear;
- durability or resistance to weathering;
- specific gravity and absorption;
- chemical stability;
- particle shape and surface texture;
- freedom from deleterious particles or substances.

The purpose of this appendix is to discuss the properties of relevance in the paragraphs below. The sections below have been restricted to the properties particularly used in, and of relevance for this study. The theory has mainly been based on WRIGHT (1996, pp. 412-415), HUANG (1993, pp. 316-317), and VAN NIEKERK (1995, pp. 17-40).

D.2 Particle size distribution

A grain-size analysis is used to determine the relative proportions of various particle sizes in a mineral aggregate mix. The grain-size data are usually plotted in a graph ordered by increasing particle size. This is called a particle size distribution curve. With the aid of the particle size distribution curve (PSDC) various parameters can be determined, describing or related to the grading, coarseness, range of particle sizes etc. See section D.3 of this appendix. It is assumed that these parameters can be used to explain:

- the achievable density such as (Modified) Maximum Proctor Density (see appendix E);
- the (Modified) Optimum Moisture Content (idemque);
- the failure behaviour: cohesion (c) and the angle of internal fraction (ϕ) (idemque);
- the elastic deformation behaviour (idemque);
- the permanent deformation behaviour (chapter 3 section 3.3).

Figure D.9 shows three particle size distributions curves. These curves represent the Dutch upper (UL) and lower (LL) limits of the grading envelope. The particle size distribution curve for each applied base course material has to be situated in between both limits. An average curve (AL) has been depicted as well.

In this study, it has been referred to these curves as well, since most of the materials analysed correspond to one of these three curves.

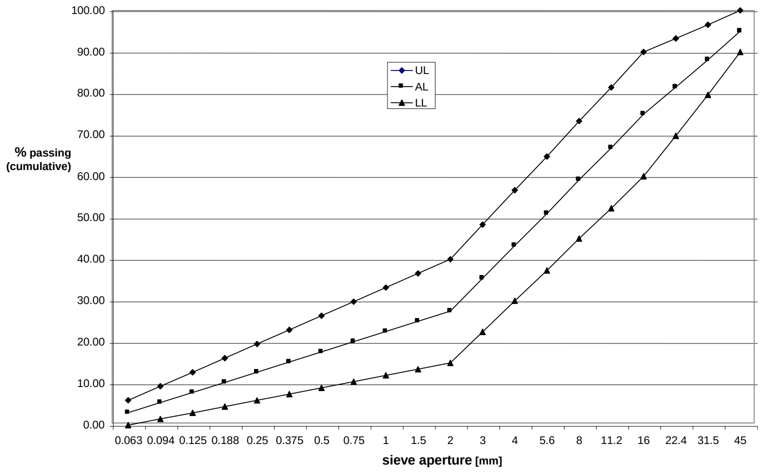


Figure D.9 Particle size distribution curve of an average distribution curve (AL) within the upper (UL) and the lower (LL) limits as prescribed in The Netherlands.

D.2.1 Sieve analysis

The aim of a sieve analysis is to obtain more insight into the particle size distribution of a granular material. The mass of particles retained on each sieve with specific sieve aperture is expressed as a percentage of the total mass of particles. Usually sieve analysis results are presented as particle size distribution curve (PSDC), see Figure D.9.

Sieve analysis test results have a wide range of practical application and are commonly used in:

- **Soil classification**: The particle size distribution and its parameters described in section D.3 are used as important input in different soil classification systems:
    - ♦ Unified Soil Classification System (USCS);
    - ♦ AASHTO;
    - ♦ Federal Aviation Agency FAA;
    - ♦ The Dutch SCW classification of sand.
- **Determination of engineering properties of soil**: Although the classification of soils is a manner of describing a certain type of soil in respect to the classification system used, the main purpose is to determine its engineering properties.
  With the use of an “engineering chart” it is possible to evaluate the suitability of a material for a specific engineering application such as a filter layer, drainage layer, fill material or as road pavement layer.
- **Composing material to a required PSDC**: Sieve analysis results are used effectively to compose different fractions of granular material or two or more

different granular materials together to comply with a specified PSDC. Accordingly, the required engineering properties should be provided.

- **Correlating PSDC parameters to material behaviour**: Apart from mineralogical composition, strongly related with the parent rock and the chemical environment, many factors influence the mechanical behaviour of the soil. Among these, the particle size and the particle size distribution can easily be deduced from sieve analysis test results.
  VAN NIEKERK [1995] and HUURMAN have already attempted to correlate the mechanical behaviour of sand and mixed granulates to parameters of PSDC such as C_{ext}, C_{curv}, and C_{uni}. The result shows that a correlation exists between these parameters and material behaviour (simple and complex) such as void ratio, maximum proctor density, and optimum moisture content (chapter 3).

D.2.2 Fuller Curve

In the particle size distribution curve, the Fuller Curve or Talbot Curve can also be plotted. These curves describe the particle size distribution that results in the best possible packing (density), based on the material consisting of spheres with diameters corresponding to the sieve sizes. See equation D.10 for the Fuller equation.

$$P = 100 * \left(\frac{d}{D_{\max}} \right)^n \qquad D.10$$

Where:

- P percentage of particles finer than the sieve aperture *d* [%]
- d sieve aperture [mm]
- D_{max} maximum particle size [mm]
- n Talbot's factor

The shape of the Fuller Curve is defined by the Talbot exponent (*n*), with values in the range 0.4–0.5 for dense-graded roadbases, 1.5 or more for open-graded mixes, and around 0.3 for well-graded sands with an excess of fines [MCNALLY 1998, pp. 128-129].

The Talbot exponent *n* = 0.5 results in the densest mix of spherical shape. However, granular material always contains particles, which are not spherical. It has proven that the Fuller equation with *n* = 0.45 gives the densest mix of non-spherical particles. See Figure D.10.

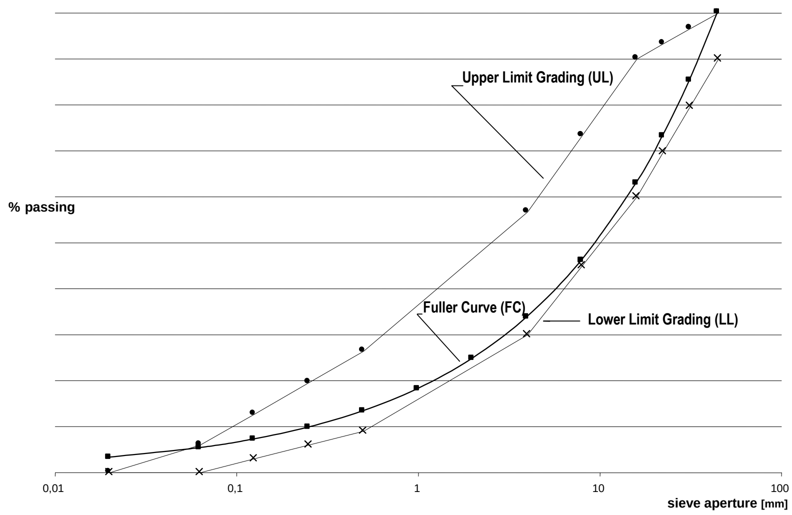


Figure D.10 Fuller Curve (n=0.45) together with the Upper Limit and Lower Limit grading.

D.3 Parameters related to grading

The parameters coefficients related to grading describe the general slope and shape of the distribution curve:

- coefficient of uniformity - C_{uni}
- coefficient of curvature - C_{curv}
- coefficient of extension - C_{ext}
- Skeletton coefficient - SC
- Z_{fine}: the percentage of (fine) particles passing the 63 μm sieve.
- D_{psdc} and A_{psdc}

The parameters above describe the ability of a material to achieve a certain degree of packing (compactibility, void ratio). This will be achieved by means of having a large variation in grain sizes, thus allowing all voids left between grains of a certain fraction to be filled by grains of smaller fractions.

All coefficients are briefly explained below. They have all been used in this study.

D.3.1 Coefficient of uniformity

The coefficient of uniformity (C_{uni}) is expressed as:

$$C_{uni} = \frac{D_{60}}{D_{10}} \qquad D.11$$

where:

D_x the sieve aperture [mm] through which x% mass of the material passes

Table D.5 gives a classification based on the Coefficient of Uniformity.

D_{60}/D_{10}	Classification
< 1.80	poorly graded
1.80 – 2.19	moderately graded
2.20 – 2.99	well graded
> 3.00	very well graded

Table D.5 Classification according to C_{uni} for sands [after VAN NIEKERK]

D.3.2 Coefficient of curvature

The coefficient of curvature may be defined in 2 ways:

$$C_{curv} = \frac{D_{30}^2}{D_{60} * D_{10}} \qquad D.12$$

or

$$C_{curv} = \frac{D_{50}^2}{D_{85} * D_{15}} \qquad D.13$$

D.3.3 Coefficient of extension

$$C_{ext} = \frac{D_{85}}{D_{15}} \qquad D.14$$

D.3.4 Skeletton Coefficient

Another aspect of the grading of a material is the potential of a material to develop a grain skeleton. A parameter to quantify the potential for skeleton development has been introduced by VAN NIEKERK (1995, p. 27) as the skeleton coefficient (SC). The SC, for instance $SC_{(60\text{-}10)}$ is defined as:

$$SC_{(60\text{-}10)} = \frac{(D_{60} - D_{10})}{(D_{60} + D_{10})/2} \qquad D.15$$

The denominator (D_{60}-D_{10}) in equation D.15 describes the width of the range of important fractions within the material, whether it is uniform or well graded. The nominator ((D60+D10)/2 makes the value of the denominator relative: a uniformly graded fine material and a uniformly graded coarse material can both build up a skeleton having equal values of SC after all.

The value of $SC_{(60\text{-}10)}$ for e.g. some Dutch sands range from:

- 0.6 – 0.7: sands which are uniform and fine, these materials can develop a reasonable skeleton of fine grains;
- 0.9 – 1.3: sands which are well graded with fine and coarse grains resulting in an inability to develop a skeleton;
- > 1.5: particularly for the crushed sands, these sands are not only very well graded but mainly consist of dominant coarse fractions (D_{50}>>) as well. Hence these materials may develop a reasonable skeleton with coarse grains.

Another skeleton coefficient (SC) with different specific fractions is given in equation D.16.

$$SC_{(85\text{-}15)} = \frac{(D_{85} - D_{15})}{(D_{85} + D_{15})/2} \qquad D.16$$

Note that while examining sand the skeleton coefficient should not be assessed by itself. VAN NIEKERK indicates that permanent deformation of sand is affected by the ability to develop a skeleton as well as the shearing resistance.

D.3.5 Fuller Curve fitting: D_{psdc} and A_{psdc}

According to VAN NIEKERK (1995, p. 24), another parameter might also be related to the grading of the unbound material particles. This parameter describes how much the Particle Size Distribution Curve (PSDC) of a material deviates from its Fuller Curve (FC). The parameter is based on the assumption that the closer the PSDC of a material is set to the FC, the better the grading of the material will be.

VAN NIEKERK (1995, p. 24) introduces two ways of quantifying the deviation between the two curves mentioned above:

1. Adding up the absolute values of the distances (h_i) on the 'percentage passing' scale at each sieve aperture between the Particle Size Distribution Curve and the Fuller Curve for a material:

   $D_{psdc} = |h_1| + |h_2| + \ldots + |h_7|$

2. Adding up the absolute values of the areas between the PDSC and the FC. These areas have been approximated by the product of the distance (h_i)on the 'percentage passing' scale between the PDSC and the FC and the corresponding distance (w_1)between the two successive sieves:

   $A_{psdc} = |h_1 * w_1| + |h_2 * w_2| + \ldots + |h_7 * w_7|$

3. Moreover, in this study the A_{psdc} has been refined to $A_{psdc,middle}$:

   $A_{psdc,middle} = |(h_1+h_2)/2 * w_1| + |(h_2+h_3)/2 * w_2| + \ldots + |(h_6+h_7)/2+ * w_7|$

D.4 Resistance to wear: Crushing Factor

D.4.1 Resistance to wear in general

Materials used in highway pavements should be hard and should resist wear due to the loading from compaction equipment, the polishing effects of traffic, and the internal abrasive effects of repeated loadings.

The most commonly accepted measure of the hardness of aggregates is the Los Angeles abrasion test. The machine used in the Los Angeles abrasion test consist of a hollow steel cylinder, closed at both ends and mounted on shafts in a horizontal position.

Various tests other tests are available as well to determine the resistance of aggregates against degradation:

- Aggregate Impact Value Test;
- 10% Fines Value Test; measuring the resistance of a material against crushing as a result an impact load (dropping of a hammer);
- Dutch Crushing Resistance Test: measuring the resistance of a material against crushing as a result of a gradually increasing load [SWEERE 1990].

The Dutch Crushing Resistance test is more or less the same in procedure as the “10% Fines value test”, with exception on the determination of Crushing Factor (CF).

D.4.2 Calculation of the Crushing Factor

According to the Dutch RAW Standards [CROW 2000], material for testing has to be sampled from the dominant fraction of four fractions given in table 2.4. A representative sample is dried and a specified amount is put in a steel mould having a diameter 159.6 mm. After compacting the material by hand shaking, a full-faced steel plunger is used to load the material such that within 90 sec, the plungers load gradually increases to 20 kN and retained for a further 30 sec. The procedure is repeated four times after which the total material in the mould is recovered and sieved through 31.5, 16, 8, 4, 0.5, and 0.125 mm sieves. Material retained on each sieve including the material retained on the preceding sieves is determined. The fineness ratio (FR) of the material is calculated as the sum of retained amount divided by 100.

The crushing factor CF is then calculated as:

$$CF = \frac{fineness\ ratio}{n} \qquad D.17$$

where

n as given in Table D.6

Fraction [mm]	Factor n [-]
11.2 – 16	7.5
16.0 – 22.4	8
22.5 –31.5	8.5
31.5 – 45.0	9.0

Table D.6 Fraction and n-factor used in Dutch Crushing Resistance test [CROW,2000]

D.4.3 Weighted Crushing Factor

In the weighted average crushing factor, the weight assigned to the CF-value of each fraction is in accordance with the distribution of the fractions. The weighted Crushing Factor ($CF_{weighted}$) is not specified in the RAW standards, where it is prescribed that the crushing factor is only determined for the dominant fraction.

D.5 Specific gravity

Specific Gravity (SG), as applied to soils, is the specific gravity of the dry soil particles or solids. The specific gravity is frequently determined by the pycnometer method, which is specified in test 60 of the Dutch RAW Standards [CROW 2000], the determination being relatively easy for a coarse-grained soil and more difficult for the finer soils. Values for the specific gravity refer to the ratio of the unit weight of soil particles to the unit weight of water at some known temperature (usually 4º C) and range numerically from 2.60 to 2.80.

The specific gravity is, amongst others, needed for calculating the void ratio of a sample and for determining the sharpness (VVS) of the material grains (see section D.7). It is defined as:

$$SG = \frac{mass\ of\ material}{volume\ of\ material} \qquad D.18$$

D.6 Particle shape

The roundness and the surface texture of the particles determine the shape of the particles. Considering an equal compactive effort and grading, round particles are able to get a greater compaction than angular particle [LEFEVRE 1998]. However, at higher compactive effort angular particles may produce higher densities than round particles.
The particle shape has not been taken into consideration in this study.

D.7 Grain shape: Volders Verhoeven Sharpness

The sharpness of base materials is thought to be an important material characteristic in road engineering. The sharpness is considered to influence the shearing resistance of a material [Study Centre for Road Construction 1979]. In the Dutch RAW specifications the sharpness is not specified as a material property.
Quantifying the sharpness of a material in an objective way is complex [VAN NIEKERK 1995, p. 33]. Methods based on visual (microscopic) inspection are inherently subjective, even if supported by fotographic records and fraction specification.

In general terms the sharpness of a material is related:

- **Grain shape**: This relates to the shape of the grain as a whole. A spherical grain is generally rated as round, i.e. lacking sharpness, whereas a grain without rounded edges is rated as sharp.
- **Grain surface**: The surface of a grain can vary from polished (non sharp) to edgy (sharp).
- **Grain diameter:** Small grains appear sharper than large grains when rolled between the fingers.

The rollability test is based on the principle that the speed with which a grain will roll from an inclined plane is influenced by the inclination, the grain size, the grain shape and the roughness of its surface. By specifying fractions, inclination, etc., the grain shape and surface can thus be quantified [Study Centre for Road Construction 1979].

Another method, based on the time required for a known amount of material to flow through a specific opening influenced by the gravity, is the outflow test according to the method developed by Volders and Verhoeven [Study Centre for Road Construction 1979]. This test uses a simple outflow test set-up, for which the material is divided into five fractions. The sharpness of the material in each of these

fractions is determined by measuring the falling velocity of two weighted quantities of each fraction.
This test results in the sharpness value of the specific fraction (VVS_i) and in sharpness for the material as a whole (VVS) as well. The lower this VVS, the more rounded the grains of the tested material are; the VVS relates the shape of the grains of the tested materials to the shape of two reference materials (glass pearls vs. reference crusher sand). The term VVS_{rinsed} is the parameter for granular materials where the material is rinsed to loosen the particles while the larger fractions are omitted.

Base materials
The nature of the base materials is completely different to that of the natural sands, regarding its components and characteristics. Base material conglomerations mainly consist of e.g. grains and masonry mortar.
Crushing the material with a rubber pestle as required for the Volders Verhoeven Test would disintegrate such conglomerations and essentially change the type of material. However, structures of interlocking grains not comprising an essential part of the material will exist as well.

E MECHANICAL PROPERTIES OF AGGREGATES

E.1 Introduction

In this appendix, the mechanical behaviour of unbound granular materials is described. The purpose for this is twofold:

1. to analyse the underlying mechanisms that might occur in granular base course materials;
2. like appendix D, to reveal and to describe the parameters of relevance needed and to gather for this study.

The sections below have been restricted to the properties particularly used in, and of relevance for this study.

It is mainly focussed on (optimum) compaction properties related to specific densities and on the resilient stiffness and deformation of base courses. These properties can be obtained by executing the Proctor test, the CBR test, and the static and cyclic triaxial test. These tests, explained below, are very common tests in road engineering. The Proctor and CBR test are described more thoroughly in the RAW standards [CROW 2000] as well.

For this appendix, much theory has been borrowed from WRIGHT (1996).

E.2 Compactive behavior of unbound granular materials

The compactive behaviour of unbound granular materials can be defined as the capacity of the material to consolidate and densify as a result of loss of internal pore space in response to the exertion of some form of compaction energy. The compaction energy is usually described in terms of the dry density that could be achieved for a certain amount of compaction effort being exerted on the material in a specific manner. This could be established by, amongst others, the standard and Modified AASHTO proctor tests (section E.3.1) or Vibratory compaction test.

The effects of stresses imposed by for instance traffic on roads and the self-weight of the fill, all can introduce changes in the orientation and packing of the solid particles, provided that they are not already formed into a dense pattern by the process of compaction. In addition, the effects of weathering caused by ingress of water, temperature variation, and chemical action, can all be reduced by the proper application of the compaction process to produce a fill with a sufficiently high value of density.
The achievement of these beneficial effects is brought about in the compaction process by the reduction of the void content in a material, which in turn reduces the

permeability to water, increases the shear strength of the soil, and increases resistance to settlement and other deformations.

Factors affecting the compactive behaviour of unbound granular base course material in situ are:

- **Particle size distribution**: a large variation in grain sizes is preferred.
- **Particle shape**: a raw texture lead to a large amount of inter granular contact areas and thus to a higher shearing resistance of the material. This will require increased compaction energy however, but the stiffness of the base course will be higher then.
- **Composition**
- **Moisture content**
- **Void content** which in turn reduces the permeability to water
- **Stiffness** of underlying medium.

E.3 Densities and moisture content

E.3.1 Proctor test

Practically every soil has an optimum moisture content at which the soil attains maximum density under a given compactive effort. R.R. Proctor first stated this fact in 1933.
In the laboratory, dynamic compaction is achieved by use of a freely falling weight impinging on a confined soil mass. This is called the Proctor test, compacting through an impact method. In the field similar compaction is secured through the use of rollers or vibratory compactors applied to relatively thin layers of soil during the construction process.

The aim of the Proctor test is to establish the relation between moisture content and the dry density for a granular sub-base or base material. During this test, the particles are being rearranged by dropping a hammer several times on the sample from a specified height in such a way that the volume of the voids is reduced.
By performing the test at different moisture contents, the optimum moisture content (OMC) can be found at which the Maximum Proctor Density (MPD) occurs. The relation between dry density and moisture content is often referred to as a 'Proctor curve', even when relating to compaction methods far removed from Proctor's method.

In laboratory, compaction is usually performed under what has come to be called 'Standard Proctor' or 'Standard AASHTO' methods. In recent years, heavier compaction equipment has come into widespread use with the result that under certain conditions a greater compactive effort may be required in the laboratory. An increased compactive effort that is frequently used is known as the 'Modified Proctor' or 'Modified AASHTO' compaction. The British Standards, however, refers to the two-compaction energy levels as "ordinary" and "heavy" compaction. Table E.7 shows standardised hammer weights and drop heights for AASHTO and BS, when using a CBR mould. The total compactive energy equals to the product of both the mass of hammer and the gravitational force and the drop height and the number of blows per layer and the number of layers as well. The test is described in the RAW [CROW, 2000] standards as well.

Type of test	Mass [kg]	Drop [mm]	Number of layers	Blows per layer
BS “normal / ordinary”	2.5	300	3	62
BS “heavy”	4.5	450	5	62
ASTM “standard”	2.5 (5.5 lb)	305 (12”)	3	61
ASTM “modified”	4.5 (10 lb)	457 (18”)	5	61

Table E.7 Different compaction methods for CBR mould

E.3.2 (Maximum) Proctor Density

From the moisture–density relations, maximum dry densities can be read and are commonly used as a reference density to control the achieved field density. The maximum values are referred to as Maximum Proctor Density (MPD) for the standard or ordinary compaction level, whereas Maximum Modified Proctor Density (MMPD) applies for modified or heavy compaction level. The corresponding moisture content (at maximum dry densities) is referred to as the Optimum Moisture Content (OMC). Increasing the compaction effort causes an increase of MPD, and a decrease of OMC, see Figure E.11 as well.

Influence of the composition on the density

The composition influences the density by means of the specific gravity of the components in an (mix) aggregate. An increase in specific gravity of the concerned components gives an increase in density at an equal void ratio and thus not necessarily an improvement of the mechanical behaviour.

E.3.3 Moisture Content

Water is an extremely important constituent of soils. The moisture content is defined as the weight of water contained in a given soil mass compared with the oven-dry weight of the soil and is usually expressed as a percentage.

Water in soils may be present in its normal liquid form, as when filling or partly filling the voids of a sand mass, or it may be present in the form of adsorbed water. It than exists as a film surrounding the separate soil particles or groups of particles, as in the case of the water remaining in a partially dried clay mass.
The water film existing in the latter case may have properties sharply differing from those exhibited by water in its normal form. Properties of fine-grained soils are greatly dependent on the properties and behaviour of the adsorbed water films.

E.3.4 Optimum Moisture Content

The typical relation between the dry density and moisture content is as shown in Figure E.11. It is obvious that as the moisture content increases, the dry density increases as well up to the Maximum Proctor Density (MPD) corresponding to the Optimum Moisture Content (OMC). Thereafter the dry density decreases asymptotically with the saturation line known as the Zero Air Void Density (ZAVD).

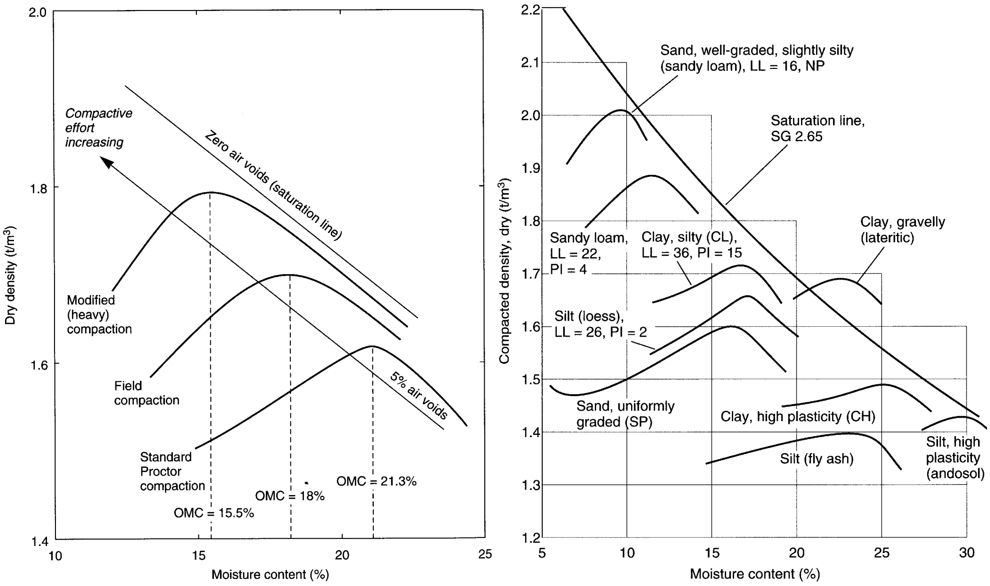


Figure E.11 Relation between the dry density and the moisture content (left) and several proctor compaction curves for different types of soil (right) [McNally, 1998]

Hence, the right moisture content is necessary for an effective compaction. The presence of water is believed to decrease the shear resistance between the particles by acting as lubricant so easing particle rearrangement. Compaction above the OMC may lead to squeezing out of fines together with water, which causes a change in particle size distribution, loss of material and segregation.
Some unbound granular materials do not have a distinct peak or rather optimum moisture content: LEFEVRE & VAN NIEKERK (1997) found that a number of distinctively different graded mixed granulates showed flat proctor relations.

For the unbound granular base materials it has been found that there is no optimum Proctor Density with one identical moisture content. For this reason, determing the Proctor Density at one single moisture content proved to be acceptable.
Comparing to the MPD, the SPPD is determined by using a different diameter (∅) for the sample mould and a different number of compaction strokes. However, the total amount of compaction energy applied per cubic millimetre is equivalent to the compaction energy required for the determination of the MPD.

E.3.5 Relationship between dry unit weight and moisture content

The unit weight of a soil is the weight of the soil mass per unit of volume, expressed in [kg/m^3].

The term ‘wet unit weight’ refers to the unit weight of a soil mass having a moisture content that is anything different from zero, whereas ‘dry unit weight’ refers to the unit weight of soil mass in an oven-dry condition. The wet unit weight, dry unit weight and moisture content are related according to equation E.19.

$$dry\,unit\,weight = \frac{wet\,unit\,weight}{\frac{(100 + w\%)}{100}} \qquad E.19$$

Where

w moisture content [%]

The wet unit weight of a soil may vary from 1440 kg/m^3 or less for saturated, organic soils to 2240 kg/m^3 or more for well-compacted granular materials.

E.4 Strength and stiffness of aggregates

Different laboratory tests are available for the determination of the strength of soil for engineering purposes. They vary from very simple to complicated tests providing empirical or fundamental behaviour parameters. The most widely and commonly used test for evaluation of strength of subgrade, subbase, and granular material in most parts of the world is the California Bearing Ratio test (CBR test).

E.4.1 California Bearing Ratio test

The development of the CBR test dates back to 1930 at the laboratory of the materials research department of the California Division. The American Society for Testing and Material (ASTM) and the British Standard (BS) adopted the test in 1944 and 1953 respectively.

Popularity and acceptability of the test worldwide is explained by the fact that:

- It can be applied to a wide variety of soil types ranging from clay to fine gravel ($d_{max} \leq 22.4$mm).
- The CBR value provides the input for empirical and empirical/mechanistic methods for the design of airfields as well as road pavements.
- It can be performed on disturbed or re-compacted materials.
- It can be performed in the field, or in the laboratory requiring rather simple equipment.
- The test is relatively simple and fast to conduct and gives an immediate result, which is easy to interpret.

However, the CBR test being an empirical test has the following practical deficiencies:

- Its test results are only applicable to pavement design with a procedure for which it has been devised, e.g. TRRL Road Note 31 in road pavement design.
- For its results to be valid and comparable, the standard procedure must be strictly adhered to.
- It does not give an insight in the fundamental mechanical behaviour of the material under consideration, which is needed for a mechanistic design approach.

E.4.2 Approximation of static failure

One characteristic soil property is that, as shear stress levels increases, the shear strain becomes progressively greater, leading to collapse if the shear stresses are too high.

As stated in chapter 2 section 2.3.3, parameters of influence for the maximum allowable shear stress are the cohesion (c) and the angle of internal friction (φ). For the large majority of soils, the shearing resistance on any plane is frequently, though somewhat empirically, given by Coulomb's law.

The Mohr Coulomb model for shear failure relates the shear strength (τ) and the normal stress (σ) according to equation E.20. However, equation E.20 can be rewritten to relate the failure stress ($\sigma_{1,f}$) as a function of the confining stress (σ_3), the cohesion (c) and angle of internal friction (φ) of the material according to equation E.21.

$$\tau = c + \sigma \tan\varphi \qquad E.20$$

$$\sigma_{1,f} = \frac{(1+\sin\varphi)\cdot\sigma_3 + 2\cdot c\cdot\cos\varphi}{1-\sin\varphi} \qquad E.21$$

The values of the cohesion and angle of internal friction can be determined by means of monotonic triaxial failure test. Basically, the monotonic triaxial failure test is a displacement controlled test that, at different levels of confining stress (σ_3), measures the axial stress in the specimen at which shear failure occurs. This is defined as the failure stress ($\sigma_{1,f}$) given in equation E.21.
The ratio of the maximum principal stress over the failure stress ($\sigma_1/\sigma_{1,f}$) describes the stress condition of a specimen in relation to its failure condition. This ratio $\sigma_1/\sigma_{1,f}$ is very important for describing both the resilient and the permanent deformation behaviour of unbound road base materials [HUURMAN 1997].

Deformations are limited if the shear stress on a specific plane is less than the critical value. If the shear stress on this plane reaches the critical value, deformations are unlimited and failure occurs. Mohr's circle can be used to graph stresses on differently oriented planes. A point on Mohr's circle represents the normal stress and the shear stress on a particular plane. For certain planes, the shear stress can be so great that Coulomb's failure condition is met.
Figure E.12 shows this failure condition. In the plane, represented by point D, the stress is just critical; in al other planes, it is sub-critical. This is called Mohr-Coulomb's failure criterion, and the theoretical position of point D is called the failure envelope.
If the stress circle falls completely within the failure envelope, no failure will occur; circles partly outside the envelope are impossible, as in some planes the shear stress will be greater than the critical shear stress [CUR (162) 1996, pp. 86-87].

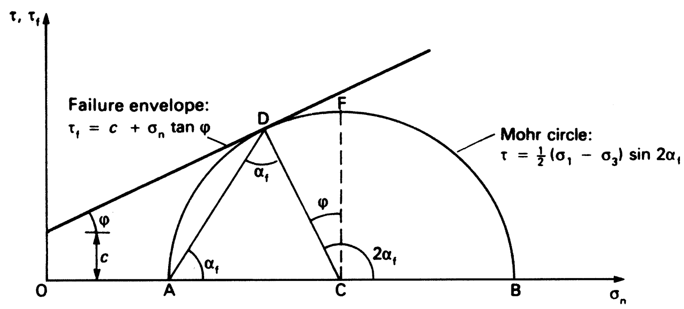


Figure E.12 Mohr Coulomb failure theory [WHITLOW, 2001]

See Figure E.12: From the geometry of the Mohr-Coulomb construction the angle of the plane of failure is:

$$\alpha_f = \frac{1}{2}(90° + \varphi) = 45° + \varphi/2 \qquad E.22$$

If a number of samples of the same soil can be brought to a state of shear slip failure or continuous yielding and the principal stresses (σ_1 and σ_3) are measured, the Mohr-Coulomb construction may be used to determine the failure envelope and thus the values for the parameters c and φ.
The stress conditions at failure (σ_3 and $\sigma_{1,f}$) can be described by drawing stress circles with centre point ½ ($\sigma_{1,f}$ + σ_3) and having a radius equal to ½ ($\sigma_{1,f}$ - σ_3). The cohesion (c) and angle of internal friction (φ) describe respectively the intercept value and the slope of this line [PARRY 1995, p. 28-30]. This has been illustrated schematically in Figure E.13.

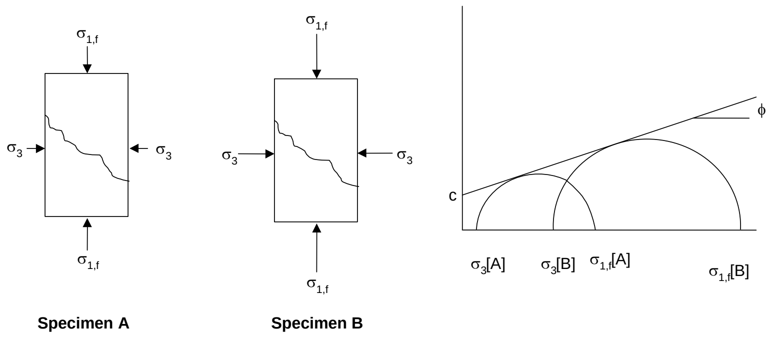


Figure E.13 Determination of the cohesion (c) and the angle of internal friction (φ), from static triaxial failure test [after VAN NIEKERK 1995]

Sands

For granular materials, such as sand, Mohr-Coulomb's criterion gives a reasonable insight into whether or not the material will fail [CUR (162) 1996, p. 89].

According to WRIGHT (1996, p. 414), for a dry sand, φ is primarily dependent on:

- density (void ratio): the lower the void ratio the higher the value of φ;
- grain shape;
- surface texture: φ is higher for a rough, angular sand than for a smooth, rounded sand having the same void ratio;
- gradation: with φ being generally higher for sands that are well graded from coarse to fine.

The angle of internal friction is relatively independent of the moisture content for sands; φ for a wet sand will be only slightly, if any, lower than φ for a dry sand, other conditions being the same.

E.4.3 Resilient deformation testing: static and cyclic triaxial tests

The resilient modulus represents the elasticity property of a soil and is more commonly used in pavement design. The resilient modulus is the elastic modulus based on the recoverable strain under repeated loads.

Pavement materials experience some permanent deformation after each load application. However, if the load is small compared to the strength of the material and is repeated for a large number of times, the deformation under each load repetition is nearly completely recovered and proportional to the load. The deformation may be considered as elastic.

Figure E.14 shows the straining of a specimen under a repeated load test. At the initial stage of load applications, there is considerable permanent deformation, as indicated by the plastic strain in the figure. As the number of repetitions increases, the plastic strain due to each load repetition decreases. After 100 to 200 repetitions, the strain is practically recoverable, as indicated by ε_r in the figure.

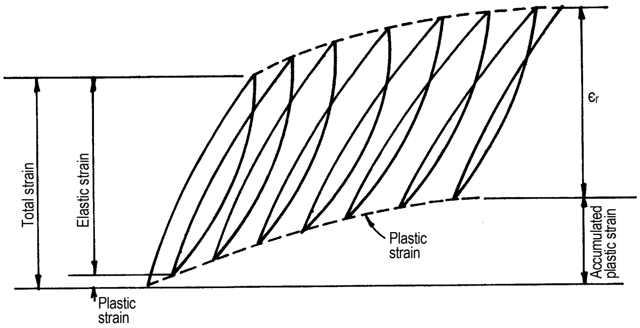


Figure E.14 Strains under repeated loads in granular pavement materials [HUANG 1993]

Static and cyclic load triaxial testing is required to determine this stress dependent resilient and permanent deformation behaviour of unbound sub base and base materials.
Triaxial testing of sub base materials, but especially coarser base materials, is very involving with respect to the equipment required, sample preparation, sample testing and data analysis and interpretation. Moreover, base materials show very large variations in the resilient modulus between labs when axial deformation is measured both outside and inside the triaxial cell. The coefficient of variation (CV) of resilient moduli, with careful equipment callibration, is as small as about 10.
For this reason triaxial testing and thus pavement design based on stress dependent behaviour of the inbound layers is by no means common practice in present road engineering [VAN NIEKERK 1995, p. 13].

With triaxial testing, an attempt is made to simulate the conditions as they occur in a pavement structure as closely as possible. In the pavement structure, a material will experience a constant confining stress (σ_3) because of overburden stress. Under traffic loading, the material will experience an axial stress resulting in axial and radial deformation and because of the latter, its radial deformation will experience an increase in σ_3.

Triaxial tests used to establish material deformation under such loading conditions have been conducted as either constant confining pressure (CCP) tests or as variable confining pressure (VCP) tests:

1. In CCP tests cyclic traffic induced component of σ_3 cannot be simulated; however, it does significantly affect the axial and radial deformations and thus the stiffness modulus (M_r) and Poisson's ratio (ν) of the material. In this test, σ_3 is set at a value somewhere in between simulating only overburden stress and simulating both overburden and traffic induced increase of confinement.
2. The VCP test is considered a closer simulation of reality. Here the confining stress is applied as both a constant component and a cyclic component in phase with the cyclic axial stress. Consequently, it simulates both the overburden stress and the traffic-induced increase of confinement.

VAN NIEKERK (1996) found that similar M_r values may be found if the constant σ_3 in the CCP test is equal to the mean of the cyclic value in the VCP test.

With the aid of the monotonic as well as the cyclic load triaxial test three types of mechanical behaviour can be determined:
1. The resilient deformation behaviour
2. The permanent deformation behaviour
3. The failure behaviour

Figure E.15 depicts a triaxial test apparatus.

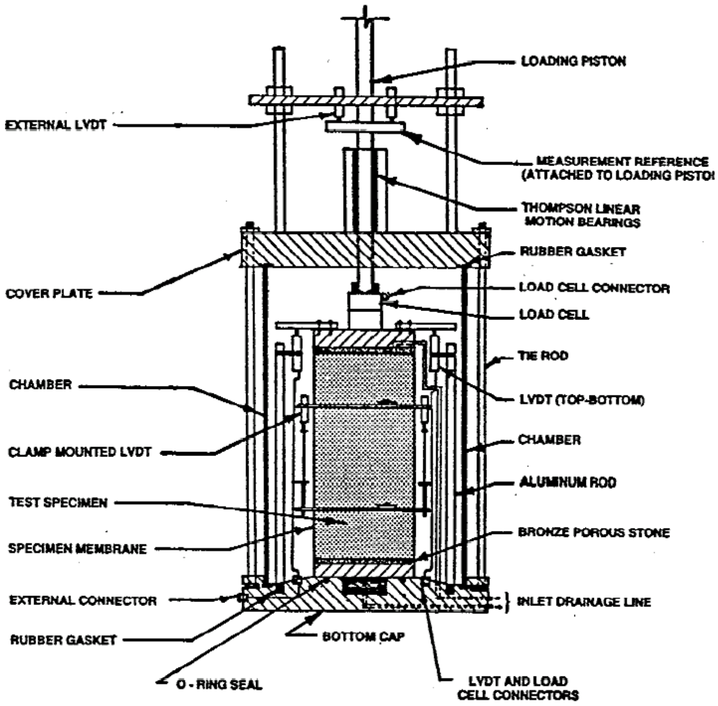


Figure E.15 Triaxial cell used to test base materials [BARKSDALE & KHOSLA 1997]

Determination of the resilient deformation behaviour

Because of the stress-dependent behaviour of unbound granular materials, the deformation behaviour has to be determined at a number of different stress levels and stress combinations. Cyclic load triaxial testing provides a means to apply stresses of different direction and magnitudes to a specimen and measure the resulting deformation.

Determination of the permanent deformation behaviour

The permanent deformation behaviour of unbound granular materials is very much affected by the loading history [SWEERE 1990]. Therefore, at each stress level a new specimen has to be tested to obtain the stress dependent permanent deformation behaviour. Each test usually involves a large number (10^5 or 10^6) of load applications (N) to each specimen, which results in a time-consuming test procedure. The aim of the test is thus to establish the development of the permanent deformation as a function of the number of load repetitions and as a function of the stresses. The deformation under each loading cycle consists of a resilient and a permanent part and the cumulative development of strain over 1000 load repetitions (N).

M_r-Theta model

The most commonly used model to describe the stress dependency of M_r is the M_r-θ model introduced by BROWN & PELL (1967, p. 487-504). For a well elaborate survey of granular material resilient modulus models (advanced models included) as well as cohesive subgrade soil resilient modulus models it is referred to BARKSDALE & KHOSLA (1997, p. 105-112).

The M_r-θ model describes the measured M_r data by a straight line when plotted against the sum of the principal stresses, θ, on a log-log scale. θ is made up of: (equation E.23)

$$\theta = \sigma_1 + \sigma_2 + \sigma_3 \qquad E.23$$

Where

The principal stress σ_1 consists of: (equation E.24)

$$\sigma_1 = \sigma_{conf} + \sigma_{cycl} + \sigma_{stat} + \sigma_{dw} \qquad E.24$$

Where

- σ_{conf} confining stress [kPa]
- σ_{cycl} maximum cyclic actuator stress [kPa]
- σ_{stat} static actuator stress [kPa]
- σ_{dw} static stresses as a result of dead weight [kPa]

In the Cyclic Load Triaxial Test the second principal stress (σ_2) equals the third principal stress (σ_3), therefore equation E.23 becomes equation E.25.

$$\theta = \sigma_1 + 2\sigma_3 \qquad E.25$$

The M_r-θ is given by equation E.26.

$$M_r = k_1 \left(\frac{\theta}{\theta_0} \right)^{k_2} \qquad E.26$$

Where

M_r resilient modulus [MPa]
θ sum of the principal stresses [kPa]
θ_0 reference stress of 1 kPa [kPa]
k_1 material parameter [MPa]
k_2 material parameter [-]

The model is widely used for its simplicity but is theoretically not correct. The model is not able to distinguish between the influences of the different stresses (σ_1 and σ_2=σ_3) on the material stiffness (M_r). Therefore it implies that the stiffness of a material increases with an increase of the first principal stress (σ_1), which is physically impossible. It suggests an infinite stiffness by increasing the θ as well, which is not realistic.
Better models for describing the M_r relate M_r to only the confining stress or to both the confining stress and the failure stress ($\sigma_{1,f}$). In this report, these models will not be discussed, since it has been found that the M_r-θ model can best describe the resilient modulus for granular unbound materials at lower σ_{conf} levels.
Other models, like the M_r-σ_3 model and the M_r-σ_3-σ_1 model do not fit the data better. The last of these models has been developed by HUURMAN (1997, p. 113) to describe the effect of a decreasing M_r with an increasing θ (thus increasing σ_1) at constant level of σ_{conf}. This effect will only occur for sands or for base materials at higher σ_{conf} levels. The latter will not occur in base courses with a thick asphalt layer situated above.

F ENTIRE DATA SET RETRIEVED IN THIS STUDY

F.1 Introduction

In this appendix the entire data set as collected in this study has been inserted.

The following remarks could be made:

- Some parameters have been calculated by means of other parameters in the same record. For instance, the D, $D_{(PSDC-FC)}$ and $A_{(PSDC-FC)}$ parameters have been calculated based on the sieve parameters. See also chapter 4;
- Fields in the records which could not be retrieved have been remained blank;
- Sample names (displayed in bold) do have the same nomenclature as used in previous studies from which most of the parameters originate;
- However not being used in this study, the records containing data of samples at the age of 28 days as established by Muraya and Kisimbi have been inserted as well. (last records at the end of this appendix)

F.2 Explanation for the nomenclature

As stated, the names of the samples do have the same nomenclature as used in previous studies. Where several codes are used simultaneously to specify a sample, the codes have been merged (Sweere).

Data originating from Van Niekerk

The samples of base materials obtained by Van Niekerk have been named after the street from which the sample material has been taken. The origin of the granular materials is sometimes unknown.

Data orignating from Sweere

For the names of the samples originating from Sweere the nomenclature used by Sweere has been combined with the description of the material, the group code, the material code, and sequence number of the sample. In the material code, some information about the grading is included. In the six-character coding-system of Sweere, the first two characters indicate the material tested and the third character the grading of the material tested. In this study, the fourth character is left out, giving information about the kind of triaxial test executed on the sample. The last two characters of the test-code indicate the sequence number of the particular test.

For instance, the sample *Crushed Gravel CO5 GGB01* (where GGB01 is Sweere's coding-system) is crushed gravel from group code *C05* and material code *GGB*. The sequence number of the sample from which the parameters are established is *01*.

Data originating from Kisimbi and Muraya

The sample names as used by Kisimbi include information about the grading curves (G1, G4, G5), composition of the base material, type of crusher used, and percentage of compaction of the sample material.
For instance, the sample *G1CJ/MJ65/35 97 % UL* contains base material according to the *G1* grading, which is an *U*pper *L*imit curve at a proctor density of *97%*. The material composition is *65*% *C*oncrete and *35*% crushed *M*asonry. Both the concrete granulates as well as the masonry granulates have been obtained with the aid of a *J*aws Crusher.

The sample *MG 16H* of Kisimbi, however, is an exception. This sample (at a compaction percentage of 100.5% of the proctor density) is a commercially graded mix granulate, originated from a crusher plant at Zestienhoven nearby Rotterdam, The Netherlands.

F.3 Added and missing material samples

Moreover, in the paragraph below material samples tested at the age of 28 days as analysed by Muraya and Kisimbi have also been integrated in the data set.

Please note that the material samples of Muraya and Kisimbi listed below are not the complete series of materials. Since crucial data for material samples with a G2, G3, and G6 grading were missing, these samples proved not to be useful for this study and hence, have been left out of consideration.

F.4 Data set

Allan NIEKERK source: **Van Niekerk**

specimen size: 400 * 800 [mm*mm]
group code: age of sample: 2 [days]

k_1	32,126	[MPa]	ϕ:	41,60°		$\sigma_{1,failure}$	263,63	[kPa]
k_2	0,433	[-]	cohesion:	45,89	[kPa]	$\tau_{\sigma 3=12kPa}$	125,82	[kPa]
volume dens. grains	2350	[kg/m^3]	degr. of comp.	1,000	[-]			
dry density	1929	[kg/m^3]	relative density	0,821	[-]	OMC	9,1	%
MPD	1929	[kg/m^3]	spec dens solids	2612	[kg/m^3]			

VVS	93,6	%
VVS_{rinsed}	83,6	%
$CF_{average}$	0,74	[-]
$CF_{weighted}$	0,75	[-]
$D_{(PSDC-FC)}$	171	%
$A_{(PSDC-FC)}$	658	% [mm]
$A_{(PSDC-FC)middle}$	526	% [mm]
$SC_{D85,D15}$	1,96	[-]
$SC_{D60,D10}$	1,91	[-]
$C_{uniformity}$	41,5	[-]
$C_{curvature\ D30,D60,D10}$	0,14	[-]
$C_{curvature\ D50,D85,D15}$	1,45	[-]
$C_{extension}$	102,9	[-]
$Z_{fines\ 75\mu m}$	1,5	%

Grading (curve):
sample taken in situ

D_{85}	20,6	[mm]
D_{60}	6,9	[mm]
D_{50}	2,4	[mm]
D_{30}	0,39	[mm]
D_{15}	0,20	[mm]
D_{10}	0,17	[mm]

Sieve [mm]	% passing	
0.063	0,8	%
0.125	4,2	%
0.25	22,1	%
0.5	35,9	%
1	42,9	%
2	48,8	%
4	54,2	%
8	62,3	%
16	79,3	%
22.4	87,2	%
31.5	94,2	%
45	98,4	%

Max Havelaar NIEKERK

source: **Van Niekerk**

specimen size: 400 * 800 [mm*mm]
group code:
age of sample: 2 [days]

k_1	61,456	[MPa]	ϕ:	43,70º		$\sigma_{1,failure}$	410,33	[kPa]
k_2	0,340	[-]	cohesion:	73,69	[kPa]	$\tau_{\sigma3=12kPa}$	199,17	[kPa]
volume dens. grains	2010	[kg/m³]	degr. of comp.	1,000	[-]			
dry density	1632	[kg/m³]	relative density	0,812	[-]	OMC	15,2	%
MPD	1632	[kg/m³]	spec dens solids	2655	[kg/m³]			

VVS	106,5	%				Sieve [mm]	% passing	
VVS_{rinsed}	127,6	%						
$CF_{average}$	0,71	[-]				0.063	1,1	%
$CF_{weighted}$	0,72	[-]				0.125	5,1	%
						0.25	11,3	%
$D_{(PSDC-FC)}$	159	%				0.5	26,2	%
$A_{(PSDC-FC)}$	774	% [mm]				1	37,1	%
$A_{(PSDC-FC)middle}$	627	% [mm]	**Grading (curve):**			2	45,2	%
$SC_{D85,D15}$	1,92	[-]	sample taken in situ			4	54,9	%
$SC_{D60,D10}$	1,84	[-]	D_{85}	15,7	[mm]	8	70,7	%
$C_{uniformity}$	23,6	[-]	D_{60}	5,3	[mm]	16	85,6	%
$C_{curvature\ D30,D60,D10}$	0,38	[-]	D_{50}	3,0	[mm]	22.4	90,6	%
$C_{curvature\ D50,D85,D15}$	1,83	[-]	D_{30}	0,67	[mm]	31.5	93,9	%
$C_{extension}$	50,2	[-]	D_{15}	0,31	[mm]	45	97,7	%
$Z_{fines\ 75\mu m}$	1,9	%	D_{10}	0,22	[mm]			

Cor Bruin NIEKERK

source: **Van Niekerk**

specimen size: 400 * 800 [mm*mm]
group code:
age of sample: 2 [days]

k_1	20,171	[MPa]	ϕ:	52,86º		$\sigma_{1,failure}$	397,31	[kPa]
k_2	0,540	[-]	cohesion:	48,88	[kPa]	$\tau_{\sigma3=12kPa}$	192,66	[kPa]
volume dens. grains	2300	[kg/m³]	degr. of comp.	1,000	[-]			
dry density	1885	[kg/m³]	relative density	0,820	[-]	OMC	10,5	%
MPD	1885	[kg/m³]	spec dens solids	2613	[kg/m³]			

VVS	116,7	%				Sieve [mm]	% passing	
VVS_{rinsed}	106,6	%						
$CF_{average}$	0,74	[-]				0.063	1,6	%
$CF_{weighted}$	0,73	[-]				0.125	2,8	%
						0.25	10,8	%
$D_{(PSDC-FC)}$	51	%				0.5	19,7	%
$A_{(PSDC-FC)}$	203	% [mm]				1	23,8	%
$A_{(PSDC-FC)middle}$	211	% [mm]	**Grading (curve):**			2	28,0	%
$SC_{D85,D15}$	1,96	[-]	sample taken in situ			4	32,2	%
$SC_{D60,D10}$	1,95	[-]	D_{85}	33,7	[mm]	8	40,0	%
$C_{uniformity}$	77,6	[-]	D_{60}	18,4	[mm]	16	55,6	%
$C_{curvature\ D30,D60,D10}$	1,99	[-]	D_{50}	13,1	[mm]	22.4	67,2	%
$C_{curvature\ D50,D85,D15}$	13,92	[-]	D_{30}	2,95	[mm]	31.5	82,7	%
$C_{extension}$	91,5	[-]	D_{15}	0,37	[mm]	45	97,1	%
$Z_{fines\ 75\mu m}$	1,8	%	D_{10}	0,24	[mm]			

Pascal NIEKERK source: **Van Niekerk**

specimen size: 400 * 800 [mm*mm]
group code: age of sample: 2 [days]

k_1	28,956	[MPa]	ϕ:	50,98°		$\sigma_{1,failure}$	483,21	[kPa]
k_2	0,394	[-]	cohesion:	68,67	[kPa]	$\tau_{\sigma 3=12kPa}$	235,60	[kPa]
volume dens. grains	2050	[kg/m³]	degr. of comp.	1,000	[-]			
dry density	1679	[kg/m³]	relative density	0,819	[-]	OMC	14,9	%
MPD	1679	[kg/m³]	spec dens solids	2644	[kg/m³]			
VVS	94,4	%						
VVS_{rinsed}	125,6	%						

$D_{(PSDC-FC)}$	55	%
$A_{(PSDC-FC)}$	171	% [mm]
$A_{(PSDC-FC)middle}$	174	% [mm]
$SC_{D85,D15}$	1,94	[-]
$SC_{D60,D10}$	1,88	[-]
$C_{uniformity}$	31,7	[-]
$C_{curvature\ D30,D60,D10}$	0,53	[-]
$C_{curvature\ D50,D85,D15}$	2,91	[-]
$C_{extension}$	64,2	[-]
$Z_{fines\ 75\mu m}$	0,3	%

Grading (curve):
sample taken in situ

D_{85}	35,0	[mm]
D_{60}	12,5	[mm]
D_{50}	7,5	[mm]
D_{30}	1,62	[mm]
D_{15}	0,55	[mm]
D_{10}	0,40	[mm]

Sieve [mm]	% passing	
0.063	0,1	%
0.125	1,2	%
0.25	4,6	%
0.5	13,9	%
1	25,9	%
2	32,5	%
4	39,8	%
8	51,6	%
16	66,4	%
22.4	74,4	%
31.5	82,2	%
45	92,9	%

lava CO1 LAB05

source: **Sweere**

			specimen size: 400 * 800 [mm*mm]			material code:	LAB	
			group code: C01	seq.№ 05		age of sample:	2	[days]
k_1	26,900	[MPa]						
k_2	0,350	[-]						
volume dens. grains	1941	[kg/m³]	degr. of comp.	1,086	[-]			
dry density	1778	[kg/m³]	relative density	0,916	[-]	OMC	11,4	%
MPD	1637	[kg/m³]				moisture content	9,7	%
MMPD	1889[kg/m³]							
			CF grading 4 - 5.6	0,66	[-]	Sieve [mm]	% passing	
			CF grading 5.6 - 8	0,70	[-]			
$CF_{average}$	0,70	[-]	CF grading 8 - 11.2	0,71	[-]	0.063	4,4	%
			CF grading 11.2-16	0,71	[-]	0.125	8,2	%
			CF grading 16-22.4	0,70	[-]	0.25	15,7	%
$D_{(PSDC\text{-}FC)}$	187	%	CF grdng 22.4-31.5	0,70	[-]	0.5	26,1	%
$A_{(PSDC\text{-}FC)}$	971	% [mm]	CF grading 31.5-45	0,69	[-]	1	37,3	%
$A_{(PSDC\text{-}FC)middle}$	810	% [mm]	**Grading (curve):**			2	50,0	%
$SC_{D85,D15}$	1,93	[-]	fine; upper limit			4	60,0	%
$SC_{D60,D10}$	1,85	[-]	D_{85}	13,1	[mm]	8	76,0	%
$C_{uniformity}$	25,8	[-]	D_{60}	4,0	[mm]	16	90,0	%
$C_{curvature\ D30,D60,D10}$	0,73	[-]	D_{50}	2,0	[mm]	22.4	95,0	%
$C_{curvature\ D50,D85,D15}$	1,28	[-]	D_{30}	0,67	[mm]	31.5	98,0	%
$C_{extension}$	55,1	[-]	D_{15}	0,24	[mm]	45	100,0	%
$Z_{fines\ 75\mu m}$	5,1	%	D_{10}	0,16	[mm]			

lava CO2 LAO07

source: **Sweere**

			specimen size: 400 * 800 [mm*mm]			material code:	LAO	
			group code: C02	seq.№ 07		age of sample:	2	[days]
k_1	19,200	[MPa]						
k_2	0,470	[-]						
volume dens. grains	1941	[kg/m³]	degr. of comp.	1,041	[-]			
dry density	1640	[kg/m³]	relative density	0,845	[-]	OMC	12,1	%
MPD	1576	[kg/m³]				moisture content	8,8	%
MMPD	1682[kg/m³]							
			CF grading 4 - 5.6	0,66	[-]	Sieve [mm]	% passing	
			CF grading 5.6 - 8	0,70	[-]			
$CF_{average}$	0,70	[-]	CF grading 8 - 11.2	0,71	[-]	0.063	1,8	%
			CF grading 11.2-16	0,71	[-]	0.125	3,3	%
			CF grading 16-22.4	0,70	[-]	0.25	6,3	%
$D_{(PSDC\text{-}FC)}$	44	%	CF grdng 22.4-31.5	0,70	[-]	0.5	10,5	%
$A_{(PSDC\text{-}FC)}$	197	% [mm]	CF grading 31.5-45	0,69	[-]	1	14,9	%
$A_{(PSDC\text{-}FC)middle}$	253	% [mm]	**Grading (curve):**			2	20,0	%
$SC_{D85,D15}$	1,90	[-]	coarse; lower limit			4	30,0	%
$SC_{D60,D10}$	1,89	[-]	D_{85}	39,4	[mm]	8	44,0	%
$C_{uniformity}$	34,0	[-]	D_{60}	16,0	[mm]	16	60,0	%
$C_{curvature\ D30,D60,D10}$	2,13	[-]	D_{50}	11,0	[mm]	22.4	69,0	%
$C_{curvature\ D50,D85,D15}$	3,01	[-]	D_{30}	4,00	[mm]	31.5	78,0	%
$C_{extension}$	38,6	[-]	D_{15}	1,02	[mm]	45	90,0	%
$Z_{fines\ 75\mu m}$	2,1	%	D_{10}	0,47	[mm]			

lava CO2 LAOS05

source: **Sweere**

specimen size: 400 * 800 [mm*mm] material code: LAOS
group code: C02 seq.№ 05 age of sample: 2 [days]

$\sigma_{1,failure}$	247,00	[kPa]
$\tau_{\sigma3=12kPa}$	117,50	[kPa]

volume dens. grains	1941	[kg/m³]	degr. of comp.	1,067	[-]				
dry density	1681	[kg/m³]	relative density	0,866	[-]	OMC	12,1	%	
MPD	1576	[kg/m³]				moisture content	6,9	%	
MMPD	1682	[kg/m³]							
			CF grading 4 - 5.6	0,66	[-]	Sieve [mm]	% passing		
			CF grading 5.6 - 8	0,70	[-]				
$CF_{average}$	0,70	[-]	CF grading 8 - 11.2	0,71	[-]	0.063	1,8	%	
			CF grading 11.2-16	0,71	[-]	0.125	3,3	%	
			CF grading 16-22.4	0,70	[-]	0.25	6,3	%	
$D_{(PSDC-FC)}$	44	%	CF grdng 22.4-31.5	0,70	[-]	0.5	10,5	%	
$A_{(PSDC-FC)}$	197	% [mm]	CF grading 31.5-45	0,69	[-]	1	14,9	%	
$A_{(PSDC-FC)middle}$	253	% [mm]	**Grading (curve):**			2	20,0	%	
$SC_{D85,D15}$	1,90	[-]	coarse; lower limit			4	30,0	%	
$SC_{D60,D10}$	1,89	[-]	D_{85}	39,4	[mm]	8	44,0	%	
$C_{uniformity}$	34,0	[-]	D_{60}	16,0	[mm]	16	60,0	%	
$C_{curvature\ D30,D60,D10}$	2,13	[-]	D_{50}	11,0	[mm]	22.4	69,0	%	
$C_{curvature\ D50,D85,D15}$	3,01	[-]	D_{30}	4,00	[mm]	31.5	78,0	%	
$C_{extension}$	38,6	[-]	D_{15}	1,02	[mm]	45	90,0	%	
$Z_{fines\ 75\mu m}$	2,1	%	D_{10}	0,47	[mm]				

porphyry CO3 POB03

source: **Sweere**

specimen size: 400 * 800 [mm*mm] material code: POB
group code: C03 seq.№ 03 age of sample: 2 [days]

k_1	29,200	[MPa]
k_2	0,320	[-]

volume dens. grains	2665	[kg/m³]	degr. of comp.	0,978	[-]			
dry density	2113	[kg/m³]	relative density	0,793	[-]	OMC	5,2	%
MPD	2160	[kg/m³]				moisture content	4,2	%
MMPD	2260	[kg/m³]						
			CF grading 4 - 5.6	0,86	[-]	Sieve [mm]	% passing	
			CF grading 5.6 - 8	0,85	[-]			
$CF_{average}$	0,86	[-]	CF grading 8 - 11.2	0,88	[-]	0.063	9,6	%
			CF grading 11.2-16	0,86	[-]	0.125	12,3	%
			CF grading 16-22.4	0,87	[-]	0.25	16,3	%
$D_{(PSDC-FC)}$	175	%	CF grdng 22.4-31.5	0,85	[-]	0.5	23,4	%
$A_{(PSDC-FC)}$	841	% [mm]				1	33,8	%
$A_{(PSDC-FC)middle}$	574	% [mm]	**Grading (curve):**			2	50,0	%
$SC_{D85,D15}$	1,94	[-]	fine; upper limit			4	60,0	%
$SC_{D60,D10}$	1,93	[-]	D_{85}	13,1	[mm]	8	76,0	%
$C_{uniformity}$	55,4	[-]	D_{60}	4,0	[mm]	16	90,0	%
$C_{curvature\ D30,D60,D10}$	2,31	[-]	D_{50}	2,0	[mm]	22.4	65,0	%
$C_{curvature\ D50,D85,D15}$	1,45	[-]	D_{30}	0,82	[mm]	31.5	98,0	%
$C_{extension}$	62,8	[-]	D_{15}	0,21	[mm]	45	100,0	%
$Z_{fines\ 75\mu m}$	10,1	%	D_{10}	0,07	[mm]			

porphyry CO4 POO01

source: **Sweere**

specimen size: 400 * 800 [mm*mm] | material code: POO
group code: C04 seq.№ 01 | age of sample: 2 [days]

k_1	22,900	[MPa]
k_2	0,430	[-]

volume dens. grains	2665	[kg/m³]	degr. of comp.	0,945	[-]			
dry density	2075	[kg/m³]	relative density	0,779	[-]	OMC	3,7	%
MPD	2196	[kg/m³]				moisture content	2	%
MMPD	2038[kg/m³]							

			CF grading			Sieve [mm]	% passing	
			CF grading 4 - 5.6	0,86	[-]			
			CF grading 5.6 - 8	0,85	[-]			
$CF_{average}$	0,86	[-]	CF grading 8 - 11.2	0,88	[-]	0.063	3,9	%
			CF grading 11.2-16	0,86	[-]	0.125	4,9	%
			CF grading 16-22.4	0,87	[-]	0.25	6,5	%
$D_{(PSDC\text{-}FC)}$	43	%	CF grdng 22.4-31.5	0,85	[-]	0.5	9,4	%
$A_{(PSDC\text{-}FC)}$	208	% [mm]				1	13,5	%
$A_{(PSDC\text{-}FC)middle}$	262	% [mm]	**Grading (curve):**			2	20,0	%
$SC_{D85,D15}$	1,88	[-]	coarse; lower limit			4	30,0	%
$SC_{D60,D10}$	1,86	[-]	D_{85}	39,4	[mm]	8	44,0	%
$C_{uniformity}$	27,9	[-]	D_{60}	16,0	[mm]	16	60,0	%
$C_{curvature\ D30,D60,D10}$	1,74	[-]	D_{50}	11,0	[mm]	22.4	68,0	%
$C_{curvature\ D50,D85,D15}$	2,50	[-]	D_{30}	4,00	[mm]	31.5	78,0	%
$C_{extension}$	32,0	[-]	D_{15}	1,23	[mm]	45	90,0	%
$Z_{fines\ 75\mu m}$	4,1	%	D_{10}	0,57	[mm]			

crushed gravel CO5 GGB01

source: **Sweere**

specimen size: 400 * 800 [mm*mm] | material code: GGB
group code: C05 seq.№ 01 | age of sample: 2 [days]

k_1	40,900	[MPa]
k_2	0,230	[-]

volume dens. grains	2563	[kg/m³]	degr. of comp.	1,040	[-]			
dry density	1968	[kg/m³]	relative density	0,768	[-]	OMC	6,6	%
MPD	1892	[kg/m³]				moisture content	5,1	%
MMPD	2002[kg/m³]							

			CF grading			Sieve [mm]	% passing	
			CF grading 4 - 5.6	0,84	[-]			
			CF grading 5.6 - 8	0,83	[-]			
$CF_{average}$	0,84	[-]	CF grading 8 - 11.2	0,87	[-]	0.063	1,1	%
			CF grading 11.2-16	0,83	[-]	0.125	4,6	%
			CF grading 16-22.4	0,85	[-]	0.25	13,4	%
$D_{(PSDC\text{-}FC)}$	191	%	CF grdng 22.4-31.5	0,84	[-]	0.5	25,9	%
$A_{(PSDC\text{-}FC)}$	973	% [mm]				1	39,5	%
$A_{(PSDC\text{-}FC)middle}$	811	% [mm]	**Grading (curve):**			2	50,0	%
$SC_{D85,D15}$	1,92	[-]	fine; upper limit			4	60,0	%
$SC_{D60,D10}$	1,81	[-]	D_{85}	13,1	[mm]	8	76,0	%
$C_{uniformity}$	19,8	[-]	D_{60}	4,0	[mm]	16	90,0	%
$C_{curvature\ D30,D60,D10}$	0,52	[-]	D_{50}	2,0	[mm]	22.4	95,0	%
$C_{curvature\ D50,D85,D15}$	1,08	[-]	D_{30}	0,65	[mm]	31.5	98,0	%
$C_{extension}$	46,6	[-]	D_{15}	0,28	[mm]	45	100,0	%
$Z_{fines\ 75\mu m}$	1,8	%	D_{10}	0,20	[mm]			

crushed gravel CO6 GGO01								source: **Sweere**
			specimen size: 400 * 800 [mm*mm]			material code:	GGO	
			group code: C06	seq.№ 01		age of sample:	2	[days]
k_1	47,200	[MPa]						
k_2	0,310	[-]						
volume dens. grains	2563	[kg/m^3]	degr. of comp.	0,971	[-]			
dry density	2042	[kg/m^3]	relative density	0,797	[-]	OMC	4,8	%
MPD	2103	[kg/m^3]				moisture content	4	%
MMPD	2029[kg/m^3]							
			CF grading 4 - 5.6	0,84	[-]			
			CF grading 5.6 - 8	0,83	[-]			
$CF_{average}$	0,84	[-]	CF grading 8 - 11.2	0,87	[-]			
			CF grading 11.2-16	0,83	[-]			
			CF grading 16-22.4	0,85	[-]			
$D_{(PSDC\text{-}FC)}$	47	%	CF grdng 22.4-31.5	0,84	[-]			
$A_{(PSDC\text{-}FC)}$	197	% [mm]						
$A_{(PSDC\text{-}FC)middle}$	253	% [mm]	**Grading (curve):**					
$SC_{D85,D15}$	1,91	[-]	coarse; lower limit					
$SC_{D60,D10}$	1,88	[-]	D_{85}	39,4	[mm]			
$C_{uniformity}$	33,3	[-]	D_{60}	16,0	[mm]			
$C_{curvature\ D30,D60,D10}$	2,08	[-]	D_{50}	11,0	[mm]			
$C_{curvature\ D50,D85,D15}$	3,32	[-]	D_{30}	4,00	[mm]			
$C_{extension}$	42,5	[-]	D_{15}	0,93	[mm]			
$Z_{fines\ 75\mu m}$	0,7	%	D_{10}	0,48	[mm]			

Sieve [mm]	% passing	
0.063	0,4	%
0.125	1,8	%
0.25	5,4	%
0.5	10,4	%
1	15,8	%
2	20,0	%
4	30,0	%
8	44,0	%
16	60,0	%
22.4	69,0	%
31.5	78,0	%
45	90,0	%

limestone CO7 KAB02

source: **Sweere**

specimen size: 400 * 800 [mm*mm]		material code:	KAB
group code: C07	seq.№ 02	age of sample:	2 [days]

k_1	156,800	[MPa]
k_2	0,140	[-]

volume dens. grains	2669	[kg/m³]	degr. of comp.	0,976	[-]			
dry density	2129	[kg/m³]	relative density	0,798	[-]	OMC	8	%
MPD	2182	[kg/m³]				moisture content	5,5	%
MMPD	2291	[kg/m³]						

						Sieve [mm]	% passing	
			CF grading 4 - 5.6	0,82	[-]	0.02	12,4	%
			CF grading 5.6 - 8	0,80	[-]	0.063	17,9	%
$CF_{average}$	0,80	[-]	CF grading 8 - 11.2	0,81	[-]	0.125	20,8	%
			CF grading 11.2-16	0,79	[-]	0.25	25,1	%
			CF grading 16-22.4	0,79	[-]	0.5	32,5	%
$D_{(PSDC-FC)}$	236	%	CF grdng 22.4-31.5	0,79	[-]	1	40,2	%
$A_{(PSDC-FC)}$	982	% [mm]				2	50,0	%
$A_{(PSDC-FC)middle}$	818	% [mm]	**Grading (curve):**			4	60,0	%
$SC_{D85,D15}$	1,99	[-]	fine; upper limit			8	76,0	%
$SC_{D60,D10}$	2,00	[-]	D_{85}	13,1	[mm]	16	90,0	%
$C_{uniformity}$	3236,2	[-]	D_{60}	4,0	[mm]	22.4	95,0	%
$C_{curvature\ D30,D60,D10}$	34,93	[-]	D_{50}	2,0	[mm]	31.5	98,0	%
$C_{curvature\ D50,D85,D15}$	7,61	[-]	D_{30}	0,42	[mm]	45	100,0	%
$C_{extension}$	328,6	[-]	D_{15}	0,04	[mm]			
$Z_{fines\ 75\mu m}$	18,5	%	D_{10}	0,00	[mm]			

limestone CO8 KAO01

source: **Sweere**

specimen size: 400 * 800 [mm*mm]		material code:	KAO
group code: C08	seq.№ 01	age of sample:	2 [days]

k_1	37,700	[MPa]
k_2	0,450	[-]

volume dens. grains	2669	[kg/m³]	degr. of comp.	1,004	[-]			
dry density	2287	[kg/m³]	relative density	0,857	[-]	OMC	5,5	%
MPD	2278	[kg/m³]				moisture content	5,9	%
MMPD	2288	[kg/m³]						

						Sieve [mm]	% passing	
			CF grading 4 - 5.6	0,82	[-]	0.02	5,0	%
			CF grading 5.6 - 8	0,80	[-]	0.063	7,2	%
$CF_{average}$	0,80	[-]	CF grading 8 - 11.2	0,81	[-]	0.125	8,4	%
			CF grading 11.2-16	0,79	[-]	0.25	10,1	%
			CF grading 16-22.4	0,79	[-]	0.5	13,0	%
$D_{(PSDC-FC)}$	32	%	CF grdng 22.4-31.5	0,79	[-]	1	16,1	%
$A_{(PSDC-FC)}$	194	% [mm]				2	20,0	%
$A_{(PSDC-FC)middle}$	250	% [mm]	**Grading (curve):**			4	30,0	%
$SC_{D85,D15}$	1,92	[-]	coarse; lower limit			8	44,0	%
$SC_{D60,D10}$	1,94	[-]	D_{85}	39,4	[mm]	16	60,0	%
$C_{uniformity}$	65,9	[-]	D_{60}	16,0	[mm]	22.4	69,0	%
$C_{curvature\ D30,D60,D10}$	4,12	[-]	D_{50}	11,0	[mm]	31.5	78,0	%
$C_{curvature\ D50,D85,D15}$	3,74	[-]	D_{30}	4,00	[mm]	45	90,0	%
$C_{extension}$	47,9	[-]	D_{15}	0,82	[mm]			
$Z_{fines\ 75\mu m}$	7,4	%	D_{10}	0,24	[mm]			

stol CO9 STN01 source: **Sweere**

specimen size: 400 * 800 [mm*mm] material code: STN
group code: C09 seq.№ 01 age of sample: 2 [days]

k_1	157,800	[MPa]
k_2	0,050	[-]

volume dens. grains	2513	[kg/m^3]	degr. of comp.	0,953	[-]			
dry density	2121	[kg/m^3]	relative density	0,844	[-]	OMC	4,7	%
MPD	2225	[kg/m^3]				moisture content	4,9	%
MMPD	2174[kg/m^3]							

			CF grading 4 - 5.6	0,91	[-]	Sieve [mm]	% passing	
			CF grading 5.6 - 8	0,87	[-]			
$CF_{average}$	0,87	[-]	CF grading 8 - 11.2	0,90	[-]	0.063	6,0	%
			CF grading 11.2-16	0,85	[-]	0.125	7,8	%
			CF grading 16-22.4	0,85	[-]	0.25	11,2	%
$D_{(PSDC-FC)}$	31	%	CF grdng 22.4-31.5	0,82	[-]	0.5	18,0	%
$A_{(PSDC-FC)}$	118	% [mm]				1	22,5	%
$A_{(PSDC-FC)middle}$	124	% [mm]	**Grading (curve):**			2	25,0	%
$SC_{D85,D15}$	1,95	[-]	natural grading			4	30,0	%
$SC_{D60,D10}$	1,95	[-]	D_{85}	30,9	[mm]	8	40,0	%
$C_{uniformity}$	77,7	[-]	D_{60}	16,0	[mm]	16	60,0	%
$C_{curvature\ D30,D60,D10}$	4,86	[-]	D_{50}	12,0	[mm]	22.4	71,0	%
$C_{curvature\ D50,D85,D15}$	11,96	[-]	D_{30}	4,00	[mm]	31.5	86,0	%
$C_{extension}$	79,3	[-]	D_{15}	0,39	[mm]	45	96,0	%
$Z_{fines\ 75\mu m}$	6,3	%	D_{10}	0,21	[mm]			

silicon manganese slag C10 SMC01 source: **Sweere**

specimen size: 400 * 800 [mm*mm] material code: SMC
group code: C10 seq.№ 01 age of sample: 2 [days]

k_1	43,500	[MPa]
k_2	0,340	[-]

volume dens. grains	2146	[kg/m^3]	degr. of comp.	1,079	[-]			
dry density	1809	[kg/m^3]	relative density	0,843	[-]	OMC	5,4	%
MPD	1676	[kg/m^3]				moisture content	4,9	%
MMPD	1857[kg/m^3]							

			CF grading 4 - 5.6	0,69	[-]	Sieve [mm]	% passing	
			CF grading 5.6 - 8	0,69	[-]			
$CF_{average}$	0,72	[-]	CF grading 8 - 11.2	0,71	[-]	0.063	3,4	%
			CF grading 11.2-16	0,72	[-]	0.125	5,2	%
			CF grading 16-22.4	0,73	[-]	0.25	8,6	%
$D_{(PSDC-FC)}$	51	%	CF grdng 22.4-31.5	0,75	[-]	0.5	12,2	%
$A_{(PSDC-FC)}$	365	% [mm]				1	15,8	%
$A_{(PSDC-FC)middle}$	285	% [mm]	**Grading (curve):**			2	21,0	%
$SC_{D85,D15}$	1,85	[-]	commercial grading			4	29,0	%
$SC_{D60,D10}$	1,90	[-]	D_{85}	23,0	[mm]	8	44,0	%
$C_{uniformity}$	38,4	[-]	D_{60}	13,3	[mm]	16	68,0	%
$C_{curvature\ D30,D60,D10}$	3,93	[-]	D_{50}	10,0	[mm]	22.4	84,0	%
$C_{curvature\ D50,D85,D15}$	4,89	[-]	D_{30}	4,27	[mm]	31.5	99,0	%
$C_{extension}$	25,9	[-]	D_{15}	0,89	[mm]	45	100,0	%
$Z_{fines\ 75\mu m}$	3,7	%	D_{10}	0,35	[mm]			

crushed masonry 1 R01 MGB07

source: **Sweere**

			specimen size: 400 * 800 [mm*mm]			material code:	MGB	
composition: 100 % MG			group code: R01		seq.№ 07	age of sample:	2	[days]
k_1	6,300	[MPa]						
k_2	0,490	[-]						
volume dens. grains	1699	[kg/m³]	degr. of comp.	1,070	[-]			
dry density	1530	[kg/m³]	relative density	0,901	[-]	OMC	21,5	%
MPD	1430	[kg/m³]				moisture content	24,5	%
MMPD	1536[kg/m³]							
			CF grading 4 - 5.6	0,65	[-]	Sieve [mm]	% passing	
			CF grading 5.6 - 8	0,63	[-]			
$CF_{average}$	0,65	[-]	CF grading 8 - 11.2	0,65	[-]	0.063	5,6	%
			CF grading 11.2-16	0,65	[-]	0.125	9,4	%
			CF grading 16-22.4	0,67	[-]	0.25	17,3	%
$D_{(PSDC-FC)}$	192	%	CF grdng 22.4-31.5	0,67	[-]	0.5	28,5	%
$A_{(PSDC-FC)}$	973	% [mm]				1	37,9	%
$A_{(PSDC-FC)middle}$	812	% [mm]	**Grading (curve):**			2	50,0	%
$SC_{D85,D15}$	1,94	[-]	fine; upper limit			4	60,0	%
$SC_{D60,D10}$	1,87	[-]	D_{85}	13,1	[mm]	8	76,0	%
$C_{uniformity}$	29,7	[-]	D_{60}	4,0	[mm]	16	90,0	%
$C_{curvature\ D30,D60,D10}$	0,62	[-]	D_{50}	2,0	[mm]	22.4	95,0	%
$C_{curvature\ D50,D85,D15}$	1,42	[-]	D_{30}	0,58	[mm]	31.5	98,0	%
$C_{extension}$	61,5	[-]	D_{15}	0,21	[mm]	45	100,0	%
$Z_{fines\ 75\mu m}$	6,3	%	D_{10}	0,13	[mm]			

crushed masonry 1 R01 MGBS03

source: **Sweere**

			specimen size: 400 * 800 [mm*mm]			material code:	MGBS	
composition: 100 % MG			group code: R01		seq.№ 03	age of sample:	2	[days]
						$\sigma_{1,failure}$	198,00	[kPa]
						$\tau_{\sigma 3=12kPa}$	93,00	[kPa]
volume dens. grains	1699	[kg/m³]	degr. of comp.	1,038	[-]			
dry density	1485	[kg/m³]	relative density	0,874	[-]	OMC	21,5	%
MPD	1430	[kg/m³]				moisture content	22	%
MMPD	1536[kg/m³]							
			CF grading 4 - 5.6	0,65	[-]	Sieve [mm]	% passing	
			CF grading 5.6 - 8	0,63	[-]			
$CF_{average}$	0,65	[-]	CF grading 8 - 11.2	0,65	[-]	0.063	5,6	%
			CF grading 11.2-16	0,65	[-]	0.125	9,4	%
			CF grading 16-22.4	0,67	[-]	0.25	17,3	%
$D_{(PSDC-FC)}$	192	%	CF grdng 22.4-31.5	0,67	[-]	0.5	28,5	%
$A_{(PSDC-FC)}$	973	% [mm]				1	37,9	%
$A_{(PSDC-FC)middle}$	812	% [mm]	**Grading (curve):**			2	50,0	%
$SC_{D85,D15}$	1,94	[-]	fine; upper limit			4	60,0	%
$SC_{D60,D10}$	1,87	[-]	D_{85}	13,1	[mm]	8	76,0	%
$C_{uniformity}$	29,7	[-]	D_{60}	4,0	[mm]	16	90,0	%
$C_{curvature\ D30,D60,D10}$	0,62	[-]	D_{50}	2,0	[mm]	22.4	95,0	%
$C_{curvature\ D50,D85,D15}$	1,42	[-]	D_{30}	0,58	[mm]	31.5	98,0	%
$C_{extension}$	61,5	[-]	D_{15}	0,21	[mm]	45	100,0	%
$Z_{fines\ 75\mu m}$	6,3	%	D_{10}	0,13	[mm]			

crushed masonry 1 R02 MGO10 source: **Sweere**

			specimen size: 400 * 800 [mm*mm]			material code:	MGO	
composition: 100 % MG			group code: R02		seq.№ 10	age of sample:	2	[days]
k_1	4,000	[MPa]						
k_2	0,650	[-]						
volume dens. grains	1699	[kg/m³]	degr. of comp.	1,060	[-]			
dry density	1523	[kg/m³]	relative density	0,896	[-]	OMC	16,6	%
MPD	1437	[kg/m³]				moisture content	17,2	%
MMPD	1534[kg/m³]							
			CF grading 4 - 5.6	0,65	[-]	Sieve [mm]	% passing	
			CF grading 5.6 - 8	0,63	[-]			
$CF_{average}$	0,65	[-]	CF grading 8 - 11.2	0,65	[-]	0.063	2,3	%
			CF grading 11.2-16	0,65	[-]	0.125	3,8	%
			CF grading 16-22.4	0,67	[-]	0.25	6,9	%
$D_{(PSDC-FC)}$	41	%	CF grdng 22.4-31.5	0,67	[-]	0.5	11,4	%
$A_{(PSDC-FC)}$	196	% [mm]				1	15,2	%
$A_{(PSDC-FC)middle}$	253	% [mm]	**Grading (curve):**			2	20,0	%
$SC_{D85,D15}$	1,90	[-]	coarse; lower limit			4	30,0	%
$SC_{D60,D10}$	1,90	[-]	D_{85}	39,4	[mm]	8	44,0	%
$C_{uniformity}$	37,9	[-]	D_{60}	16,0	[mm]	16	60,0	%
$C_{curvature\ D30,D60,D10}$	2,37	[-]	D_{50}	11,0	[mm]	22.4	69,0	%
$C_{curvature\ D50,D85,D15}$	3,16	[-]	D_{30}	4,00	[mm]	31.5	78,0	%
$C_{extension}$	40,4	[-]	D_{15}	0,97	[mm]	45	90,0	%
$Z_{fines\ 75μm}$	2,6	%	D_{10}	0,42	[mm]			

crushed masonry 2 R03 M2B01

source: **Sweere**

	specimen size: 400 * 800 [mm*mm]	material code:	M2B
composition: 100 % M2	group code: R03 seq.№ 01	age of sample:	2 [days]

k_1	27,500	[MPa]
k_2	0,300	[-]

volume dens. grains	1697	[kg/m^3]	degr. of comp.	1,044	[-]			
dry density	1585	[kg/m^3]	relative density	0,934	[-]	OMC	16,5	%
MPD	1518	[kg/m^3]				moisture content	16	%
MMPD	1629	[kg/m^3]						

			CF grading 4 - 5.6	0,67	[-]	Sieve [mm]	% passing	
			CF grading 5.6 - 8	0,67	[-]			
$CF_{average}$	0,68	[-]	CF grading 8 - 11.2	0,67	[-]	0.063	8,9	%
			CF grading 11.2-16	0,65	[-]	0.125	14,5	%
			CF grading 16-22.4	0,70	[-]	0.25	27,9	%
$D_{(PSDC-FC)}$	232	%	CF grdng 22.4-31.5	0,69	[-]	0.5	40,9	%
$A_{(PSDC-FC)}$	991	% [mm]				1	46,2	%
$A_{(PSDC-FC)middle}$	825	% [mm]	**Grading (curve):**			2	50,0	%
$SC_{D85,D15}$	1,96	[-]	fine; upper limit			4	60,0	%
$SC_{D60,D10}$	1,93	[-]	D_{85}	13,1	[mm]	8	76,0	%
$C_{uniformity}$	53,2	[-]	D_{60}	4,0	[mm]	16	90,0	%
$C_{curvature\ D30,D60,D10}$	0,28	[-]	D_{50}	2,0	[mm]	22.4	95,0	%
$C_{curvature\ D50,D85,D15}$	2,35	[-]	D_{30}	0,29	[mm]	31.5	98,0	%
$C_{extension}$	101,4	[-]	D_{15}	0,13	[mm]	45	100,0	%
$Z_{fines\ 75\mu m}$	10,0	%	D_{10}	0,08	[mm]			

crushed masonry 2 R04 M2O02

source: **Sweere**

	specimen size: 400 * 800 [mm*mm]	material code:	M2O
composition: 100 % M2	group code: R04 seq.№ 02	age of sample:	2 [days]

k_1	18,300	[MPa]
k_2	0,430	[-]

volume dens. grains	1697	[kg/m^3]	degr. of comp.	0,970	[-]			
dry density	1516	[kg/m^3]	relative density	0,893	[-]	OMC	14	%
MPD	1563	[kg/m^3]				moisture content	13,7	%
MMPD	1570	[kg/m^3]						

			CF grading 4 - 5.6	0,67	[-]	Sieve [mm]	% passing	
			CF grading 5.6 - 8	0,67	[-]			
$CF_{average}$	0,68	[-]	CF grading 8 - 11.2	0,67	[-]	0.063	3,6	%
			CF grading 11.2-16	0,65	[-]	0.125	5,8	%
			CF grading 16-22.4	0,70	[-]	0.25	11,2	%
$D_{(PSDC-FC)}$	35	%	CF grdng 22.4-31.5	0,69	[-]	0.5	16,4	%
$A_{(PSDC-FC)}$	194	% [mm]				1	18,5	%
$A_{(PSDC-FC)middle}$	250	% [mm]	**Grading (curve):**			2	20,0	%
$SC_{D85,D15}$	1,96	[-]	coarse; lower limit			4	30,0	%
$SC_{D60,D10}$	1,95	[-]	D_{85}	39,4	[mm]	8	44,0	%
$C_{uniformity}$	72,0	[-]	D_{60}	16,0	[mm]	16	60,0	%
$C_{curvature\ D30,D60,D10}$	4,50	[-]	D_{50}	11,0	[mm]	22.4	69,0	%
$C_{curvature\ D50,D85,D15}$	7,10	[-]	D_{30}	4,00	[mm]	31.5	78,0	%
$C_{extension}$	91,0	[-]	D_{15}	0,43	[mm]	45	90,0	%
$Z_{fines\ 75\mu m}$	4,0	%	D_{10}	0,22	[mm]			

crushed concrete 1 R05 BGB01

source: **Sweere**

composition: 100 % BG			specimen size: 400 * 800 [mm*mm] group code: R05 seq.№ 01			material code: BGB age of sample: 2 [days]		
k_1	21,100	[MPa]						
k_2	0,480	[-]						
volume dens. grains	2207	[kg/m³]	degr. of comp.	1,048	[-]			
dry density	1863	[kg/m³]	relative density	0,844	[-]	OMC	12,1	%
MPD	1778	[kg/m³]				moisture content	13,5	%
MMPD	1864	[kg/m³]						
			CF grading 4 - 5.6	0,79	[-]	Sieve [mm]	% passing	
			CF grading 5.6 - 8	0,78	[-]			
$CF_{average}$	0,79	[-]	CF grading 8 - 11.2	0,78	[-]	0.063	3,0	%
			CF grading 11.2-16	0,79	[-]	0.125	6,6	%
			CF grading 16-22.4	0,84	[-]	0.25	14,0	%
$D_{(PSDC-FC)}$	186	%	CF grdng 22.4-31.5	0,75	[-]	0.5	25,8	%
$A_{(PSDC-FC)}$	971	% [mm]				1	37,7	%
$A_{(PSDC-FC)middle}$	810	% [mm]	**Grading (curve):**			2	50,0	%
$SC_{D85,D15}$	1,92	[-]	fine; upper limit			4	60,0	%
$SC_{D60,D10}$	1,83	[-]	D_{85}	13,1	[mm]	8	76,0	%
$C_{uniformity}$	21,9	[-]	D_{60}	4,0	[mm]	16	90,0	%
$C_{curvature\ D30,D60,D10}$	0,63	[-]	D_{50}	2,0	[mm]	22.4	95,0	%
$C_{curvature\ D50,D85,D15}$	1,12	[-]	D_{30}	0,68	[mm]	31.5	98,0	%
$C_{extension}$	48,5	[-]	D_{15}	0,27	[mm]	45	100,0	%
$Z_{fines\ 75\mu m}$	3,7	%	D_{10}	0,18	[mm]			

crushed concrete 1 R05 BGBS04

source: **Sweere**

composition: 100 % BG			specimen size: 400 * 800 [mm*mm] group code: R05 seq.№ 04			material code: BGBS age of sample: 2 [days]		
						$\sigma_{1,failure}$	190,00	[kPa]
						$\tau_{\sigma3=12kPa}$	89,00	[kPa]
volume dens. grains	2207	[kg/m³]	degr. of comp.	1,021	[-]			
dry density	1815	[kg/m³]	relative density	0,822	[-]	OMC	12,1	%
MPD	1778	[kg/m³]				moisture content	10,7	%
MMPD	1864	[kg/m³]						
			CF grading 4 - 5.6	0,79	[-]	Sieve [mm]	% passing	
			CF grading 5.6 - 8	0,78	[-]			
$CF_{average}$	0,79	[-]	CF grading 8 - 11.2	0,78	[-]	0.063	3,0	%
			CF grading 11.2-16	0,79	[-]	0.125	6,6	%
			CF grading 16-22.4	0,84	[-]	0.25	14,0	%
$D_{(PSDC-FC)}$	186	%	CF grdng 22.4-31.5	0,75	[-]	0.5	25,8	%
$A_{(PSDC-FC)}$	971	% [mm]				1	37,7	%
$A_{(PSDC-FC)middle}$	810	% [mm]	**Grading (curve):**			2	50,0	%
$SC_{D85,D15}$	1,92	[-]	fine; upper limit			4	60,0	%
$SC_{D60,D10}$	1,83	[-]	D_{85}	13,1	[mm]	8	76,0	%
$C_{uniformity}$	21,9	[-]	D_{60}	4,0	[mm]	16	90,0	%
$C_{curvature\ D30,D60,D10}$	0,63	[-]	D_{50}	2,0	[mm]	22.4	95,0	%
$C_{curvature\ D50,D85,D15}$	1,12	[-]	D_{30}	0,68	[mm]	31.5	98,0	%
$C_{extension}$	48,5	[-]	D_{15}	0,27	[mm]	45	100,0	%
$Z_{fines\ 75\mu m}$	3,7	%	D_{10}	0,18	[mm]			

crushed concrete 1 R06 BGO01

source: **Sweere**

composition: 100 % BG	specimen size: 400 * 800 [mm*mm]	material code:	BGO
	group code: R06 seq.№ 01	age of sample:	2 [days]

k_1	11,200	[MPa]
k_2	0,590	[-]

volume dens. grains	2207	[kg/m³]	degr. of comp.	1,040	[-]			
dry density	1878	[kg/m³]	relative density	0,851	[-]	OMC	8	%
MPD	1806	[kg/m³]				moisture content	7,8	%
MMPD	1884	[kg/m³]						

			CF grading 4 - 5.6	0,79	[-]
			CF grading 5.6 - 8	0,78	[-]
$CF_{average}$	0,79	[-]	CF grading 8 - 11.2	0,78	[-]
			CF grading 11.2-16	0,79	[-]
			CF grading 16-22.4	0,84	[-]
			CF grdng 22.4-31.5	0,75	[-]

$D_{(PSDC\text{-}FC)}$	46	%
$A_{(PSDC\text{-}FC)}$	198	% [mm]
$A_{(PSDC\text{-}FC)middle}$	253	% [mm]
$SC_{D85,D15}$	1,90	[-]
$SC_{D60,D10}$	1,88	[-]
$C_{uniformity}$	33,1	[-]
$C_{curvature\ D30,D60,D10}$	2,07	[-]
$C_{curvature\ D50,D85,D15}$	3,11	[-]
$C_{extension}$	39,8	[-]
$Z_{fines\ 75\mu m}$	1,5	%

Grading (curve):
coarse; lower limit

D_{85}	39,4	[mm]
D_{60}	16,0	[mm]
D_{50}	11,0	[mm]
D_{30}	4,00	[mm]
D_{15}	0,99	[mm]
D_{10}	0,48	[mm]

Sieve [mm]	% passing	
0.063	1,2	%
0.125	2,6	%
0.25	5,6	%
0.5	10,3	%
1	15,1	%
2	20,0	%
4	30,0	%
8	44,0	%
16	60,0	%
22.4	69,0	%
31.5	78,0	%
45	90,0	%

crushed concrete 1 R06 BGBS04

source: **Sweere**

composition: 100 % BG	specimen size: 400 * 800 [mm*mm]	material code:	BGOS
	group code: R06 seq.№ 04	age of sample:	2 [days]

$\sigma_{1,failure}$	221,00	[kPa]
$\tau_{\sigma3=12kPa}$	104,50	[kPa]

volume dens. grains	2207	[kg/m³]	degr. of comp.	1,042	[-]			
dry density	1882	[kg/m³]	relative density	0,853	[-]	OMC	8	%
MPD	1806	[kg/m³]				moisture content	8	%
MMPD	1884	[kg/m³]						

			CF grading 4 - 5.6	0,79	[-]
			CF grading 5.6 - 8	0,78	[-]
$CF_{average}$	0,79	[-]	CF grading 8 - 11.2	0,78	[-]
			CF grading 11.2-16	0,79	[-]
			CF grading 16-22.4	0,84	[-]
			CF grdng 22.4-31.5	0,75	[-]

$D_{(PSDC\text{-}FC)}$	46	%
$A_{(PSDC\text{-}FC)}$	198	% [mm]
$A_{(PSDC\text{-}FC)middle}$	253	% [mm]
$SC_{D85,D15}$	1,90	[-]
$SC_{D60,D10}$	1,88	[-]
$C_{uniformity}$	33,1	[-]
$C_{curvature\ D30,D60,D10}$	2,07	[-]
$C_{curvature\ D50,D85,D15}$	3,11	[-]
$C_{extension}$	39,8	[-]
$Z_{fines\ 75\mu m}$	1,5	%

Grading (curve):
coarse; lower limit

D_{85}	39,4	[mm]
D_{60}	16,0	[mm]
D_{50}	11,0	[mm]
D_{30}	4,00	[mm]
D_{15}	0,99	[mm]
D_{10}	0,48	[mm]

Sieve [mm]	% passing	
0.063	1,2	%
0.125	2,6	%
0.25	5,6	%
0.5	10,3	%
1	15,1	%
2	20,0	%
4	30,0	%
8	44,0	%
16	60,0	%
22.4	69,0	%
31.5	78,0	%
45	90,0	%

crushed clinker R07 KGB01

source: **Sweere**

composition: 100 % KG

specimen size: 400 * 800 [mm*mm]
group code: R07 seq.№ 01

material code: KGB
age of sample: 2 [days]

k_1	41,800	[MPa]						
k_2	0,280	[-]						
volume dens. grains	2086	[kg/m^3]	degr. of comp.	1,016	[-]			
dry density	1803	[kg/m^3]	relative density	0,864	[-]	OMC	9,7	%
MPD	1775	[kg/m^3]				moisture content	7,6	%
MMPD	1828	[kg/m^3]						

CF grading 4 - 5.6	0,76	[-]			
CF grading 5.6 - 8	0,76	[-]			
$CF_{average}$ 0,77 [-]					
CF grading 8 - 11.2	0,79	[-]			
CF grading 11.2-16	0,77	[-]			
CF grading 16-22.4	0,79	[-]			
CF grdng 22.4-31.5	0,74	[-]			

$D_{(PSDC\text{-}FC)}$	217	%
$A_{(PSDC\text{-}FC)}$	983	% [mm]
$A_{(PSDC\text{-}FC)middle}$	819	% [mm]
$SC_{D85,D15}$	1,96	[-]
$SC_{D60,D10}$	1,93	[-]
$C_{uniformity}$	52,5	[-]
$C_{curvature\ D30,D60,D10}$	0,54	[-]
$C_{curvature\ D50,D85,D15}$	2,38	[-]
$C_{extension}$	102,8	[-]
$Z_{fines\ 75\mu m}$	9,9	%

Grading (curve):
fine; upper limit

D_{85}	13,1	[mm]
D_{60}	4,0	[mm]
D_{50}	2,0	[mm]
D_{30}	0,41	[mm]
D_{15}	0,13	[mm]
D_{10}	0,08	[mm]

Sieve [mm]	% passing	
0.063	8,7	%
0.125	14,8	%
0.25	23,4	%
0.5	33,9	%
1	42,5	%
2	50,0	%
4	60,0	%
8	76,0	%
16	90,0	%
22.4	95,0	%
31.5	98,0	%
45	100,0	%

crushed clinker R08 KGO01

source: **Sweere**

	specimen size: 400 * 800 [mm*mm]	material code: KGO
composition: 100 % KG	group code: R08 seq.№ 01	age of sample: 2 [days]

k_1	18,600	[MPa]
k_2	0,450	[-]

volume dens. grains	2086	$[kg/m^3]$	degr. of comp.	0,963	[-]			
dry density	1695	$[kg/m^3]$	relative density	0,813	[-]	OMC	6,7	%
MPD	1761	$[kg/m^3]$				moisture content	5,3	%
MMPD	1699	$[kg/m^3]$						

CF grading 4 - 5.6	0,76	[-]
CF grading 5.6 - 8	0,76	[-]
CF grading 8 - 11.2	0,79	[-]
CF grading 11.2-16	0,77	[-]
CF grading 16-22.4	0,79	[-]
CF grdng 22.4-31.5	0,74	[-]

$CF_{average}$	0,77	[-]
$D_{(PSDC-FC)}$	32	%
$A_{(PSDC-FC)}$	193	% [mm]
$A_{(PSDC-FC)middle}$	250	% [mm]
$SC_{D85,D15}$	1,93	[-]
$SC_{D60,D10}$	1,93	[-]
$C_{uniformity}$	56,0	[-]
$C_{curvature\ D30,D60,D10}$	3,50	[-]
$C_{curvature\ D50,D85,D15}$	4,35	[-]
$C_{extension}$	55,8	[-]
$Z_{fines\ 75\mu m}$	4,0	%

Grading (curve):
coarse; lower limit

D_{85}	39,4	[mm]
D_{60}	16,0	[mm]
D_{50}	11,0	[mm]
D_{30}	4,00	[mm]
D_{15}	0,71	[mm]
D_{10}	0,29	[mm]

Sieve [mm]	% passing	
0.063	3,5	%
0.125	5,9	%
0.25	9,4	%
0.5	13,6	%
1	17,0	%
2	20,0	%
4	30,0	%
8	44,0	%
16	60,0	%
22.4	69,0	%
31.5	78,0	%
45	90,0	%

crushed masonry/concrete (65/35) R09 FFB01

source: **Sweere**

	specimen size: 400 * 800 [mm*mm]	material code: FFB
composition: 50 % M2	group code: R09 seq.№ 01	age of sample: 2 [days]

k_1	77,300	[MPa]
k_2	0,170	[-]

volume dens. grains	2024	$[kg/m^3]$	degr. of comp.	1,017	[-]			
dry density	1660	$[kg/m^3]$	relative density	0,820	[-]	OMC	13,9	%
MPD	1632	$[kg/m^3]$				moisture content	14,6	%
MMPD	1758	$[kg/m^3]$						

CF grading 4 - 5.6	0,74	[-]
CF grading 5.6 - 8	0,72	[-]
CF grading 8 - 11.2	0,75	[-]
CF grading 11.2-16	0,74	[-]
CF grading 16-22.4	0,74	[-]
CF grdng 22.4-31.5	0,73	[-]
CF grading 31.5-45	0,72	[-]

$CF_{average}$	0,73	[-]
$D_{(PSDC-FC)}$	206	%
$A_{(PSDC-FC)}$	981	% [mm]
$A_{(PSDC-FC)middle}$	817	% [mm]
$SC_{D85,D15}$	1,95	[-]
$SC_{D60,D10}$	1,89	[-]
$C_{uniformity}$	33,8	[-]
$C_{curvature\ D30,D60,D10}$	0,40	[-]
$C_{curvature\ D50,D85,D15}$	1,70	[-]
$C_{extension}$	73,4	[-]
$Z_{fines\ 75\mu m}$	6,8	%

Grading (curve):
fine; upper limit

D_{85}	13,1	[mm]
D_{60}	4,0	[mm]
D_{50}	2,0	[mm]
D_{30}	0,44	[mm]
D_{15}	0,18	[mm]
D_{10}	0,12	[mm]

Sieve [mm]	% passing	
0.063	5,9	%
0.125	10,5	%
0.25	20,9	%
0.5	33,1	%
1	41,9	%
2	50,0	%
4	60,0	%
8	76,0	%
16	90,0	%
22.4	95,0	%
31.5	98,0	%
45	100,0	%

crushed masonry/concrete (65/35) R10 FFO01 source: **Sweere**

composition: 50 % BG | specimen size: 400 * 800 [mm*mm] | group code: R10 seq.№ 01 | material code: FFO | age of sample: 2 [days]

k_1	22,600	[MPa]						
k_2	0,440	[-]						
volume dens. grains	2024	[kg/m³]	degr. of comp.	0,978	[-]			
dry density	1676	[kg/m³]	relative density	0,828	[-]	OMC	11,9	%
MPD	1714	[kg/m³]				moisture content	12,1	%
MMPD	1713	[kg/m³]						
			CF grading 4 - 5.6	0,74	[-]	Sieve [mm]	% passing	
			CF grading 5.6 - 8	0,72	[-]			
$CF_{average}$	0,73	[-]	CF grading 8 - 11.2	0,75	[-]	0.063	2,4	%
			CF grading 11.2-16	0,74	[-]	0.125	4,2	%
			CF grading 16-22.4	0,74	[-]	0.25	8,4	%
$D_{(PSDC-FC)}$	36	%	CF grdng 22.4-31.5	0,73	[-]	0.5	13,3	%
$A_{(PSDC-FC)}$	193	% [mm]	CF grading 31.5-45	0,72	[-]	1	16,8	%
$A_{(PSDC-FC)middle}$	250	% [mm]	**Grading (curve):**			2	20,0	%
$SC_{D85,D15}$	1,93	[-]	coarse; lower limit			4	30,0	%
$SC_{D60,D10}$	1,92	[-]	D_{85}	39,4	[mm]	8	44,0	%
$C_{uniformity}$	48,2	[-]	D_{60}	16,0	[mm]	16	60,0	%
$C_{curvature\ D30,D60,D10}$	3,02	[-]	D_{50}	11,0	[mm]	22.4	69,0	%
$C_{curvature\ D50,D85,D15}$	4,14	[-]	D_{30}	4,00	[mm]	31.5	78,0	%
$C_{extension}$	53,0	[-]	D_{15}	0,74	[mm]	45	90,0	%
$Z_{fines\ 75μm}$	2,7	%	D_{10}	0,33	[mm]			

crushed concrete 2 R11 B2C01 source: **Sweere**

composition: commercial | specimen size: 400 * 800 [mm*mm] | group code: R11 seq.№ 01 | material code: B2C | age of sample: 2 [days]

k_1	71,800	[MPa]						
k_2	0,210	[-]						
volume dens. grains	2303	[kg/m³]	degr. of comp.	1,032	[-]			
dry density	1858	[kg/m³]	relative density	0,807	[-]	OMC	8	%
MPD	1800	[kg/m³]				moisture content	10,6	%
MMPD	1922	[kg/m³]						
			CF grading 4 - 5.6	0,81	[-]	Sieve [mm]	% passing	
			CF grading 5.6 - 8	0,79	[-]			
$CF_{average}$	0,79	[-]	CF grading 8 - 11.2	0,83	[-]	0.063	1,9	%
			CF grading 11.2-16	0,79	[-]	0.125	3,1	%
			CF grading 16-22.4	0,78	[-]	0.25	7,7	%
$D_{(PSDC-FC)}$	42	%	CF grdng 22.4-31.5	0,76	[-]	0.5	12,8	%
$A_{(PSDC-FC)}$	260	% [mm]				1	18,3	%
$A_{(PSDC-FC)middle}$	198	% [mm]	**Grading (curve):**			2	23,0	%
$SC_{D85,D15}$	1,89	[-]	commercial grading			4	30,0	%
$SC_{D60,D10}$	1,89	[-]	D_{85}	25,2	[mm]	8	44,0	%
$C_{uniformity}$	36,8	[-]	D_{60}	13,3	[mm]	16	68,0	%
$C_{curvature\ D30,D60,D10}$	3,31	[-]	D_{50}	10,0	[mm]	22.4	81,0	%
$C_{curvature\ D50,D85,D15}$	5,67	[-]	D_{30}	4,00	[mm]	31.5	94,0	%
$C_{extension}$	36,0	[-]	D_{15}	0,70	[mm]	45	100,0	%
$Z_{fines\ 75μm}$	2,1	%	D_{10}	0,36	[mm]			

crushed rubble 1 R12 K1C01

source: **Sweere**

composition: commercial			specimen size: 400 * 800 [mm*mm] group code: R12		seq.№ 01	material code: age of sample:	K1C 2	[days]
k_1	34,800	[MPa]						
k_2	0,350	[-]						
volume dens. grains	2040	[kg/m³]	degr. of comp.	1,010	[-]			
dry density	1704	[kg/m³]	relative density	0,835	[-]	OMC	7,5	%
MPD	1687	[kg/m³]				moisture content	9	%
MMPD	1783[kg/m³]							
			CF grading 4 - 5.6	0,72	[-]	Sieve [mm]	% passing	
			CF grading 5.6 - 8	0,70	[-]			
$CF_{average}$	0,72	[-]	CF grading 8 - 11.2	0,75	[-]	0.063	2,7	%
			CF grading 11.2-16	0,73	[-]	0.125	4,5	%
			CF grading 16-22.4	0,73	[-]	0.25	7,7	%
$D_{(PSDC-FC)}$	30	%	CF grdng 22.4-31.5	0,70	[-]	0.5	13,5	%
$A_{(PSDC-FC)}$	140	% [mm]				1	17,6	%
$A_{(PSDC-FC)middle}$	100	% [mm]	**Grading (curve):**			2	22,0	%
$SC_{D85,D15}$	1,91	[-]	commercial grading			4	29,0	%
$SC_{D60,D10}$	1,90	[-]	D_{85}	28,9	[mm]	8	42,0	%
$C_{uniformity}$	40,8	[-]	D_{60}	14,3	[mm]	16	65,0	%
$C_{curvature\ D30,D60,D10}$	3,73	[-]	D_{50}	10,8	[mm]	22.4	74,9	%
$C_{curvature\ D50,D85,D15}$	5,89	[-]	D_{30}	4,31	[mm]	31.5	89,0	%
$C_{extension}$	42,3	[-]	D_{15}	0,68	[mm]	45	100,0	%
$Z_{fines\ 75\mu m}$	3,0	%	D_{10}	0,35	[mm]			

crushed rubble 2 R13 K2C01

source: **Sweere**

composition: commercial			specimen size: 400 * 800 [mm*mm] group code: R13		seq.№ 01	material code: age of sample:	K2C 2	[days]
k_1	36,100	[MPa]						
k_2	0,340	[-]						
volume dens. grains	2030	[kg/m³]	degr. of comp.	1,021	[-]			
dry density	1712	[kg/m³]	relative density	0,843	[-]	OMC	10,1	%
MPD	1677	[kg/m³]				moisture content	11,3	%
MMPD	1806[kg/m³]							
			CF grading 4 - 5.6	0,75	[-]	Sieve [mm]	% passing	
			CF grading 5.6 - 8	0,75	[-]			
$CF_{average}$	0,75	[-]	CF grading 8 - 11.2	0,78	[-]	0.063	3,0	%
			CF grading 11.2-16	0,74	[-]	0.125	5,4	%
			CF grading 16-22.4	0,75	[-]	0.25	12,9	%
$D_{(PSDC-FC)}$	78	%	CF grdng 22.4-31.5	0,72	[-]	0.5	20,0	%
$A_{(PSDC-FC)}$	413	% [mm]				1	26,5	%
$A_{(PSDC-FC)middle}$	341	% [mm]	**Grading (curve):**			2	32,0	%
$SC_{D85,D15}$	1,95	[-]	commercial grading			4	40,0	%
$SC_{D60,D10}$	1,92	[-]	D_{85}	23,8	[mm]	8	53,0	%
$C_{uniformity}$	52,3	[-]	D_{60}	10,5	[mm]	16	75,0	%
$C_{curvature\ D30,D60,D10}$	1,26	[-]	D_{50}	7,1	[mm]	22.4	83,3	%
$C_{curvature\ D50,D85,D15}$	6,51	[-]	D_{30}	1,64	[mm]	31.5	95,0	%
$C_{extension}$	73,3	[-]	D_{15}	0,32	[mm]	45	100,0	%
$Z_{fines\ 75\mu m}$	3,5	%	D_{10}	0,20	[mm]			

crushed rubble 3 R14 K3C01 source: **Sweere**

composition: commercial			specimen size: 400 * 800 [mm*mm] group code: R14 seq.№ 01			material code: age of sample:		K3C 2	[days]
k_1	30,100	[MPa]							
k_2	0,360	[-]							
volume dens. grains	2095	[kg/m^3]	degr. of comp.	1,003	[-]				
dry density	1710	[kg/m^3]	relative density	0,816	[-]	OMC		8,7	%
MPD	1705	[kg/m^3]				moisture content		9,6	%
MMPD	1742[kg/m^3]								
			CF grading 4 - 5.6	0,73	[-]	Sieve [mm]	% passing		
			CF grading 5.6 - 8	0,72	[-]				
$CF_{average}$	0,74	[-]	CF grading 8 - 11.2	0,77	[-]	0.063	3,4	%	
			CF grading 11.2-16	0,71	[-]	0.125	8,0	%	
			CF grading 16-22.4	0,77	[-]	0.25	11,1	%	
$D_{(PSDC-FC)}$	43	%	CF grdng 22.4-31.5	0,71	[-]	0.5	15,5	%	
$A_{(PSDC-FC)}$	230	% [mm]				1	18,1	%	
$A_{(PSDC-FC)middle}$	171	% [mm]	**Grading (curve):**			2	21,0	%	
$SC_{D85,D15}$	1,94	[-]	commercial grading			4	25,0	%	
$SC_{D60,D10}$	1,95	[-]	D_{85}	29,6	[mm]	8	37,0	%	
$C_{uniformity}$	84,9	[-]	D_{60}	17,5	[mm]	16	57,0	%	
$C_{curvature\ D30,D60,D10}$	8,95	[-]	D_{50}	13,2	[mm]	22.4	70,2	%	
$C_{curvature\ D50,D85,D15}$	12,50	[-]	D_{30}	5,67	[mm]	31.5	89,0	%	
$C_{extension}$	62,7	[-]	D_{15}	0,47	[mm]	45	100,0	%	
$Z_{fines\ 75\mu m}$	4,3	%	D_{10}	0,21	[mm]				

G4CJ/MJ50/50 AL 100% rel.comp. source: **Kisimbi**

composition: 50% concr 50% mas			specimen size: 300 * 600 [mm*mm] group code: AL			age of sample:	3	[days]
k_1	7,308	[MPa]						
k_2	0,555	[-]						
volume dens. grains	2056	[kg/m³]	degr. of comp.	1,000	[-]	CBR:	97,4	%
dry density	1718	[kg/m³]	relative density	0,836	[-]	OMC	7,8	%
MPD	1718	[kg/m³]	spec dens solids	2585	[kg/m³]			
VVS	123,6	%				Sieve [mm]	% passing	
$CF_{average}$	0,70	[-]				0.063	3,0	%
			CF grading 11.2-16	0,72	[-]	0.125	7,9	%
			CF grading 16-22.4	0,73	[-]	0.25	12,8	%
$D_{(PSDC-FC)}$	68	%	CF grdng 22.4-31.5	0,70	[-]	0.5	17,7	%
$A_{(PSDC-FC)}$	353	% [mm]	CF grading 31.5-45	0,64	[-]	1	22,6	%
$A_{(PSDC-FC)middle}$	290	% [mm]	**Grading (curve):**			2	27,5	%
$SC_{D85,D15}$	1,95	[-]	(G4) AL; average grading			4	43,3	%
$SC_{D60,D10}$	1,92	[-]	D_{85}	27,2	[mm]	8	59,2	%
$C_{uniformity}$	47,1	[-]	D_{60}	8,4	[mm]	16	75,0	%
$C_{curvature\ D30,D60,D10}$	3,58	[-]	D_{50}	5,7	[mm]	22.4	81,5	%
$C_{curvature\ D50,D85,D15}$	3,28	[-]	D_{30}	2,32	[mm]	31.5	88,1	%
$C_{extension}$	75,2	[-]	D_{15}	0,36	[mm]	45	95,0	%
$Z_{fines\ 75\mu m}$	3,9	%	D_{10}	0,18	[mm]			

G4CJ/MJ65/35 AL 100% rel.comp. source: **Kisimbi**

composition: 65% concr 35% mas			specimen size: 300 * 600 [mm*mm] group code: AL			age of sample:	3	[days]
k_1	13,637	[MPa]						
k_2	0,510	[-]						
volume dens. grains	2130,7	[kg/m³]	degr. of comp.	1,000	[-]	CBR:	154,9	%
dry density	1735	[kg/m³]	relative density	0,814	[-]	OMC	8,4	%
MPD	1735	[kg/m³]	spec dens solids	2578	[kg/m³]			
VVS	119,6	%				Sieve [mm]	% passing	
$CF_{average}$	0,72	[-]				0.063	3,0	%
			CF grading 11.2-16	0,74	[-]	0.125	7,9	%
			CF grading 16-22.4	0,74	[-]	0.25	12,8	%
$D_{(PSDC-FC)}$	68	%	CF grdng 22.4-31.5	0,72	[-]	0.5	17,7	%
$A_{(PSDC-FC)}$	353	% [mm]	CF grading 31.5-45	0,68	[-]	1	22,6	%
$A_{(PSDC-FC)middle}$	290	% [mm]	**Grading (curve):**			2	27,5	%
$SC_{D85,D15}$	1,95	[-]	(G4) AL; average grading			4	43,3	%
$SC_{D60,D10}$	1,92	[-]	D_{85}	27,2	[mm]	8	59,2	%
$C_{uniformity}$	47,1	[-]	D_{60}	8,4	[mm]	16	75,0	%
$C_{curvature\ D30,D60,D10}$	3,58	[-]	D_{50}	5,7	[mm]	22.4	81,5	%
$C_{curvature\ D50,D85,D15}$	3,28	[-]	D_{30}	2,32	[mm]	31.5	88,1	%
$C_{extension}$	75,2	[-]	D_{15}	0,36	[mm]	45	95,0	%
$Z_{fines\ 75\mu m}$	3,9	%	D_{10}	0,18	[mm]			

G4CJ/MJ80/20 AL 100% rel.comp. source: **Kisimbi**

composition: 80% concr 20% mas | specimen size: 300 * 600 [mm*mm] | group code: AL | age of sample: 3 [days]

k_1	41,615	[MPa]						
k_2	0,332	[-]						
volume dens. grains	2205,4	[kg/m^3]	degr. of comp.	1,000	[-]	CBR:	154,9	%
dry density	1787	[kg/m^3]	relative density	0,810	[-]	OMC	8,2	%
MPD	1787	[kg/m^3]	spec dens solids	2570	[kg/m^3]			
VVS	115,7	%						
$CF_{average}$	0,74	[-]						
			CF grading 11.2-16	0,76	[-]			
			CF grading 16-22.4	0,76	[-]			
$D_{(PSDC-FC)}$	68	%	CF grdng 22.4-31.5	0,73	[-]			
$A_{(PSDC-FC)}$	353	% [mm]	CF grading 31.5-45	0,69	[-]			
$A_{(PSDC-FC)middle}$	290	% [mm]	**Grading (curve):**					
$SC_{D85,D15}$	1,95	[-]	(G4) AL; average grading					
$SC_{D60,D10}$	1,92	[-]	D_{85}	27,2	[mm]			
$C_{uniformity}$	47,1	[-]	D_{60}	8,4	[mm]			
$C_{curvature\ D30,D60,D10}$	3,58	[-]	D_{50}	5,7	[mm]			
$C_{curvature\ D50,D85,D15}$	3,28	[-]	D_{30}	2,32	[mm]			
$C_{extension}$	75,2	[-]	D_{15}	0,36	[mm]			
$Z_{fines\ 75\mu m}$	3,9	%	D_{10}	0,18	[mm]			

Sieve [mm]	% passing	
0.063	3,0	%
0.125	7,9	%
0.25	12,8	%
0.5	17,7	%
1	22,6	%
2	27,5	%
4	43,3	%
8	59,2	%
16	75,0	%
22.4	81,5	%
31.5	88,1	%
45	95,0	%

MG 16H 94.7% rel.comp. source: **Kisimbi**

composition: commercial | specimen size: 300 * 600 [mm*mm] | group code: | age of sample: 3 [days]

k_1	29,154	[MPa]	ϕ:	44,63°		$\sigma_{1,failure}$	139,88	[kPa]
k_2	0,362	[-]	cohesion:	14,88	[kPa]	$\tau_{\sigma3=12kPa}$	63,94	[kPa]
volume dens. grains	2200	[kg/m^3]	degr. of comp.	0,947	[-]			
dry density	1684	[kg/m^3]	relative density	0,765	[-]	OMC	7,7	%
MPD	1778	[kg/m^3]	spec dens solids	2530	[kg/m^3]			
$D_{(PSDC-FC)}$	102	%						
$A_{(PSDC-FC)}$	421	% [mm]						
$A_{(PSDC-FC)middle}$	334	% [mm]	**Grading (curve):**					
$SC_{D85,D15}$	1,95	[-]	commercial grading					
$SC_{D60,D10}$	1,91	[-]	D_{85}	25,9	[mm]			
$C_{uniformity}$	43,1	[-]	D_{60}	9,3	[mm]			
$C_{curvature\ D30,D60,D10}$	0,35	[-]	D_{50}	5,3	[mm]			
$C_{curvature\ D50,D85,D15}$	3,42	[-]	D_{30}	0,84	[mm]			
$C_{extension}$	81,8	[-]	D_{15}	0,32	[mm]			
$Z_{fines\ 75\mu m}$	0,9	%	D_{10}	0,22	[mm]			

Sieve [mm]	% passing	
0.125	4,5	%
0.25	12,1	%
0.5	23,1	%
1	33,3	%
2	39,7	%
4	46,4	%
8	57,6	%
16	72,2	%
22.4	80,5	%
31.5	92,4	%
45	100,0	%

MG 16H 98% rel.comp.								source: **Kisimbi**	
composition: commercial			specimen size: 300 * 600 [mm*mm] group code:			age of sample:		3	[days]
k_1	25,571	[MPa]	ϕ:	43,25º		$\sigma_{1,failure}$		239,24	[kPa]
k_2	0,358	[-]	cohesion:	37,82	[kPa]	$\tau_{\sigma3=12kPa}$		113,62	[kPa]
volume dens. grains	2200	[kg/m^3]	degr. of comp.	0,980	[-]				
dry density	1742	[kg/m^3]	relative density	0,792	[-]	OMC		7,7	%
MPD	1778	[kg/m^3]	spec dens solids	2530	[kg/m^3]				
						Sieve [mm]	% passing		
						0.125	4,5	%	
						0.25	12,1	%	
$D_{(PSDC-FC)}$	102	%				0.5	23,1	%	
$A_{(PSDC-FC)}$	421	% [mm]				1	33,3	%	
$A_{(PSDC-FC)middle}$	334	% [mm]	**Grading (curve):**			2	39,7	%	
$SC_{D85,D15}$	1,95	[-]	commercial grading			4	46,4	%	
$SC_{D60,D10}$	1,91	[-]	D_{85}	25,9	[mm]	8	57,6	%	
$C_{uniformity}$	43,1	[-]	D_{60}	9,3	[mm]	16	72,2	%	
$C_{curvature\ D30,D60,D10}$	0,35	[-]	D_{50}	5,3	[mm]	22.4	80,5	%	
$C_{curvature\ D50,D85,D15}$	3,42	[-]	D_{30}	0,84	[mm]	31.5	92,4	%	
$C_{extension}$	81,8	[-]	D_{15}	0,32	[mm]	45	100,0	%	
$Z_{fines\ 75\mu m}$	0,9	%	D_{10}	0,22	[mm]				

MG 16H 100.5% rel.comp.								source: **Kisimbi**	
composition: commercial			specimen size: 300 * 600 [mm*mm] group code:			age of sample:		3	[days]
k_1	26,767	[MPa]	ϕ:	47,26º		$\sigma_{1,failure}$		352,54	[kPa]
k_2	0,356	[-]	cohesion:	53,64	[kPa]	$\tau_{\sigma3=12kPa}$		170,27	[kPa]
volume dens. grains	2200	[kg/m^3]	degr. of comp.	1,005	[-]				
dry density	1787	[kg/m^3]	relative density	0,812	[-]	OMC		7,7	%
MPD	1778	[kg/m^3]	spec dens solids	2530	[kg/m^3]				
						Sieve [mm]	% passing		
						0.125	4,5	%	
						0.25	12,1	%	
$D_{(PSDC-FC)}$	102	%				0.5	23,1	%	
$A_{(PSDC-FC)}$	421	% [mm]				1	33,3	%	
$A_{(PSDC-FC)middle}$	334	% [mm]	**Grading (curve):**			2	39,7	%	
$SC_{D85,D15}$	1,95	[-]	commercial grading			4	46,4	%	
$SC_{D60,D10}$	1,91	[-]	D_{85}	25,9	[mm]	8	57,6	%	
$C_{uniformity}$	43,1	[-]	D_{60}	9,3	[mm]	16	72,2	%	
$C_{curvature\ D30,D60,D10}$	0,35	[-]	D_{50}	5,3	[mm]	22.4	80,5	%	
$C_{curvature\ D50,D85,D15}$	3,42	[-]	D_{30}	0,84	[mm]	31.5	92,4	%	
$C_{extension}$	81,8	[-]	D_{15}	0,32	[mm]	45	100,0	%	
$Z_{fines\ 75\mu m}$	0,9	%	D_{10}	0,22	[mm]				

MG 16H 102,3% rel.comp. source: **Kisimbi**

composition: commercial			specimen size: 300 * 600 [mm*mm] group code:			age of sample:	3	[days]
k_1	30,726	[MPa]	ϕ:	44,48°		$\sigma_{1,failure}$	299,95	[kPa]
k_2	0,353	[-]	cohesion:	48,62	[kPa]	$\tau_{\sigma 3=12kPa}$	143,98	[kPa]
volume dens. grains	2200	[kg/m³]	degr. of comp.	1,023	[-]			
dry density	1819	[kg/m³]	relative density	0,827	[-]	OMC	7,7	%
MPD	1778	[kg/m³]	spec dens solids	2530	[kg/m³]			

						Sieve [mm]	% passing	
						0.125	4,5	%
						0.25	12,1	%
$D_{(PSDC-FC)}$	102	%				0.5	23,1	%
$A_{(PSDC-FC)}$	421	% [mm]				1	33,3	%
$A_{(PSDC-FC)middle}$	334	% [mm]	**Grading (curve):**			2	39,7	%
$SC_{D85,D15}$	1,95	[-]	commercial grading			4	46,4	%
$SC_{D60,D10}$	1,91	[-]	D_{85}	25,9	[mm]	8	57,6	%
$C_{uniformity}$	43,1	[-]	D_{60}	9,3	[mm]	16	72,2	%
$C_{curvature\ D30,D60,D10}$	0,35	[-]	D_{50}	5,3	[mm]	22.4	80,5	%
$C_{curvature\ D50,D85,D15}$	3,42	[-]	D_{30}	0,84	[mm]	31.5	92,4	%
$C_{extension}$	81,8	[-]	D_{15}	0,32	[mm]	45	100,0	%
$Z_{fines\ 75\mu m}$	0,9	%	D_{10}	0,22	[mm]			

MG 16H 104.9% rel.comp.

source: **Kisimbi**

composition: commercial			specimen size: 300 * 600 [mm*mm] group code:			age of sample:	3	[days]
k_1	40,207	[MPa]	ϕ:	47,88°		$\sigma_{1,failure}$	760,35	[kPa]
k_2	0,384	[-]	cohesion:	130,81	[kPa]	$\tau_{\sigma3=12kPa}$	374,17	[kPa]
volume dens. grains	2200	[kg/m³]	degr. of comp.	1,049	[-]			
dry density	1865	[kg/m³]	relative density	0,848	[-]	OMC	7,7	%
MPD	1778	[kg/m³]	spec dens solids	2530	[kg/m³]			

						Sieve [mm]	% passing	
						0.125	4,5	%
						0.25	12,1	%
$D_{(PSDC-FC)}$	102	%				0.5	23,1	%
$A_{(PSDC-FC)}$	421	% [mm]				1	33,3	%
$A_{(PSDC-FC)middle}$	334	% [mm]	**Grading (curve):**			2	39,7	%
$SC_{D85,D15}$	1,95	[-]	commercial grading			4	46,4	%
$SC_{D60,D10}$	1,91	[-]	D_{85}	25,9	[mm]	8	57,6	%
$C_{uniformity}$	43,1	[-]	D_{60}	9,3	[mm]	16	72,2	%
$C_{curvature\ D30,D60,D10}$	0,35	[-]	D_{50}	5,3	[mm]	22.4	80,5	%
$C_{curvature\ D50,D85,D15}$	3,42	[-]	D_{30}	0,84	[mm]	31.5	92,4	%
$C_{extension}$	81,8	[-]	D_{15}	0,32	[mm]	45	100,0	%
$Z_{fines\ 75\mu m}$	0,9	%	D_{10}	0,22	[mm]			

G1CJ/MJ65/35 97% rel.comp. UL

source: **Muraya**

composition: 65% concr 35% mas			specimen size: 300 * 600 [mm*mm] group code: UL			age of sample:	4	[days]
k_1	33,187	[MPa]	ϕ:	35,10°		$\sigma_{1,failure}$	313,21	[kPa]
k_2	0,329	[-]	cohesion:	69,8	[kPa]	$\tau_{\sigma3=12kPa}$	150,61	[kPa]
volume dens. grains	2130,7	[kg/m³]	degr. of comp.	0,970	[-]			
dry density	1702	[kg/m³]	relative density	0,799	[-]	OMC	10	%
MPD	1755	[kg/m³]	spec dens solids	2578	[kg/m³]			

						Sieve [mm]	% passing	
VVS	119,6	%						
$CF_{average}$	0,72	[-]				0.063	6,0	%
			CF grading 11.2-16	0,74	[-]	0.125	12,7	%
			CF grading 16-22.4	0,74	[-]	0.25	19,6	%
$D_{(PSDC-FC)}$	172	%	CF grdng 22.4-31.5	0,72	[-]	0.5	26,4	%
$A_{(PSDC-FC)}$	879	% [mm]	CF grading 31.5-45	0,68	[-]	1	33,2	%
$A_{(PSDC-FC)middle}$	738	% [mm]	**Grading (curve):**			2	40,0	%
$SC_{D85,D15}$	1,95	[-]	(G1) UL; upper limit, fine			4	56,7	%
$SC_{D60,D10}$	1,92	[-]	D_{85}	13,6	[mm]	8	73,3	%
$C_{uniformity}$	47,9	[-]	D_{60}	4,8	[mm]	16	90,0	%
$C_{curvature\ D30,D60,D10}$	1,22	[-]	D_{50}	3,2	[mm]	22.4	93,3	%
$C_{curvature\ D50,D85,D15}$	4,51	[-]	D_{30}	0,76	[mm]	31.5	96,6	%
$C_{extension}$	81,6	[-]	D_{15}	0,17	[mm]	45	100,0	%
$Z_{fines\ 75\mu m}$	7,3	%	D_{10}	0,10	[mm]			

G1CJ/MJ65/35 100% rel.comp. UL

source: **Muraya**

composition: 65% concr 35% mas

specimen size: 300 * 600 [mm*mm]

group code: UL

age of sample: 4 [days]

k_1	21,106	[MPa]	ϕ:	28,30°		$\sigma_{1,failure}$	513,12	[kPa]
k_2	0,411	[-]	cohesion:	143,2	[kPa]	$\tau_{\sigma3=12kPa}$	250,56	[kPa]

volume dens. grains	2130,7	[kg/m³]	degr. of comp.	1,000	[-]			
dry density	1755	[kg/m³]	relative density	0,824	[-]	OMC	10	%
MPD	1755	[kg/m³]	spec dens solids	2578	[kg/m³]			

VVS	119,6	%
$CF_{average}$	0,72	[-]
$D_{(PSDC-FC)}$	172	%
$A_{(PSDC-FC)}$	879	% [mm]
$A_{(PSDC-FC)middle}$	738	% [mm]
$SC_{D85,D15}$	1,95	[-]
$SC_{D60,D10}$	1,92	[-]
$C_{uniformity}$	47,9	[-]
$C_{curvature\ D30,D60,D10}$	1,22	[-]
$C_{curvature\ D50,D85,D15}$	4,51	[-]
$C_{extension}$	81,6	[-]
$Z_{fines\ 75\mu m}$	7,3	%

CF grading 11.2-16	0,74	[-]
CF grading 16-22.4	0,74	[-]
CF grdng 22.4-31.5	0,72	[-]
CF grading 31.5-45	0,68	[-]

Grading (curve):

(G1) UL; upper limit, fine

D_{85}	13,6	[mm]
D_{60}	4,8	[mm]
D_{50}	3,2	[mm]
D_{30}	0,76	[mm]
D_{15}	0,17	[mm]
D_{10}	0,10	[mm]

Sieve [mm]	% passing	
0.063	6,0	%
0.125	12,7	%
0.25	19,6	%
0.5	26,4	%
1	33,2	%
2	40,0	%
4	56,7	%
8	73,3	%
16	90,0	%
22.4	93,3	%
31.5	96,6	%
45	100,0	%

G1CJ/MJ65/35 103% rel.comp. UL

source: **Muraya**

composition: 65% concr 35% mas

specimen size: 300 * 600 [mm*mm]

group code: UL

age of sample: 4 [days]

k_1	23,854	[MPa]	ϕ:	36,00°		$\sigma_{1,failure}$	568,67	[kPa]
k_2	0,464	[-]	cohesion:	133,1	[kPa]	$\tau_{\sigma3=12kPa}$	278,33	[kPa]

volume dens. grains	2130,7	[kg/m³]	degr. of comp.	1,030	[-]			
dry density	1807,65	[kg/m³]	relative density	0,848	[-]	OMC	10	%
MPD	1755	[kg/m³]	spec dens solids	2578	[kg/m³]			

VVS	119,6	%
$CF_{average}$	0,72	[-]
$D_{(PSDC-FC)}$	172	%
$A_{(PSDC-FC)}$	879	% [mm]
$A_{(PSDC-FC)middle}$	738	% [mm]
$SC_{D85,D15}$	1,95	[-]
$SC_{D60,D10}$	1,92	[-]
$C_{uniformity}$	47,9	[-]
$C_{curvature\ D30,D60,D10}$	1,22	[-]
$C_{curvature\ D50,D85,D15}$	4,51	[-]
$C_{extension}$	81,6	[-]
$Z_{fines\ 75\mu m}$	7,3	%

CF grading 11.2-16	0,74	[-]
CF grading 16-22.4	0,74	[-]
CF grdng 22.4-31.5	0,72	[-]
CF grading 31.5-45	0,68	[-]

Grading (curve):

(G1) UL; upper limit, fine

D_{85}	13,6	[mm]
D_{60}	4,8	[mm]
D_{50}	3,2	[mm]
D_{30}	0,76	[mm]
D_{15}	0,17	[mm]
D_{10}	0,10	[mm]

Sieve [mm]	% passing	
0.063	6,0	%
0.125	12,7	%
0.25	19,6	%
0.5	26,4	%
1	33,2	%
2	40,0	%
4	56,7	%
8	73,3	%
16	90,0	%
22.4	93,3	%
31.5	96,6	%
45	100,0	%

G4CJ/MJ65/35 97% rel.comp. AL

source: **Muraya**

composition: 65% concr 35% mas			specimen size: 300 * 600 [mm*mm] group code: AL			age of sample:	3	[days]
k_1	48,108	[MPa]	ϕ:	36,90º		$\sigma_{1,failure}$	270,21	[kPa]
k_2	0,266	[-]	cohesion:	55,5	[kPa]	$\tau_{\sigma3=12kPa}$	129,10	[kPa]
volume dens. grains	2130,7	[kg/m³]	degr. of comp.	0,970	[-]			
dry density	1683	[kg/m³]	relative density	0,790	[-]	OMC	10	%
MPD	1735	[kg/m³]	spec dens solids	2578	[kg/m³]			
VVS	119,6	%				Sieve [mm]	% passing	
$CF_{average}$	0,72	[-]				0.063	3,0	%
			CF grading 11.2-16	0,74	[-]	0.125	7,9	%
			CF grading 16-22.4	0,74	[-]	0.25	12,8	%
$D_{(PSDC-FC)}$	68	%	CF grdng 22.4-31.5	0,72	[-]	0.5	17,7	%
$A_{(PSDC-FC)}$	353	% [mm]	CF grading 31.5-45	0,68	[-]	1	22,6	%
$A_{(PSDC-FC)middle}$	290	% [mm]	**Grading (curve):**			2	27,5	%
$SC_{D85,D15}$	1,95	[-]	(G4) AL; average grading			4	43,3	%
$SC_{D60,D10}$	1,92	[-]	D_{85}	27,2	[mm]	8	59,2	%
$C_{uniformity}$	47,1	[-]	D_{60}	8,4	[mm]	16	75,0	%
$C_{curvature\ D30,D60,D10}$	3,58	[-]	D_{50}	5,7	[mm]	22.4	81,5	%
$C_{curvature\ D50,D85,D15}$	3,28	[-]	D_{30}	2,32	[mm]	31.5	88,1	%
$C_{extension}$	75,2	[-]	D_{15}	0,36	[mm]	45	95,0	%
$Z_{fines\ 75\mu m}$	3,9	%	D_{10}	0,18	[mm]			

G4CJ/MJ65/35 100% rel.comp. AL

source: **Muraya**

composition: 65% concr 35% mas			specimen size: 300 * 600 [mm*mm] group code: AL			age of sample:	3	[days]
k_1	14,947	[MPa]	ϕ:	40,50º		$\sigma_{1,failure}$	481,62	[kPa]
k_2	0,465	[-]	cohesion:	98	[kPa]	$\tau_{\sigma3=12kPa}$	234,81	[kPa]
volume dens. grains	2130,7	[kg/m³]	degr. of comp.	1,000	[-]			
dry density	1735	[kg/m³]	relative density	0,814	[-]	OMC	10	%
MPD	1735	[kg/m³]	spec dens solids	2578	[kg/m³]			
VVS	119,6	%				Sieve [mm]	% passing	
$CF_{average}$	0,72	[-]				0.063	3,0	%
			CF grading 11.2-16	0,74	[-]	0.125	7,9	%
			CF grading 16-22.4	0,74	[-]	0.25	12,8	%
$D_{(PSDC-FC)}$	68	%	CF grdng 22.4-31.5	0,72	[-]	0.5	17,7	%
$A_{(PSDC-FC)}$	353	% [mm]	CF grading 31.5-45	0,68	[-]	1	22,6	%
$A_{(PSDC-FC)middle}$	290	% [mm]	**Grading (curve):**			2	27,5	%
$SC_{D85,D15}$	1,95	[-]	(G4) AL; average grading			4	43,3	%
$SC_{D60,D10}$	1,92	[-]	D_{85}	27,2	[mm]	8	59,2	%
$C_{uniformity}$	47,1	[-]	D_{60}	8,4	[mm]	16	75,0	%
$C_{curvature\ D30,D60,D10}$	3,58	[-]	D_{50}	5,7	[mm]	22.4	81,5	%
$C_{curvature\ D50,D85,D15}$	3,28	[-]	D_{30}	2,32	[mm]	31.5	88,1	%
$C_{extension}$	75,2	[-]	D_{15}	0,36	[mm]	45	95,0	%
$Z_{fines\ 75\mu m}$	3,9	%	D_{10}	0,18	[mm]			

G4CJ/MJ65/35 103% rel.comp. AL

source: **Muraya**

composition: 65% concr 35% mas			specimen size: 300 * 600 [mm*mm] group code: AL			age of sample:	3	[days]
k_1	26,902	[MPa]	ϕ:	42,90°		$\sigma_{1,failure}$	473,86	[kPa]
k_2	0,439	[-]	cohesion:	89,5	[kPa]	$\tau_{\sigma3=12kPa}$	230,93	[kPa]
volume dens. grains	2130,7	[kg/m³]	degr. of comp.	1,030	[-]			
dry density	1787	[kg/m³]	relative density	0,839	[-]	OMC	10	%
MPD	1735	[kg/m³]	spec dens solids	2578	[kg/m³]			
VVS	119,6	%				Sieve [mm]	% passing	
$CF_{average}$	0,72	[-]				0.063	3,0	%
			CF grading 11.2-16	0,74	[-]	0.125	7,9	%
			CF grading 16-22.4	0,74	[-]	0.25	12,8	%
$D_{(PSDC-FC)}$	68	%	CF grdng 22.4-31.5	0,72	[-]	0.5	17,7	%
$A_{(PSDC-FC)}$	353	% [mm]	CF grading 31.5-45	0,68	[-]	1	22,6	%
$A_{(PSDC-FC)middle}$	290	% [mm]	**Grading (curve):**			2	27,5	%
$SC_{D85,D15}$	1,95	[-]	(G4) AL; average grading			4	43,3	%
$SC_{D60,D10}$	1,92	[-]	D_{85}	27,2	[mm]	8	59,2	%
$C_{uniformity}$	47,1	[-]	D_{60}	8,4	[mm]	16	75,0	%
$C_{curvature\ D30,D60,D10}$	3,58	[-]	D_{50}	5,7	[mm]	22.4	81,5	%
$C_{curvature\ D50,D85,D15}$	3,28	[-]	D_{30}	2,32	[mm]	31.5	88,1	%
$C_{extension}$	75,2	[-]	D_{15}	0,36	[mm]	45	95,0	%
$Z_{fines\ 75\mu m}$	3,9	%	D_{10}	0,18	[mm]			

G4CJ/MJ65/35 105% rel.comp. AL

source: **Muraya**

composition: 65% concr 35% mas			specimen size: 300 * 600 [mm*mm] group code: AL			age of sample:	4	[days]
k_1	43,499	[MPa]	ϕ:	38,10º		$\sigma_{1,failure}$	798,22	[kPa]
k_2	0,385	[-]	cohesion:	181,9	[kPa]	$\tau_{\sigma3=12kPa}$	393,11	[kPa]
volume dens. grains	2130,7	[kg/m^3]	degr. of comp.	1,050	[-]			
dry density	1821	[kg/m^3]	relative density	0,855	[-]	OMC	10	%
MPD	1735	[kg/m^3]	spec dens solids	2578	[kg/m^3]			
VVS	119,6	%						
$CF_{average}$	0,72	[-]						

CF grading 11.2-16	0,74	[-]
CF grading 16-22.4	0,74	[-]
CF grdng 22.4-31.5	0,72	[-]
CF grading 31.5-45	0,68	[-]

$D_{(PSDC-FC)}$	68	%
$A_{(PSDC-FC)}$	353	% [mm]
$A_{(PSDC-FC)middle}$	290	% [mm]
$SC_{D85,D15}$	1,95	[-]
$SC_{D60,D10}$	1,92	[-]
$C_{uniformity}$	47,1	[-]
$C_{curvature\ D30,D60,D10}$	3,58	[-]
$C_{curvature\ D50,D85,D15}$	3,28	[-]
$C_{extension}$	75,2	[-]
$Z_{fines\ 75\mu m}$	3,9	%

Grading (curve):
(G4) AL; average grading

D_{85}	27,2	[mm]
D_{60}	8,4	[mm]
D_{50}	5,7	[mm]
D_{30}	2,32	[mm]
D_{15}	0,36	[mm]
D_{10}	0,18	[mm]

Sieve [mm]	% passing	
0.063	3,0	%
0.125	7,9	%
0.25	12,8	%
0.5	17,7	%
1	22,6	%
2	27,5	%
4	43,3	%
8	59,2	%
16	75,0	%
22.4	81,5	%
31.5	88,1	%
45	95,0	%

G5CJ/MJ65/35 97% rel.comp. LL

source: **Muraya**

composition: 65% concr 35% mas			specimen size: 300 * 600 [mm*mm] group code: LL			age of sample:	4	[days]
k_1	15,663	[MPa]	ϕ:	41,10º		$\sigma_{1,failure}$	285,46	[kPa]
k_2	0,463	[-]	cohesion:	51,7	[kPa]	$\tau_{\sigma3=12kPa}$	136,73	[kPa]
volume dens. grains	2130,7	[kg/m^3]	degr. of comp.	0,970	[-]			
dry density	1615	[kg/m^3]	relative density	0,758	[-]	OMC	8,6	%
MPD	1665	[kg/m^3]	spec dens solids	2578	[kg/m^3]			
VVS	119,6	%						
$CF_{average}$	0,72	[-]						

CF grading 11.2-16	0,74	[-]
CF grading 16-22.4	0,74	[-]
CF grdng 22.4-31.5	0,72	[-]
CF grading 31.5-45	0,68	[-]

$D_{(PSDC-FC)}$	52	%
$A_{(PSDC-FC)}$	173	% [mm]
$A_{(PSDC-FC)middle}$	232	% [mm]
$SC_{D85,D15}$	1,80	[-]
$SC_{D60,D10}$	1,84	[-]
$C_{uniformity}$	24,0	[-]
$C_{curvature\ D30,D60,D10}$	1,50	[-]
$C_{curvature\ D50,D85,D15}$	1,48	[-]
$C_{extension}$	19,2	[-]
$Z_{fines\ 75\mu m}$	0,6	%

Grading (curve):
(G5) LL; lower limit, coarse

D_{85}	38,4	[mm]
D_{60}	16,0	[mm]
D_{50}	10,7	[mm]
D_{30}	4,00	[mm]
D_{15}	2,00	[mm]
D_{10}	0,67	[mm]

Sieve [mm]	% passing	
0.125	3,0	%
0.25	6,0	%
0.5	9,0	%
1	12,0	%
2	15,0	%
4	30,0	%
8	45,0	%
16	60,0	%
22.4	69,8	%
31.5	79,7	%
45	90,0	%

G5CJ/MJ65/35 100% rel.comp. LL source: **Muraya**

composition: 65% concr 35% mas			specimen size: 300 * 600 [mm*mm] group code: LL			age of sample:	4	[days]
k_1	15,663	[MPa]	ϕ:	35,50°		$\sigma_{1,failure}$	344,64	[kPa]
k_2	0,463	[-]	cohesion:	77,1	[kPa]	$\tau_{\sigma3=12kPa}$	166,32	[kPa]
volume dens. grains	2130,7	[kg/m³]	degr. of comp.	1,000	[-]			
dry density	1665	[kg/m³]	relative density	0,781	[-]	OMC	8,6	%
MPD	1665	[kg/m³]	spec dens solids	2578	[kg/m³]			
VVS	119,6	%				Sieve [mm]	% passing	
$CF_{average}$	0,72	[-]						
			CF grading 11.2-16	0,74	[-]	0.125	3,0	%
			CF grading 16-22.4	0,74	[-]	0.25	6,0	%
$D_{(PSDC-FC)}$	52	%	CF grdng 22.4-31.5	0,72	[-]	0.5	9,0	%
$A_{(PSDC-FC)}$	173	% [mm]	CF grading 31.5-45	0,68	[-]	1	12,0	%
$A_{(PSDC-FC)middle}$	232	% [mm]	**Grading (curve):**			2	15,0	%
$SC_{D85,D15}$	1,80	[-]	(G5) LL; lower limit, coarse			4	30,0	%
$SC_{D60,D10}$	1,84	[-]	D_{85}	38,4	[mm]	8	45,0	%
$C_{uniformity}$	24,0	[-]	D_{60}	16,0	[mm]	16	60,0	%
$C_{curvature\ D30,D60,D10}$	1,50	[-]	D_{50}	10,7	[mm]	22.4	69,8	%
$C_{curvature\ D50,D85,D15}$	1,48	[-]	D_{30}	4,00	[mm]	31.5	79,7	%
$C_{extension}$	19,2	[-]	D_{15}	2,00	[mm]	45	90,0	%
$Z_{fines\ 75\mu m}$	0,6	%	D_{10}	0,67	[mm]			

G5CJ/MJ65/35 103% rel.comp. LL source: **Muraya**

composition: 65% concr 35% mas			specimen size: 300 * 600 [mm*mm] group code: LL			age of sample:	4	[days]
k_1	33,024	[MPa]	ϕ:	41,60°		$\sigma_{1,failure}$	517,78	[kPa]
k_2	0,376	[-]	cohesion:	103	[kPa]	$\tau_{\sigma3=12kPa}$	252,89	[kPa]
volume dens. grains	2130,7	[kg/m³]	degr. of comp.	1,030	[-]			
dry density	1715	[kg/m³]	relative density	0,805	[-]	OMC	8,6	%
MPD	1665	[kg/m³]	spec dens solids	2578	[kg/m³]			
VVS	119,6	%				Sieve [mm]	% passing	
$CF_{average}$	0,72	[-]						
			CF grading 11.2-16	0,74	[-]	0.125	3,0	%
			CF grading 16-22.4	0,74	[-]	0.25	6,0	%
$D_{(PSDC-FC)}$	52	%	CF grdng 22.4-31.5	0,72	[-]	0.5	9,0	%
$A_{(PSDC-FC)}$	173	% [mm]	CF grading 31.5-45	0,68	[-]	1	12,0	%
$A_{(PSDC-FC)middle}$	232	% [mm]	**Grading (curve):**			2	15,0	%
$SC_{D85,D15}$	1,80	[-]	(G5) LL; lower limit, coarse			4	30,0	%
$SC_{D60,D10}$	1,84	[-]	D_{85}	38,4	[mm]	8	45,0	%
$C_{uniformity}$	24,0	[-]	D_{60}	16,0	[mm]	16	60,0	%
$C_{curvature\ D30,D60,D10}$	1,50	[-]	D_{50}	10,7	[mm]	22.4	69,8	%
$C_{curvature\ D50,D85,D15}$	1,48	[-]	D_{30}	4,00	[mm]	31.5	79,7	%
$C_{extension}$	19,2	[-]	D_{15}	2,00	[mm]	45	90,0	%
$Z_{fines\ 75\mu m}$	0,6	%	D_{10}	0,67	[mm]			

G5CJ/MJ65/35 105% rel.comp. LL source: **Muraya**

composition: 65% concr 35% mas			specimen size: 300 * 600 [mm*mm] group code: LL			age of sample:	4	[days]
k_1	20,015	[MPa]	ϕ:	(42,6º)		$\sigma_{1,failure}$	519,92	[kPa]
k_2	0,451	[-]	cohesion:	(85.7)	[kPa]	$\tau_{\sigma3=12kPa}$	253,96	[kPa]
volume dens. grains	2130,7	[kg/m³]	degr. of comp.	1,050	[-]			
dry density	1748	[kg/m³]	relative density	0,820	[-]	OMC	8,6	%
MPD	1665	[kg/m³]	spec dens solids	2578	[kg/m³]			
VVS	119,6	%				Sieve [mm]	% passing	
$CF_{average}$	0,72	[-]						
			CF grading 11.2-16	0,74	[-]	0.125	3,0	%
			CF grading 16-22.4	0,74	[-]	0.25	6,0	%
$D_{(PSDC-FC)}$	52	%	CF grdng 22.4-31.5	0,72	[-]	0.5	9,0	%
$A_{(PSDC-FC)}$	173	% [mm]	CF grading 31.5-45	0,68	[-]	1	12,0	%
$A_{(PSDC-FC)middle}$	232	% [mm]	**Grading (curve):**			2	15,0	%
$SC_{D85,D15}$	1,80	[-]	(G5) LL; lower limit, coarse			4	30,0	%
$SC_{D60,D10}$	1,84	[-]	D_{85}	38,4	[mm]	8	45,0	%
$C_{uniformity}$	24,0	[-]	D_{60}	16,0	[mm]	16	60,0	%
$C_{curvature\ D30,D60,D10}$	1,50	[-]	D_{50}	10,7	[mm]	22.4	69,8	%
$C_{curvature\ D50,D85,D15}$	1,48	[-]	D_{30}	4,00	[mm]	31.5	79,7	%
$C_{extension}$	19,2	[-]	D_{15}	2,00	[mm]	45	90,0	%
$Z_{fines\ 75\mu m}$	0,6	%	D_{10}	0,67	[mm]			

G4CJ/MJ50/50 100% rel.comp. AL source: **Muraya**

composition: 50% concr 50% mas			specimen size: 300 * 600 [mm*mm] group code: AL			age of sample:	4	[days]
k_1	17,053	[MPa]	ϕ:	39,50º		$\sigma_{1,failure}$	464,44	[kPa]
k_2	0,491	[-]	cohesion:	96,8	[kPa]	$\tau_{\sigma3=12kPa}$	226,22	[kPa]
volume dens. grains	2056	[kg/m³]	degr. of comp.	1,000	[-]			
dry density	1718	[kg/m³]	relative density	0,836	[-]	OMC	7,8	%
MPD	1718	[kg/m³]	spec dens solids	2585	[kg/m³]			
VVS	123,6	%				Sieve [mm]	% passing	
$CF_{average}$	0,72	[-]				0.063	3,0	%
			CF grading 11.2-16	0,74	[-]	0.125	7,9	%
			CF grading 16-22.4	0,74	[-]	0.25	12,8	%
$D_{(PSDC-FC)}$	68	%	CF grdng 22.4-31.5	0,72	[-]	0.5	17,7	%
$A_{(PSDC-FC)}$	353	% [mm]	CF grading 31.5-45	0,68	[-]	1	22,6	%
$A_{(PSDC-FC)middle}$	290	% [mm]	**Grading (curve):**			2	27,5	%
$SC_{D85,D15}$	1,95	[-]	(G4) AL; average grading			4	43,3	%
$SC_{D60,D10}$	1,92	[-]	D_{85}	27,2	[mm]	8	59,2	%
$C_{uniformity}$	47,1	[-]	D_{60}	8,4	[mm]	16	75,0	%
$C_{curvature\ D30,D60,D10}$	3,58	[-]	D_{50}	5,7	[mm]	22.4	81,5	%
$C_{curvature\ D50,D85,D15}$	3,28	[-]	D_{30}	2,32	[mm]	31.5	88,1	%
$C_{extension}$	75,2	[-]	D_{15}	0,36	[mm]	45	95,0	%
$Z_{fines\ 75\mu m}$	3,9	%	D_{10}	0,18	[mm]			

G4CJ/MJ80/20 100% rel.comp. AL source: **Muraya**

			specimen size: 300 * 600 [mm*mm]					
composition: 80% concr 20% mas			group code: AL			age of sample:	4	[days]
k_1	37,220	[MPa]	ϕ:	38,70°		$\sigma_{1,failure}$	574,75	[kPa]
k_2	0,387	[-]	cohesion:	125,5	[kPa]	$\tau_{\sigma3=12kPa}$	281,37	[kPa]
volume dens. grains	2205,4	[kg/m³]	degr. of comp.	1,000	[-]			
dry density	1787	[kg/m³]	relative density	0,810	[-]	OMC	8,2	%
MPD	1787	[kg/m³]	spec dens solids	2570	[kg/m³]			
VVS	115,7	%						
$CF_{average}$	0,72	[-]						
			CF grading 11.2-16	0,74	[-]			
			CF grading 16-22.4	0,74	[-]			
$D_{(PSDC-FC)}$	68	%	CF grdng 22.4-31.5	0,72	[-]			
$A_{(PSDC-FC)}$	353	% [mm]	CF grading 31.5-45	0,68	[-]			
$A_{(PSDC-FC)middle}$	290	% [mm]	**Grading (curve):**					
$SC_{D85,D15}$	1,95	[-]	(G4) AL; average grading					
$SC_{D60,D10}$	1,92	[-]	D_{85}	27,2	[mm]			
$C_{uniformity}$	47,1	[-]	D_{60}	8,4	[mm]			
$C_{curvature\ D30,D60,D10}$	3,58	[-]	D_{50}	5,7	[mm]			
$C_{curvature\ D50,D85,D15}$	3,28	[-]	D_{30}	2,32	[mm]			
$C_{extension}$	75,2	[-]	D_{15}	0,36	[mm]			
$Z_{fines\ 75\mu m}$	3,9	%	D_{10}	0,18	[mm]			

Sieve [mm]	% passing	
0.063	3,0	%
0.125	7,9	%
0.25	12,8	%
0.5	17,7	%
1	22,6	%
2	27,5	%
4	43,3	%
8	59,2	%
16	75,0	%
22.4	81,5	%
31.5	88,1	%
45	95,0	%

G1CJ/MJ65/35 97% rel.comp. UL 28

source: **Muraya**

			specimen size: 300 * 600 [mm*mm]			material code:	28 D	
composition: 65% concr 35% mas			group code: UL			age of sample:	28	[days]
k_1	15,008	[MPa]	ϕ:	41,50°		$\sigma_{1,failure}$	476,04	[kPa]
k_2	0,524	[-]	cohesion:	93,9	[kPa]	$\tau_{\sigma3=12kPa}$	232,02	[kPa]
volume dens. grains	2130,7	[kg/m^3]	degr. of comp.	0,970	[-]			
dry density	1702	[kg/m^3]	relative density	0,799	[-]	OMC	10	%
MPD	1755	[kg/m^3]	spec dens solids	2578	[kg/m^3]			
VVS	119,6	%				Sieve [mm]	% passing	
$CF_{average}$	0,72	[-]				0.063	6,0	%
			CF grading 11.2-16	0,74	[-]	0.125	12,7	%
			CF grading 16-22.4	0,74	[-]	0.25	19,6	%
$D_{(PSDC-FC)}$	172	%	CF grdng 22.4-31.5	0,72	[-]	0.5	26,4	%
$A_{(PSDC-FC)}$	879	% [mm]	CF grading 31.5-45	0,68	[-]	1	33,2	%
$A_{(PSDC-FC)middle}$	738	% [mm]	**Grading (curve):**			2	40,0	%
$SC_{D85,D15}$	1,95	[-]	(G1) UL; upper limit, fine			4	56,7	%
$SC_{D60,D10}$	1,92	[-]	D_{85}	13,6	[mm]	8	73,3	%
$C_{uniformity}$	47,9	[-]	D_{60}	4,8	[mm]	16	90,0	%
$C_{curvature\ D30,D60,D10}$	1,22	[-]	D_{50}	3,2	[mm]	22.4	93,3	%
$C_{curvature\ D50,D85,D15}$	4,51	[-]	D_{30}	0,76	[mm]	31.5	96,6	%
$C_{extension}$	81,6	[-]	D_{15}	0,17	[mm]	45	100,0	%
$Z_{fines\ 75\mu m}$	7,3	%	D_{10}	0,10	[mm]			

G1CJ/MJ65/35 100% rel.comp. UL 28

source: **Muraya**

			specimen size: 300 * 600 [mm*mm]			material code:	28 D	
composition: 65% concr 35% mas			group code: UL			age of sample:	28	[days]
k_1	31,915	[MPa]	ϕ:	40,60°		$\sigma_{1,failure}$	336,75	[kPa]
k_2	0,362	[-]	cohesion:	64,4	[kPa]	$\tau_{\sigma3=12kPa}$	162,38	[kPa]
volume dens. grains	2130,7	[kg/m^3]	degr. of comp.	1,000	[-]			
dry density	1755	[kg/m^3]	relative density	0,824	[-]	OMC	10	%
MPD	1755	[kg/m^3]	spec dens solids	2578	[kg/m^3]			
VVS	119,6	%				Sieve [mm]	% passing	
$CF_{average}$	0,72	[-]				0.063	6,0	%
			CF grading 11.2-16	0,74	[-]	0.125	12,7	%
			CF grading 16-22.4	0,74	[-]	0.25	19,6	%
$D_{(PSDC-FC)}$	172	%	CF grdng 22.4-31.5	0,72	[-]	0.5	26,4	%
$A_{(PSDC-FC)}$	879	% [mm]	CF grading 31.5-45	0,68	[-]	1	33,2	%
$A_{(PSDC-FC)middle}$	738	% [mm]	**Grading (curve):**			2	40,0	%
$SC_{D85,D15}$	1,95	[-]	(G1) UL; upper limit, fine			4	56,7	%
$SC_{D60,D10}$	1,92	[-]	D_{85}	13,6	[mm]	8	73,3	%
$C_{uniformity}$	47,9	[-]	D_{60}	4,8	[mm]	16	90,0	%
$C_{curvature\ D30,D60,D10}$	1,22	[-]	D_{50}	3,2	[mm]	22.4	93,3	%
$C_{curvature\ D50,D85,D15}$	4,51	[-]	D_{30}	0,76	[mm]	31.5	96,6	%
$C_{extension}$	81,6	[-]	D_{15}	0,17	[mm]	45	100,0	%
$Z_{fines\ 75\mu m}$	7,3	%	D_{10}	0,10	[mm]			

G1CJ/MJ65/35 103% rel.comp. UL 28 source: **Muraya**

			specimen size: 300 * 600 [mm*mm]			material code:	28 D	
composition: 65% concr 35% mas			group code: UL			age of sample:	28	[days]
k_1	18,558	[MPa]	ϕ:	45,90°		$\sigma_{1,failure}$	674,56	[kPa]
k_2	0,517	[-]	cohesion:	121,8	[kPa]	$\tau_{\sigma3=12kPa}$	331,28	[kPa]
volume dens. grains	2130,7	[kg/m^3]	degr. of comp.	1,030	[-]			
dry density	1807,65	[kg/m^3]	relative density	0,848	[-]	OMC	10	%
MPD	1755	[kg/m^3]	spec dens solids	2578	[kg/m^3]			
VVS	119,6	%				Sieve [mm]	% passing	
$CF_{average}$	0,72	[-]				0.063	6,0	%
			CF grading 11.2-16	0,74	[-]	0.125	12,7	%
			CF grading 16-22.4	0,74	[-]	0.25	19,6	%
$D_{(PSDC-FC)}$	172	%	CF grdng 22.4-31.5	0,72	[-]	0.5	26,4	%
$A_{(PSDC-FC)}$	879	% [mm]	CF grading 31.5-45	0,68	[-]	1	33,2	%
$A_{(PSDC-FC)middle}$	738	% [mm]	**Grading (curve):**			2	40,0	%
$SC_{D85,D15}$	1,95	[-]	(G1) UL; upper limit, fine			4	56,7	%
$SC_{D60,D10}$	1,92	[-]	D_{85}	13,6	[mm]	8	73,3	%
$C_{uniformity}$	47,9	[-]	D_{60}	4,8	[mm]	16	90,0	%
$C_{curvature\ D30,D60,D10}$	1,22	[-]	D_{50}	3,2	[mm]	22.4	93,3	%
$C_{curvature\ D50,D85,D15}$	4,51	[-]	D_{30}	0,76	[mm]	31.5	96,6	%
$C_{extension}$	81,6	[-]	D_{15}	0,17	[mm]	45	100,0	%
$Z_{fines\ 75\mu m}$	7,3	%	D_{10}	0,10	[mm]			

G4CJ/MJ65/35 97% rel.comp. AL 28 source: **Muraya**

			specimen size: 300 * 600 [mm*mm]			material code:	28 D	
composition: 65% concr 35% mas			group code: AL			age of sample:	28	[days]
k_1	11,562	[MPa]	ϕ:	39,20°		$\sigma_{1,failure}$	450,83	[kPa]
k_2	0,544	[-]	cohesion:	94,4	[kPa]	$\tau_{\sigma3=12kPa}$	219,42	[kPa]
volume dens. grains	2130,7	[kg/m^3]	degr. of comp.	0,970	[-]			
dry density	1683	[kg/m^3]	relative density	0,790	[-]	OMC	10	%
MPD	1735	[kg/m^3]	spec dens solids	2578	[kg/m^3]			
VVS	119,6	%				Sieve [mm]	% passing	
$CF_{average}$	0,72	[-]				0.063	3,0	%
			CF grading 11.2-16	0,74	[-]	0.125	7,9	%
			CF grading 16-22.4	0,74	[-]	0.25	12,8	%
$D_{(PSDC-FC)}$	68	%	CF grdng 22.4-31.5	0,72	[-]	0.5	17,7	%
$A_{(PSDC-FC)}$	353	% [mm]	CF grading 31.5-45	0,68	[-]	1	22,6	%
$A_{(PSDC-FC)middle}$	290	% [mm]	**Grading (curve):**			2	27,5	%
$SC_{D85,D15}$	1,95	[-]	(G4) AL; average grading			4	43,3	%
$SC_{D60,D10}$	1,92	[-]	D_{85}	27,2	[mm]	8	59,2	%
$C_{uniformity}$	47,1	[-]	D_{60}	8,4	[mm]	16	75,0	%
$C_{curvature\ D30,D60,D10}$	3,58	[-]	D_{50}	5,7	[mm]	22.4	81,5	%
$C_{curvature\ D50,D85,D15}$	3,28	[-]	D_{30}	2,32	[mm]	31.5	88,1	%
$C_{extension}$	75,2	[-]	D_{15}	0,36	[mm]	45	95,0	%
$Z_{fines\ 75\mu m}$	3,9	%	D_{10}	0,18	[mm]			

G4CJ/MJ65/35 100% rel.comp. AL 28 source: **Muraya**

			specimen size: 300 * 600 [mm*mm]			material code:	28 D	
composition: 65% concr 35% mas			group code: AL			age of sample:	28	[days]
k_1	8,022	[MPa]	ϕ:	38,00º		$\sigma_{1,failure}$	369,88	[kPa]
k_2	0,597	[-]	cohesion:	77,9	[kPa]	$\tau_{\sigma3=12kPa}$	178,94	[kPa]
volume dens. grains	2130,7	[kg/m³]	degr. of comp.	1,000	[-]			
dry density	1735	[kg/m³]	relative density	0,814	[-]	OMC	10	%
MPD	1735	[kg/m³]	spec dens solids	2578	[kg/m³]			
VVS	119,6	%				Sieve [mm]	% passing	
$CF_{average}$	0,72	[-]				0.063	3,0	%
			CF grading 11.2-16	0,74	[-]	0.125	7,9	%
			CF grading 16-22.4	0,74	[-]	0.25	12,8	%
$D_{(PSDC-FC)}$	68	%	CF grdng 22.4-31.5	0,72	[-]	0.5	17,7	%
$A_{(PSDC-FC)}$	353	% [mm]	CF grading 31.5-45	0,68	[-]	1	22,6	%
$A_{(PSDC-FC)middle}$	290	% [mm]	**Grading (curve):**			2	27,5	%
$SC_{D85,D15}$	1,95	[-]	(G4) AL; average grading			4	43,3	%
$SC_{D60,D10}$	1,92	[-]	D_{85}	27,2	[mm]	8	59,2	%
$C_{uniformity}$	47,1	[-]	D_{60}	8,4	[mm]	16	75,0	%
$C_{curvature\ D30,D60,D10}$	3,58	[-]	D_{50}	5,7	[mm]	22.4	81,5	%
$C_{curvature\ D50,D85,D15}$	3,28	[-]	D_{30}	2,32	[mm]	31.5	88,1	%
$C_{extension}$	75,2	[-]	D_{15}	0,36	[mm]	45	95,0	%
$Z_{fines\ 75\mu m}$	3,9	%	D_{10}	0,18	[mm]			

G4CJ/MJ65/35 103% rel.comp. AL 28 source: **Muraya**

			specimen size: 300 * 600 [mm*mm]			material code:	28 D	
composition: 65% concr 35% mas			group code: AL			age of sample:	28	[days]
k_1	12,169	[MPa]	ϕ:	44,80º		$\sigma_{1,failure}$	646,30	[kPa]
k_2	0,582	[-]	cohesion:	120,1	[kPa]	$\tau_{\sigma3=12kPa}$	317,15	[kPa]
volume dens. grains	2130,7	[kg/m³]	degr. of comp.	1,030	[-]			
dry density	1787	[kg/m³]	relative density	0,839	[-]	OMC	10	%
MPD	1735	[kg/m³]	spec dens solids	2578	[kg/m³]			
VVS	119,6	%				Sieve [mm]	% passing	
$CF_{average}$	0,72	[-]				0.063	3,0	%
			CF grading 11.2-16	0,74	[-]	0.125	7,9	%
			CF grading 16-22.4	0,74	[-]	0.25	12,8	%
$D_{(PSDC-FC)}$	68	%	CF grdng 22.4-31.5	0,72	[-]	0.5	17,7	%
$A_{(PSDC-FC)}$	353	% [mm]	CF grading 31.5-45	0,68	[-]	1	22,6	%
$A_{(PSDC-FC)middle}$	290	% [mm]	**Grading (curve):**			2	27,5	%
$SC_{D85,D15}$	1,95	[-]	(G4) AL; average grading			4	43,3	%
$SC_{D60,D10}$	1,92	[-]	D_{85}	27,2	[mm]	8	59,2	%
$C_{uniformity}$	47,1	[-]	D_{60}	8,4	[mm]	16	75,0	%
$C_{curvature\ D30,D60,D10}$	3,58	[-]	D_{50}	5,7	[mm]	22.4	81,5	%
$C_{curvature\ D50,D85,D15}$	3,28	[-]	D_{30}	2,32	[mm]	31.5	88,1	%
$C_{extension}$	75,2	[-]	D_{15}	0,36	[mm]	45	95,0	%
$Z_{fines\ 75\mu m}$	3,9	%	D_{10}	0,18	[mm]			

G4CJ/MJ65/35 105% rel.comp. AL 28 source: **Muraya**

			specimen size: 300 * 600 [mm*mm]			material code:	28 D	
composition: 65% concr 35% mas			group code: AL			age of sample:	28	[days]
k_1	20,824	[MPa]	ϕ:	43,80º		$\sigma_{1,failure}$	733,19	[kPa]
k_2	0,518	[-]	cohesion:	142,3	[kPa]	$\tau_{\sigma3=12kPa}$	360,60	[kPa]
volume dens. grains	2130,7	[kg/m³]	degr. of comp.	1,050	[-]			
dry density	1821	[kg/m³]	relative density	0,855	[-]	OMC	10	%
MPD	1735	[kg/m³]	spec dens solids	2578	[kg/m³]			
VVS	119,6	%				Sieve [mm]	% passing	
$CF_{average}$	0,72	[-]				0.063	3,0	%
			CF grading 11.2-16	0,74	[-]	0.125	7,9	%
			CF grading 16-22.4	0,74	[-]	0.25	12,8	%
$D_{(PSDC-FC)}$	68	%	CF grdng 22.4-31.5	0,72	[-]	0.5	17,7	%
$A_{(PSDC-FC)}$	353	% [mm]	CF grading 31.5-45	0,68	[-]	1	22,6	%
$A_{(PSDC-FC)middle}$	290	% [mm]	**Grading (curve):**			2	27,5	%
$SC_{D85,D15}$	1,95	[-]	(G4) AL; average grading			4	43,3	%
$SC_{D60,D10}$	1,92	[-]	D_{85}	27,2	[mm]	8	59,2	%
$C_{uniformity}$	47,1	[-]	D_{60}	8,4	[mm]	16	75,0	%
$C_{curvature\ D30,D60,D10}$	3,58	[-]	D_{50}	5,7	[mm]	22.4	81,5	%
$C_{curvature\ D50,D85,D15}$	3,28	[-]	D_{30}	2,32	[mm]	31.5	88,1	%
$C_{extension}$	75,2	[-]	D_{15}	0,36	[mm]	45	95,0	%
$Z_{fines\ 75\mu m}$	3,9	%	D_{10}	0,18	[mm]			

G5CJ/MJ65/35 97% rel.comp. LL 28

source: **Muraya**

			specimen size: 300 * 600 [mm*mm]			material code:	28 D	
composition: 65% concr 35% mas			group code: LL			age of sample:	28	[days]
k_1	42,452	[MPa]	ϕ:	42,90º		$\sigma_{1,failure}$	237,54	[kPa]
k_2	0,331	[-]	cohesion:	38	[kPa]	$\tau_{\sigma3=12kPa}$	112,77	[kPa]
volume dens. grains	2130,7	[kg/m^3]	degr. of comp.	0,970	[-]			
dry density	1615	[kg/m^3]	relative density	0,758	[-]	OMC	8,6	%
MPD	1665	[kg/m^3]	spec dens solids	2578	[kg/m^3]			
VVS	119,6	%				Sieve [mm]	% passing	
$CF_{average}$	0,72	[-]						
			CF grading 11.2-16	0,74	[-]	0.125	3,0	%
			CF grading 16-22.4	0,74	[-]	0.25	6,0	%
$D_{(PSDC-FC)}$	52	%	CF grdng 22.4-31.5	0,72	[-]	0.5	9,0	%
$A_{(PSDC-FC)}$	173	% [mm]	CF grading 31.5-45	0,68	[-]	1	12,0	%
$A_{(PSDC-FC)middle}$	232	% [mm]	**Grading (curve):**			2	15,0	%
$SC_{D85,D15}$	1,80	[-]	(G5) LL; lower limit, coarse			4	30,0	%
$SC_{D60,D10}$	1,84	[-]	D_{85}	38,4	[mm]	8	45,0	%
$C_{uniformity}$	24,0	[-]	D_{60}	16,0	[mm]	16	60,0	%
$C_{curvature\ D30,D60,D10}$	1,50	[-]	D_{50}	10,7	[mm]	22.4	69,8	%
$C_{curvature\ D50,D85,D15}$	1,48	[-]	D_{30}	4,00	[mm]	31.5	79,7	%
$C_{extension}$	19,2	[-]	D_{15}	2,00	[mm]	45	90,0	%
$Z_{fines\ 75\mu m}$	0,6	%	D_{10}	0,67	[mm]			

G5CJ/MJ65/35 100% rel.comp. LL 28

source: **Muraya**

			specimen size: 300 * 600 [mm*mm]			material code:	28 D	
composition: 65% concr 35% mas			group code: LL			age of sample:	28	[days]
k_1	8,374	[MPa]	ϕ:	38,70º		$\sigma_{1,failure}$	288,20	[kPa]
k_2	0,569	[-]	cohesion:	56,7	[kPa]	$\tau_{\sigma3=12kPa}$	138,10	[kPa]
volume dens. grains	2130,7	[kg/m^3]	degr. of comp.	1,000	[-]			
dry density	1665	[kg/m^3]	relative density	0,781	[-]	OMC	8,6	%
MPD	1665	[kg/m^3]	spec dens solids	2578	[kg/m^3]			
VVS	119,6	%				Sieve [mm]	% passing	
$CF_{average}$	0,72	[-]						
			CF grading 11.2-16	0,74	[-]	0.125	3,0	%
			CF grading 16-22.4	0,74	[-]	0.25	6,0	%
$D_{(PSDC-FC)}$	52	%	CF grdng 22.4-31.5	0,72	[-]	0.5	9,0	%
$A_{(PSDC-FC)}$	173	% [mm]	CF grading 31.5-45	0,68	[-]	1	12,0	%
$A_{(PSDC-FC)middle}$	232	% [mm]	**Grading (curve):**			2	15,0	%
$SC_{D85,D15}$	1,80	[-]	(G5) LL; lower limit, coarse			4	30,0	%
$SC_{D60,D10}$	1,84	[-]	D_{85}	38,4	[mm]	8	45,0	%
$C_{uniformity}$	24,0	[-]	D_{60}	16,0	[mm]	16	60,0	%
$C_{curvature\ D30,D60,D10}$	1,50	[-]	D_{50}	10,7	[mm]	22.4	69,8	%
$C_{curvature\ D50,D85,D15}$	1,48	[-]	D_{30}	4,00	[mm]	31.5	79,7	%
$C_{extension}$	19,2	[-]	D_{15}	2,00	[mm]	45	90,0	%
$Z_{fines\ 75\mu m}$	0,6	%	D_{10}	0,67	[mm]			

G5CJ/MJ65/35 103% rel.comp. LL 28

source: **Muraya**

composition: 65% concr 35% mas			specimen size: 300 * 600 [mm*mm]			material code:	28 D	
			group code: LL			age of sample:	28	[days]
k_1	13,397	[MPa]	ϕ:	44,70°		$\sigma_{1,failure}$	476,31	[kPa]
k_2	0,519	[-]	cohesion:	85	[kPa]	$\tau_{\sigma3=12kPa}$	232,16	[kPa]
volume dens. grains	2130,7	$[kg/m^3]$	degr. of comp.	1,030	[-]			
dry density	1715	$[kg/m^3]$	relative density	0,805	[-]	OMC	8,6	%
MPD	1665	$[kg/m^3]$	spec dens solids	2578	$[kg/m^3]$			
VVS	119,6	%				Sieve [mm]	% passing	
$CF_{average}$	0,72	[-]						
			CF grading 11.2-16	0,74	[-]	0.125	3,0	%
			CF grading 16-22.4	0,74	[-]	0.25	6,0	%
$D_{(PSDC-FC)}$	52	%	CF grdng 22.4-31.5	0,72	[-]	0.5	9,0	%
$A_{(PSDC-FC)}$	173	% [mm]	CF grading 31.5-45	0,68	[-]	1	12,0	%
$A_{(PSDC-FC)middle}$	232	% [mm]	**Grading (curve):**			2	15,0	%
$SC_{D85,D15}$	1,80	[-]	(G5) LL; lower limit, coarse			4	30,0	%
$SC_{D60,D10}$	1,84	[-]	D_{85}	38,4	[mm]	8	45,0	%
$C_{uniformity}$	24,0	[-]	D_{60}	16,0	[mm]	16	60,0	%
$C_{curvature\ D30,D60,D10}$	1,50	[-]	D_{50}	10,7	[mm]	22.4	69,8	%
$C_{curvature\ D50,D85,D15}$	1,48	[-]	D_{30}	4,00	[mm]	31.5	79,7	%
$C_{extension}$	19,2	[-]	D_{15}	2,00	[mm]	45	90,0	%
$Z_{fines\ 75\mu m}$	0,6	%	D_{10}	0,67	[mm]			

G5CJ/MJ65/35 105% rel.comp. LL 28

source: **Muraya**

composition: 65% concr 35% mas			specimen size: 300 * 600 [mm*mm]			material code:	28 D	
			group code: LL			age of sample:	28	[days]
k_1	12,375	[MPa]	ϕ:	42,60°		$\sigma_{1,failure}$	452,73	[kPa]
k_2	0,528	[-]	cohesion:	85,7	[kPa]	$\tau_{\sigma3=12kPa}$	220,37	[kPa]
volume dens. grains	2130,7	$[kg/m^3]$	degr. of comp.	1,050	[-]			
dry density	1748	$[kg/m^3]$	relative density	0,820	[-]	OMC	8,6	%
MPD	1665	$[kg/m^3]$	spec dens solids	2578	$[kg/m^3]$			
VVS	119,6	%				Sieve [mm]	% passing	
$CF_{average}$	0,72	[-]						
			CF grading 11.2-16	0,74	[-]	0.125	3,0	%
			CF grading 16-22.4	0,74	[-]	0.25	6,0	%
$D_{(PSDC-FC)}$	52	%	CF grdng 22.4-31.5	0,72	[-]	0.5	9,0	%
$A_{(PSDC-FC)}$	173	% [mm]	CF grading 31.5-45	0,68	[-]	1	12,0	%
$A_{(PSDC-FC)middle}$	232	% [mm]	**Grading (curve):**			2	15,0	%
$SC_{D85,D15}$	1,80	[-]	(G5) LL; lower limit, coarse			4	30,0	%
$SC_{D60,D10}$	1,84	[-]	D_{85}	38,4	[mm]	8	45,0	%
$C_{uniformity}$	24,0	[-]	D_{60}	16,0	[mm]	16	60,0	%
$C_{curvature\ D30,D60,D10}$	1,50	[-]	D_{50}	10,7	[mm]	22.4	69,8	%
$C_{curvature\ D50,D85,D15}$	1,48	[-]	D_{30}	4,00	[mm]	31.5	79,7	%
$C_{extension}$	19,2	[-]	D_{15}	2,00	[mm]	45	90,0	%
$Z_{fines\ 75\mu m}$	0,6	%	D_{10}	0,67	[mm]			

G4CJ/MJ50/50 100% rel.comp. AL 28 source: **Kisimbi**

composition: 50% concr 50% mas			specimen size: 300 * 600 [mm*mm]			material code:	28 D	
			group code: AL			age of sample:	28	[days]
k_1	10,162	[MPa]						
k_2	0,527	[-]						
volume dens. grains	2056	[kg/m³]	degr. of comp.	1,000	[-]	CBR:	97,4	%
dry density	1718	[kg/m³]	relative density	0,836	[-]	OMC	7,8	%
MPD	1718	[kg/m³]	spec dens solids	2585	[kg/m³]			
VVS	123,6	%				Sieve [mm]	% passing	
$CF_{average}$	0,70	[-]				0.063	3,0	%
			CF grading 11.2-16	0,72	[-]	0.125	7,9	%
			CF grading 16-22.4	0,73	[-]	0.25	12,8	%
$D_{(PSDC-FC)}$	68	%	CF grdng 22.4-31.5	0,70	[-]	0.5	17,7	%
$A_{(PSDC-FC)}$	353	% [mm]	CF grading 31.5-45	0,64	[-]	1	22,6	%
$A_{(PSDC-FC)middle}$	290	% [mm]	**Grading (curve):**			2	27,5	%
$SC_{D85,D15}$	1,95	[-]	(G4) AL; average grading			4	43,3	%
$SC_{D60,D10}$	1,92	[-]	D_{85}	27,2	[mm]	8	59,2	%
$C_{uniformity}$	47,1	[-]	D_{60}	8,4	[mm]	16	75,0	%
$C_{curvature\ D30,D60,D10}$	3,58	[-]	D_{50}	5,7	[mm]	22.4	81,5	%
$C_{curvature\ D50,D85,D15}$	3,28	[-]	D_{30}	2,32	[mm]	31.5	88,1	%
$C_{extension}$	75,2	[-]	D_{15}	0,36	[mm]	45	95,0	%
$Z_{fines\ 75\mu m}$	3,9	%	D_{10}	0,18	[mm]			

G4CJ/MJ65/35 100% rel.comp. AL 28 source: **Kisimbi**

composition: 65% concr 35% mas			specimen size: 300 * 600 [mm*mm]			material code:	28 D	
			group code: AL			age of sample:	28	[days]
k_1	7,627	[MPa]						
k_2	0,606	[-]						
volume dens. grains	2130,7	[kg/m³]	degr. of comp.	1,000	[-]	CBR:	154,9	%
dry density	1735	[kg/m³]	relative density	0,814	[-]	OMC	8,4	%
MPD	1735	[kg/m³]	spec dens solids	2578	[kg/m³]			
VVS	119,6	%				Sieve [mm]	% passing	
$CF_{average}$	0,72	[-]				0.063	3,0	%
			CF grading 11.2-16	0,74	[-]	0.125	7,9	%
			CF grading 16-22.4	0,74	[-]	0.25	12,8	%
$D_{(PSDC-FC)}$	68	%	CF grdng 22.4-31.5	0,72	[-]	0.5	17,7	%
$A_{(PSDC-FC)}$	353	% [mm]	CF grading 31.5-45	0,68	[-]	1	22,6	%
$A_{(PSDC-FC)middle}$	290	% [mm]	**Grading (curve):**			2	27,5	%
$SC_{D85,D15}$	1,95	[-]	(G4) AL; average grading			4	43,3	%
$SC_{D60,D10}$	1,92	[-]	D_{85}	27,2	[mm]	8	59,2	%
$C_{uniformity}$	47,1	[-]	D_{60}	8,4	[mm]	16	75,0	%
$C_{curvature\ D30,D60,D10}$	3,58	[-]	D_{50}	5,7	[mm]	22.4	81,5	%
$C_{curvature\ D50,D85,D15}$	3,28	[-]	D_{30}	2,32	[mm]	31.5	88,1	%
$C_{extension}$	75,2	[-]	D_{15}	0,36	[mm]	45	95,0	%
$Z_{fines\ 75\mu m}$	3,9	%	D_{10}	0,18	[mm]			

G4CJ/MJ80/20 100% rel.comp. AL 28 source: **Kisimbi**

composition: 80% concr 20% mas			specimen size: 300 * 600 [mm*mm] group code: AL			material code: age of sample:	28 D 28	[days]
k_1	35,744	[MPa]						
k_2	0,393	[-]						
volume dens. grains	2205,4	[kg/m^3]	degr. of comp.	1,000	[-]	CBR:	154,9	%
dry density	1787	[kg/m^3]	relative density	0,810	[-]	OMC	8,2	%
MPD	1787	[kg/m^3]	spec dens solids	2570	[kg/m^3]			
VVS	115,7	%						
$CF_{average}$	0,74	[-]						
			CF grading 11.2-16	0,76	[-]			
			CF grading 16-22.4	0,76	[-]			
$D_{(PSDC-FC)}$	68	%	CF grdng 22.4-31.5	0,73	[-]			
$A_{(PSDC-FC)}$	353	% [mm]	CF grading 31.5-45	0,69	[-]			
$A_{(PSDC-FC)middle}$	290	% [mm]	**Grading (curve):**					
$SC_{D85,D15}$	1,95	[-]	(G4) AL; average grading					
$SC_{D60,D10}$	1,92	[-]	D_{85}	27,2	[mm]			
$C_{uniformity}$	47,1	[-]	D_{60}	8,4	[mm]			
$C_{curvature\ D30,D60,D10}$	3,58	[-]	D_{50}	5,7	[mm]			
$C_{curvature\ D50,D85,D15}$	3,28	[-]	D_{30}	2,32	[mm]			
$C_{extension}$	75,2	[-]	D_{15}	0,36	[mm]			
$Z_{fines\ 75\mu m}$	3,9	%	D_{10}	0,18	[mm]			

Sieve [mm]	% passing	
0.063	3,0	%
0.125	7,9	%
0.25	12,8	%
0.5	17,7	%
1	22,6	%
2	27,5	%
4	43,3	%
8	59,2	%
16	75,0	%
22.4	81,5	%
31.5	88,1	%
45	95,0	%

G DATA SET FOR ANALYSIS IN SPSS

G.1 Introduction

The data set inserted in this appendix is an extracted overview of the data set placed in appendix F, containing only the data as used as input for analysis with SPSS. Section G.2 shows the natural values, whereas the same data set has been translated into natural logarithmic values in section G.3.

G.2 SPSS data set with natural values

	Description	k1	k2	φ	c	tau 12kPa	dry d	vol d gr	rel d	degr-comp
1	Allan NIEKERK	32.126	0.433	41.6	45.9	125.82	1929	2350	0.8209	1.0000
2	Max Havelaar NIEKERK	61.456	0.340	43.7	73.7	199.17	1632	2010	0.8119	1.0000
3	Cor Bruin NIEKERK	20.171	0.540	52.9	48.9	192.66	1885	2300	0.8196	1.0000
4	Pascal NIEKERK	28.956	0.394	51.0	68.7	235.60	1679	2050	0.8190	1.0000
5	lava CO1 LAB05	26.900	0.350				1778	1941	0.9160	1.0861
6	lava CO2 LAO07	19.200	0.470				1640	1941	0.8449	1.0406
7	lava CO2 LAOS05					117.50	1681	1941	0.8660	1.0666
8	porphyry CO3 POB03	29.200	0.320				2113	2665	0.7929	0.9782
9	porphyry CO4 POO01	22.900	0.430				2075	2665	0.7786	0.9449
10	crushed gravel CO5 GGB01	40.900	0.230				1968	2563	0.7679	1.0402
11	crushed gravel CO6 GGO01	47.200	0.310				2042	2563	0.7967	0.9710
12	limestone CO7 KAB02	156.800	0.140				2129	2669	0.7977	0.9757
13	limestone CO8 KAO01	37.700	0.450				2287	2669	0.8569	1.0040
14	stol CO9 STN01	157.800	0.050				2121	2513	0.8440	0.9533
15	silicon manganese slag C10 SMC01	43.500	0.340				1809	2146	0.8430	1.0794
16	crushed masonry 1 R01 MGB07	6.300	0.490				1530	1699	0.9005	1.0699
17	crushed masonry 1 R01 MGBS03					93.00	1485	1699	0.8740	1.0385
18	crushed masonry 1 R02 MGO10	4.000	0.650				1523	1699	0.8964	1.0598
19	crushed masonry 2 R03 M2B01	27.500	0.300				1585	1697	0.9340	1.0441
20	crushed masonry 2 R04 M2O02	18.300	0.430				1516	1697	0.8933	0.9699
21	crushed concrete 1 R05 BGB01	21.100	0.480				1863	2207	0.8441	1.0478
22	crushed concrete 1 R05 BGBS04					89.00	1815	2207	0.8224	1.0208
23	crushed concrete 1 R06 BGO01	11.200	0.590				1878	2207	0.8509	1.0399
24	crushed concrete 1 R06 BGBS04					104.50	1882	2207	0.8527	1.0421
25	crushed clinker R07 KGB01	41.800	0.280				1803	2086	0.8643	1.0158
26	crushed clinker R08 KGO01	18.600	0.450				1695	2086	0.8126	0.9625
27	crshd mas'y/concr(65/35) R09 FFB01	77.300	0.170				1660	2024	0.8202	1.0172
28	crshd mas'y/concr(65/35) R10 FFO01	22.600	0.440				1676	2024	0.8281	0.9778
29	crushed concrete 2 R11 B2C01	71.800	0.210				1858	2303	0.8068	1.0322
30	crushed rubble 1 R12 K1C01	34.800	0.350				1704	2040	0.8353	1.0101
31	crushed rubble 2 R13 K2C01	36.100	0.340				1712	2030	0.8433	1.0209
32	crushed rubble 3 R14 K3C01	30.100	0.360				1710	2095	0.8162	1.0029
33	G4CJ/MJ50/50 100% rel.comp. AL	7.308	0.555				1718	2056	0.8356	1.0000
34	G4CJ/MJ65/35 100% rel.comp. AL	13.637	0.510				1735	2131	0.8143	1.0000
35	G4CJ/MJ80/20 100% rel.comp. AL	41.615	0.332				1787	2205	0.8103	1.0000
36	MG 16H 94.7% rel.comp.	29.154	0.362	44.63	14.88	63.94	1684	2200	0.7655	0.9471
37	MG 16H 98% rel.comp.	25.571	0.358	43.25	37.82	113.62	1742	2200	0.7918	0.9798
38	MG 16H 100.5% rel.comp.	26.767	0.356	47.26	53.64	170.27	1787	2200	0.8123	1.0051
39	MG 16H 102,3% rel.comp.	30.726	0.353	44.48	48.62	143.98	1819	2200	0.8268	1.0231
40	MG 16H 104.9% rel.comp.	40.207	0.384	47.88	130.81	374.17	1865	2200	0.8477	1.0489
41	G1CJ/MJ65/35 97% rel.comp. UL	33.187	0.329	35.1	69.8	150.61	1702	2131	0.7988	0.9698
42	G1CJ/MJ65/35 100% rel.comp. UL	21.106	0.411	28.3	143.2	250.56	1755	2131	0.8237	1.0000
43	G1CJ/MJ65/35 103% rel.comp. UL	23.854	0.464	36	133.1	278.33	1808	2131	0.8484	1.0300
44	G4CJ/MJ65/35 97% rel.comp. AL	48.108	0.266	36.9	55.5	129.10	1683	2131	0.7899	0.9700
45	G4CJ/MJ65/35 100% rel.comp. AL	14.947	0.465	40.5	98	234.81	1735	2131	0.8143	1.0000
46	G4CJ/MJ65/35 103% rel.comp. AL	26.902	0.439	42.9	89.5	230.93	1787	2131	0.8387	1.0300
47	G4CJ/MJ65/35 105% rel.comp. AL	43.499	0.385	38.1	181.9	393.11	1821	2131	0.8546	1.0496
48	G5CJ/MJ65/35 97% rel.comp. LL	15.663	0.463	41.1	51.7	136.73	1615	2131	0.7580	0.9700
49	G5CJ/MJ65/35 100% rel.comp. LL	15.663	0.463	35.5	77.1	166.32	1665	2131	0.7814	1.0000
50	G5CJ/MJ65/35 103% rel.comp. LL	33.024	0.376	41.6	103	252.89	1715	2131	0.8049	1.0300
51	G5CJ/MJ65/35 105% rel.comp. LL	20.015	0.451				1748	2131	0.8204	1.0498
52	G4CJ/MJ50/50 100% rel.comp. AL	17.053	0.491	39.5	96.8	226.22	1718	2056	0.8356	1.0000
53	G4CJ/MJ80/20 100% rel.comp. AL	37.220	0.387	38.7	125.5	281.37	1787	2205	0.8103	1.0000

	MPD	MMPD	OMC	VVS	CF-av	D85	D60	D50	D30	D15	D10	D(PSDC-FC)	A(PSDC-FC)	A(P-FC)m
1	1929		9.1	93.57	0.741	20.62	6.86	2.44	0.39	0.20	0.17	171.10	657.52	526.38
2	1632		15.2	106.54	0.714	15.68	5.29	2.99	0.67	0.31	0.22	158.50	774.05	627.15
3	1885		10.5	116.65	0.735	33.66	18.43	13.13	2.95	0.37	0.24	50.68	203.16	210.78
4	1679		14.9	94.39		35.03	12.54	7.46	1.62	0.55	0.40	55.27	171.48	173.67
5	1637	1889	11.4		0.696	13.14	4.00	2.00	0.67	0.24	0.16	186.96	970.94	809.89
6	1576	1682	12.1		0.696	39.38	16.00	11.00	4.00	1.02	0.47	43.74	197.35	253.30
7	1576	1682	12.1		0.696	39.38	16.00	11.00	4.00	1.02	0.47	43.74	197.35	253.30
8	2160	2260	5.2		0.862	13.14	4.00	2.00	0.82	0.21	0.07	175.18	840.62	574.34
9	2196	2038	3.7		0.862	39.38	16.00	11.00	4.00	1.23	0.57	43.34	208.02	262.22
10	1892	2002	6.6		0.843	13.14	4.00	2.00	0.65	0.28	0.20	191.30	972.84	811.08
11	2103	2029	4.8		0.843	39.38	16.00	11.00	4.00	0.93	0.48	46.74	197.00	253.05
12	2182	2291	8		0.800	13.14	4.00	2.00	0.42	0.04	0.00	236.36	981.97	818.20
13	2278	2288	5.5		0.800	39.38	16.00	11.00	4.00	0.82	0.24	32.07	193.73	250.42
14	2225	2174	4.7		0.867	30.89	16.00	12.00	4.00	0.39	0.21	31.10	118.38	123.79
15	1676	1857	5.4		0.715	23.01	13.33	10.00	4.27	0.89	0.35	51.30	364.66	284.97
16	1430	1536	21.5		0.653	13.14	4.00	2.00	0.58	0.21	0.13	192.36	973.26	811.66
17	1430	1536	21.5		0.653	13.14	4.00	2.00	0.58	0.21	0.13	192.36	973.26	811.66
18	1437	1534	16.6		0.653	39.38	16.00	11.00	4.00	0.97	0.42	40.94	196.36	252.55
19	1518	1629	16.5		0.675	13.14	4.00	2.00	0.29	0.13	0.08	232.06	991.26	825.04
20	1563	1570	14		0.675	39.38	16.00	11.00	4.00	0.43	0.22	35.45	194.06	249.85
21	1778	1864	12.1		0.788	13.14	4.00	2.00	0.68	0.27	0.18	186.10	970.77	809.77
22	1778	1864	12.1		0.788	13.14	4.00	2.00	0.68	0.27	0.18	186.10	970.77	809.77
23	1806	1884	8		0.788	39.38	16.00	11.00	4.00	0.99	0.48	45.74	197.55	253.46
24	1806	1884	8		0.788	39.38	16.00	11.00	4.00	0.99	0.48	45.74	197.55	253.46
25	1775	1828	9.7		0.768	13.14	4.00	2.00	0.41	0.13	0.08	216.96	982.96	818.82
26	1761	1699	6.7		0.768	39.38	16.00	11.00	4.00	0.71	0.29	31.94	192.90	249.65
27	1632	1758	13.9		0.734	13.14	4.00	2.00	0.44	0.18	0.12	205.96	980.62	817.17
28	1714	1713	11.9		0.734	39.38	16.00	11.00	4.00	0.74	0.33	35.64	193.48	250.32
29	1800	1922	8		0.793	25.20	13.33	10.00	4.00	0.70	0.36	42.23	260.18	197.57
30	1687	1783	7.5		0.722	28.92	14.26	10.78	4.31	0.68	0.35	30.00	139.95	99.54
31	1677	1806	10.1		0.748	23.75	10.55	7.08	1.64	0.32	0.20	78.46	413.19	341.05
32	1705	1742	8.7		0.735	29.56	17.45	13.20	5.67	0.47	0.21	43.34	230.18	171.30
33	1718		7.8	123.57	0.698	27.23	8.41	5.69	2.32	0.36	0.18	67.66	352.66	290.06
34	1735		8.4	119.64	0.720	27.23	8.41	5.69	2.32	0.36	0.18	67.66	352.66	290.06
35	1787		8.2	115.71	0.736	27.23	8.41	5.69	2.32	0.36	0.18	67.66	352.66	290.06
36	1778		7.7			25.86	9.30	5.29	0.84	0.32	0.22	101.96	420.87	334.45
37	1778		7.7			25.86	9.30	5.29	0.84	0.32	0.22	101.96	420.87	334.45
38	1778		7.7			25.86	9.30	5.29	0.84	0.32	0.22	101.96	420.87	334.45
39	1778		7.7			25.86	9.30	5.29	0.84	0.32	0.22	101.96	420.87	334.45
40	1778		7.7			25.86	9.30	5.29	0.84	0.32	0.22	101.96	420.87	334.45
41	1755		10	119.64	0.720	13.60	4.80	3.20	0.76	0.17	0.10	172.46	879.36	738.00
42	1755		10	119.64	0.720	13.60	4.80	3.20	0.76	0.17	0.10	172.46	879.36	738.00
43	1755		10	119.64	0.720	13.60	4.80	3.20	0.76	0.17	0.10	172.46	879.36	738.00
44	1735		10	119.64	0.720	27.23	8.41	5.69	2.32	0.36	0.18	67.66	352.66	290.06
45	1735		10	119.64	0.720	27.23	8.41	5.69	2.32	0.36	0.18	67.66	352.66	290.06
46	1735		10	119.64	0.720	27.23	8.41	5.69	2.32	0.36	0.18	67.66	352.66	290.06
47	1735		10	119.64	0.720	27.23	8.41	5.69	2.32	0.36	0.18	67.66	352.66	290.06
48	1665		8.6	119.64	0.720	38.45	16.00	10.67	4.00	2.00	0.67	52.04	173.00	232.31
49	1665		8.6	119.64	0.720	38.45	16.00	10.67	4.00	2.00	0.67	52.04	173.00	232.31
50	1665		8.6	119.64	0.720	38.45	16.00	10.67	4.00	2.00	0.67	52.04	173.00	232.31
51	1665		8.6	119.64	0.720	38.45	16.00	10.67	4.00	2.00	0.67	52.04	173.00	232.31
52	1718		7.8	123.57	0.720	27.23	8.41	5.69	2.32	0.36	0.18	67.66	352.66	290.06
53	1787		8.2	115.71	0.720	27.23	8.41	5.69	2.32	0.36	0.18	67.66	352.66	290.06

	SC85-15	SC60-10	Cuni	Ccurv306010	Ccurv508515	Cext	Z fine	S 1	S 2	S 4	S 8
1	1.96	1.91	41.47	0.14	1.45	102.87	1.5	42.9	48.8	54.2	62.3
2	1.92	1.84	23.64	0.38	1.83	50.24	1.9	37.1	45.2	54.9	70.7
3	1.96	1.95	77.59	1.99	13.92	91.46	1.8	23.8	28.0	32.2	40.0
4	1.94	1.88	31.74	0.53	2.91	64.18	0.3	25.9	32.5	39.8	51.6
5	1.93	1.85	25.81	0.73	1.28	55.14	5.1	37.3	50.0	60.0	76.0
6	1.90	1.89	34.03	2.13	3.01	38.62	2.1	14.9	20.0	30.0	44.0
7	1.90	1.89	34.03	2.13	3.01	38.62	2.1	14.9	20.0	30.0	44.0
8	1.94	1.93	55.41	2.31	1.45	62.77	10.1	33.8	50.0	60.0	76.0
9	1.88	1.86	27.91	1.74	2.50	31.99	4.1	13.5	20.0	30.0	44.0
10	1.92	1.81	19.83	0.52	1.08	46.61	1.8	39.5	50.0	60.0	76.0
11	1.91	1.88	33.33	2.08	3.32	42.53	0.7	15.8	20.0	30.0	44.0
12	1.99	2.00	3236.25	34.93	7.61	328.57	18.5	40.2	50.0	60.0	76.0
13	1.92	1.94	65.94	4.12	3.74	47.87	7.4	16.1	20.0	30.0	44.0
14	1.95	1.95	77.71	4.86	11.96	79.27	6.3	22.5	25.0	30.0	40.0
15	1.85	1.90	38.40	3.93	4.89	25.88	3.7	15.8	21.0	29.0	44.0
16	1.94	1.87	29.74	0.62	1.42	61.53	6.3	37.9	50.0	60.0	76.0
17	1.94	1.87	29.74	0.62	1.42	61.53	6.3	37.9	50.0	60.0	76.0
18	1.90	1.90	37.89	2.37	3.16	40.44	2.6	15.2	20.0	30.0	44.0
19	1.96	1.93	53.21	0.28	2.35	101.36	10.0	46.2	50.0	60.0	76.0
20	1.96	1.95	72.00	4.50	7.10	91.00	4.0	18.5	20.0	30.0	44.0
21	1.92	1.83	21.93	0.63	1.12	48.46	3.7	37.7	50.0	60.0	76.0
22	1.92	1.83	21.93	0.63	1.12	48.46	3.7	37.7	50.0	60.0	76.0
23	1.90	1.88	33.05	2.07	3.11	39.79	1.5	15.1	20.0	30.0	44.0
24	1.90	1.88	33.05	2.07	3.11	39.79	1.5	15.1	20.0	30.0	44.0
25	1.96	1.93	52.48	0.54	2.38	102.75	9.9	42.5	50.0	60.0	76.0
26	1.93	1.93	56.00	3.50	4.35	55.78	4.0	17.0	20.0	30.0	44.0
27	1.95	1.89	33.82	0.40	1.70	73.39	6.8	41.9	50.0	60.0	76.0
28	1.93	1.92	48.25	3.02	4.14	53.00	2.7	16.8	20.0	30.0	44.0
29	1.89	1.89	36.76	3.31	5.67	36.00	2.1	18.3	23.0	30.0	44.0
30	1.91	1.90	40.85	3.73	5.89	42.34	3.0	17.6	22.0	29.0	42.0
31	1.95	1.92	52.29	1.26	6.51	73.32	3.5	26.5	32.0	40.0	53.0
32	1.94	1.95	84.87	8.95	12.50	62.69	4.3	18.1	21.0	25.0	37.0
33	1.95	1.92	47.07	3.58	3.28	75.16	3.9	22.6	27.5	43.3	59.2
34	1.95	1.92	47.07	3.58	3.28	75.16	3.9	22.6	27.5	43.3	59.2
35	1.95	1.92	47.07	3.58	3.28	75.16	3.9	22.6	27.5	43.3	59.2
36	1.95	1.91	43.07	0.35	3.42	81.77	0.9	33.3	39.7	46.4	57.6
37	1.95	1.91	43.07	0.35	3.42	81.77	0.9	33.3	39.7	46.4	57.6
38	1.95	1.91	43.07	0.35	3.42	81.77	0.9	33.3	39.7	46.4	57.6
39	1.95	1.91	43.07	0.35	3.42	81.77	0.9	33.3	39.7	46.4	57.6
40	1.95	1.91	43.07	0.35	3.42	81.77	0.9	33.3	39.7	46.4	57.6
41	1.95	1.92	47.94	1.22	4.51	81.63	7.3	33.2	40.0	56.7	73.3
42	1.95	1.92	47.94	1.22	4.51	81.63	7.3	33.2	40.0	56.7	73.3
43	1.95	1.92	47.94	1.22	4.51	81.63	7.3	33.2	40.0	56.7	73.3
44	1.95	1.92	47.07	3.58	3.28	75.16	3.9	22.6	27.5	43.3	59.2
45	1.95	1.92	47.07	3.58	3.28	75.16	3.9	22.6	27.5	43.3	59.2
46	1.95	1.92	47.07	3.58	3.28	75.16	3.9	22.6	27.5	43.3	59.2
47	1.95	1.92	47.07	3.58	3.28	75.16	3.9	22.6	27.5	43.3	59.2
48	1.80	1.84	24.00	1.50	1.48	19.22	0.6	12.0	15.0	30.0	45.0
49	1.80	1.84	24.00	1.50	1.48	19.22	0.6	12.0	15.0	30.0	45.0
50	1.80	1.84	24.00	1.50	1.48	19.22	0.6	12.0	15.0	30.0	45.0
51	1.80	1.84	24.00	1.50	1.48	19.22	0.6	12.0	15.0	30.0	45.0
52	1.95	1.92	47.07	3.58	3.28	75.16	3.9	22.6	27.5	43.3	59.2
53	1.95	1.92	47.07	3.58	3.28	75.16	3.9	22.6	27.5	43.3	59.2

G.3 SPSS data set with natural logarithmic values

	Description	ln_k1	ln_k2	ln_f	ln_c	ln_tau	ln_dry_d
1	Allan NIEKERK	3.469665671	-0.837017551	3.728100167	3.826247228	4.834823107	7.564757013
2	Max Havelaar NIEKERK	4.118321472	-1.078809661	3.777348102	4.299867105	5.294143914	7.397561536
3	Cor Bruin NIEKERK	3.004245929	-0.616186139	3.967646909	3.889368315	5.260909513	7.5416831
4	Pascal NIEKERK	3.365777436	-0.93140437	3.931433399	4.229312423	5.462154366	7.425953657
5	lava CO1 LAB05	3.292126287	-1.049822124				7.483244416
6	lava CO2 LAO07	2.954910279	-0.755022584				7.402451521
7	lava CO2 LAOS05					4.766438334	7.427144133
8	porphyry CO3 POB03	3.374168709	-1.139434283				7.655864018
9	porphyry CO4 POO01	3.131136911	-0.84397007				7.637716433
10	crushed gravel CO5 GGB01	3.711130063	-1.46967597				7.584773078
11	crushed gravel CO6 GGO01	3.854393893	-1.171182982				7.621684999
12	limestone CO7 KAB02	5.054971108	-1.966112856				7.663407665
13	limestone CO8 KAO01	3.629660094	-0.798507696				7.734996194
14	stol CO9 STN01	5.061328408	-2.995732274				7.659642955
15	silicon manganese slag C10 SMC01	3.772760938	-1.078809661				7.500529485
16	crushed masonry 1 R01 MGB07	1.840549633	-0.713349888				7.333023014
17	crushed masonry 1 R01 MGBS03					4.532599493	7.303170051
18	crushed masonry 1 R02 MGO10	1.386294361	-0.430782916				7.328437353
19	crushed masonry 2 R03 M2B01	3.314186005	-1.203972804				7.368339686
20	crushed masonry 2 R04 M2O02	2.90690106	-0.84397007				7.323830566
21	crushed concrete 1 R05 BGB01	3.04927304	-0.733969175				7.529943371
22	crushed concrete 1 R05 BGBS04					4.48863637	7.503840747
23	crushed concrete 1 R06 BGO01	2.415913778	-0.527632742				7.53796266
24	crushed concrete 1 R06 BGBS04					4.649187071	7.54009032
25	crushed clinker R07 KGB01	3.73289634	-1.272965676				7.497207223
26	crushed clinker R08 KGO01	2.923161581	-0.798507696				7.43543802
27	crshd mas'y/concr(65/35) R09 FFB01	4.347693956	-1.771956842				7.414572881
28	crshd mas'y/concr(65/35) R10 FFO01	3.117949906	-0.820980552				7.424165281
29	crushed concrete 2 R11 B2C01	4.273884476	-1.560647748				7.527255919
30	crushed rubble 1 R12 K1C01	3.549617387	-1.049822124				7.440733707
31	crushed rubble 2 R13 K2C01	3.586292865	-1.078809661				7.445417557
32	crushed rubble 3 R14 K3C01	3.404525172	-1.021651248				7.444248649
33	G4CJ/MJ50/50 100% rel.comp. AL	1.988969639	-0.588787165				7.448916103
34	G4CJ/MJ65/35 100% rel.comp. AL	2.612786687	-0.673344553				7.458762692
35	G4CJ/MJ80/20 100% rel.comp. AL	3.728460679	-1.10262031				7.488293515
36	MG 16H 94.7% rel.comp.	3.372592125	-1.016111067	3.798406279	2.700018029	4.157907432	7.428927195
37	MG 16H 98% rel.comp.	3.241458897	-1.027222293	3.766997233	3.632838063	4.732850526	7.462789157
38	MG 16H 100.5% rel.comp.	3.287169786	-1.032824548	3.855664272	3.982295058	5.137397633	7.488293515
39	MG 16H 102,3% rel.comp.	3.425109202	-1.041287222	3.79503965	3.884034969	4.969653892	7.506042179
40	MG 16H 104.9% rel.comp.	3.69404111	-0.957112726	3.868697881	4.873745889	5.924718525	7.531016332
41	G1CJ/MJ65/35 97% rel.comp. UL	3.502158233	-1.111697528	3.55820113	4.24563401	5.014669566	7.439559309
42	G1CJ/MJ65/35 100% rel.comp. UL	3.04955736	-0.889162064	3.342861805	4.964242255	5.523705677	7.470224136
43	G1CJ/MJ65/35 103% rel.comp. UL	3.171951918	-0.767870727	3.583518938	4.891100725	5.628823622	7.499782938
44	G4CJ/MJ65/35 97% rel.comp. AL	3.873448483	-1.32425897	3.608211551	4.016383021	4.860622042	7.428333194
45	G4CJ/MJ65/35 100% rel.comp. AL	2.704510611	-0.765717873	3.701301974	4.584967479	5.458777374	7.458762692
46	G4CJ/MJ65/35 103% rel.comp. AL	3.292200633	-0.823255866	3.758871826	4.494238625	5.442116128	7.488293515
47	G4CJ/MJ65/35 105% rel.comp. AL	3.772737949	-0.954511945	3.640214282	5.203457086	5.974095342	7.50714108
48	G5CJ/MJ65/35 97% rel.comp. LL	2.751301243	-0.770028225	3.716008122	3.945457782	4.918022004	7.387090236
49	G5CJ/MJ65/35 100% rel.comp. LL	2.751301243	-0.770028225	3.569532696	4.345103281	5.113902997	7.417580402
50	G5CJ/MJ65/35 103% rel.comp. LL	3.49723457	-0.978166136	3.728100167	4.634728988	5.532961881	7.44716836
51	G5CJ/MJ65/35 105% rel.comp. LL	2.996481992	-0.796287939				7.466227556
52	G4CJ/MJ50/50 100% rel.comp. AL	2.836326141	-0.711311151	3.676300672	4.572646994	5.421505709	7.448916103
53	G4CJ/MJ80/20 100% rel.comp. AL	3.616846251	-0.949330586	3.6558396	4.832305759	5.63968432	7.488293515

	ln_vol_d	ln_rel_d	ln_deg_c	ln_mpd	ln_mmpd	ln_omc	ln_vvs	ln_cf
1	7.762170607	-0.197413594	0	7.564757013		2.208274414	4.538709819	-0.299754654
2	7.605890001	-0.208328466	0	7.397561536		2.721295428	4.668520501	-0.336872317
3	7.740664402	-0.198981302	0	7.5416831		2.351375257	4.759177998	-0.30788478
4	7.625595072	-0.199641415	0	7.425953657		2.701361213	4.547435135	
5	7.570958583	-0.087714167	0.082623839	7.400620577	7.543802868	2.433613355		-0.362816212
6	7.570958583	-0.168507062	0.03980625	7.36264527	7.427738841	2.493205453		-0.362816212
7	7.570958583	-0.14381445	0.064498863	7.36264527	7.427738841	2.493205453		-0.362816212
8	7.887959337	-0.232095319	-0.021999483	7.677863501	7.723120092	1.648658626		-0.148886781
9	7.887959337	-0.250242904	-0.05667637	7.694392803	7.619724214	1.30833282		-0.148886781
10	7.848933726	-0.264160649	0.039383328	7.54538975	7.60190196	1.887069649		-0.170392986
11	7.848933726	-0.227248728	-0.029435177	7.651120176	7.61529834	1.568615918		-0.170392986
12	7.889459149	-0.226051485	-0.024589501	7.687997166	7.736743682	2.079441542		-0.223143551
13	7.889459149	-0.154462955	0.00394305	7.731053144	7.735433352	1.704748092		-0.223143551
14	7.829232538	-0.169589583	-0.04786924	7.707512195	7.684324068	1.547562509		-0.143100844
15	7.671360923	-0.170831438	0.076364204	7.424165281	7.526717561	1.686398954		-0.335472736
16	7.437795122	-0.104772107	0.067593291	7.265429723	7.336936914	3.068052935		-0.425667815
17	7.437795122	-0.13462507	0.037740328	7.265429723	7.336936914	3.068052935		-0.425667815
18	7.437795122	-0.109357769	0.058124467	7.270312886	7.335633982	2.809402695		-0.425667815
19	7.436617265	-0.068277579	0.043190728	7.325148958	7.395721609	2.803360381		-0.393042588
20	7.436617265	-0.112786699	-0.030531764	7.35436233	7.358830898	2.63905733		-0.393042588
21	7.699389406	-0.169446036	0.046698955	7.483244416	7.530479995	2.493205453		-0.237834267
22	7.699389406	-0.19554866	0.020596331	7.483244416	7.530479995	2.493205453		-0.237834267
23	7.699389406	-0.161426746	0.039092926	7.498869734	7.541152455	2.079441542		-0.237834267
24	7.699389406	-0.159299086	0.041220586	7.498869734	7.541152455	2.079441542		-0.237834267
25	7.643003636	-0.145796412	0.015651521	7.481555702	7.510977752	2.272125886		-0.263531612
26	7.643003636	-0.207565616	-0.038199089	7.473637108	7.437795122	1.902107526		-0.263531612
27	7.61283103	-0.198258149	0.017011346	7.397561536	7.471932078	2.63188884		-0.30885707
28	7.61283103	-0.188665749	-0.022419818	7.446585099	7.446001498	2.4765384		-0.30885707
29	7.7419679	-0.21471198	0.031713975	7.495541944	7.56112159	2.079441542		-0.231511801
30	7.620705087	-0.179971379	0.010026625	7.430707083	7.486052618	2.014903021		-0.326191927
31	7.615791072	-0.170373515	0.020655795	7.424761762	7.498869734	2.312535424		-0.289906767
32	7.647308832	-0.203060183	0.00292826	7.44132039	7.462789157	2.163323026		-0.30788478
33	7.628517627	-0.179601524	0	7.448916103		2.054123734	4.816807797	-0.360252765
34	7.664205843	-0.205443151	0	7.458762692		2.128231706	4.784487234	-0.328035427
35	7.698664177	-0.210370662	0	7.488293515		2.104134154	4.751087061	-0.306457228
36	7.696212639	-0.267285445	-0.054317221	7.483244416		2.041220329		
37	7.696212639	-0.233423482	-0.020455259	7.483244416		2.041220329		
38	7.696212639	-0.207919124	0.005049099	7.483244416		2.041220329		
39	7.696212639	-0.190170461	0.022797762	7.483244416		2.041220329		
40	7.696212639	-0.165196307	0.047771916	7.483244416		2.041220329		
41	7.664205843	-0.224646534	-0.030664827	7.470224136		2.302585093	4.784487234	-0.328035427
42	7.664205843	-0.193981707	0	7.470224136		2.302585093	4.784487234	-0.328035427
43	7.664205843	-0.164422905	0.029558802	7.470224136		2.302585093	4.784487234	-0.328035427
44	7.664205843	-0.235872649	-0.030429498	7.458762692		2.302585093	4.784487234	-0.328035427
45	7.664205843	-0.205443151	0	7.458762692		2.302585093	4.784487234	-0.328035427
46	7.664205843	-0.175912328	0.029530823	7.458762692		2.302585093	4.784487234	-0.328035427
47	7.664205843	-0.157064763	0.048378387	7.458762692		2.302585093	4.784487234	-0.328035427
48	7.664205843	-0.277115608	-0.030490167	7.417580402		2.151762203	4.784487234	-0.328035427
49	7.664205843	-0.246625441	0	7.417580402		2.151762203	4.784487234	-0.328035427
50	7.664205843	-0.217037484	0.029587957	7.417580402		2.151762203	4.784487234	-0.328035427
51	7.664205843	-0.197978287	0.048647154	7.417580402		2.151762203	4.784487234	-0.328035427
52	7.628517627	-0.179601524	0	7.448916103		2.054123734	4.816807797	-0.328035427
53	7.698664177	-0.210370662	0	7.488293515		2.104134154	4.751087061	-0.328035427

	ln_d85	ln_d60	ln_d50	ln_d30	ln_d15	ln_d10	d_p_f	a_p_f
1	3.026150974	1.92631914	0.893817876	-0.933650693	-1.607345132	-1.798767206	5.142274528	6.488474429
2	2.752249038	1.66603358	1.095169944	-0.394062476	-1.164493993	-1.497045725	5.065783035	6.651634411
3	3.516198774	2.913848792	2.574762979	1.082611947	-0.999733408	-1.437587656	3.925554105	5.314004372
4	3.556282204	2.52896664	2.009237283	0.483174092	-0.6054416	-0.928461267	4.012304865	5.144490752
5	2.575878428	1.386294361	0.693147181	-0.394366215	-1.434085025	-1.864330162	5.230876218	6.878262419
6	3.673131097	2.772588722	2.397895273	1.386294361	0.019418086	-0.754516127	3.778258459	5.284986003
7	3.673131097	2.772588722	2.397895273	1.386294361	0.019418086	-0.754516127	3.778258459	5.284986003
8	2.575878428	1.386294361	0.693147181	-0.201739643	-1.563628376	-2.628520445	5.165801589	6.734144423
9	3.673131097	2.772588722	2.397895273	1.386294361	0.207639365	-0.556571646	3.769071398	5.337640099
10	2.575878428	1.386294361	0.693147181	-0.429652334	-1.265848208	-1.600951299	5.253866441	6.88021542
11	3.673131097	2.772588722	2.397895273	1.386294361	-0.076961041	-0.733969175	3.844596065	5.283207389
12	2.575878428	1.386294361	0.693147181	-0.878175099	-3.218875825	-6.69587492	5.46535691	6.889558191
13	3.673131097	2.772588722	2.397895273	1.386294361	-0.195308752	-1.416147324	3.467883813	5.266442846
14	3.430540411	2.772588722	2.48490665	1.386294361	-0.942362972	-1.580450376	3.437083823	4.773864732
15	3.135784029	2.590267165	2.302585093	1.450832882	-0.117783036	-1.057790294	3.937618763	5.898979108
16	2.575878428	1.386294361	0.693147181	-0.545094081	-1.543614616	-2.006238138	5.259381245	6.880654729
17	2.575878428	1.386294361	0.693147181	-0.545094081	-1.543614616	-2.006238138	5.259381245	6.880654729
18	3.673131097	2.772588722	2.397895273	1.386294361	-0.026668247	-0.862223511	3.712102712	5.279939122
19	2.575878428	1.386294361	0.693147181	-1.236548975	-2.042807409	-2.587889043	5.447006427	6.898972296
20	3.673131097	2.772588722	2.397895273	1.386294361	-0.837728409	-1.504077397	3.568044731	5.268142993
21	2.575878428	1.386294361	0.693147181	-0.390866309	-1.304948722	-1.701375408	5.226308387	6.878087619
22	2.575878428	1.386294361	0.693147181	-0.390866309	-1.304948722	-1.701375408	5.226308387	6.878087619
23	3.673131097	2.772588722	2.397895273	1.386294361	-0.0104713	-0.725582456	3.822968832	5.285997392
24	3.673131097	2.772588722	2.397895273	1.386294361	-0.0104713	-0.725582456	3.822968832	5.285997392
25	2.575878428	1.386294361	0.693147181	-0.898591155	-2.056452023	-2.574221721	5.379724201	6.890563926
26	3.673131097	2.772588722	2.397895273	1.386294361	-0.348306694	-1.252762968	3.463820662	5.262148624
27	2.575878428	1.386294361	0.693147181	-0.82902324	-1.719886135	-2.134862336	5.32769377	6.888184489
28	3.673131097	2.772588722	2.397895273	1.386294361	-0.297251523	-1.103727389	3.573434117	5.26515454
29	3.226843995	2.590267165	2.302585093	1.386294361	-0.356674944	-1.014054901	3.743164911	5.5613761
30	3.364417987	2.657519392	2.37793453	1.460402333	-0.381367557	-1.052288217	3.401363279	4.941275565
31	3.167584323	2.355694918	1.95683922	0.492476485	-1.127185661	-1.60113911	4.362620906	6.023909726
32	3.386506329	2.859518106	2.58021683	1.734601055	-0.751643387	-1.581603113	3.769152706	5.438867313
33	3.304163495	2.128834297	1.737925158	0.8400383	-1.015434782	-1.722766598	4.21444412	5.865510403
34	3.304163495	2.128834297	1.737925158	0.8400383	-1.015434782	-1.722766598	4.21444412	5.865510403
35	3.304163495	2.128834297	1.737925158	0.8400383	-1.015434782	-1.722766598	4.21444412	5.865510403
36	3.252845099	2.229849259	1.66503286	-0.177695197	-1.151076953	-1.532933021	4.624613173	6.042334455
37	3.252845099	2.229849259	1.66503286	-0.177695197	-1.151076953	-1.532933021	4.624613173	6.042334455
38	3.252845099	2.229849259	1.66503286	-0.177695197	-1.151076953	-1.532933021	4.624613173	6.042334455
39	3.252845099	2.229849259	1.66503286	-0.177695197	-1.151076953	-1.532933021	4.624613173	6.042334455
40	3.252845099	2.229849259	1.66503286	-0.177695197	-1.151076953	-1.532933021	4.624613173	6.042334455
41	2.610421967	1.567611397	1.162402027	-0.268263987	-1.791759469	-2.30243585	5.150179411	6.779189451
42	2.610421967	1.567611397	1.162402027	-0.268263987	-1.791759469	-2.30243585	5.150179411	6.779189451
43	2.610421967	1.567611397	1.162402027	-0.268263987	-1.791759469	-2.30243585	5.150179411	6.779189451
44	3.304163495	2.128834297	1.737925158	0.8400383	-1.015434782	-1.722766598	4.21444412	5.865510403
45	3.304163495	2.128834297	1.737925158	0.8400383	-1.015434782	-1.722766598	4.21444412	5.865510403
46	3.304163495	2.128834297	1.737925158	0.8400383	-1.015434782	-1.722766598	4.21444412	5.865510403
47	3.304163495	2.128834297	1.737925158	0.8400383	-1.015434782	-1.722766598	4.21444412	5.865510403
48	3.649270316	2.772588722	2.367123614	1.386294361	0.693147181	-0.405465108	3.952008824	5.153265705
49	3.649270316	2.772588722	2.367123614	1.386294361	0.693147181	-0.405465108	3.952008824	5.153265705
50	3.649270316	2.772588722	2.367123614	1.386294361	0.693147181	-0.405465108	3.952008824	5.153265705
51	3.649270316	2.772588722	2.367123614	1.386294361	0.693147181	-0.405465108	3.952008824	5.153265705
52	3.304163495	2.128834297	1.737925158	0.8400383	-1.015434782	-1.722766598	4.21444412	5.865510403
53	3.304163495	2.128834297	1.737925158	0.8400383	-1.015434782	-1.722766598	4.21444412	5.865510403

	a_p_f_m	ln_sc85	ln_sc60	ln_cu	ln_cc_30	ln_cc_50	ln_ce	ln_zfine
1	6.266031199	0.673705138	0.644915796	3.725086346	-1.994853319	0.36882991	4.633496106	0.377109882
2	6.441188457	0.653330277	0.608506085	3.163079305	-0.957112807	0.602584844	3.916743031	0.628178459
3	5.350819089	0.671279492	0.667369181	4.351436448	0.688962758	2.633060591	4.515932182	0.605549121
4	5.157155086	0.661983305	0.630104897	3.457427907	-0.634157187	1.067633962	4.161723805	-1.161861319
5	6.696893162	0.656875088	0.615608355	3.250624523	-0.310696629	0.244500958	4.009963453	1.636174069
6	5.534584918	0.641345995	0.634350486	3.527104849	0.754516127	1.103241363	3.653713011	0.737318399
7	5.534584918	0.641345995	0.634350486	3.527104849	0.754516127	1.103241363	3.653713011	0.737318399
8	6.353214374	0.661283072	0.657050669	4.014814807	0.838746799	0.37404431	4.139506804	2.314768636
9	5.569175359	0.630611546	0.621470168	3.329160368	0.556571646	0.915020084	3.465491732	1.40941217
10	6.698366339	0.65022755	0.592209295	2.98724566	-0.64464773	0.076264141	3.841726636	0.575162512
11	5.53357771	0.64610735	0.633129171	3.506557897	0.733969175	1.19962049	3.750092138	-0.399034218
12	6.707101276	0.687060205	0.692529181	8.082169281	3.553230361	2.029291758	5.794754253	2.915676125
13	5.523157878	0.651359227	0.662813973	4.188736047	1.416147324	1.317968201	3.868439849	2.005829724
14	4.818596632	0.667916717	0.667410466	4.353039098	1.580450376	2.481635861	4.372903383	1.84820078
15	5.652400905	0.615836408	0.641052069	3.64805746	1.369188893	1.587169193	3.253567065	1.32132564
16	6.699080706	0.660638814	0.625874986	3.392532499	-0.470244385	0.354030549	4.119493044	1.846166191
17	6.699080706	0.660638814	0.625874986	3.392532499	-0.470244385	0.354030549	4.119493044	1.846166191
18	5.53162756	0.64368012	0.640357147	3.634812233	0.862223511	1.149327696	3.699799344	0.951782416
19	6.715434689	0.673415035	0.655553468	3.974183404	-1.271503268	0.853223342	4.618685836	2.300970888
20	5.520876883	0.671168274	0.665367616	4.276666119	1.504077397	1.960387858	4.510859507	1.392725251
21	6.696747741	0.651873821	0.601867639	3.087669769	-0.466651571	0.115364655	3.88082715	1.3074606
22	6.696747741	0.651873821	0.601867639	3.087669769	-0.466651571	0.115364655	3.88082715	1.3074606
23	5.535189545	0.642872043	0.632623393	3.498171179	0.725582456	1.133130748	3.683602397	0.385920512
24	5.535189545	0.642872043	0.632623393	3.498171179	0.725582456	1.133130748	3.683602397	0.385920512
25	6.707859548	0.673682461	0.655036011	3.960516083	-0.609254949	0.866867957	4.632330451	2.290577809
26	5.520066043	0.657288997	0.657429098	4.025351691	1.252762968	1.470966143	4.021437791	1.377383812
27	6.705841068	0.665893194	0.633999508	3.521156697	-0.909478506	0.530302068	4.295764563	1.915498449
28	5.522733006	0.655410277	0.651687161	3.876316112	1.103727389	1.419910972	3.970382621	1.011014229
29	5.286086335	0.637577329	0.638721985	3.604322066	1.196376457	1.735001135	3.583518938	0.757181542
30	4.600597794	0.645904257	0.644172928	3.709807609	1.315573491	1.77281863	3.745785544	1.11461263
31	5.832024441	0.665866071	0.654895391	3.956834028	0.230397162	1.873279777	4.294769985	1.242572978
32	5.14339808	0.661239793	0.66958065	4.441121219	2.191287118	2.525570718	4.138149716	1.456361924
33	5.670100058	0.666535155	0.650649391	3.851600895	1.274008901	1.187121604	4.319598277	1.373307166
34	5.670100058	0.666535155	0.650649391	3.851600895	1.274008901	1.187121604	4.319598277	1.373307166
35	5.670100058	0.666535155	0.650649391	3.851600895	1.274008901	1.187121604	4.319598277	1.373307166
36	5.81247561	0.668687397	0.646700735	3.762782279	-1.052306631	1.228297574	4.403922051	-0.137239563
37	5.81247561	0.668687397	0.646700735	3.762782279	-1.052306631	1.228297574	4.403922051	-0.137239563
38	5.81247561	0.668687397	0.646700735	3.762782279	-1.052306631	1.228297574	4.403922051	-0.137239563
39	5.81247561	0.668687397	0.646700735	3.762782279	-1.052306631	1.228297574	4.403922051	-0.137239563
40	5.81247561	0.668687397	0.646700735	3.762782279	-1.052306631	1.228297574	4.403922051	-0.137239563
41	6.60393763	0.668644781	0.651426362	3.870047248	0.19829648	1.506141555	4.402181437	1.987432359
42	6.60393763	0.668644781	0.651426362	3.870047248	0.19829648	1.506141555	4.402181437	1.987432359
43	6.60393763	0.668644781	0.651426362	3.870047248	0.19829648	1.506141555	4.402181437	1.987432359
44	5.670100058	0.666535155	0.650649391	3.851600895	1.274008901	1.187121604	4.319598277	1.373307166
45	5.670100058	0.666535155	0.650649391	3.851600895	1.274008901	1.187121604	4.319598277	1.373307166
46	5.670100058	0.666535155	0.650649391	3.851600895	1.274008901	1.187121604	4.319598277	1.373307166
47	5.670100058	0.666535155	0.650649391	3.851600895	1.274008901	1.187121604	4.319598277	1.373307166
48	5.448068057	0.589012776	0.609765572	3.17805383	0.405465108	0.391829732	2.956123135	-0.543615447
49	5.448068057	0.589012776	0.609765572	3.17805383	0.405465108	0.391829732	2.956123135	-0.543615447
50	5.448068057	0.589012776	0.609765572	3.17805383	0.405465108	0.391829732	2.956123135	-0.543615447
51	5.448068057	0.589012776	0.609765572	3.17805383	0.405465108	0.391829732	2.956123135	-0.543615447
52	5.670100058	0.666535155	0.650649391	3.851600895	1.274008901	1.187121604	4.319598277	1.373307166
53	5.670100058	0.666535155	0.650649391	3.851600895	1.274008901	1.187121604	4.319598277	1.373307166

	ln_s1	ln_s2	ln_s4	ln_s8
1	3.758871826	3.887730313	3.992680908	4.131961426
2	3.61361697	3.811097087	4.005513349	4.258445573
3	3.169685581	3.33220451	3.471966453	3.688879454
4	3.254242969	3.481240089	3.683866912	3.943521672
5	3.618993327	3.912023005	4.094344562	4.33073334
6	2.701361213	2.995732274	3.401197382	3.784189634
7	2.701361213	2.995732274	3.401197382	3.784189634
8	3.520460802	3.912023005	4.094344562	4.33073334
9	2.602689685	2.995732274	3.401197382	3.784189634
10	3.676300672	3.912023005	4.094344562	4.33073334
11	2.76000994	2.995732274	3.401197382	3.784189634
12	3.693866996	3.912023005	4.094344562	4.33073334
13	2.778819272	2.995732274	3.401197382	3.784189634
14	3.113515309	3.218875825	3.401197382	3.688879454
15	2.76000994	3.044522438	3.36729583	3.784189634
16	3.634951112	3.912023005	4.094344562	4.33073334
17	3.634951112	3.912023005	4.094344562	4.33073334
18	2.721295428	2.995732274	3.401197382	3.784189634
19	3.832979798	3.912023005	4.094344562	4.33073334
20	2.917770732	2.995732274	3.401197382	3.784189634
21	3.629660094	3.912023005	4.094344562	4.33073334
22	3.629660094	3.912023005	4.094344562	4.33073334
23	2.714694744	2.995732274	3.401197382	3.784189634
24	2.714694744	2.995732274	3.401197382	3.784189634
25	3.749504076	3.912023005	4.094344562	4.33073334
26	2.833213344	2.995732274	3.401197382	3.784189634
27	3.735285827	3.912023005	4.094344562	4.33073334
28	2.821378886	2.995732274	3.401197382	3.784189634
29	2.90690106	3.135494216	3.401197382	3.784189634
30	2.867898902	3.091042453	3.36729583	3.737669618
31	3.277144733	3.465735903	3.688879454	3.970291914
32	2.895911938	3.044522438	3.218875825	3.610917913
33	3.117949906	3.314186005	3.768152635	4.080921542
34	3.117949906	3.314186005	3.768152635	4.080921542
35	3.117949906	3.314186005	3.768152635	4.080921542
36	3.505887669	3.680506471	3.836979679	4.054046025
37	3.505887669	3.680506471	3.836979679	4.054046025
38	3.505887669	3.680506471	3.836979679	4.054046025
39	3.505887669	3.680506471	3.836979679	4.054046025
40	3.505887669	3.680506471	3.836979679	4.054046025
41	3.502549876	3.688879454	4.037774211	4.294560609
42	3.502549876	3.688879454	4.037774211	4.294560609
43	3.502549876	3.688879454	4.037774211	4.294560609
44	3.117949906	3.314186005	3.768152635	4.080921542
45	3.117949906	3.314186005	3.768152635	4.080921542
46	3.117949906	3.314186005	3.768152635	4.080921542
47	3.117949906	3.314186005	3.768152635	4.080921542
48	2.48490665	2.708050201	3.401197382	3.80666249
49	2.48490665	2.708050201	3.401197382	3.80666249
50	2.48490665	2.708050201	3.401197382	3.80666249
51	2.48490665	2.708050201	3.401197382	3.80666249
52	3.117949906	3.314186005	3.768152635	4.080921542
53	3.117949906	3.314186005	3.768152635	4.080921542

H DATA ANALYSIS

H.1 General descriptive statistic analysis

In the general descriptive statistic analyses, the outliers as discussed in chapter 5 are still included in the data set.

	N	Range	Minimum	Maximum	Mean		Std. Deviation	Variance
	Statistic	Statistic	Statistic	Statistic	Statistic	Std. Error	Statistic	Statistic
k1 value	49	153.8	4	157.8	34.92929	4.22547	29.57829	874.876
k2 value	49	0.6	0.05	0.65	0.38647	1.60E-02	0.11213	1.26E-02
Angle of internal friction	22	24.6	28.3	52.9	41.452	1.185	5.558	30.888
Cohesion	22	167	14.9	181.9	84.227	8.681	40.72	1658.084
Tau at 12 kPa	26	329.17	63.94	393.11	192.6222	16.6047	84.6676	7168.606
Dry density	53	802	1485	2287	1779.97	22.49	163.73	26807.375
Volume Density	53	972	1697	2669	2152.53	32.62	237.46	56387.95
Relative Density	53	0.176	0.758	0.934	0.829329	5.04E-03	3.67E-02	1.35E-03
Degree of Compaction	53	0.1412	0.9449	1.0861	1.01161	4.70E-03	3.42E-02	1.17E-03
Max Proctor Dens	53	848	1430	2278	1762.7	25.63	186.58	34813.484
Mod Max Proctor Dens	28	757	1534	2291	1848	41.6	220.15	48465.926
Optimum Moisture Content	53	17.8	3.7	21.5	9.798	0.509	3.704	13.72
Volders Verh Sharpness	20	30	93.57	123.57	116.2695	1.8725	8.3739	70.123
Crushing Factor	47	0.213	0.653	0.867	0.74157	7.87E-03	5.39E-02	2.91E-03
D 85	53	26.23	13.14	39.38	26.6597	1.3727	9.9931	99.862
D 60	53	14.43	4	18.43	10.3504	0.6809	4.9572	24.574
D 50	53	11.2	2	13.2	6.829	0.5207	3.7907	14.369
D 30	53	5.38	0.29	5.67	2.3217	0.2148	1.5635	2.444
D 15	53	1.96	0.04	2	0.5708	6.88E-02	0.5009	0.251
D 10	53	0.67	0	0.67	0.2669	2.32E-02	0.1691	2.86E-02
D (PSDC-FC)	53	206.36	30	236.36	98.171	8.9314	65.0213	4227.768
A (PSDC-FC)	53	872.88	118.38	991.26	466.3346	43.2488	314.8562	99134.413
A (PSDC-FC) middle	53	725.5	99.54	825.04	409.0791	32.9797	240.0962	57646.168
SC (85-15)	53	0.19	1.8	1.99	1.9242	5.87E-03	4.28E-02	1.83E-03
SC (60-10)	53	0.19	1.81	2	1.8988	5.21E-03	3.79E-02	1.44E-03
Cu (coeff of uniformity)	53	3216.41	19.83	3236.25	102.6367	60.2955	438.958	192684.108
Cc (coeff of curvature) D30D60/D10	53	34.79	0.14	34.93	2.7283	0.6603	4.8074	23.111
Cc (coeff of curvature) D50D85/D15	53	12.84	1.08	13.92	3.7172	0.3718	2.7065	7.325
Ce (extension coeff)	53	309.35	19.22	328.57	66.8928	5.9091	43.0186	1850.602
Perc passing 2mm sieve	53	35	15	50	31.9685	1.6949	12.3388	152.246
Perc passing 4mm sieve	53	35	25	60	42.7514	1.6811	12.2387	149.785
Perc passing 8mm sieve	53	39	37	76	57.084	1.8121	13.1925	174.042
Z fine (fine particles)	53	18.1	0.3	18.5	3.915	0.449	3.27	10.696

	N	Range	Minimum	Maximum	Mean		Std. Deviation	Variance
	Statistic	Statistic	Statistic	Statistic	Statistic	Std. Error	Statistic	Statistic
LN k1	49	3.675034	1.386294	5.061328	3.32266085	9.65E-02	0.6753745	0.456
LN k2	49	2.564949	-2.995732	-0.430783	-1.01248254	5.88E-02	0.4114674	0.169
LN Phi	22	0.624785	3.342862	3.967647	3.71565022	2.94E-02	0.13801322	1.91E-02
LN Cohesion	22	2.503439	2.700018	5.203457	4.30463425	0.11895753	0.55796027	0.311
LN tau	26	1.816188	4.157907	5.974095	5.16451846	8.97E-02	0.45729653	0.209
LN dry dens	53	0.431826	7.30317	7.734996	7.48036794	1.23E-02	8.93E-02	7.98E-03
LN vol dens grains	53	0.452842	7.436617	7.889459	7.66845303	1.51E-02	0.11022073	1.22E-02
LN rel. Density	53	0.208838	-0.277116	-0.068278	-0.18808508	6.01E-03	4.38E-02	1.92E-03
LN Degree of compaction	53	0.1393	-0.056676	0.082624	1.10E-02	4.64E-03	3.38E-02	1.14E-03
LN MPD	53	0.465623	7.26543	7.731053	7.46938475	1.40E-02	0.10194179	1.04E-02
LN MMPD	28	0.40111	7.335634	7.736744	7.51519316	2.21E-02	0.11692219	1.37E-02
LN OMC	53	1.75972	1.308333	3.068053	2.21877804	4.90E-02	0.3570688	0.127
LN VVS	20	0.278098	4.53871	4.816808	4.753174	1.74E-02	7.79E-02	6.07E-03
LN CF	47	0.282567	-0.425668	-0.143101	-0.30149542	1.04E-02	7.12E-02	5.07E-03
LN D85	53	1.097253	2.575878	3.673131	3.20248504	5.80E-02	0.4226096	0.179
LN D60	53	1.527554	1.386294	2.913849	2.20208833	7.55E-02	0.54999175	0.302
LN D50	53	1.88707	0.693147	2.580217	1.72644743	9.26E-02	0.6744995	0.455
LN D30	53	2.97115	-1.236549	1.734601	0.52963111	0.11975689	0.8718433	0.76
LN D15	53	3.912023	-3.218876	0.693147	-0.86993246	0.10886149	0.79252361	0.628
LN D10	53	6.29041	-6.695875	-0.405465	-1.56866932	0.12659535	0.92162808	0.849
LN D(PSDC-FC)	53	2.063994	3.401363	5.465357	4.37644661	8.93E-02	0.6504762	0.423
LN A(PSDC-FC)	53	2.125108	4.773865	6.898972	5.9220906	9.25E-02	0.67337125	0.453
LN A(PSDC-FC) midden	53	2.114837	4.600598	6.715435	5.85816589	7.62E-02	0.55480666	0.308
LN SC (85-15)	53	0.098047	0.589013	0.68706	0.65427172	3.11E-03	2.27E-02	5.14E-04
LN SC (60-10)	53	0.10032	0.592209	0.692529	0.64100175	2.75E-03	2.00E-02	4.02E-04
LN Cu	53	5.094924	2.987246	8.082169	3.77075765	9.55E-02	0.69501915	0.483
LN Cc 306010	53	5.548084	-1.994853	3.55323	0.42584322	0.14487301	1.05469143	1.112
LN Cc 508515	53	2.556796	0.076264	2.633061	1.12034229	8.33E-02	0.60659961	0.368
LN Ce	53	2.838631	2.956123	5.794754	4.0724175	6.97E-02	0.5074954	0.258
LN Perc passing 2 mm sieve	53	1.203973	2.70805	3.912023	3.38918526	5.45E-02	0.39647437	0.157
LN Perc passing 4 mm sieve	53	0.875469	3.218876	4.094345	3.714455	3.99E-02	0.29020761	8.42E-02
LN Perc passing 8 mm sieve	53	0.719815	3.610918	4.330733	4.01833877	3.17E-02	0.23106353	5.34E-02
LN Zfine	53	4.077537	-1.161861	2.915676	1.01702466	0.12462967	0.90731767	0.823

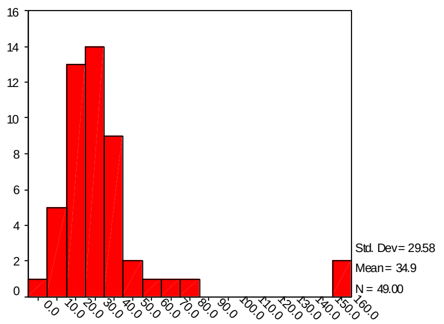
		k1 value	k2 value	phi	Cohesion	Tau at 12 kPa	Dry density	Vol Dens	Rel Dens	Degr of comp
N	**Valid**	49	49	22	22	26	53	53	53	53
	Missing	4	4	31	31	27	0	0	0	0
Mean		34.92929	0.38647	41.452	84.227	192.6222	1779.97	2152.53	0.829329	1.01161
Std. Error of Mean		4.22547	1.60E-02	1.185	8.681	16.6047	22.49	32.62	5.04E-03	4.70E-03
Median		28.956	0.385	41.35	75.395	181.4644	1748	2130.7	0.822383	1.003951
Mode		15.663	0.34	41.1	14.9	63.94	1787	2131	0.8103	1
Std. Deviation		29.57829	0.11213	5.558	40.72	84.6676	163.73	237.46	3.67E-02	3.42E-02
Variance		874.87551	1.26E-02	30.888	1658.084	7168.6058	26807.37	56387.95	1.35E-03	1.17E-03
Range		153.8	0.6	24.6	167	329.17	802	972	0.176	0.1412
Minimum		4	0.05	28.3	14.9	63.94	1485	1697	0.758	0.9449
Maximum		157.8	0.65	52.9	181.9	393.11	2287	2669	0.934	1.0861
Sum		1711.535	18.937	911.9	1853	5008.18	94339	114084	43.9544	53.6154
Percentiles	**25**	19.6075	0.336	37.8	50.995	123.7372	1682	2045	0.808529	0.989876
	50	28.956	0.385	41.35	75.395	181.4644	1748	2130.7	0.822383	1.003951
	75	40.5535	0.463	44.518	110.125	251.1443	1860.5	2207	0.848055	1.040018

		MPD	MMPD	OMC	VVS	CF	D 85	D 60	D 50	D 30
N	**Valid**	53	28	53	20	47	53	53	53	53
	Missing	0	25	0	33	6	0	0	0	0
Mean		1762.7	1848	9.798	116.2695	0.74157	26.6597	10.3504	6.829	2.3217
Std. Error of Mean		25.63	4.16E+01	0.509	1.8725	0.0078671	1.3727	0.6809	5.21E-01	2.15E-01
Median		1735	1842.5	8.6	119.64	0.72034	27.2258	9.2985	5.6855	2.3165
Mode		1778	1536	10	119.64	0.72	13.14	16	2	4
Std. Deviation		186.58	220.15	3.704	8.3739	0.053934	9.9931	4.9572	3.79E+00	1.56E+00
Variance		34813.48	4.85E+04	13.72	70.1227	0.0029089	99.8623	24.5736	1.44E+01	2.44E+00
Range		848	757	17.8	30	0.213	26.23	14.43	11.2	5.38
Minimum		1430	1534	3.7	93.57	0.653	13.14	4	2	0.29
Maximum		2278	2291	21.5	123.57	0.867	39.38	18.43	13.2	5.67
Sum		93423	51744	519.3	2325.39	34.854	1412.96	548.57	361.94	123.05
Percentiles	**25**	1665	1686.25	7.7	115.945	0.72034	13.6048	4.7952	3.0936	0.7647
	50	1735	1842.5	8.6	119.64	0.72034	27.2258	9.2985	5.6855	2.3165
	75	1787	1982	11.65	119.64	0.78833	38.4466	16	11	4

		D 15	D 10	D (PSDC)	A (PSDC)	A (PSDC)m	SC (85-15)	SC (60-10)	C uni	C curv 306010
N	**Valid**	53	53	53	53	53	53	53	53	53
	Missing	0	0	0	0	0	0	0	0	0
Mean		0.5708	0.2669	98.171	466.3346	409.0791	1.9242	1.8988	102.6367	2.7283
Std. Error of Mean		0.06881	2.32E-02	8.9314	43.2488	32.9797	0.005873	0.005205	6.03E+01	6.60E-01
Median		0.3622	0.2059	67.6565	352.6621	290.0636	1.9386	1.9092	43.0681	1.9916
Mode		0.36	0.18	67.66	352.66	290.06	1.95	1.92	47.07	3.58
Std. Deviation		0.5009	0.1691	65.0213	314.8562	240.0962	0.04275	0.03789	4.39E+02	4.81E+00
Variance		0.2509	2.86E-02	4227.7679	99134.4126	57646.1676	0.001828	0.001436	1.93E+05	2.31E+01
Range		1.96	0.67	206.36	872.88	725.5	0.19	0.19	3216.41	34.79
Minimum		0.04	0	30	118.38	99.54	1.8	1.81	19.83	0.14
Maximum		2	0.67	236.36	991.26	825.04	1.99	2	3236.25	34.93
Sum		30.25	14.15	5203.06	24715.73	21681.19	101.98	100.63	5439.75	144.6
Percentiles	**25**	0.2712	0.1786	45.7398	197.1761	250.3714	1.9079	1.8802	32.3951	0.6248
	50	0.3622	0.2059	67.6565	352.6621	290.0636	1.9386	1.9092	43.0681	1.9916
	75	0.7827	0.3559	172.4624	859.9898	682.5736	1.9516	1.9183	47.9447	3.5752

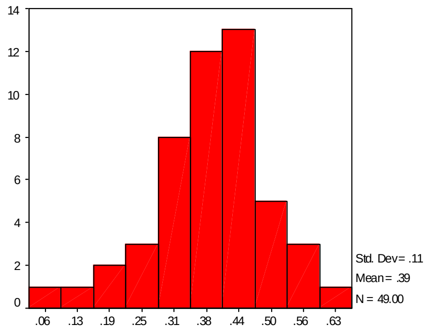
		C curv 855015	C ext	2 mm sieve	4 mm sieve	8 mm sieve	Z fines
N	**Valid**	53	53	53	53	53	53
	Missing	0	0	0	0	0	0
Mean		3.7172	66.8928	31.9685	42.7514	57.084	3.915
Std. Error of Mean		0.3718	5.91E+00	1.6949	1.6811	1.8121	0.449
Median		3.2776	64.1821	27.5	43.3	57.6302	3.748
Mode		3.28	75.16	20	30	44	3.9
Std. Deviation		2.7065	43.0186	12.3388	12.2387	13.1925	3.27
Variance		7.3249	1.85E+03	152.2462	149.7852	174.042	10.696
Range		12.84	309.35	35	35	39	18.1
Minimum		1.08	19.22	15	25	37	0.3
Maximum		13.92	328.57	50	60	76	18.5
Sum		197.01	3545.32	1694.33	2265.83	3025.45	207.5
Percentiles	**25**	1.7631	42.4336	20	30	44	1.471
	50	3.2776	64.1821	27.5	43.3	57.6302	3.748
	75	4.2451	81.6287	42.6	56.7	73.3	4.713

k1 value



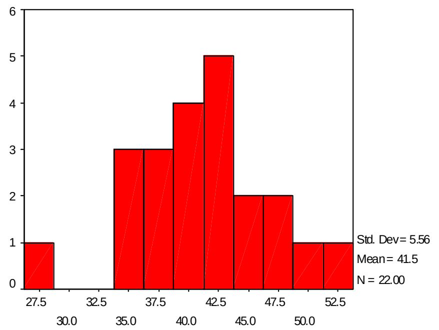
k1 value

k2 value



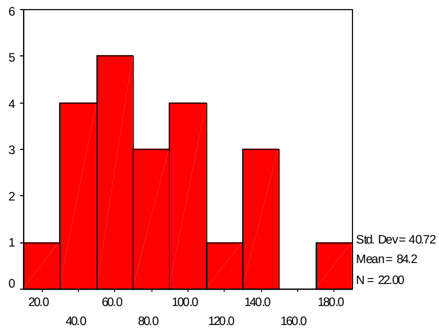
k2 value

Angle of internal friction



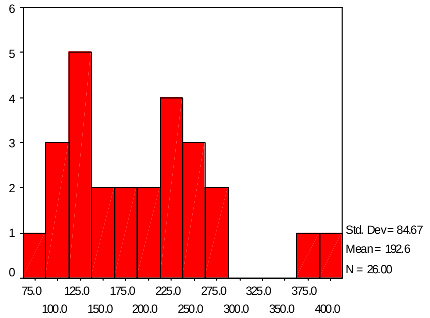
Angle of internal friction

Cohesion



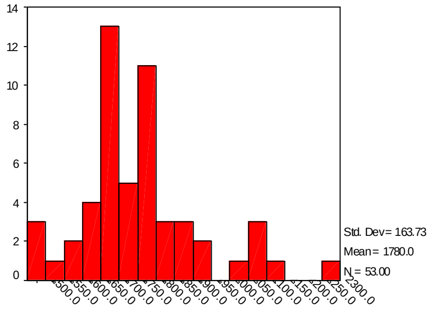
Cohesion

Tau at 12 kPa



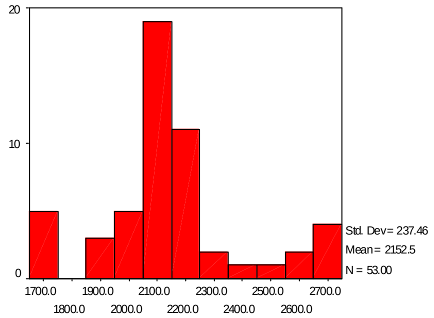
Tau at 12 kPa

Dry density



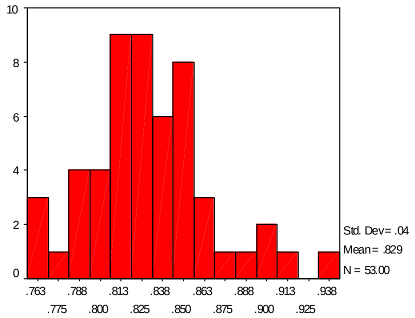
Dry density

Volume Density



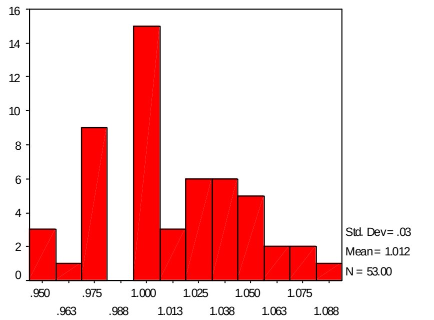
Volume Density

Relative Density



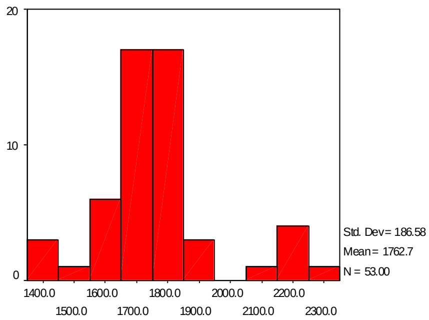
Relative Density

Degree of Compaction



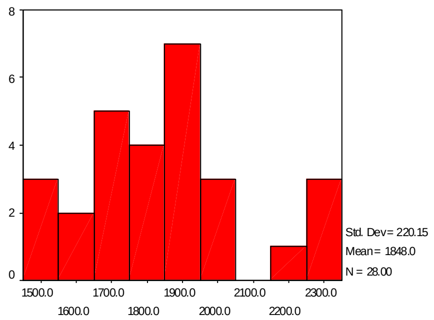
Degree of Compaction

Max Proctor Dens



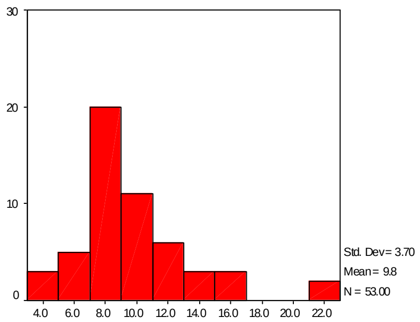
Max Proctor Dens

Mod Max Proctor Dens



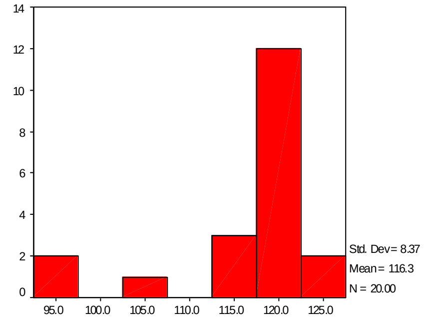
Mod Max Proctor Dens

Optimum Moisture Content



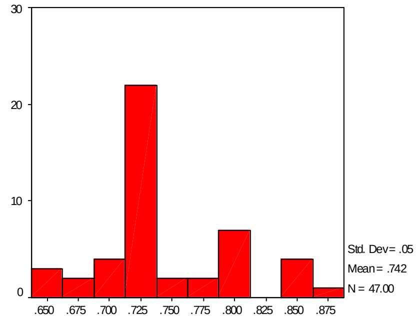
Optimum Moisture Content

Volders Verh Sharpness



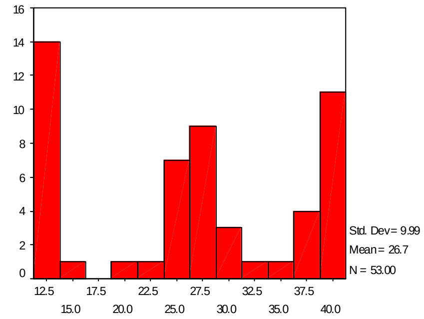
Volders Verh Sharpness

Crushing Factor



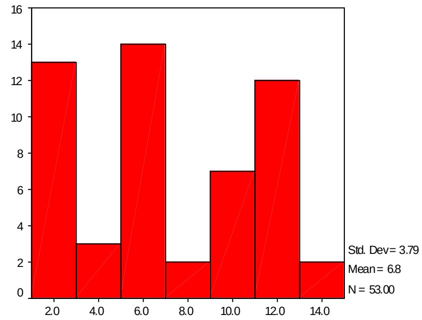
Crushing Factor

D 85



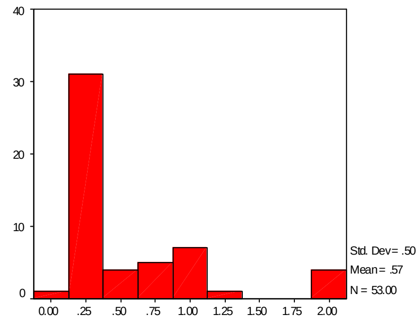
D 85

D 50



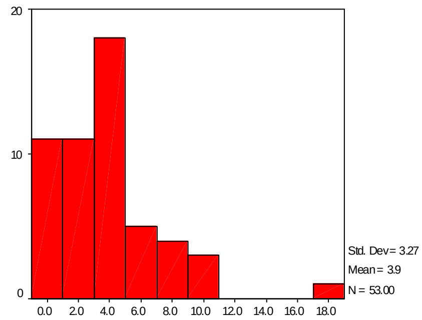
D 50

D 15



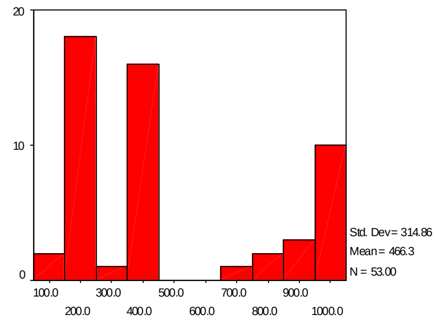
D 15

Z fine (fine particles)



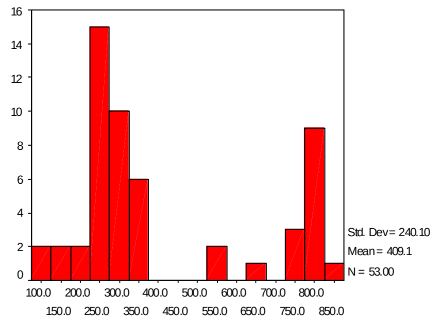
Z fine (fine particles)

A (PSDC-FC)



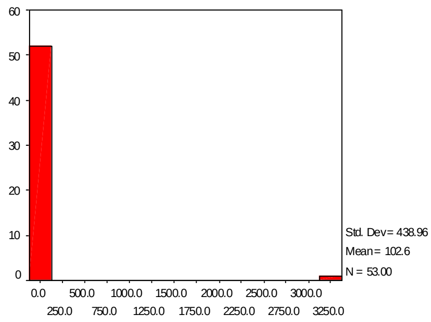
A (PSDC-FC)

A (PSDC-FC) middle



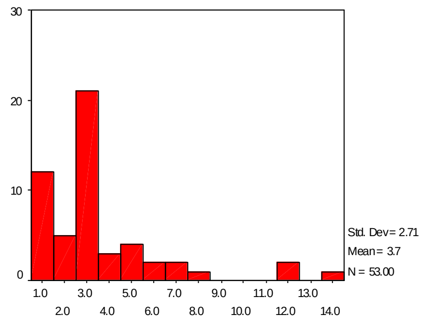
A (PSDC-FC) middle

Cu (coeff of uniformity)



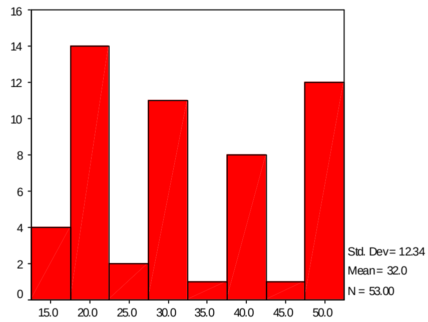
Cu (coeff of uniformity)

Cc (coeff of curvature) D50D85/D15



Cc (coeff of curvature) D50D85/D15

Perc passing 2mm sieve



Perc passing 2mm sieve

H.2 Tables with Pearson Correlations

In this section two bivariate correlation tables are depicted, the so-called pearson correlation tables. These are bivariate correlations: Correlations between natural material parameters have been analysed as well as correlations between the logarithmic values of these parameters.

In the tables, *N* indicates the number of materials. The number of materials on which the pearson correlation is based is of influence on the value of the correlation as well.
The cells that are remained empty contain material parameters, which could not be computed because at least one of the variables was constant or not available.

Because of the symmetrical characteristic of the correlation matrix, the second quadrant of both tables has not been depicted.

		k1	k2	PHI	C	Tau 12 kPa	Dry dens	Vol dens	Rel dens	MPD	MMPD	OMC	VVS	CF	D 85	D 60	D 50
k1	**Pearson Corr.**	1	-0.823	0.073	0.103	0.178	0.479	0.437	-0.203	0.006	0.585	-0.315	-0.325	0.467	-0.24	-0.121	-0.088
	Sig. (2-tailed)	.	0	0.745	0.649	0.428	0	0.002	0.163	0.976	0.003	0.054	0.162	0.002	0.097	0.407	0.549
	N	49	49	22	22	22	49	49	49	25	24	38	20	43	49	49	49
k2	**Pearson Corr.**	-0.823	1	0.104	0.155	0.182	-0.335	-0.33	0.224	0.033	-0.486	0.306	0.188	-0.455	0.415	0.288	0.257
	Sig. (2-tailed)	0	.	0.647	0.492	0.416	0.019	0.02	0.122	0.875	0.016	0.062	0.428	0.002	0.003	0.045	0.075
	N	49	49	22	22	22	49	49	49	25	24	38	20	43	49	49	49
PHI	**Pearson Corr.**	0.073	0.104	1	-0.444	-0.075	0.225	-0.066	0.475	0.205	.	0.367	-0.482	0.416	0.385	0.429	0.336
	Sig. (2-tailed)	0.745	0.647	.	0.038	0.739	0.314	0.77	0.026	0.36	.	0.267	0.05	0.109	0.077	0.046	0.126
	N	22	22	22	22	22	22	22	22	22	0	11	17	16	22	22	22
C	**Pearson Corr.**	0.103	0.155	-0.444	1	0.919	0.223	-0.035	0.105	-0.212	.	0	0.414	-0.409	-0.155	-0.224	-0.124
	Sig. (2-tailed)	0.649	0.492	0.038	.	0	0.318	0.878	0.642	0.344	.	0.999	0.099	0.115	0.49	0.316	0.581
	N	22	22	22	22	22	22	22	22	22	0	11	17	16	22	22	22
Tau 12 kPa	**Pearson Corr.**	0.178	0.182	-0.075	0.919	1	0.33	-0.079	0.306	-0.148	.	0.12	0.241	-0.315	-0.028	-0.094	-0.023
	Sig. (2-tailed)	0.428	0.416	0.739	0	.	0.134	0.727	0.166	0.51	.	0.725	0.352	0.235	0.901	0.676	0.918
	N	22	22	22	22	22	22	22	22	22	0	11	17	16	22	22	22
Dry dens	**Pearson Corr.**	0.479	-0.335	0.225	0.223	0.33	1	0.925	-0.138	0.813	0.976	-0.762	-0.188	0.848	-0.046	0.006	0.01
	Sig. (2-tailed)	0	0.019	0.314	0.318	0.134	.	0	0.344	0	0	0	0.426	0	0.753	0.967	0.946
	N	49	49	22	22	22	49	49	49	25	24	38	20	43	49	49	49
Vol dens	**Pearson Corr.**	0.437	-0.33	-0.066	-0.035	-0.079	0.925	1	-0.383	0.735	0.939	-0.792	-0.06	0.876	0.02	0.066	0.072
	Sig. (2-tailed)	0.002	0.02	0.77	0.878	0.727	0	.	0.007	0	0	0	0.8	0	0.893	0.652	0.625
	N	49	49	22	22	22	49	49	49	25	24	38	20	43	49	49	49
Rel dens	**Pearson Corr.**	-0.203	0.224	0.475	0.105	0.306	-0.138	-0.383	1	0.39	-0.544	0.348	0.079	-0.339	0.031	0.071	0.066
	Sig. (2-tailed)	0.163	0.122	0.026	0.642	0.166	0.344	0.007	.	0.054	0.006	0.033	0.741	0.026	0.832	0.63	0.651
	N	49	49	22	22	22	49	49	49	25	24	38	20	43	49	49	49
MPD	**Pearson Corr.**	0.006	0.033	0.205	-0.212	-0.148	0.813	0.735	0.39	1	.	-0.446	-0.253	0.677	-0.312	-0.192	-0.245
	Sig. (2-tailed)	0.976	0.875	0.36	0.344	0.51	0	0	0.054	.	.	0.11	0.282	0.001	0.129	0.357	0.237
	N	25	25	22	22	22	25	25	25	25	0	14	20	19	25	25	25
MMPD	**Pearson Corr.**	0.585	-0.486	.	.	.	0.976	0.939	-0.544	.	1	-0.8	.	0.834	-0.119	-0.101	-0.092
	Sig. (2-tailed)	0.003	0.016	.	.	.	0	0	0.006	.	.	0	.	0	0.581	0.637	0.667
	N	24	24	0	0	0	24	24	24	0	24	24	0	24	24	24	24
OMC	**Pearson Corr.**	-0.315	0.306	0.367	0	0.12	-0.762	-0.792	0.348	-0.446	-0.8	1	-0.634	-0.777	-0.065	-0.072	-0.08
	Sig. (2-tailed)	0.054	0.062	0.267	0.999	0.725	0	0	0.033	0.11	0	.	0.067	0	0.698	0.667	0.631
	N	38	38	11	11	11	38	38	38	14	24	38	9	32	38	38	38
VVS	**Pearson Corr.**	-0.325	0.188	-0.482	0.414	0.241	-0.188	-0.06	0.079	-0.253	.	-0.634	1	-0.565	0.081	0.065	0.218
	Sig. (2-tailed)	0.162	0.428	0.05	0.099	0.352	0.426	0.8	0.741	0.282	.	0.067	.	0.012	0.733	0.785	0.357
	N	20	20	17	17	17	20	20	20	20	0	9	20	19	20	20	20
CF	**Pearson Corr.**	0.467	-0.455	0.416	-0.409	-0.315	0.848	0.876	-0.339	0.677	0.834	-0.777	-0.565	1	0.014	0.078	0.08
	Sig. (2-tailed)	0.002	0.002	0.109	0.115	0.235	0	0	0.026	0.001	0	0	0.012	.	0.927	0.62	0.612
	N	43	43	16	16	16	43	43	43	19	24	32	19	43	43	43	43
D 85	**Pearson Corr.**	-0.24	0.415	0.385	-0.155	-0.028	-0.046	0.02	0.031	-0.312	-0.119	-0.065	0.081	0.014	1	0.923	0.889
	Sig. (2-tailed)	0.097	0.003	0.077	0.49	0.901	0.753	0.893	0.832	0.129	0.581	0.698	0.733	0.927	.	0	0
	N	49	49	22	22	22	49	49	49	25	24	38	20	43	49	49	49

		k1	k2	PHI	C	Tau 12 kPa	Dry dens	Vol dens	Rel dens	MPD	MMPD	OMC	VVS	CF	D 85	D 60	D 50
D 60	Pearson Corr.	-0.121	0.288	0.429	-0.224	-0.094	0.006	0.066	0.071	-0.192	-0.101	-0.072	0.065	0.078	0.923	1	0.989
	Sig. (2-tailed)	0.407	0.045	0.046	0.316	0.676	0.967	0.652	0.63	0.357	0.637	0.667	0.785	0.62	0	.	0
	N	49	49	22	22	22	49	49	49	25	24	38	20	43	49	49	49
D 50	Pearson Corr.	-0.088	0.257	0.336	-0.124	-0.023	0.01	0.072	0.066	-0.245	-0.092	-0.08	0.218	0.08	0.889	0.989	1
	Sig. (2-tailed)	0.549	0.075	0.126	0.581	0.918	0.946	0.625	0.651	0.237	0.667	0.631	0.357	0.612	0	0	.
	N	49	49	22	22	22	49	49	49	25	24	38	20	43	49	49	49
D 30	Pearson Corr.	-0.095	0.244	-0.038	0.125	0.103	-0.006	0.081	-0.068	-0.454	-0.093	-0.101	0.449	0.058	0.825	0.908	0.943
	Sig. (2-tailed)	0.517	0.091	0.868	0.579	0.649	0.968	0.581	0.642	0.023	0.666	0.548	0.047	0.711	0	0	0
	N	49	49	22	22	22	49	49	49	25	24	38	20	43	49	49	49
D 15	Pearson Corr.	-0.228	0.294	-0.064	-0.015	-0.065	-0.098	0.045	-0.23	-0.564	-0.058	-0.133	0.186	-0.017	0.702	0.691	0.658
	Sig. (2-tailed)	0.116	0.04	0.776	0.947	0.774	0.502	0.758	0.113	0.003	0.787	0.425	0.433	0.916	0	0	0
	N	49	49	22	22	22	49	49	49	25	24	38	20	43	49	49	49
D 10	Pearson Corr.	-0.257	0.314	0.104	-0.107	-0.095	-0.113	0.02	-0.19	-0.554	-0.133	-0.047	0.028	0.031	0.756	0.745	0.703
	Sig. (2-tailed)	0.074	0.028	0.646	0.637	0.673	0.438	0.893	0.19	0.004	0.535	0.78	0.905	0.843	0	0	0
	N	49	49	22	22	22	49	49	49	25	24	38	20	43	49	49	49
D (PSDC)	Pearson Corr.	0.194	-0.333	-0.36	0.026	-0.11	0.048	-0.016	-0.008	0.301	0.087	0.122	-0.278	-0.002	-0.897	-0.876	-0.885
	Sig. (2-tailed)	0.181	0.02	0.1	0.908	0.625	0.743	0.914	0.956	0.144	0.687	0.464	0.235	0.991	0	0	0
	N	49	49	22	22	22	49	49	49	25	24	38	20	43	49	49	49
A (PSDC)	Pearson Corr.	0.153	-0.308	-0.468	0.157	-0.009	0.035	-0.031	-0.013	0.233	0.062	0.127	-0.106	-0.014	-0.932	-0.9	-0.889
	Sig. (2-tailed)	0.292	0.031	0.028	0.486	0.968	0.812	0.831	0.928	0.262	0.774	0.447	0.656	0.93	0	0	0
	N	49	49	22	22	22	49	49	49	25	24	38	20	43	49	49	49
A (PSDC)m	Pearson Corr.	0.129	-0.259	-0.529	0.181	-0.012	0.016	-0.047	-0.003	0.151	0.02	0.159	-0.079	-0.027	-0.862	-0.84	-0.835
	Sig. (2-tailed)	0.376	0.072	0.011	0.421	0.958	0.915	0.749	0.982	0.472	0.924	0.34	0.74	0.861	0	0	0
	N	49	49	22	22	22	49	49	49	25	24	38	20	43	49	49	49
SC (85-15)	Pearson Corr.	0.224	-0.213	0.131	-0.013	0.062	0.11	-0.033	0.291	0.617	0.048	0.103	-0.189	0.016	-0.482	-0.523	-0.505
	Sig. (2-tailed)	0.123	0.142	0.56	0.956	0.784	0.451	0.823	0.042	0.001	0.824	0.537	0.424	0.918	0	0	0
	N	49	49	22	22	22	49	49	49	25	24	38	20	43	49	49	49
SC (60-10)	Pearson Corr.	0.327	-0.172	0.032	0.065	0.097	0.202	0.109	0.294	0.719	0.181	-0.173	0.153	0.02	-0.041	0.007	0.047
	Sig. (2-tailed)	0.022	0.237	0.887	0.773	0.667	0.164	0.455	0.04	0	0.397	0.3	0.52	0.901	0.782	0.96	0.747
	N	49	49	22	22	22	49	49	49	25	24	38	20	43	49	49	49
Cu (uni)	Pearson Corr.	0.606	-0.324	0.135	0.023	0.084	0.312	0.316	-0.093	0.72	0.403	-0.197	0.192	0.17	-0.201	-0.185	-0.182
	Sig. (2-tailed)	0	0.023	0.55	0.919	0.711	0.029	0.027	0.524	0	0.051	0.235	0.418	0.276	0.165	0.203	0.21
	N	49	49	22	22	22	49	49	49	25	24	38	20	43	49	49	49
Cc D30D60	Pearson Corr.	0.602	-0.294	-0.31	0.43	0.351	0.317	0.336	-0.116	-0.104	0.405	-0.232	0.602	0.172	-0.064	-0.025	0.007
	Sig. (2-tailed)	0	0.04	0.16	0.046	0.109	0.027	0.018	0.426	0.622	0.05	0.161	0.005	0.271	0.661	0.867	0.963
	N	49	49	22	22	22	49	49	49	25	24	38	20	43	49	49	49
Cc D50D85	Pearson Corr.	0.38	-0.191	0.331	-0.087	0.031	0.169	0.146	0.267	0.518	0.109	-0.08	0.133	0.126	0.156	0.402	0.464
	Sig. (2-tailed)	0.007	0.188	0.133	0.701	0.89	0.246	0.315	0.064	0.008	0.611	0.633	0.575	0.422	0.286	0.004	0.001
	N	49	49	22	22	22	49	49	49	25	24	38	20	43	49	49	49
Ce (ext)	Pearson Corr.	0.557	-0.357	0.124	-0.069	-0.008	0.243	0.188	0.088	0.789	0.309	-0.124	-0.206	0.072	-0.407	-0.42	-0.422
	Sig. (2-tailed)	0	0.012	0.583	0.761	0.973	0.093	0.195	0.548	0	0.142	0.459	0.385	0.646	0.004	0.003	0.003
	N	49	49	22	22	22	49	49	49	25	24	38	20	43	49	49	49
Z fine	Pearson Corr.	0.478	-0.378	-0.683	0.487	0.266	0.306	0.224	0.069	0.109	0.405	-0.127	0.402	0.158	-0.54	-0.486	-0.43
	Sig. (2-tailed)	0.001	0.007	0	0.022	0.232	0.033	0.121	0.64	0.605	0.05	0.447	0.079	0.312	0	0	0.002
	N	49	49	22	22	22	49	49	49	25	24	38	20	43	49	49	49

		D 30	D 15	D 10	) (PSDC	(PSDC	A (PSDC)m	SC (85-15)	SC (60-10)	Cu (uni)	Cc D30D60	Cc D50D8	Ce (ext)	Z fine
D 60	**Pearson Corr.**	0.908	0.691	0.745	-0.876	-0.9	-0.84	-0.523	0.007	-0.185	-0.025	0.402	-0.42	-0.486
	Sig. (2-tailed)	0	0	0	0	0	0	0	0.96	0.203	0.867	0.004	0.003	0
	N	49	49	49	49	49	49	49	49	49	49	49	49	49
D 50	**Pearson Corr.**	0.943	0.658	0.703	-0.885	-0.889	-0.835	-0.505	0.047	-0.182	0.007	0.464	-0.422	-0.43
	Sig. (2-tailed)	0	0	0	0	0	0	0	0.747	0.21	0.963	0.001	0.003	0.002
	N	49	49	49	49	49	49	49	49	49	49	49	49	49
D 30	**Pearson Corr.**	1	0.678	0.681	-0.859	-0.831	-0.782	-0.566	0	-0.173	0.069	0.352	-0.461	-0.334
	Sig. (2-tailed)	.	0	0	0	0	0	0	1	0.234	0.639	0.013	0.001	0.019
	N	49	49	49	49	49	49	49	49	49	49	49	49	49
D 15	**Pearson Corr.**	0.678	1	0.956	-0.551	-0.593	-0.506	-0.945	-0.505	-0.164	-0.12	-0.2	-0.548	-0.459
	Sig. (2-tailed)	0	.	0	0	0	0	0	0	0.261	0.411	0.167	0	0.001
	N	49	49	49	49	49	49	49	49	49	49	49	49	49
D 10	**Pearson Corr.**	0.681	0.956	1	-0.615	-0.658	-0.574	-0.894	-0.565	-0.24	-0.212	-0.183	-0.607	-0.611
	Sig. (2-tailed)	0	0	.	0	0	0	0	0	0.096	0.143	0.207	0	0
	N	49	49	49	49	49	49	49	49	49	49	49	49	49
D (PSDC)	**Pearson Corr.**	-0.859	-0.551	-0.615	1	0.98	0.968	0.393	-0.051	0.311	0.099	-0.307	0.475	0.575
	Sig. (2-tailed)	0	0	0	.	0	0	0.005	0.728	0.03	0.497	0.032	0.001	0
	N	49	49	49	49	49	49	49	49	49	49	49	49	49
A (PSDC)	**Pearson Corr.**	-0.831	-0.593	-0.658	0.98	1	0.985	0.403	-0.068	0.244	0.062	-0.301	0.403	0.583
	Sig. (2-tailed)	0	0	0	0	.	0	0.004	0.644	0.091	0.673	0.036	0.004	0
	N	49	49	49	49	49	49	49	49	49	49	49	49	49
A (PSDC)m	**Pearson Corr.**	-0.782	-0.506	-0.574	0.968	0.985	1	0.333	-0.124	0.254	0.061	-0.331	0.378	0.577
	Sig. (2-tailed)	0	0	0	0	0	.	0.019	0.397	0.079	0.679	0.02	0.007	0
	N	49	49	49	49	49	49	49	49	49	49	49	49	49
SC (85-15)	**Pearson Corr.**	-0.566	-0.945	-0.894	0.393	0.403	0.333	1	0.664	0.224	0.2	0.299	0.631	0.44
	Sig. (2-tailed)	0	0	0	0.005	0.004	0.019	.	0	0.121	0.167	0.037	0	0.002
	N	49	49	49	49	49	49	49	49	49	49	49	49	49
SC (60-10)	**Pearson Corr.**	0	-0.505	-0.565	-0.051	-0.068	-0.124	0.664	1	0.405	0.513	0.645	0.64	0.543
	Sig. (2-tailed)	1	0	0	0.728	0.644	0.397	0	.	0.004	0	0	0	0
	N	49	49	49	49	49	49	49	49	49	49	49	49	49
Cu (uni)	**Pearson Corr.**	-0.173	-0.164	-0.24	0.311	0.244	0.254	0.224	0.405	1	0.945	0.224	0.865	0.642
	Sig. (2-tailed)	0.234	0.261	0.096	0.03	0.091	0.079	0.121	0.004	.	0	0.123	0	0
	N	49	49	49	49	49	49	49	49	49	49	49	49	49
Cc D30D60	**Pearson Corr.**	0.069	-0.12	-0.212	0.099	0.062	0.061	0.2	0.513	0.945	1	0.38	0.787	0.628
	Sig. (2-tailed)	0.639	0.411	0.143	0.497	0.673	0.679	0.167	0	0	.	0.007	0	0
	N	49	49	49	49	49	49	49	49	49	49	49	49	49
Cc D50D85	**Pearson Corr.**	0.352	-0.2	-0.183	-0.307	-0.301	-0.331	0.299	0.645	0.224	0.38	1	0.298	0.164
	Sig. (2-tailed)	0.013	0.167	0.207	0.032	0.036	0.02	0.037	0	0.123	0.007	.	0.037	0.259
	N	49	49	49	49	49	49	49	49	49	49	49	49	49
Ce (ext)	**Pearson Corr.**	-0.461	-0.548	-0.607	0.475	0.403	0.378	0.631	0.64	0.865	0.787	0.298	1	0.699
	Sig. (2-tailed)	0.001	0	0	0.001	0.004	0.007	0	0	0	0	0.037	.	0
	N	49	49	49	49	49	49	49	49	49	49	49	49	49
Z fine	**Pearson Corr.**	-0.334	-0.459	-0.611	0.575	0.583	0.577	0.44	0.543	0.642	0.628	0.164	0.699	1
	Sig. (2-tailed)	0.019	0.001	0	0	0	0	0.002	0	0	0	0.259	0	.
	N	49	49	49	49	49	49	49	49	49	49	49	49	49

		LN k1	LN k2	LN Phi	LN C	LN tau	LN dry d	LN vol d	LN Rel D	LN MPD	LN MMPD	LN OMC	LN VVS	LN CF	LN D85	LN D60	LN D50
LN k1	**Pearson Corr.**	1	-0.825	0.122	0.033	0.076	0.503	0.481	-0.194	0.112	0.659	-0.385	-0.375	0.518	-0.258	-0.169	-0.164
	Sig. (2-tailed)	.	0	0.588	0.884	0.738	0	0	0.181	0.595	0	0.017	0.104	0	0.074	0.245	0.259
	N	49	49	22	22	22	49	49	49	25	24	38	20	43	49	49	49
LN k2	**Pearson Corr.**	-0.825	1	0.083	0.22	0.287	-0.379	-0.346	0.106	0.021	-0.488	0.315	0.174	-0.485	0.292	0.195	0.185
	Sig. (2-tailed)	0	.	0.715	0.326	0.195	0.007	0.015	0.468	0.922	0.016	0.054	0.463	0.001	0.042	0.179	0.204
	N	49	49	22	22	22	49	49	49	25	24	38	20	43	49	49	49
LN Phi	**Pearson Corr.**	0.122	0.083	1	-0.418	-0.11	0.2	-0.094	0.336	0.175	.	0.374	-0.453	0.379	0.473	0.498	0.358
	Sig. (2-tailed)	0.588	0.715	.	0.053	0.625	0.372	0.678	0.126	0.436	.	0.257	0.068	0.148	0.026	0.018	0.102
	N	22	22	22	22	22	22	22	22	22	0	11	17	16	22	22	22
LN C	**Pearson Corr.**	0.033	0.22	-0.418	1	0.942	0.187	-0.024	0.238	-0.279	.	0.14	0.43	-0.516	-0.139	-0.196	-0.044
	Sig. (2-tailed)	0.884	0.326	0.053	.	0	0.405	0.916	0.286	0.209	.	0.681	0.085	0.041	0.537	0.383	0.846
	N	22	22	22	22	22	22	22	22	22	0	11	17	16	22	22	22
LN tau	**Pearson Corr.**	0.076	0.287	-0.11	0.942	1	0.296	-0.057	0.399	-0.216	.	0.225	0.242	-0.362	-0.006	-0.048	0.075
	Sig. (2-tailed)	0.738	0.195	0.625	0	.	0.181	0.802	0.066	0.333	.	0.505	0.349	0.168	0.978	0.831	0.739
	N	22	22	22	22	22	22	22	22	22	0	11	17	16	22	22	22
LN dry d	**Pearson Corr.**	0.503	-0.379	0.2	0.187	0.296	1	0.92	-0.301	0.808	0.979	-0.789	-0.194	0.855	-0.06	-0.026	-0.043
	Sig. (2-tailed)	0	0.007	0.372	0.405	0.181	.	0	0.036	0	0	0	0.412	0	0.684	0.858	0.77
	N	49	49	22	22	22	49	49	49	25	24	38	20	43	49	49	49
LN vol d	**Pearson Corr.**	0.481	-0.346	-0.094	-0.024	-0.057	0.92	1	-0.65	0.718	0.941	-0.811	-0.059	0.874	0.022	0.05	0.04
	Sig. (2-tailed)	0	0.015	0.678	0.916	0.802	0	.	0	0	0	0	0.804	0	0.883	0.733	0.785
	N	49	49	22	22	22	49	49	49	25	24	38	20	43	49	49	49
LN Rel D	**Pearson Corr.**	-0.194	0.106	0.336	0.238	0.399	-0.301	-0.65	1	0.039	-0.564	0.562	-0.174	-0.501	-0.168	-0.173	-0.181
	Sig. (2-tailed)	0.181	0.468	0.126	0.286	0.066	0.036	0	.	0.854	0.004	0	0.464	0.001	0.248	0.235	0.214
	N	49	49	22	22	22	49	49	49	25	24	38	20	43	49	49	49
LN MPD	**Pearson Corr.**	0.112	0.021	0.175	-0.279	-0.216	0.808	0.718	0.039	1	.	-0.414	-0.259	0.663	-0.234	-0.183	-0.311
	Sig. (2-tailed)	0.595	0.922	0.436	0.209	0.333	0	0	0.854	.	.	0.141	0.27	0.002	0.26	0.381	0.131
	N	25	25	22	22	22	25	25	25	25	0	14	20	19	25	25	25
LN MMPD	**Pearson Corr.**	0.659	-0.488	.	.	.	0.979	0.941	-0.564	.	1	-0.793	.	0.85	-0.116	-0.098	-0.092
	Sig. (2-tailed)	0	0.016	.	.	.	0	0	0.004	.	.	0	.	0	0.589	0.649	0.668
	N	24	24	0	0	0	24	24	24	0	24	24	0	24	24	24	24
LN OMC	**Pearson Corr.**	-0.385	0.315	0.374	0.14	0.225	-0.789	-0.811	0.562	-0.414	-0.793	1	-0.634	-0.796	-0.106	-0.116	-0.122
	Sig. (2-tailed)	0.017	0.054	0.257	0.681	0.505	0	0	0	0.141	0	.	0.067	0	0.528	0.487	0.464
	N	38	38	11	11	11	38	38	38	14	24	38	9	32	38	38	38
LN VVS	**Pearson Corr.**	-0.375	0.174	-0.453	0.43	0.242	-0.194	-0.059	-0.174	-0.259	.	-0.634	1	-0.546	0.065	0.052	0.292
	Sig. (2-tailed)	0.104	0.463	0.068	0.085	0.349	0.412	0.804	0.464	0.27	.	0.067	.	0.016	0.786	0.829	0.212
	N	20	20	17	17	17	20	20	20	20	0	9	20	19	20	20	20
LN CF	**Pearson Corr.**	0.518	-0.485	0.379	-0.516	-0.362	0.855	0.874	-0.501	0.663	0.85	-0.796	-0.546	1	-0.004	0.041	0.022
	Sig. (2-tailed)	0	0.001	0.148	0.041	0.168	0	0	0.001	0.002	0	0	0.016	.	0.98	0.794	0.888
	N	43	43	16	16	16	43	43	43	19	24	32	19	43	43	43	43
LN D85	**Pearson Corr.**	-0.258	0.292	0.473	-0.139	-0.006	-0.06	0.022	-0.168	-0.234	-0.116	-0.106	0.065	-0.004	1	0.953	0.932
	Sig. (2-tailed)	0.074	0.042	0.026	0.537	0.978	0.684	0.883	0.248	0.26	0.589	0.528	0.786	0.98	.	0	0
	N	49	49	22	22	22	49	49	49	25	24	38	20	43	49	49	49

		LN k1	LN k2	LN Phi	LN C	LN tau	LN dry d	LN vol d	LN Rel D	LN MPD	LN MMPD	LN OMC	LN VVS	LN CF	LN D85	LN D60	LN D50
LN D60	**Pearson Corr.**	-0.169	0.195	0.498	-0.196	-0.048	-0.026	0.05	-0.173	-0.183	-0.098	-0.116	0.052	0.041	0.953	1	0.985
	Sig. (2-tailed)	0.245	0.179	0.018	0.383	0.831	0.858	0.733	0.235	0.381	0.649	0.487	0.829	0.794	0	.	0
	N	49	49	22	22	22	49	49	49	25	24	38	20	43	49	49	49
LN D50	**Pearson Corr.**	-0.164	0.185	0.358	-0.044	0.075	-0.043	0.04	-0.181	-0.311	-0.092	-0.122	0.292	0.022	0.932	0.985	1
	Sig. (2-tailed)	0.259	0.204	0.102	0.846	0.739	0.77	0.785	0.214	0.131	0.668	0.464	0.212	0.888	0	0	.
	N	49	49	22	22	22	49	49	49	25	24	38	20	43	49	49	49
LN D30	**Pearson Corr.**	-0.206	0.201	0.015	0.255	0.266	-0.021	0.091	-0.264	-0.456	-0.048	-0.162	0.519	0.04	0.86	0.892	0.934
	Sig. (2-tailed)	0.156	0.166	0.946	0.252	0.231	0.884	0.532	0.067	0.022	0.825	0.33	0.019	0.799	0	0	0
	N	49	49	22	22	22	49	49	49	25	24	38	20	43	49	49	49
LN D15	**Pearson Corr.**	-0.324	0.34	0.126	0.029	0.043	-0.127	-0.002	-0.24	-0.596	-0.155	-0.094	0.159	-0.007	0.815	0.821	0.808
	Sig. (2-tailed)	0.023	0.017	0.575	0.898	0.851	0.386	0.988	0.096	0.002	0.471	0.575	0.502	0.965	0	0	0
	N	49	49	22	22	22	49	49	49	25	24	38	20	43	49	49	49
LN D10	**Pearson Corr.**	-0.388	0.389	0.326	-0.118	-0.045	-0.256	-0.176	-0.068	-0.522	-0.333	0.12	-0.058	-0.092	0.654	0.661	0.644
	Sig. (2-tailed)	0.006	0.006	0.139	0.601	0.844	0.076	0.227	0.643	0.007	0.112	0.474	0.809	0.557	0	0	0
	N	49	49	22	22	22	49	49	49	25	24	38	20	43	49	49	49
LN D(PSDC)	**Pearson Corr.**	0.158	-0.15	-0.329	-0.057	-0.164	0.016	-0.051	0.155	0.33	0.073	0.119	-0.255	-0.052	-0.922	-0.944	-0.963
	Sig. (2-tailed)	0.279	0.303	0.136	0.801	0.466	0.914	0.728	0.287	0.107	0.733	0.475	0.279	0.742	0	0	0
	N	49	49	22	22	22	49	49	49	25	24	38	20	43	49	49	49
LN A(PSDC)	**Pearson Corr.**	0.15	-0.125	-0.409	0.058	-0.066	0.023	-0.058	0.186	0.342	0.047	0.104	-0.068	-0.063	-0.953	-0.964	-0.959
	Sig. (2-tailed)	0.304	0.393	0.058	0.798	0.771	0.878	0.691	0.202	0.094	0.829	0.535	0.775	0.689	0	0	0
	N	49	49	22	22	22	49	49	49	25	24	38	20	43	49	49	49
LN A(PSDC) m	**Pearson Corr.**	0.066	-0.059	-0.531	0.113	-0.052	0.006	-0.067	0.175	0.211	0.01	0.102	-0.044	-0.061	-0.881	-0.909	-0.917
	Sig. (2-tailed)	0.653	0.688	0.011	0.616	0.817	0.967	0.648	0.23	0.312	0.965	0.543	0.852	0.698	0	0	0
	N	49	49	22	22	22	49	49	49	25	24	38	20	43	49	49	49
LN SC(85-15)	**Pearson Corr.**	0.199	-0.207	0.105	-0.098	-0.035	0.113	-0.043	0.324	0.626	0.022	0.194	-0.189	0.018	-0.43	-0.477	-0.462
	Sig. (2-tailed)	0.171	0.154	0.641	0.664	0.876	0.44	0.768	0.023	0.001	0.92	0.244	0.425	0.909	0.002	0.001	0.001
	N	49	49	22	22	22	49	49	49	25	24	38	20	43	49	49	49
LN SC(60-10)	**Pearson Corr.**	0.224	-0.222	0.001	-0.031	0.008	0.188	0.094	0.135	0.734	0.146	-0.145	0.144	0.019	0.01	0.039	0.074
	Sig. (2-tailed)	0.121	0.126	0.998	0.89	0.97	0.195	0.519	0.355	0	0.498	0.384	0.544	0.904	0.945	0.789	0.612
	N	49	49	22	22	22	49	49	49	25	24	38	20	43	49	49	49
LN Cu	**Pearson Corr.**	0.387	-0.368	0.032	-0.032	0.021	0.318	0.27	-0.04	0.742	0.354	-0.231	0.174	0.152	-0.148	-0.123	-0.111
	Sig. (2-tailed)	0.006	0.009	0.888	0.888	0.925	0.026	0.061	0.785	0	0.09	0.163	0.462	0.33	0.31	0.4	0.448
	N	49	49	22	22	22	49	49	49	25	24	38	20	43	49	49	49
LN Cc3060	**Pearson Corr.**	0.092	-0.113	-0.369	0.51	0.423	0.201	0.275	-0.279	-0.258	0.34	-0.292	0.804	0.14	0.338	0.36	0.449
	Sig. (2-tailed)	0.529	0.438	0.091	0.015	0.05	0.165	0.056	0.052	0.213	0.104	0.076	0	0.37	0.017	0.011	0.001
	N	49	49	22	22	22	49	49	49	25	24	38	20	43	49	49	49
LN Cc508515	**Pearson Corr.**	0.246	-0.246	0.137	-0.034	0.072	0.115	0.075	0.039	0.517	0.049	-0.1	0.233	0.06	0.269	0.408	0.472
	Sig. (2-tailed)	0.089	0.089	0.544	0.882	0.75	0.433	0.607	0.79	0.008	0.818	0.552	0.323	0.703	0.061	0.004	0.001
	N	49	49	22	22	22	49	49	49	25	24	38	20	43	49	49	49
LN Ce	**Pearson Corr.**	0.293	-0.291	0.1	-0.123	-0.064	0.147	0.02	0.236	0.702	0.146	0.05	-0.189	0.008	-0.46	-0.507	-0.503
	Sig. (2-tailed)	0.041	0.043	0.659	0.585	0.777	0.314	0.889	0.103	0	0.496	0.767	0.424	0.962	0.001	0	0
	N	49	49	22	22	22	49	49	49	25	24	38	20	43	49	49	49
LN Zfine	**Pearson Corr.**	0.168	-0.265	-0.596	0.411	0.254	0.176	0.076	0.157	0.235	0.198	-0.125	0.412	0.049	-0.538	-0.504	-0.427
	Sig. (2-tailed)	0.248	0.066	0.003	0.058	0.254	0.226	0.604	0.281	0.258	0.353	0.456	0.071	0.756	0	0	0.002
	N	49	49	22	22	22	49	49	49	25	24	38	20	43	49	49	49

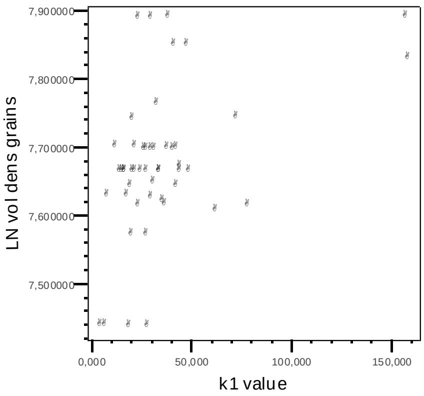
		LN D30	LN D15	LN D10	LN D(PSDC)	LN A(PSDC)	LN A(PSDC) m	LN SC(85-15)	LN SC(60-10)	LN Cu	LN Cc3060	LN Cc508515	LN Ce	LN Zfine
LN D60	**Pearson Corr.**	0.892	0.821	0.661	-0.944	-0.964	-0.909	-0.477	0.039	-0.123	0.36	0.408	-0.507	-0.504
	Sig. (2-tailed)	0	0	0	0	0	0	0.001	0.789	0.4	0.011	0.004	0	0
	N	49	49	49	49	49	49	49	49	49	49	49	49	49
LN D50	**Pearson Corr.**	0.934	0.808	0.644	-0.963	-0.959	-0.917	-0.462	0.074	-0.111	0.449	0.472	-0.503	-0.427
	Sig. (2-tailed)	0	0	0	0	0	0	0.001	0.612	0.448	0.001	0.001	0	0.002
	N	49	49	49	49	49	49	49	49	49	49	49	49	49
LN D30	**Pearson Corr.**	1	0.821	0.619	-0.956	-0.907	-0.867	-0.518	-0.001	-0.149	0.623	0.359	-0.58	-0.263
	Sig. (2-tailed)	.	0	0	0	0	0	0	1	0.307	0	0.011	0	0.068
	N	49	49	49	49	49	49	49	49	49	49	49	49	49
LN D15	**Pearson Corr.**	0.821	1	0.866	-0.783	-0.817	-0.708	-0.83	-0.468	-0.528	0.156	-0.119	-0.89	-0.608
	Sig. (2-tailed)	0	.	0	0	0	0	0	0.001	0	0.284	0.415	0	0
	N	49	49	49	49	49	49	49	49	49	49	49	49	49
LN D10	**Pearson Corr.**	0.619	0.866	1	-0.622	-0.644	-0.584	-0.624	-0.553	-0.826	-0.205	-0.189	-0.811	-0.647
	Sig. (2-tailed)	0	0	.	0	0	0	0	0	0	0.157	0.194	0	0
	N	49	49	49	49	49	49	49	49	49	49	49	49	49
LN D(PSDC)	**Pearson Corr.**	-0.956	-0.783	-0.622	1	0.964	0.937	0.396	-0.094	0.113	-0.525	-0.431	0.473	0.316
	Sig. (2-tailed)	0	0	0	.	0	0	0.005	0.52	0.438	0	0.002	0.001	0.027
	N	49	49	49	49	49	49	49	49	49	49	49	49	49
LN A(PSDC)	**Pearson Corr.**	-0.907	-0.817	-0.644	0.964	1	0.953	0.471	-0.02	0.127	-0.416	-0.357	0.5	0.475
	Sig. (2-tailed)	0	0	0	0	.	0	0.001	0.893	0.384	0.003	0.012	0	0.001
	N	49	49	49	49	49	49	49	49	49	49	49	49	49
LN A(PSDC) m	**Pearson Corr.**	-0.867	-0.708	-0.584	0.937	0.953	1	0.338	-0.124	0.089	-0.432	-0.459	0.39	0.435
	Sig. (2-tailed)	0	0	0	0	0	.	0.017	0.395	0.543	0.002	0.001	0.006	0.002
	N	49	49	49	49	49	49	49	49	49	49	49	49	49
LN SC(85-15)	**Pearson Corr.**	-0.518	-0.83	-0.624	0.396	0.471	0.338	1	0.662	0.467	-0.05	0.386	0.932	0.511
	Sig. (2-tailed)	0	0	0	0.005	0.001	0.017	.	0	0.001	0.731	0.006	0	0
	N	49	49	49	49	49	49	49	49	49	49	49	49	49
LN SC(60-10)	**Pearson Corr.**	-0.001	-0.468	-0.553	-0.094	-0.02	-0.124	0.662	1	0.761	0.461	0.772	0.724	0.521
	Sig. (2-tailed)	1	0.001	0	0.52	0.893	0.395	0	.	0	0.001	0	0	0
	N	49	49	49	49	49	49	49	49	49	49	49	49	49
LN Cu	**Pearson Corr.**	-0.149	-0.528	-0.826	0.113	0.127	0.089	0.467	0.761	1	0.542	0.557	0.691	0.477
	Sig. (2-tailed)	0.307	0	0	0.438	0.384	0.543	0.001	0	.	0	0	0	0.001
	N	49	49	49	49	49	49	49	49	49	49	49	49	49
LN Cc3060	**Pearson Corr.**	0.623	0.156	-0.205	-0.525	-0.416	-0.432	-0.05	0.461	0.542	1	0.538	0.027	0.391
	Sig. (2-tailed)	0	0.284	0.157	0	0.003	0.002	0.731	0.001	0	.	0	0.853	0.005
	N	49	49	49	49	49	49	49	49	49	49	49	49	49
LN Cc508515	**Pearson Corr.**	0.359	-0.119	-0.189	-0.431	-0.357	-0.459	0.386	0.772	0.557	0.538	1	0.394	0.241
	Sig. (2-tailed)	0.011	0.415	0.194	0.002	0.012	0.001	0.006	0	0	0	.	0.005	0.095
	N	49	49	49	49	49	49	49	49	49	49	49	49	49
LN Ce	**Pearson Corr.**	-0.58	-0.89	-0.811	0.473	0.5	0.39	0.932	0.724	0.691	0.027	0.394	1	0.507
	Sig. (2-tailed)	0	0	0	0.001	0	0.006	0	0	0	0.853	0.005	.	0
	N	49	49	49	49	49	49	49	49	49	49	49	49	49
LN Zfine	**Pearson Corr.**	-0.263	-0.608	-0.647	0.316	0.475	0.435	0.511	0.521	0.477	0.391	0.241	0.507	1
	Sig. (2-tailed)	0.068	0	0	0.027	0.001	0.002	0	0	0.001	0.005	0.095	0	.
	N	49	49	49	49	49	49	49	49	49	49	49	49	49

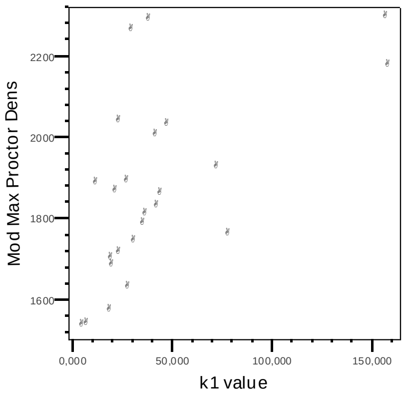
H.3 Scatterplots as generated in SPSS

H.3.1 k_1 k_2 relationships

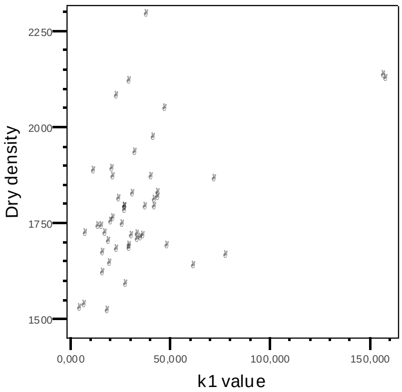
See chapter 5. It appeared that the k_1 parameter is not related to the density and relative density. A slight correlation can be seen with the volume density of the grains, not taking into account the outliers. It is very clear to see that for the different materials several degrees of compaction have been used. Furthermore the use of mixed granulates with different composition can be distinguished.

For the MMPD (Sweere materials only) the same trend can be seen:





H.3.2 Scatterplots for relationships with k_1



H.3.3 Scatterplots for relationships with k_2

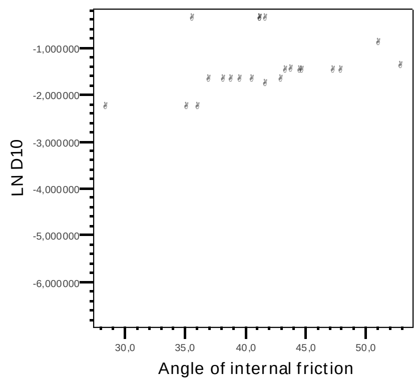
It was not possible to find any correlated scatter plot for the k_2 parameter. It might give the impression that several trend lines fit in the scatters.

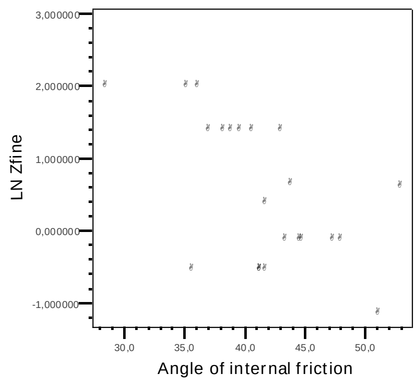
H.3.4 Cohesion scatterplots

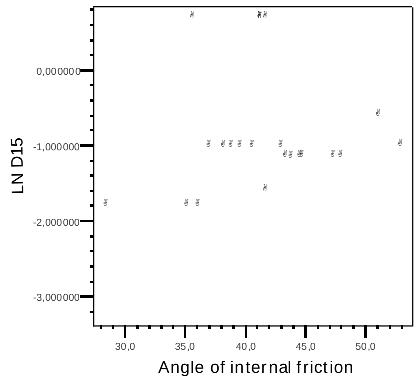
An expected relationship between cohesion and Z_{fines} could not be found.

H.3.5 Angle of internal friction

As for the cohesion, it was not possible to incorporate the Sweere materials, since there was a lack of data for the failure behaviour of the Sweere materials
The angle of internal friction does not correlate with k_1, neither with k_2. For the smaller grain size fractions, some relationships might be distinguished,

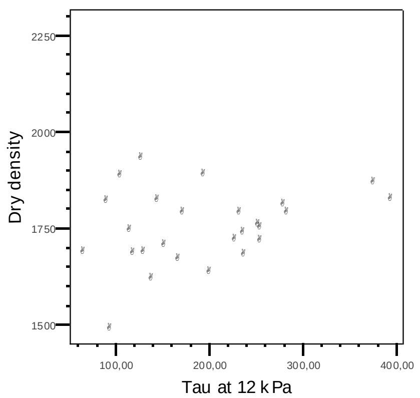


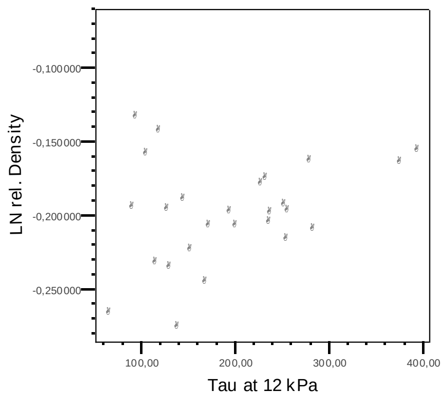


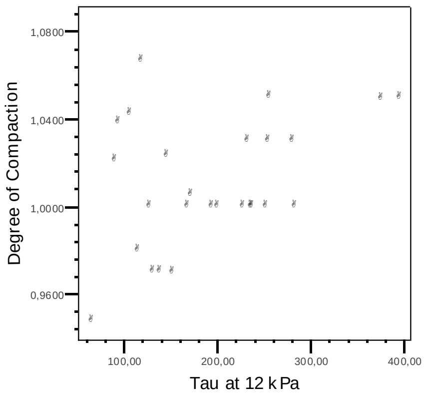


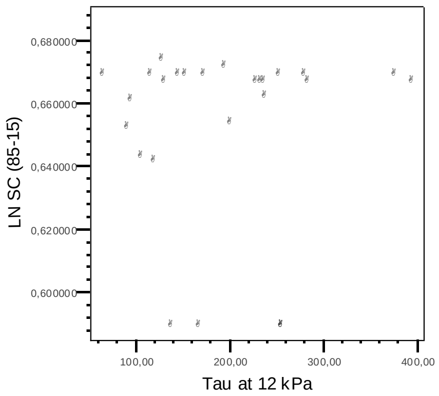
H.3.6 Scatterplots for shear stress relationships

These scatterplots have been generated especially to incorporate the Sweere materials as well. For these materials, the shear stress appeared only five times available



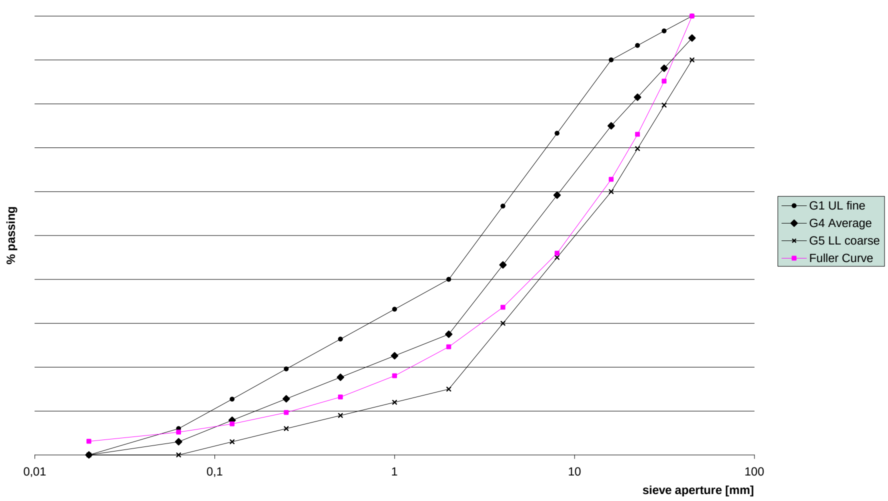


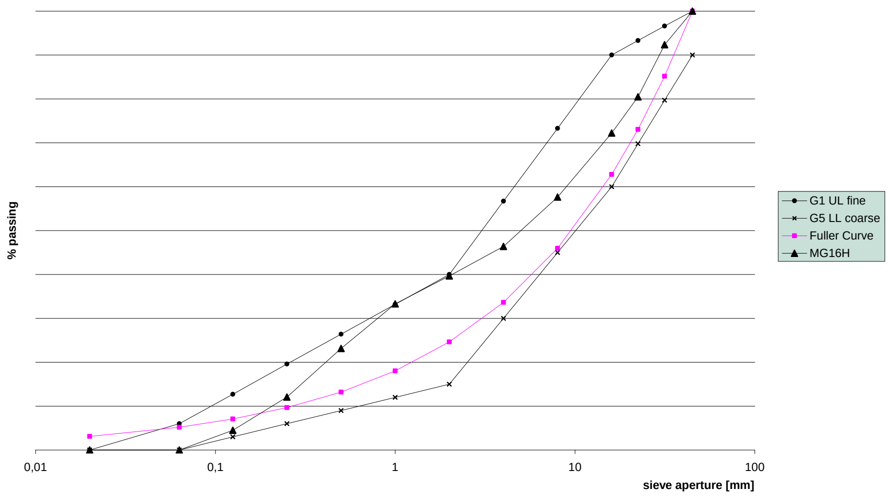


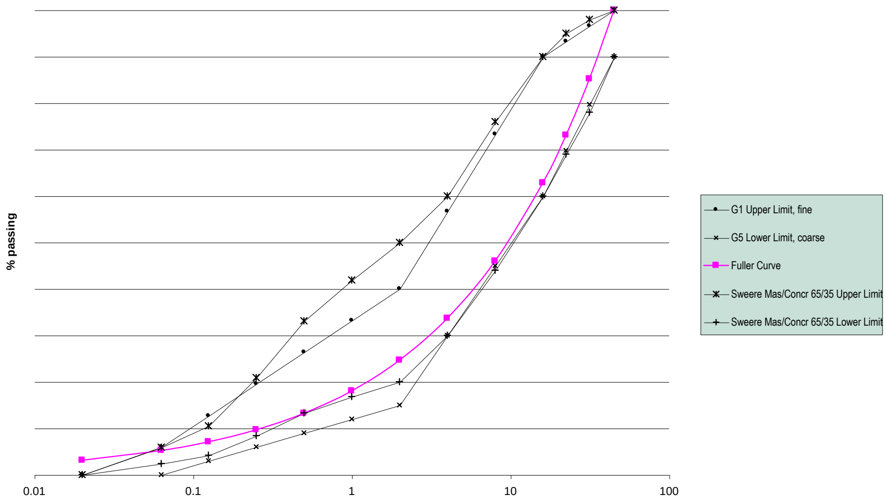


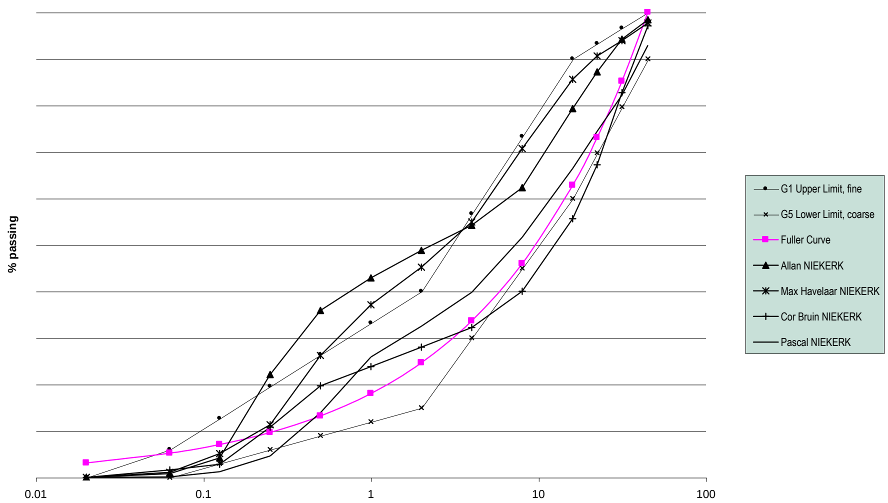
H.4 Particle size distribution curves

There is limited variation in grading curves available in this data set The particle size distribution curves for the mix granulates tested by Van Niekerk, Lefevre, Muraya, and Kisimbi are depicted below.




% passing
0,01
0,1
1
10
100
sieve aperture [mm]
G1 UL fine
G5 LL coarse
Fuller Curve
MG16H


% passing
0.01
0.1
1
10
100
G1 Upper Limit, fine
G5 Lower Limit, coarse
Fuller Curve
Sweere Mas/Concr 65/35 Upper Limit
Sweere Mas/Concr 65/35 Lower Limit


% passing
0.01
0.1
1
10
100
G1 Upper Limit, fine
G5 Lower Limit, coarse
Fuller Curve
Allan NIEKERK
Max Havelaar NIEKERK
Cor Bruin NIEKERK
Pascal NIEKERK

I GENERAL DESCRIPTION REGRESSION ANALYSIS

I.1 Introduction

The general purpose of multiple regression (the term was first used by Pearson, 1908) is to learn more about the relationship between several independent or predictor variables and a dependent or criterion variable. This will be explained briefly in this appendix, together with some basic rules and points of attention. The theory is focussed on the regression techniques as applied in this study.

I.2 Meaning of a linear model

When we are concerned with the dependence of a random variable Y on a quantity X that is variable but not randomly variable, an equation that relates Y to (predictor or input variable) X is usually called a regression equation. Although the name is, strictly speaking, incorrect, it is well established and conventional. A (straight-line) relationship may also be a valuable one even when we know that such a relationship cannot be true. For instance, a (straight-line) relationship evaluated from observations in a certain range might provide a perfectly adequate representation of the function in this range [DRAPER & SMITH 1998, p. 19]. The relationship thus fitted might not apply to values of X outside this restricted range and may not be used for predictive purposes outside this range.
Similar remarks can be made when more than one predictor variable is involved.

When a model is linear or non-linear, it is referred to linearity or non-linearity in the parameters. The value of the highest power of a predictor variable in the model is called the order of the model. See equation I.27

$$Y = \beta_0 + \beta_1 X + \varepsilon \qquad I.27$$

where:

- Y : response variable or output variable or dependent variable
- X : predictor variable or input variable or independent variable
- ε : increment by which any individual Y may fall off the regression line
- β_i : parameters

Equation I.27 represents the model of what we believe. That is, for a given X, the value of a corresponding observation Y consists of the value $\beta_0+\beta_1 X$ plus an amount ε, the increment by which any individual Y may fall off the regression line.

I.3 Least squares estimation

In the scatterplot, we have an independent or *X* variable, and a dependent or *Y* variable. The goal of linear regression procedures is to fit a line through the points.

Specifically, the program will compute a line so that the squared deviations of the observed points from that line are minimised. Thus, this general procedure is sometimes also referred to as least squares estimation. [Statsoft 2002]

Where equation I.27 represents the model of what we believe, equation I.28 is considered as the predictive equation for a linear regression analysis. Substitution for a value of X would provide a prediction of the true mean value of Y for that X.

$$\hat{Y} = b_0 + b_1 X \qquad I.28$$

where:

$\hat{Y}$: predicted value of Y for a given X

b_0, b_1 estimates of β_0 and β_1

The regression line for a variable Y is found by using the least squares procedure. In other words, the estimates b_0 and b_1 of equation I.28 shall be chosen to be values that, when substituted for β_0 and β_1 in equation I.27, produce the least possible sum of squares of deviation from the estimated regression line [DRAPER & SMITH 1998, p. 23].
The estimates of β_0 and β_1, of b_0, b_1, are called partial slope coefficients representing the effect of one independent variable on the dependent variable with al other variables held constant.

In the most general terms, least squares estimation is aimed at minimising the sum of squared deviations of the observed values for the dependent variable from those predicted by the model.

I.3.1 The meaning of the correlation coefficient: goodness-of-fit

The goodness-of-fit is important to get an indication of the regression model. Whereas the regression equation shows in detail how the dependent variable changes for a unit change in the dependent variable, the meaning of the correlation coefficient (*r*), or rather its square (r^2), is that it denotes the part of the variance (square of the standard deviation) of the dependent variable. This is explained by the correlation, and thus contains an overall statement of the relationship.
In other words, if we have an *r-square* of 0.4 then we know that the variability of the *Y* values around the regression line is 1-0.4 times the original variance; in other words we have explained 40% of the original variability, and are left with 60% residual variability. Ideally, we would like to explain most if not all of the original variability.

The r^2-value is defined in equation I.29.

$$r^2 = \frac{(Sum\ of\ Squares\ due\ to\ regression\ given\ b_0)}{(Total\ Sum\ of\ Squares, corrected\ for\ the\ mean\ \bar{Y})} = \frac{\sum \left(\hat{Y}_i - \bar{Y}\right)^2}{\sum \left(Y_i - \bar{Y}\right)^2} \qquad I.29$$

where:

$\hat{Y}_i$: predicted value of Y for observation *i*

Y_i : response value of Y for observation *i*

$\bar{Y}$: mean value of the Y's

In equation I.29 both summations are over $i = 1, 2, \ldots, n$. Then r^2 measures the "proportion of total variation about the mean $\bar{Y}$ explained by the regression". In fact, r is the correlation between Y and $\bar{Y}$ and is usually called the multiple correlation coefficient. r^2 is then "the square of the multiple correlation coefficient."
r^2 will always vary between 0 and 1. It can be interpreted as the proportion of the original variance in Y that is accounted for by the regression equation. It can also be shown that r^2 is the square of the correlation between Y and the estimated values [BERRY & FELDMAN 1985, p. 15].

I.3.2 Significance of r^2; r^2 can be deceptive

A researcher should be careful to recognise the limitations of r^2 as a measure of goodness-of-fit. To begin with, it is very sample specific; regressions in two different samples may produce identical partial slope coefficients, but r^2 may differ considerably from one to another due to differences in the variance of the dependent variable in the samples [BERRY & FELDMAN 1985, p. 15].

It is important to realise that, if there is no pure error, r^2 can be made unity simply by employing n properly selected coefficients in the model, including β_0, since a model can then be chosen that fits the data exactly.

Often, r^2 is used as a convenient measure of the success of the regression equation in explaining the variation in the data. Therefore, one has to be sure that an improvement in r^2 due to adding a new term to the model has some real significance. This improvement may not occur because of the number of parameters in the model getting close to saturation point. That is, the number of distinct X-sites. This is an *especial* danger when there are *repeat* observations [DRAPER & SMITH 1998, p. 139].

In other words, the number of observations and the effect it has upon the reliability of the correlation coefficient has to be taken into account too. As a rule, if the probability P of r is greater than 0.1, that is, if the observed value of r could arise by chance more often than once in 10 cases, r is considered to be without significance. If P is less than 0.05, r is taken to be definitely or highly significant. If P lies between 0.1 and 0.05, the result is regarded as doubtful.
From the function which connects the chance of occurrence of r with the number of observations, the Table I.8 has been calculated. This results in the graph constructed in Figure I.16, enabling to test a correlation coefficient resulting form a given series of bi-variate observations for significance [HERDAN, 1953, pp. 219-221].

Pairs of Observations	P = Probability of correlation being accidental			
	P = 0.1	**P = 0.05**	**P = 0.02**	**P = 0.01**
n = 10	r = 0.55	r = 0.63	r = 0.72	r = 0.76
15	0.44	0.51	0.59	0.64
20	0.38	0.44	0.52	0.56
27	0.32	0.38	0.45	0.49
32	0.30	0.35	0.41	0.45
37	0.28	0.32	0.38	0.42
42	0.26	0.30	0.36	0.39
50	0.23	0.28	0.33	0.35
60	0.21	0.25	0.30	0.33
70	0.20	0.23	0.28	0.30
80	0.18	0.22	0.26	0.28
90	0.17	0.20	0.24	0.27
100	0.16	0.20	0.23	0.26

Table I.8 Significance of the correlation coefficient depending on the given series of bi-variate observations [after LEVY & PREIDEL 1944]

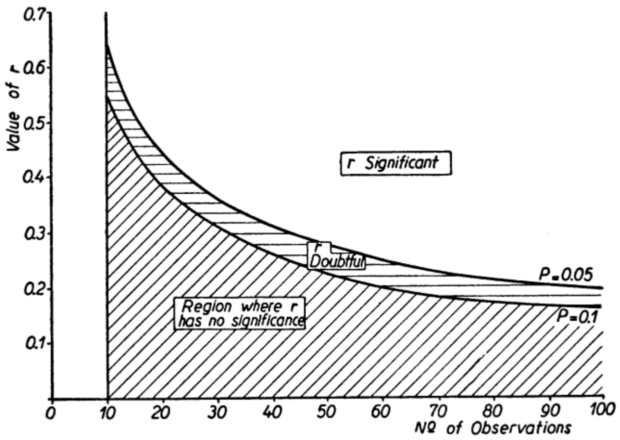


Figure I.16 Significance of r given the number of observations [after LEVY & PREIDEL 1944]

I.3.3 Adjusted correlation coefficient

The use of r^2 can also be misleading if one is trying to compare the relative goodness-of-fit of two regression models with differing numbers of independent variables. This is because r^2 will always increase (to some degree) when new variables are added to the equation, even when they may have no effect on the dependent variable. Moreover, as the number ofindependent variables (k) gets close to the number of cases in the sample (n), r^2 will necessarily get close to 1.0. One way around this problem is to compute an 'adjusted' r^2, defined in eq. I.30

$$\bar{r}^2 = \left(r^2 - \frac{k}{n-1}\right)\cdot\left(\frac{n-1}{n-k-1}\right) \qquad I.30$$

Constructed this way, the adjusted r^2 can decrease when a new variable is added to regression model, even though r^2 will always increase [BERRY & FELDMAN 1985, p. 16].

I.3.4 The Importance of Residual Analysis

The deviation of a particular point from the regression line (its predicted value) is called the *residual* value.

Even though most assumptions of multiple regression cannot be tested explicitly, gross violations can be detected and should be dealt with appropriately. In particular outliers (i.e., extreme cases) can seriously bias the results by "pulling" or "pushing" the regression line in a particular direction, thereby leading to biased regression coefficients. Often, excluding just a single extreme case can yield a completely different set of results. [Statsoft 2002]

I.3.5 Confidence intervals

In the model $Y_i = \beta_0 + \beta_1 X_i + \varepsilon_i$, $i = 1, 2, \ldots, n$, the following assumptions can be made [DRAPER & SMITH 1998, pp. 34-35]:

1. ε_i is a random variable with mean zero and variance σ^2 (unknown);
2. ε_i and ε_j are uncorrelated, $i \neq j$, so that cov $(\varepsilon_i, \varepsilon_j) = 0$. Thus

$$\begin{aligned} E(Y_i) &= \beta_0 + \beta_1 X_i \\ Var(Y_i) &= \sigma^2 \end{aligned} \qquad I.31$$

   And Y_i and Y_j, $i \neq j$, are uncorrelated.
3. ε_i is a normally distributed random variable, with mean zero and variance σ^2 by assumption 1; that is,

$$\varepsilon_i \sim N(0, \sigma^2) \qquad I.32$$

   There is a tendency for errors that occur in many real situations to be normally distributed due to the Central Limit Theorem: If an error term such as ε is a sum of errors from several sources, and no source dominates, then no matter what the probability distribution of the separate errors may be, their sum ε will have a distribution that will tend more an more to the normal distribution as the number of components increases.

I.3.6 Another important goodness-of-fit

Another important goodness-of-fit statistic is the standard error of the estimate of Y, commonly denoted s_e.

I.4 F-test for significance of regression

Since the Y_i are random variables, any function of them is also a random variable. Two particular functions are MS_{Reg}, the mean square due to regression, and s^2, the mean square due to residual variation, which arise in the analysis of variance tables. These functions then have their own distribution, mean, variance and moments. It can be shown that the mean values are as follows (I.33):

$$\begin{aligned} E(MS_{Reg}) &= \sigma^2 + \beta_1^2 \sum (X_i - \overline{X})^2 \\ E(s^2) &= \sigma^2 \end{aligned} \qquad I.33$$

Suppose that the errors ε_i are independent $N(0,\sigma^2)$ variables. Then it can be shown that if β_1=0, the variable MS_{Reg} multiplied by its degrees of freedom and divided by

σ^2 follows an χ^2 distribution with the same number of degrees of freedom. A statistical theorem tells that the ratio

$$F = \frac{MS_{Reg}}{s^2} \qquad I.34$$

follows an F-distribution with (n-2) degrees of freedom provided that $\beta_1 = 0$. This fact can be used to compare the ratio $F = MS_{Reg}/s^2$ with the 100(1-α)% point of the tabulated F(1, n – 2) distribution in order to determine whether β_1 can be considered nonzero on the basis of the data analysed [DRAPER & SMITH 1998, pp. 38-39].

I.4.1 $F = t^2$

For the test of H_0: $\beta_1 = 0$ versus H_1: $\beta_1 \neq 0$, both the t-test and the F-test are available. In fact, both tests are equivalent and mathematically related here, due to the theoretical fact that $F(1,\upsilon) = \{ t(\upsilon) \}^2$; that is, the square of a t-variable with υ df is an F-variable with 1 and υ df.

Since the variable $F(1, n-2)$ is the square of the $t(n-2)$ variable, and this carries over to the percentage points (upper α tail of the F and two-tailed t, total of α) exactly the same test result shall be found. When there are more regression coefficients the overall F-test for regression, which is the extension to the one given here, does not correspond to the t-test of a coefficient. This is why both t- and F-tests should be known, in general. However, tests for individual coefficients can be made either in t or $t^2 = F$ form by a similar argument. The t-form is often seen in computer programs [DRAPER & SMITH 1998, pp. 39-40].

I.4.2 *p*-Values for *t*-statistics

As in the case of the F-statistic, many computer programs print out a tail area for the observed t-statistic. This is typically the two-tailed probability value, that is, the area outside the t-value observed and outside minus the t-value observed. Each user can then decide on the message he or she reads from this, depending on the user's chosen α-level. In regression contexts where $F(1,v) = t^2(v)$, the one-sided F-level corresponds to the two-sided t-level [DRAPER & SMITH 1998, p. 40].

I.5 Multicollinearity

Perfect multicollinearity exists when one of the independent variables in a regression equation is perfectly linearly related to one or more of the other independent variables in the equation. Usually, a less extreme case of multicollinearity occurs: A case in which the independent variables in a regression equation are intercorrelated, but not perfectly.

Three points of attention should be taken care of:

1. Multicollinearity is a problem referring to correlated independent variables in a specific sample of data, and not in the overall problem.
2. Setting aside the case of perfect collinearity, even a high degree of multicollinearity does not violate the assumptions of regression. However multicollinearity poses other problems. See section II.5.1 below.
3. Multicollinearity should not be conceived as something that either exists or does not. Rather, multicollinearity exists in degrees, and the degree determines how important a problem is posed.

I.5.1 Consequences of multicollinearity

1. The standard errors of regression coefficient estimators increase as the correlations among the independent variables increase. After all, the partial slope coefficients represent the effect of one independent variable on the dependent variable with al other variables held constant. But when the independent variables in an equation are highly correlated, it is impossible to separate out the effect of one - all others holding constant - with any degree of precision. However, it should be borne in mind that when the increase of the standard error occurs, there is no guarantee that it is a consequence of multicollinearity.
2. When high multicollinearity is present, confidence intervals for coefficients tend to be very wide, and t-statistics for significance tests tend to be very small.
3. Large covariances between coefficient estimators: The larger the correlations among the independent variables in a regression equation, the larger the correlations among the partial slope coefficient estimators. Thus, when two independent variables in a regression equation are highly and positively correlated, their slope coefficient estimators are going to be highly and negatively correlated.

I.5.2 Detecting high multicollinearity

When high multicollinearity is present, confidence intervals for coefficients tend to be very wide, and t-statistics for significance tests tend to be very small.
In general, the standard errors of regression coefficient estimators increase as the correlations among the independent variables increase.
One common warning signal that multicollinearity is present is that all individual partial slope coefficient estimates failing to be significantly different from zero, although the overall equation shows a good fit to the data. A common rule of thumb is that multicollinearity should be suspected when none of the t-ratios for the regression coefficients for independent variables is sufficiently large to indicate statistical significance at the 0.05 percent level, yet the F-statistic for the full model is significant. [BERRY & FELDMAN 1985, p. 42]

I.5.3 Testing for multicollinearity

The most commonly used test for multicollinearity is the inspection of a matrix of bivariate correlations. Here one examines the correlations between all pairs of independent variables, and concludes that multicollinearity is not a problem if no correlation exceeds some predefined cut-off value - typically around 0.80.

But this test is unsatisfactory for several reasons. First, it is possible that a severe multicollinearity problem may not be reflected in bivariate correlations; one independent variable may be approximately a linear combination of several other independent variables in the model, yet that variable may not be highly correlated with any other single independent variable.
Second, it is very difficult to define a cut-off value that will always be appropriate. One always needs to look at the standard errors of slope coefficients estimates, the width of confidence intervals, and the purposes for which the analysis is being performed to assess how much of a problem multicollinearity poses.

The most reasonable test for multicollinearity is to regress each independent variable in the equation on all other independent variables, and look at the correlation coefficients for these regressions. This test is superior to the examination

of bivariate correlations, as the use will never mistakenly reject the possibility of severe multicollinearity because the pattern of intercorrelation is not reflected in the bivariate correlations.
[BERRY & FELDMAN 1985, p. 43]

I.6 Choice of the Number of Variables.

Multiple regression is a seductive technique: "plug in" as many predictor variables as you can think of and usually at least a few of them will come out significant. This is because one is capitalising on chance when simply including as many variables as one can think of as predictors of some other variable of interest. This problem is compounded when, in addition, the number of observations is relatively low.
Most authors recommend that one should have at least 10 to 20 times as many observations (cases, respondents) as one has variables, otherwise the estimates of the regression line are probably very unstable and unlikely to replicate if one were to do the study again.

J RESULTS OF THE REGRESSION ANALYSES

J.1 Regression results for the cohesion

J.1.1 Regression algorithm

```
REGRESSION
  /DESCRIPTIVES MEAN STDDEV CORR SIG N
  /MISSING PAIRWISE
  /STATISTICS COEFF OUTS CI BCOV R ANOVA COLLIN TOL CHANGE ZPP
  /CRITERIA=PIN(.05) POUT(.10) CIN(95)
  /NOORIGIN
  /DEPENDENT ln_c
  /METHOD=ENTER z_fine ln_deg_c
  /PARTIALPLOT ALL
  /SCATTERPLOT=(*ZPRED ,ln_c ) (*ZRESID ,ln_c ) (*DRESID ,ln_c ) (*ADJPRED
  ,ln_c ) (*SRESID ,ln_c ) (*SDRESID ,ln_c )
  /RESIDUALS DURBIN
  /SAVE PRED ZPRED ADJPRED SEPRED MAHAL COOK LEVER MCIN RESID
  ZRESID SRESID
  DRESID SDRESID DFBETA SDBETA DFFIT SDFIT COVRATIO .
```

J.1.2 Regression output

J.2 Regression results for the k_1 relationship

J.2.1 Regression algorithm

```
REGRESSION
 /DESCRIPTIVES MEAN STDDEV CORR SIG N
 /MISSING PAIRWISE
 /STATISTICS COEFF OUTS CI BCOV R ANOVA COLLIN TOL CHANGE ZPP
 /CRITERIA=PIN(.05) POUT(.10) CIN(95)
 /NOORIGIN
 /DEPENDENT k1
 /METHOD=ENTER d85 c_unif ln_vol_d
 /PARTIALPLOT ALL
 /SCATTERPLOT=(*ZPRED ,k1 ) (*ZRESID ,k1 ) (*DRESID ,k1 ) (*ADJPRED
 ,k1 ) (*SRESID ,k1 ) (*SDRESID ,k1 )
 /RESIDUALS DURBIN
 /SAVE PRED ZPRED ADJPRED SEPRED MAHAL COOK LEVER MCIN RESID
ZRESID SRESID
 DRESID SDRESID DFBETA SDBETA DFFIT SDFIT COVRATIO .
```

J.2.2 Regression output

J.3 Regression results for relationship between k_2 and k_1

J.3.1 Regression algorithm

```
REGRESSION
  /DESCRIPTIVES MEAN STDDEV CORR SIG N
  /MISSING PAIRWISE
  /STATISTICS COEFF OUTS CI BCOV R ANOVA COLLIN TOL CHANGE ZPP
  /CRITERIA=PIN(.05) POUT(.10) CIN(95)
  /NOORIGIN
  /DEPENDENT ln_k2
  /METHOD=ENTER k1 d_pdscfc c_unif
  /PARTIALPLOT ALL
  /SCATTERPLOT=(*ZPRED ,ln_k2 ) (*ZRESID ,ln_k2 ) (*DRESID ,ln_k2 )
(*ADJPRED
  ,ln_k2 ) (*SRESID ,ln_k2 ) (*SDRESID ,ln_k2 )
  /RESIDUALS DURBIN
  /SAVE PRED ZPRED ADJPRED SEPRED MAHAL COOK LEVER MCIN RESID
ZRESID SRESID
  DRESID SDRESID DFBETA SDBETA DFFIT SDFIT COVRATIO .
```

J.3.2 Regression output

J.3.3 Relationship between LN k_2 and k_1 without other material properties

[redacted]

[redacted]

[redacted]