An Engineering Geological Classification of Limestone Material

Memoirs of the Centre for Engineering Geology in the Netherlands No. 49

November 1987

P.D. Swart

TU Delft

Delft University of Technology

Faculty of Mining and Petroleum Engineering
Section Engineering Geology

AN ENGINEERING GEOLOGICAL CLASSIFICATION

OF LIMESTONE MATERIAL

BY P.D. SWART

November 1987

This report is a thesis study submitted to Professor D.G. Price of the Section Engineering Geology of the Department Mining and Petroleum Engineering at the Delft University of Technology in conformity with the requirements for the degree of Mijningenieur (Mining Engineer).

Abstract

In engineering practice there exists no complete classification for pure limestone material. Although there are a number of classification systems, which rely on useful parameters, the problem is that there are no indications of quality regarding the requirements of the various engineering disciplines. In order to develop a classification system and to obtain a better insight in the behaviour of limestone, samples of twelve types of limestone from different geological formations were extensively tested with both mechanical and physical techniques. A simple test to indicate the solubility of a limestone can be performed with hydrochloric acid. Based on the results of the tests an empirical classification system is proposed for four engineering fields who are concerned with limestone: Tunelling, Foundation, Excavation and Aggregates.

Acknowledgements

The realisation of this study has been a task which could not have been done without valuable support to solve the many problems encountered.

Especially I wish to thank Prof. D.G. Price, who has given inexpensible advice regarding the achievement of the classification system. Secondly Ing. W. Verwaal has my special gratitude for his technical support during the mechanical testing and for the use of his excellent data acquisition programs.

Furthermore I thank A.A. van Dijk for his help with the preparation of the samples and the thin sections; W. de Grauw and Th. Verkroost for their help with the deter-mination of the calcium- and magnesium-carbonate contents; R. de Haas for his help with the determination of the porosity; the quarry managers, who gave permission to sample the limestone blocks; and the members of the staff of the Engineering Geology section, who helped and advised me.

1. Introduction

Upon searching the literature for a classification of carbonate rocks it was discovered that none of the existing classifications of carbonate rock material seem to render any satisfactory information as to the engineering behaviour of these rocks.

The existing classifications appear to be developed only for a singular purpose, they were required to serve. Generally the complexity and confusing nomenclature of these classifications contribute to a limited interpretation of their engineering quality. Consequently the parameters of such a system, which can be of geological or engineering origin, can not render enough clear information for complete understanding of the behaviour of the carbonate material.

Apparently in all of these systems there seems to be no direct relationship between the amount of calcium carbonate ($CaCO_3$) present in the rock and its geotechnical properties (Datta,1982). This hypothesis should make it rather difficult to distinguish limestone from other types of rock. The aim of this study is then to develop a classification system which will relate the different carbonate rocks in such a way that the information conveyed is of practical use to the engineering disciplines concerned.

In order to achieve this end the physical and mechanical properties of a number of European limestones were compared and contrasted. The properties determined have been chosen in relation to the requirements of the engineering disciplines involved with foundation, construction and excavation of the massive material of carbonate rocks.

1.1 Geological Backgrounds

For full comprehension of the classification systems for carbonate rocks it is necessary to understand the factors that influence the origin and formation of these rocks.

Pure limestones, which are generally considered to be those carbonates composed of more than 90% calcium carbonate $CaCO_3$ (fig. 2.2.1 Fookes & Higginbottom 1975), are a group of sedimentary rocks, which occur in a wide variety of forms and degrees of induration. The minerals calcite and aragonite (also $CaCO_3$), both for the main part chemical precipitates from seawater, form the basis of the major components of these rocks. Aragonite is an unstable combination, which transforms after consolidation into calcite. Aside from this the minerals dolomite

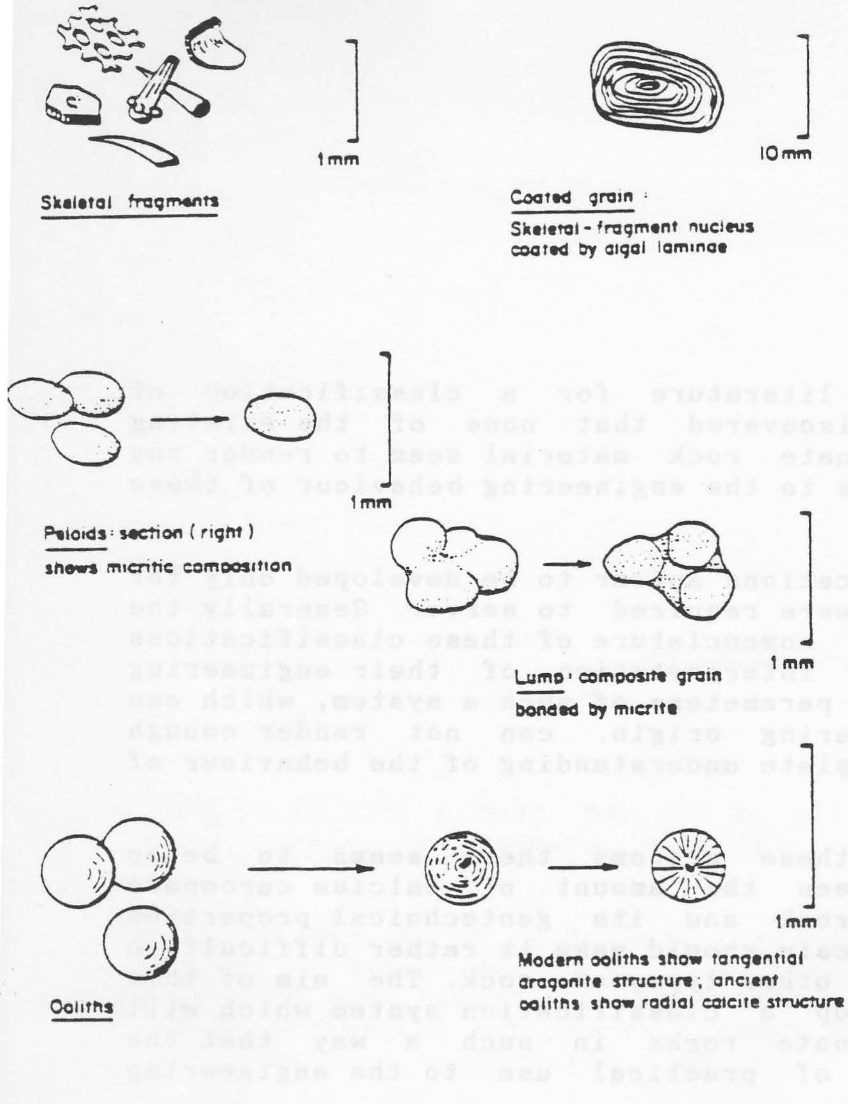
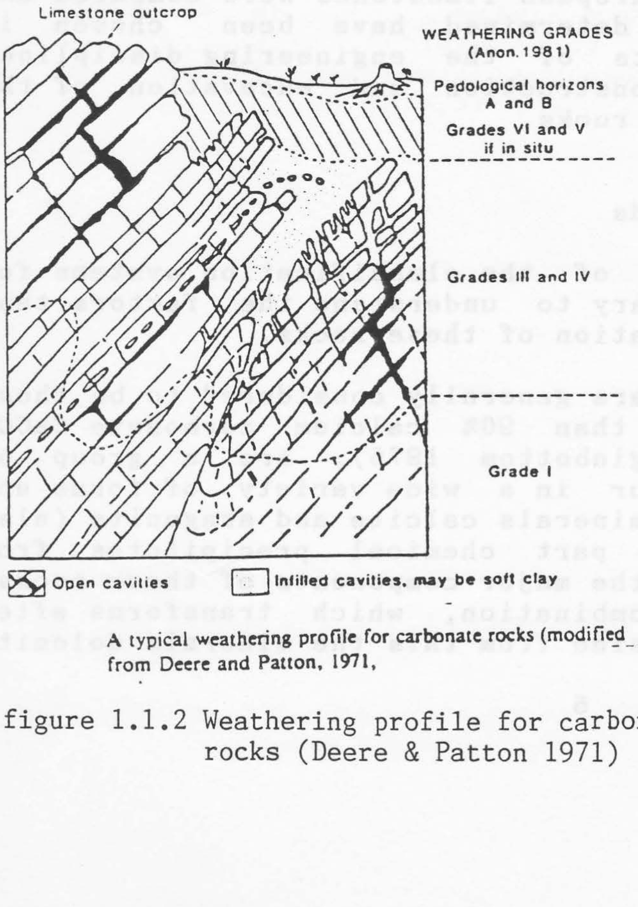


figure 1.1.1 Constituents of carbonate rocks



A typical weathering profile for carbonate rocks (modified from Deere and Patton, 1971,

figure 1.1.2 Weathering profile for carbonate rocks (Deere & Patton 1971)

	Great Limestone	Four Fathom Limestone
R.Q.D. %	79 - 95	82 - 97
Weathering	Unweathered - moderately	Unweathered
Rock Strength	100 - 200 MPa	100 - 200 MPa
Joint Spacing	0.3 - 1 m	1 - 3 m
Joint Separation	5 mm	0.1 - 1 mm
Joint Continuity	Continuous no gouge	Continuous with gouge
Number of localities	10	5
Rock Class	II - III Good, Fair	II Good
Stand-up Time	6 months - 1 week	6 months

Application of the CSIR (Bieniawski, 1973) classification to the limestones in the Kielder tunnels, N.E. England.

	Great Limestone	Four Fathom Limestone
R.Q.D. %	79 - 95	82 - 97
Jn	3 - 4	4 - 15
Jr	1 3	1,5 - 2,0
Ja	1 4	0,75- 1,0
S.R.F.	2,5 - 5,0	1 - 5,0
Rock quality	Q = 7 - 16,5	Q = 1,1 - 16,3

Application of the NGI (Barton et al., 1974) classification to the limestones in the Kielder tunnels, N.E. England. Jn is joint set number; Jr is joint roughness number; Ja is joint alteration number; SRF is stress reduction factor.

figure 1.2.1 Rock mass classification for limestone (1974,1973) associated with pressure solution.

When consolidated carbonate rocks are exposed to the surface, they weather by solution, leaving behind the insoluble parts of the original rock. An extensive review of the mechanisms is given by Trudgill (1985). The rate of solution depends on the acidity of the water, the amount of CO_2 dissoluted, the temperature, the waterflow, the previous saturation by CO_3, and the solubility of the rock. When the surface area of the rock is exposed to such conditions weathering may occur in many forms. Deere and Patton (1971) have illustrated a typical weathering profile for carbonate rocks (fig 1.1.1). A description of weathering features of rocks recommended by the IAEG (the International Association of Engineering Geology (1970, 1972)) is presented in table 1.1.2 .

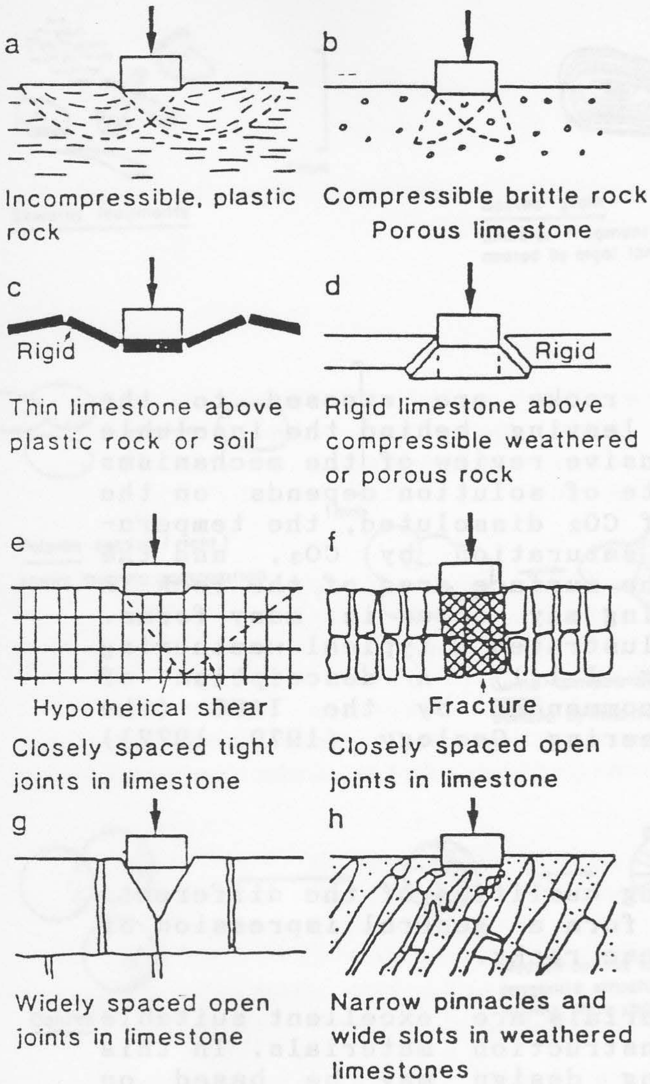
1.2 Engineering Considerations

An impression of the engineering qualities of the different carbonates may aid the reader to form a general impression of todays uses of and problems with these rocks.

The strong sound limestone materials are excellent suitable for foundations, tunnels and construction materials. In this category of rocks the engineering design may be based on classification systems for rock mass such as the CSIR (Bieniawski 1973) or the NGI (Barton 1974). An example applied on limestones is given in fig. 1.2.1 . A rock material classification is made by Deere and Miller (1966), who related the Unconfined Compressive Strength and the Elastic Modulus of intact rock (fig. 1.2.2).

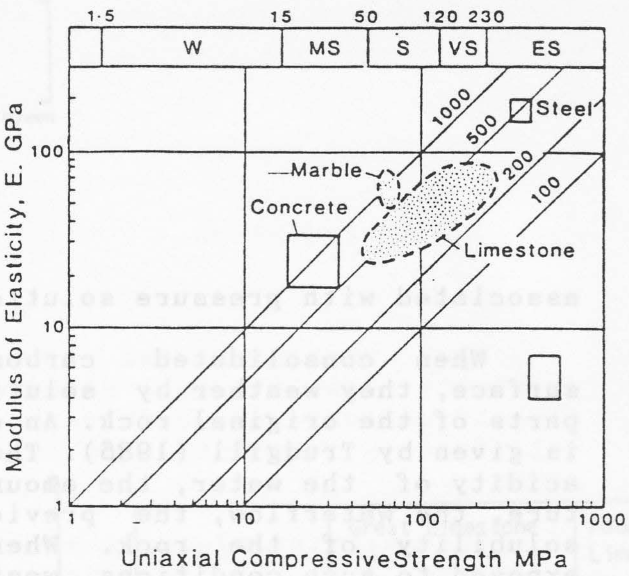
Regarding the weakest carbonates, the spectrum ranges from slightly indurated soils to well cemented limestone or weathered and fractured limestone. The usefulness of cemented carbonate soils depends on the degree of induration and the percentage of carbonate material. The varying foundation conditions in this respect pose a serious problem. Sowers (1976) presented a qualitative approach to the types of foundation failures for limestones (figure 1.2.3). The degree of anisotropy, the influences of other media, and the discontinuity condition are accounted for. Hence the bearing capacity can be assessed from the compressibility of the limestone mass with the help of tests. Indications of the bearing capacity are noted in figure 1.2.4 according to the Code of Practice for Foundations (1972).

Regarding the use of carbonates as construction material, the suitability of weak cemented limestones as road aggregate is discussed by Netterberg (1982). As an example of characteristic limestone testing techniques used in road aggragate practice figure 1.2.5 presents data of the British Road Research Laboratory. The suitability of limestones as building stone requires a certain strength and is reversely proportional to the amount of fractures present in the rock. The physical and



Foundations on limestones. Varying modes of failure by:
(a) General shear; (b) Local shear;
(c) Slat action; (d) Punching shear;
(e) Rankine shear; (f) Unconfirmed compression;
(g) Splitting; (h) Local crushing.

figure 1.2.3 Varying foundation conditions in limestones (Sowers 1976)



A general engineering classification of limestones, dolomites and marbles in terms of elastic modulus and unconfined compressive strength (after Deere and Miller, 1966).

figure 1.2.2 A rock material classification for limestone (Deere & Miller 1966)

CLASS	ROCK TYPE	PRESUMED BEARING VALUE in kN/m^2	REMARKS
2	Hard limestones	4 000	These values are based on the assumption that the foundations are carried down to unweathered rock
6	Hard sound chalk, soft limestone	600	
7	Thinly bedded limestones	to be assessed after inspection	

Presumed bearing values for limestones under vertical static load from CP2004: 1972, Code of Practice for Foundations (Anon. 1972).

figure 1.2.4 Indication of bearing capacity (Code of Practice for foundations 1972)

PHYSICAL PROPERTY	DENSITY OF LIMESTONE Low	Medium	High
Absorption by weight, max, %	12	7.5	3
Density, min, kg/m^3	1760	2160	2560
Compressive strength, min, MPa	12	28	55
Modulus of rupture, min, MPa	2.9	3.4	6.9
Abrasion resistance, min, hardness*	10	10	10

*Relates to stone subject to foot traffic.

ASTM C568—79. Physical requirements for limestone building stone.

figure 1.2.6 requirements for limestone buildingstone (ASTM-C568 79) and siderite often occur in these rocks as transformation products of calcium carbonate.

The origin of the carbonate components can be distinguished with reference to their fabric. A report from Delft Geotechnics (1986) on carbonate sediments recognizes the components given in table 1.1.1 .

bioclasts	: skeletal fragments formed by corals, crinoids, algae, brachiopods and foraminiferae etc.
coated grains (ooides)	: particles with a layered frame of calcium carbonate; when concentric and with a kernel they are called oolites
peloids	: indurated homogeneous spheres of faecal origin
detrital particles	: formed by mechanical disintegration of well consolidated carbonate rocks; occur in conglomerates and breccia
calcareous mud	: clastic products of micro organisms also known under the name of micrite
cement	: chemical precipitation of calcium carbonate between particles

Table 1.1.1 Basic components of carbonate rocks (after report of Delft Geotechnics 1986)

Compaction and induration of carbonate sediments, influenced by temperature and previous cementation, leads to the formation of limestone. During these processes reorientation of particles, solution of lime and fracturing of clastic material result in a decreasing porosity. The compaction of the sediments is inversely proportional to their grainsizes. Evidence of this fact is found in arid climates where early cemented carbonate sands display a relative low degree of compaction under static load, while water saturated carbonate muds under load show a volume reduction up to 90 % .

Should the limestone become sufficiently deeply buried, diagenetic and metamorphic processes may be initiated whereby significant changes in the rock can occur. Such processes can be recognized by the presence of stylolites, the replacement of calcite by dolomite, and the recrystallisation of calcite. The replacement of calcite by dolomite can occur under favourable conditions of salinity (Pannekoek 1973). Stylolites are features and siderite often occur in these rocks as transformation products of calcium carbonate.

The origin of the carbonate components can be distinguished with reference to their fabric. A report from Delft Geotechnics (1989) on carbonate sediments recognizes the components given in table 1.2.1 .

bioclasts	:	skeletal fragments formed by corals, crinoids, algae, brachiopods and foraminiferae etc.
coated grains (ooides)	:	particles with a layered frame of calcium carbonate; when concentric and with a kernel they are called oolites
peloids	:	indurated homogeneous spheres of faecal origin
detrital particles	:	formed by mechanical disintegration of well consolidated carbonate rocks; occur in conglomerates and breccia
calcareous mud	:	clastic products of micro organisms also known under the name of micrite
cement	:	chemical precipitation of calcium carbonate between particles

Table Basic components of carbonate rocks (after report of Delft Geotechnics 1989)

Compaction and induration of carbonate sediments, influenced by temperature and previous cementation, lead to the formation of limestone. During these processes reorientation of particles, solution of fine and fracturing of clastic material result in a decreasing porosity. The compaction of the sediments is inversely proportional to their grainsizes. Evidence of this fact is found in arid estuaries where early cemented carbonate sands display a relative low degree of compaction under static load, while water saturated carbonate muds under load show a volume reduction up to 90 %.

Should the limestone become sufficiently deeply buried, diagenetic and metamorphic processes may be initiated whereby significant changes in the rock can occur. Such processes can be recognized by the presence of stylolites, the replacement of calcite by dolomite, and the recrystallization of calcite. The replacement of calcite by dolomite can occur under favourable conditions of salinity (Pannekoek 1973). Stylolites are features mechanical requirements for limestones as building stone are indicated in the ASTM C568-79 report (figure 1.2.6). Quality investigation could then focus on crushing characteristics, the degree of fissuring and the behaviour of minor fractions present in the material (Ashurst and Dimes 1977).

A major problem with the moderately weak to strong limestones is the solution effect, which results in the formation of cavities. Without adequate investigation of the limestone mass the risk of collapse is may be too high. From an engineering point of view the important factors to be assessed are the size and distribution of the fissures and the solution rate constant as defined by James (1982).

	Aggregate crushing value	Aggregate impact value	Aggregate abrasion value	Water absorption (per cent)	Specific gravity	Polished-stone coefficient
Mean	24	23	13.7	1.0	2.66	0.43
Range	(11-37)	(17-33)	(7-26)	(0.2-2.9)	(2.8-2.9)	(0.30-0.75)
No. of Samples	164	61	34	42	42	51

Summary of values for tests on limestone aggregates.

figure 1.2.5 (British Road Research Laboratory 1959)

Depositional Texture recognizable					Depositional texture not recognizable
Original components not bound together during depositions				Original components were bound together during deposition... as shown by intergrown skeletal matter, lamination contrary to gravity, or sediment-floored cavities that are roofed over by organic or questionably organic matter and are too large to be interstices.	Crystalline carbonate
Contains mud (particles of clay and fine silt size)			Lacks mud and is grain-supported		
Mud-supported		Grain-supported			
Less than 10% grains	More than 10% grains				(Subdivide according to classifications designed to bear on physical texture or diagenesis.)
Mudstone	Wackstone	Packstone	Grainstone	Boundstone	

figure 2.1.1 Scheme for the classification of carbonate rocks (Dunham 1962)

figure 2.1.2 a (Folk 1962)

TABLE CLASSIFICATION OF CARBONATE ROCKS

Volumetric Allochem Composition	Limestones, Partly Dolomitized Limestones, and Primary Dolomites (see Notes 1 to 6): >10% Allochems, Allochemical Rocks (I and II): Sparry Calcite Cement > Microcrystalline Ooze Matrix — Sparry Allochemical Rocks (I)	Microcrystalline Ooze Matrix > Sparry Calcite Cement — Microcrystalline Alochemical Rocks (II)	<10% Allochems, Microcrystalline Rocks (III): 1-10% Allochems (Most Abundant Allochem)	<1% Allochems	Undisturbed Bioherm Rocks (IV)	Replacement Dolomites[7] (V): Allochem Ghosts (Evident Allochem)	No Allochem Ghosts
>25% Intraclasts (i)	Intrasparrudite (Ii:Lr) Intrasparite (Ii:La)	Intramicrudite* (IIi:Lr) Intramicrite* (IIi:La)	Intraclasts: Intraclast-bearing Micrite* (IIIi:Lr or La)	Micrite (IIIm:L); if disturbed, Dismicrite (IIImX:L); if primary dolomite, Dolomicrite (IIIm:D)	Biolithite (IV:L)	Finely Crystalline Intraclastic Dolomite (Vi:D3) etc.	Medium Crystalline Dolomite (V:D4)
<25% Intraclasts, >25% Oölites (o)	Oösparrudite (Io:Lr) Oösparite (Io:La)	Oömicrudite* (IIo:Lr) Oömicrite* (IIo:La)	Oölites: Oölite-bearing Micrite* (IIIo:Lr or La)			Coarsely Crystalline Oölitic Dolomite (Vo:D5) etc.	Finely Crystalline Dolomite (V:D3)
<25% Intraclasts, <25% Oölites, Volume Ratio of Fossils to Pellets >3:1 (b)	Biosparrudite (Ib:Lr) Biosparite (Ib:La)	Biomicrudite (IIb:Lr) Biomicrite (IIb:La)	Fossils: Fossiliferous Micrite (IIIb: Lr, La, or Ll)			Aphanocrystalline Biogenic Dolomite (Vb:Dl) etc.	
<25% Intraclasts, <25% Oölites, Volume Ratio of Fossils to Pellets 3:1-1:3 (bp)	Biopelsparite (Ibp:La)	Biopelmicrite (IIbp:La)	Pellets: Pelletiferous Micrite (IIIp:La)			Very Finely Crystalline Pellet Dolomite (Vp:D2) etc.	etc.
<25% Intraclasts, <25% Oölites, Volume Ratio of Fossils to Pellets <1:3 (p)	Pelsparite (Ip:La)	Pelmicrite (IIp:La)					

NOTES TO TABLE

* Designates rare rock types.

1 Names and symbols in the body of the table refer to limestones. If the rock contains more than 10 per cent replacement dolomite, prefix the term "dolomitized" to the rock name, and use DLr or DLa for the symbol (e.g., dolomitized intrasparite, Li:DLa). If the rock contains more than 10 per cent dolomite of uncertain origin, prefix the term "dolomitic" to the rock name, and use dLr or dLa for the symbol (e.g., dolomitic pelsparite, Ip:dLa). If the rock consists of primary (directly deposited) dolomite, prefix the term "primary dolomite" to the rock name, and use Dr or Da for the symbol (e.g., primary dolomite intramicrite, IIi:Da). Instead of "primary dolomite micrite" (IIIm:D) the term "dolomicrite" may be used.

2 Upper name in each box refers to calcirudites (median allochem size larger than 1.0 mm.); and lower name refers to all rocks with median allochem size smaller than 1.0 mm. Grain size and quantity of ooze matrix, cements or terrigenous grains are ignored.

3 If the rock contains more than 10 per cent terrigenous material, prefix "sandy," "silty," or "clayey" to the rock name, and "Ts," "Tz," or "Tc" to the symbol depending on which is dominant (e.g., sandy biosparite, TsIb:La, or silty dolomitized pelmicrite, TzIIp:DLa). Glauconite, collophane, chert, pyrite, or other modifiers may also be prefixed.

4 If the rock contains other allochems in significant quantities that are not mentioned in the main rock name, these should be prefixed as qualifiers preceding the main rock name (e.g., fossiliferous intrasparite, oölitic pelmicrite, pelletiferous oösparite, or intraclastic biomicrudite). This can be shown symbolically as Ii(b), Io(p), IIb(i), respectively.

5 If the fossils are of rather uniform type or one type is dominant, this fact should be shown in the rock name (e.g., pelecypod biosparrudite, crinoid biomicrite).

6 If the rock was originally microcrystalline and can be shown to have recrystallized to microspar (5-15 micron, clear calcite) the terms "microsparite," "biomicrosparite," etc. can be used instead of "micrite" or "biomicrite."

ROBERT L. FOLK

2 Existing Classifications of Carbonate Rocks

The factors that play a dominant role in the classification systems of carbonate rocks appear to depend largely on the purpose the classifications were designed to serve. A large number of classifications were developed because of the interest of the oil industry in the porosity and permeability of these rocks. Their aim was mainly to correlate the texture and depositional origin of the limestones to porosity values.

Upon reviewing the existing classifications it was found that they can be grouped into one of three catagories ; geological, geotechnical or engineering geological classifications.

2.1 Geological Classifications

The two systems most commonly used for the classification of pure carbonates are those proposed by Dunham (1962) and Folk (1959, 1962).

The main criterium in Dunham's classification is the relation between particles and matrix. The terms packstone, grainstone, mudstone etc. should qualify the rock ranging from grain to matrix supported. Although the textural basis provides an insight in the depositional environments, it offers no room for an indication of the induration degree (fig 2.1.).

Folk's classification is based on three elements ; particles (allochems), microcrystalline ooze (orthochems) and sparry (coarse) calcite cement. Each class may then be further divided giving an insight into their depositional maturity. By combining texture with the type of constituent a sequential nomenclature is developed (fig. 2.1.2). This leads to rock descriptions such as intra-bio-pel-micrite. This system is more suited to microscope studies than field use. As for the nomenclature according to grain size he presented a classification (fig. 2.1.3), which is based on the Wentworth scale. A weak point in his classification is that cementation degrees can not be derived.

Schmidt (1965) tackled the spectrum between limestone and dolomite in extension of the division made by Petijohn (1959) (fig. 2.1.4).

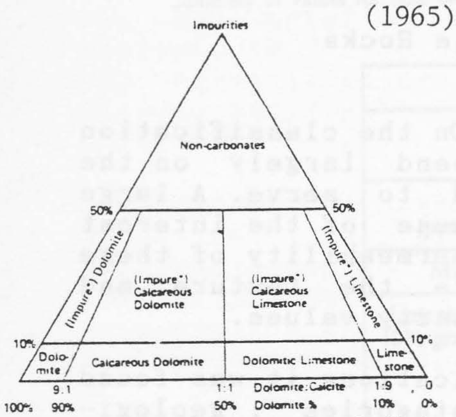
Leighton and Pendexter (1962) proposed a classification considering three variables : grain size, the proportions of the matrix to the allochems (particles) and a terminology for the composition of carbonate rocks. The grainsizes of the different allochems are compared to the type of allochem, thus classifying the texture, while the geological descriptive terms, like an argillaceous limestone, supply information regarding the

Volume percent of rock	Detailed Classification	Standard Classification
Traces – 2 vol %	Extremely slightly dolomitic	
2 – 5 vol %	Very slightly dolomitic	
5 – 10 vol %	Slightly dolomitic	
10 – 25 vol %	Fairly dolomitic	Dolomitic
25 – 50 vol %	Highly dolomitic	

(b) Schmidt's detailed classification of calcite-dolomite mixtures.

Classification of limestone-dolomite mixtures

figure 2.1.4 (Schmidt) (1965)



*An appropriate compositional term should be substituted for the word "impure"

Leighton and Pendexter's compositional terminology for carbonate rocks

figure 2.1.5 (Leighton & Pendexter 1962)

ROBERT L. FOLK

TABLE GRAIN-SIZE SCALE FOR CARBONATE ROCKS

	Transported Constituents	Authigenic Constituents	
	Very coarse calcirudite		
64 mm			
	Coarse calcirudite	Extremely coarsely crystalline	
16 mm			
	Medium calcirudite		
4 mm			4 mm
	Fine calcirudite	Very coarsely crystalline	
1 mm			1 mm
	Coarse calcarenite		
0.5 mm		Coarsely crystalline	
	Medium calcarenite		
0.25 mm			0.25 mm
	Fine calcarenite	Medium crystalline	
0.125 mm			
	Very fine calcarenite		
0.062 mm			0.062 mm
	Coarse calcilutite		
0.031 mm		Finely crystalline	
	Medium calcilutite		
0.016 mm			0.016 mm
	Fine calcilutite		
0.008 mm		Very finely crystalline	
0.004 mm	Very fine calcilutite		0.004 mm
		Aphanocrystalline	

Carbonate rocks contain both physically transported particles (oölites, intraclasts, fossils, and pellets) and chemically precipitated minerals (either as pore-filling cement, primary ooze, or as products of recrystallization and replacement). Therefore, the size scale must be a double one, so that one can distinguish which constituent is being considered (e.g., coarse calcirudites may be cemented with very finely crystalline dolomite, and fine calcarenites may be cemented with coarsely crystalline calcite). The size scale for transported constituents uses the terms of Grabau but retains the finer divisions of Wentworth except in the calcirudite range; for dolomites of obviously allochemical origin, the terms "dolorudite," "dolarenite," and "dololutite" are substituted for those shown. The most common crystal size for dolomite appears to be between .062 and .25 mm and for this reason that interval was chosen as the "medium crystalline" class.

figure 2.1.3 (Folk 1962)

LEIGHTON & PENDEXTER'S TEXTURAL CLASSIFICATION OF LIMESTONES

Grain/micrite ratio	% Grains	Grain type: Detrital	Skeletal	Pellets	Lumps	Coated Grains	Organic frame builders	No organic frame builders
		Detrital Lst	Skeletal Lst	Pellet-Lst	Lump-Lst	Oolitic Lst Pisolitic Lst Algal encr Lst	Coralline Lst Algal Lst etc	
9:1	90							
		Detrital Micritic Lst	Skeletal Micritic Lst	Pellet-Micritic Lst	Lump-Micritic Lst	Oolitic (Pisolitic etc) -Micritic Lst	Coralline-micritic. Lst Algal-micritic Lst etc	
1:1	50							
		Micritic-Detrital Lst	Micritic-Skeletal Lst	Micritic-Pellet Lst	Micritic-Lump Lst	Micritic-oolitic (Pisolitic etc) Lst	Micritic-coralline. Micritic-algal Lst etc	
1:9	10							
		← Micritic Limestone →						

	OVER 2/3 LIME MUD MATRIX (Micrite)				SUBEQUAL SPAR AND LIME MUD	OVER 2/3 SPARRY CEMENT (Sparite)		
Percent Particles	0 – 1%	1–10 %	10–50 %	> 50 %		SORTING POOR	SORTING GOOD	ROUNDED & ABRADED
Representative Rock Terms	MICRITE & DISMICRITE	FOSSILIFEROUS MICRITE	SPARSE BIOMICRITE	PACKED BIOMICRITE	POORLY WASHED BIOSPARITE	UNSORTED BIOSPARITE	SORTED BIOSPARITE	ROUNDED BIOSPARITE
Terminology Folk 1959	Micrite & Dismicrite	Fossiliferous Micrite	Biomicrite			Biosparite		
Terrigenous Analogues	Claystone		Sandy Claystone	Clayey or Immature Sandstone		Submature Sandstone	Mature Sandstone	Supermature Sandstone

LIME MUD MATRIX   SPARRY CALCITE CEMENT

Figure 2.1.2 ab
a simplified scheme
(Folk 1962)

percentages of limestone, dolomite and impurities (fig. 2.1.5).

A Classification in which the porosity plays a significant role is represented in the unified system of Choquette & Pray (1970). In this system an important distinction is made between the terms "fabric selective" and "not fabric selective" porosity. The term fabric selective means that pores are bounded by particle boundaries. The system is designed for carbonate rocks but is only a partial description (fig. 2.1.6).

2.2 Geotechnical Classifications

Due to rapid expansion of engineering developments during the 70's, one of the first geotechnical oriented classifications was developed by Fookes and Higginbottom (1975). Their classification of near-shore carbonate rocks included a degree of induration, grain size, mineral composition and the origin of the carbonate material. They connected differences in strength and grain size to common known names for pure and impure limestones. This classification formed a basis for many modifications and extensions (fig. 2.2.1 a). Apart from the classification for engineering purposes, they defined a nomenclature for pure and impure carbonate sediments (fig. 2.2.1 b & c).

Clark and Walker (1977) modified the nomenclature and encompassed the impure carbonates as well, still using the same four variables as Fookes and Higginbottom . The engineering behaviour was quantified by boundaries using ranges of approximate Unconfined Compressive Strength (UCS) values in relation to the degree of induration (fig. 2.2.2).

For slightly cemented sands Beringen (1982) adjusted the Clark & Walker system to the use of the cone penetration test. The link between cone resistance and the cementation is quantitative described for indurated carbonate soils (fig. 2.2.3).

Regarding pure carbonate sediments the Clark and Walker classification was modified by Fugro (1978) for the North Rankin Project in Australia (fig. 2.2.4). Mainly concerned with cemented soils this classification discerns cementation and induration; the induration should be the result of cementation and cohesion. The parameters used are grainsize, name, degree of cementation, bedding and lamination, origin of carbonate, colour, and the minor fractions.

With regard to carbonate sands in India, Datta (1982) modified the Clark & Walker classification and stated some remarks for a new classification. Although Datta is not directly involved with limestones, the cemented carbonate sands he is concerned with overlap the spectrum of weak to very weak limestones. According to his paper, aspects which could supply

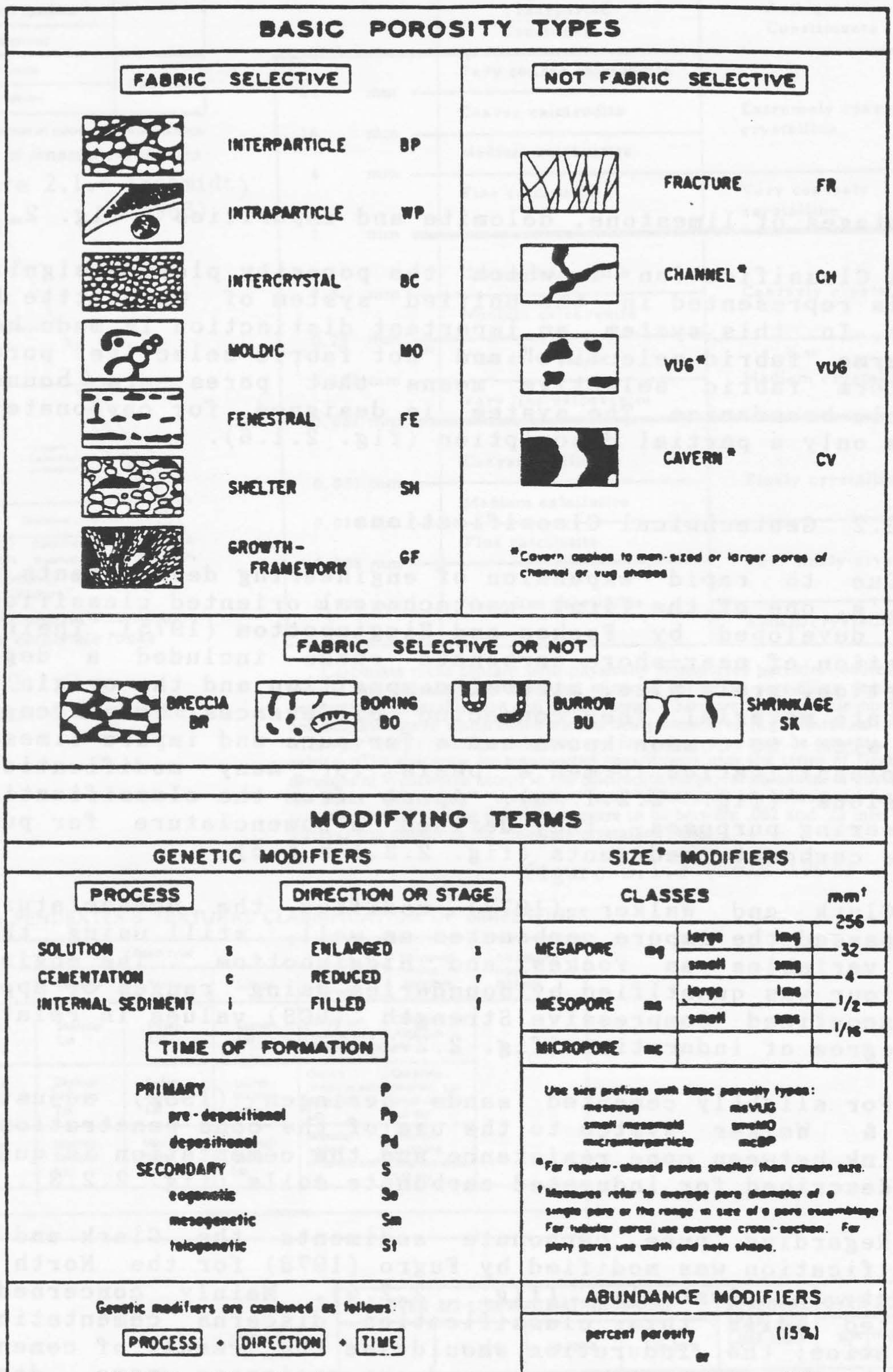


figure 2.1.6 : Classification of the porosity of carbonate rocks (Choquette & Pray 1970)

useful information for the evolvement of a further classification system, are :

cementation
grainsize distribution and plasticity
nature of carbonate components
nature of non-carbonate components

To specify the geotechnical properties he suggested the following descriptive terms should be included in a classification system for carbonate soils :

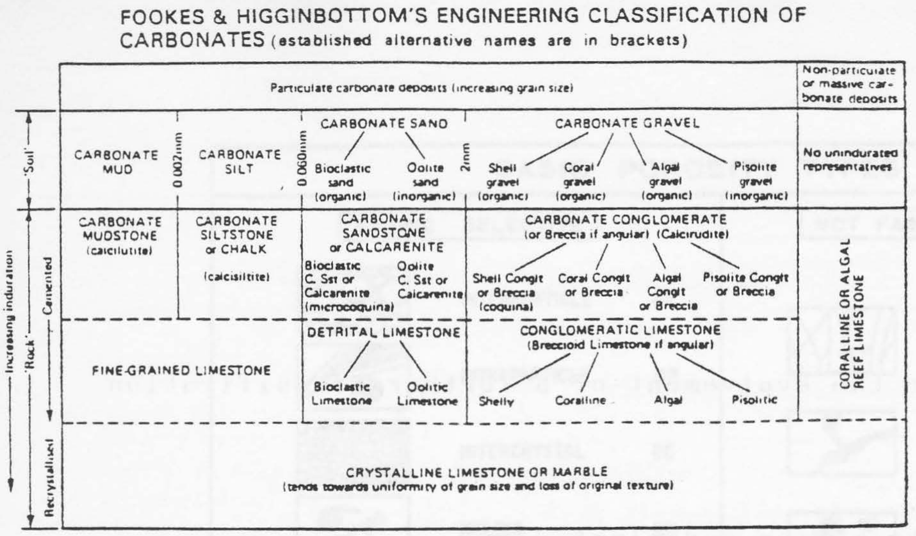
susceptibility to crushing
degree of uniformity and cementation
influence of carbonate material in relation to non-carbonate material

The scheme proposed by Datta for geotechnical description is listed in fig. 2.2.5 .

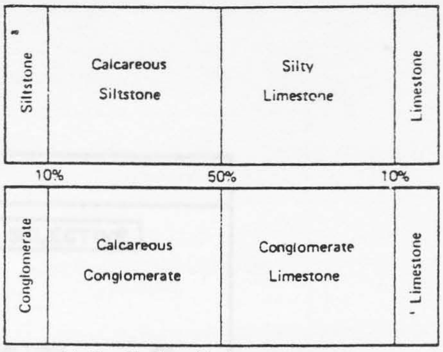
2.3 Engineering Geological Classifications

An engineering geological classification of carbonate rocks with a descriptive character was published by Burnett and Epps (1979). They suggested a double ternary diagram of pure limestone and admixtures in addition to individual classification tables for grain size, joint spacing, density, weathering, texture and strength. Unfortunately the terminology they propose becomes somewhat extensive. A description sheet which, could be used for the sampling of carbonate rocks, is given in appendix A.1 .

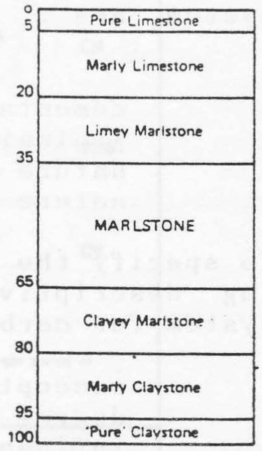
Dearman (1981) considered the engineering geological description system in which he accounts for carbonate rocks as a material as well as their rock mass. In his paper he recognizes the importance of different properties to the various engineering fields involved with limestone. Furthermore he shows that correlations exist between engineering index properties and geological properties. As example he presents a correlation between the engineering geological grade and the mechanical properties of chalk at Mundford (after Ward et al. 1968) in figure 2.3.1 This figure has been widely used as a preliminary estimate in the logging of drill cores and site investigation pits and trenches. Visual description then enables to derive deformation characteristics of the chalk, based on comparison with a known deformation and description.



figures 2.2.1 a t/m c : Classification of carbonates (Fookes & Higginbottom 1975)



(a) Classification of indurated silt-carbonate and gravel-carbonate sediments.



(b) Classification of indurated clay-carbonate sediments.

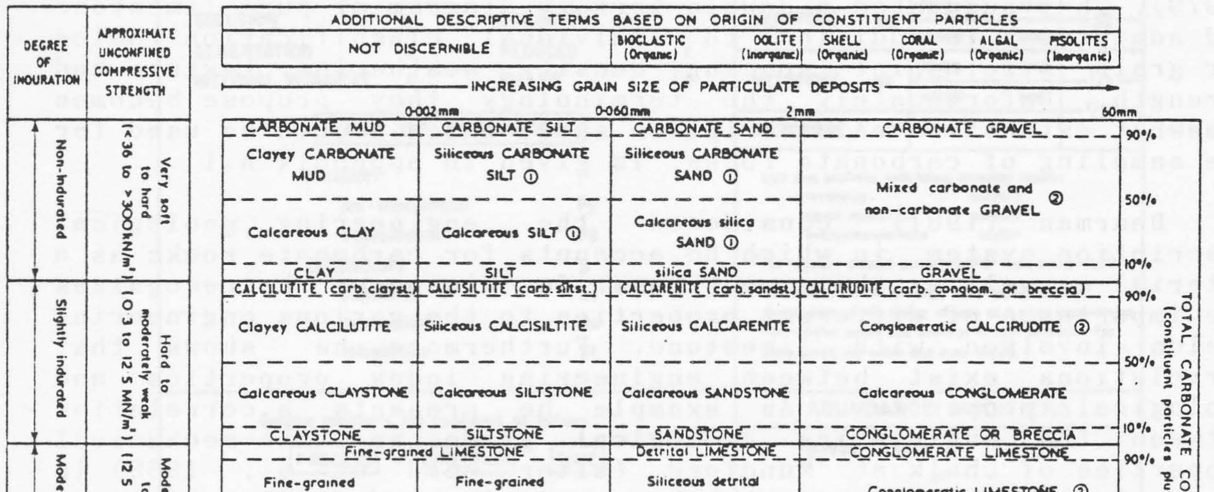
Higginbottom and Fookes' compositional classification of impure carbonate sediments

① Non-carbonate constituents are likely to be siliceous apart from local concentrations of minerals such as felspar and mixed heavy minerals (Emery 1956).

② In description the rough proportions of carbonate and non-carbonate constituents should be quoted and details of both the particle minerals and matrix minerals should be included.

③ The preferred lithological nomenclature has been shown in block capitals; alternatives have been given in brackets and these may be substituted in description if the need arises.

④ Calcareous is suggested as a general term to indicate the presence of unidentified carbonate. Where applicable, when mineral identification is possible calcareous referring to calcite or alternative adjectives such as dolomitic, aragonitic, sideritic etc. should be used.



Proposed classification chart for description of Middle Eastern sedimentary rocks

figure 2.2.2 : Classification of Middle Eastern sedimentary rocks (Clark & Walker 1977)

2.4 Restrictions on Classification for Engineering Purposes

A striking fact is the differentiation of classification systems with reference to the nature of the carbonate rocks or soils, to which the system was applied. For example the Clark & Walker system encompasses the Middle Eastern sedimentary rocks, while Datta used his description for slightly cemented soils in India. The problem is that the definition of what is rock and what is soil has not been unambiguously assessed for the carbonate sediments. Hence due to subjective interpretation of the boundaries, the nomenclatures of two such systems can cause confusion when they are applied to the same carbonate.

In pursuit of prediction of engineering behavior many different factors play roles of alternating importance, like ranges of induration where cemented soils must be treated differently than sound rocks. Therefore it is desirable that standard values should discriminate between important boundaries.

Effective prediction of engineering properties to various carbonate rocks can be enhanced by relating their engineering uses. According to the standard procedures the most required properties of the following engineering fields were compared.

- Underground Excavation (Bieniawski 1979 and OPAC 1987)
- Dredging (PIANC 1984)
- Foundation Engineering (Fugro 1978, Dearman 1981)
- Construction Materials (ASTM-C 33 and ASTM C 568 1979)

Strength, particle size and bulk density appear to be essential engineering properties and additional information may be supplied about crushing and deformation characteristics.

For strength several classifications exist, some with rather poor boundary restrictions. In general the most suitable seems to be the strength of intact rock developed by the Geological Society (1970) given in table 2.4.1.

very weak	0 - 1.25	MPa
weak	1.25- 5	MPa
moderately weak	5 - 12.5	MPa
moderately strong	12.5 - 50	MPa
strong	50 -100	MPa
very strong	100 -200	MPa
extremely strong	>200	MPa

Table 2.4.1 Strength classification of the Geological Society (1970)

		FINE GRAINED		MEDIUM–COARSE GRAINED	
		INCREASING GRAINSIZE →			
			0.002 mm – 0.006 mm – 0.02 mm – 0.06 mm	0.2 mm – 0.6 mm – 2 mm	6 mm – 20 mm – 60 mm
DEGREE OF INDURATION	APPROX UNCONF COMPR STRENGTH		fine | med | coarse	fine | medium | coarse	fine | medium | coarse
SOIL: very soft	0 – 12.5 KN/m2	CARBONATE MUD	CARBONATE SILT	CARBONATE SAND (clastic/bioclastic/oolitic)	CARBONATE GRAVEL (clastic/bioclastic)
SOIL: soft	12.5 – 25 KN/m2				
SOIL: firm	25 – 50 KN/m2				
SOIL: stiff	50 – 100 KN/m2				
SOIL: very stiff	100 – 200 KN/m				
SOIL: hard	200–300 KN/m2				
ROCK: weak – mod. weak	0.3–12.5 MN/m2	CALCILUTITE (carb. mudstone)	CALCISILTITE (carb. siltstone)	CALCARENITE (carb. sandstone) clastic/bioclastic/oolitic	CALCIRUDITE (carb. congl. or breccia) clastic/bioclastic
ROCK: mod. strong – strong	12.5–100 MN/m2	FINE GRAINED LIMESTONE		DETRITAL LIMESTONE clastic/bioclastic/oolitic	CONGLOMERATE LIMESTONE clastic/bioclastic
ROCK: strong – extr. strong	70 –>200 MN/m2	CRYSTALLINE LIMESTONE		CRYSTALLINE LIMESTONE	

DEGREE OF CEMENTATION	APPROX. UNCONF. COMPR STRENGTH
uncemented	0 – 25 KN/m2
very weakly cemented	25 – 50 KN/m2
weakly cemented	50 – 100 KN/m2
firmly cemented	100 – 300 KN/m2
well cemented	0.3 – 12.5 MN/m2
hard cemented	12.5 – 100 MN/m2

CLASSIFICATION OF CARBONATE SEDIMENTS (90 – 100% carbonate)
(modified after Clark and Walker, 1977)

figure 2.2.4 (fugro 1987) geotechnical classification of carbonate sediments

DEGREE OF INDURATION CEMENTATION	CONE RESIS TANCE q_c MN m^{-2}
VERY WEAKLY INDURATED CEMENTED	0 - 2
WEAKLY INDURATED CEMENTED	2 4
FIRMLY INDURATED/CEMENTED	4 - 10
WELL INDURATED CEMENTED	>10

figure 2.2.3
(Beringen 1982)
the relation between cone resistance and degree of cementation or induration.

TABLE *Proposed system of description.*

Description of	Remarks
1. Cementation	
(*a*) No cementation	
(*b*) Weak cementation	
(c) Strong cementation	
(i) uniform	the soil has a soft rock-like appearance. Unconfined compressive strength should be indicated
(ii) partial	the soil contains cemented aggregates—this should be noted
2. Grain Size Distribution (GSD) and Plasticity	
(*a*) Grain size distribution	for strongly cemented soils, GSD is not very relevant; for uniform cementation, size of constituent particles should be indicated; for partial cementation, GSD of soil after removing aggregates should be indicated and size and proportion of aggregates noted separately
(*b*) Plasticity	for fine-grained soils in which intraparticle voids cause error in GSD and Atterberg limits, field classification procedures may be used for providing the relevant information in a qualitative sense
3. Nature of Carbonate Component	
(*a*) Carbonate content	soils having more than 30% carbonate content should be termed as carbonate soils
(*b*) Particle size of carbonate material	the carbonate content in the sand and in the silt-clay fractions should be determined separately and indicated. Microscopic studies mentioned below will also give information about particle size
(*c*) Particle characteristics and origin	microscopic studies—optical microscope for sands and scanning electron microscope for fine-grained soils—should be conducted. Presence of thin-walled material and intraparticle voids should be highlighted
(*d*) Mineralogy	X-ray diffraction analysis should be performed
(*e*) Geologic name	if possible to identify, the geologic name may be indicated
4. Nature of Noncarbonate Component	information on noncarbonate material is determined by dissolving the carbonate material in HCl, separating the remaining soil, and conducting the following tests on it
(*a*) Particle size	grain size distribution analysis
(*b*) Particle characteristics	microscopic studies
(*c*) Mineralogy	X-ray diffraction analysis

figure 2.2.5 Proposed system of description (Datta 1982) of carbonate soils

For dominant particle sizes the norms of MIT, DIN 4023, BS 1377 and the PIANC agree at convenient boundaries. Even more they are the same boundaries used by Clark & Walker and are therefore assumed to be suitable to carbonate rocks (table 2.4.2).

cobbles	200 - 60	mm
gravel	60 - 2	mm
sand	2 - 0.06	mm
silt	0.06- 0.002	mm
clay	< 0.002	mm

Table 2.4.2 Particle Size boundaries used by BS 1377, DIN 4023, MIT and the PIANC.

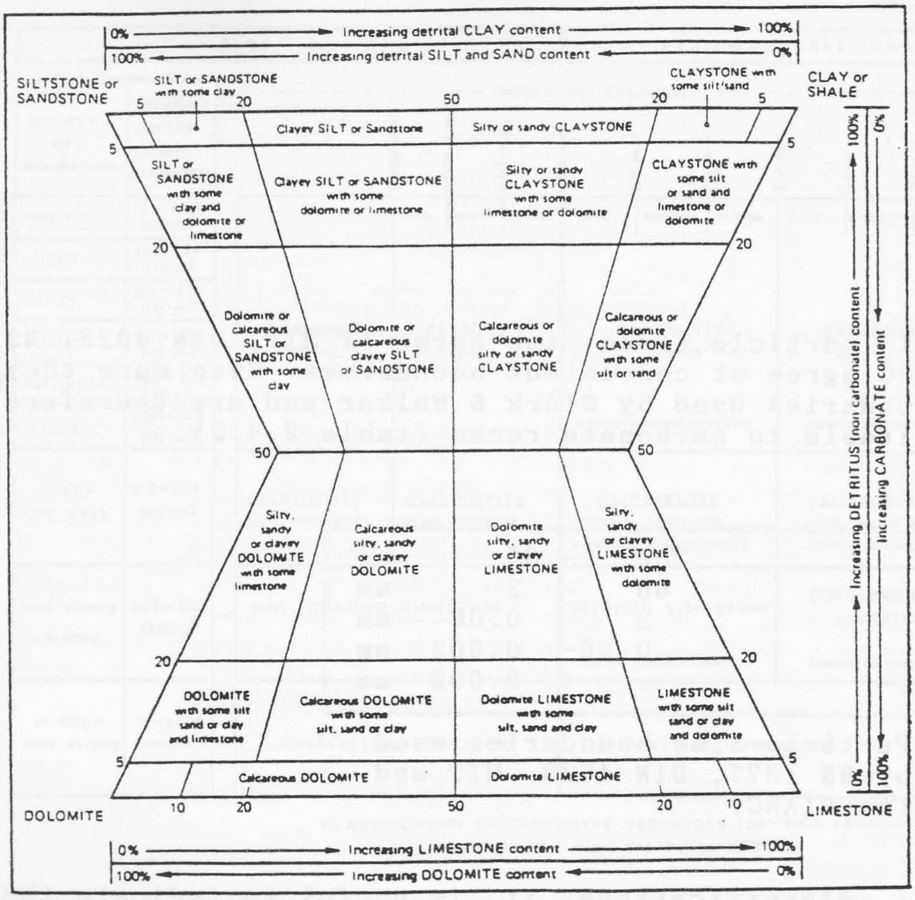
As in soil classifications it is useful to indicate the grainsize distribution. In most cases for limestones a distinction between particle and matrix sizes and percentages is probably generally sufficient.

Concerning bulk density the existing ranges are indicated for limestone building stone by the ASTM (American Society of Testing Materials) as given in table 2.4.3 . The quality of a building stone is not directly related to the density .

Low density	:	1.76 - 2.16 (g/cm^3)
Medium density	:	2.16 - 2.56 (g/cm^3)
High density	:	2.56 - (g/cm^3)

table 2.4.3 Density division for limestone building stone (ASTM C568-79)

Complementary to the engineering parameters the important geological factors which were recognized are texture and mineral composition. Both these factors give a qualitative indication for parameters such as abrasion, drillability and cuttability. The description of carbonate and non-carbonate constituents is of great significance to the engineering behaviour of the rock. For example in limestones the presence of quartz does increase their abrasive capacity and clay minerals may cause swelling. Textural division must distinguish between clastic particles and crystalline components.



Proposed classification of pure and admixtures of carbonate rocks

figures 2.3.1 a t/m f (Burnett & Epps 1979)
engineering geological classification of carbonate rocks

STRENGTH CLASSIFICATION

Field Definition	Extrudes between fingers when squeezed	Very easily moulded with fingers	Moderate finger pressure required to mould	Moulded only by strong finger pressure	Cannot be moulded with fingers	Brittle or very tough	Crumbles in hand	Thin slabs break easily in hand	Thin slabs broken by heavy hand pressure	Lumps or core broken by light hammer blows	Lumps or core broken by heavy hammer blows	Lumps only chip by heavy hammer blows. Dull ringing sound	Rocks ring on hammer blow. Sparks fly
Description	Very soft	Soft	Firm	Stiff	Very Stiff	Hard	Very Weak	Weak	Moderately Weak	Moderately Strong	Strong	Very Strong	Extremely Strong

Strength Categories:
Shear Strengths of Clays (kN/m²) +: 18 – 36 – 72 – 144 – 288
Unconfined compressive Strengths of Rocks (MN/m²): 1.25 – 5 – 12.5 – 50 – 100 – 200
Point Load Strengths of Rocks (MN/m²) •: 0.075 – 0.3 – 0.75 – 3 – 6 – 12

• Based on the approximate relation:- Comp. Strength = 16 Point Load Comp. Strength
+ Various published strength categories exist – quote reference used

SIZE, SPACING, DENSITY AND PLASTICITY CLASSIFICATIONS

Soil & Rock Discontinuity Spacing Descriptions									Extremely Narrow	Very Narrow	Narrow	Mod. Wide	Wide	Very Wide
Bedding Spacing Descriptions								Thinly Laminated	Thickly Laminated	Very Thin	Thin	Medium	Thick	Very Thick
Rock Grain Size Descriptions	Very Fine	Fine			Medium			Coarse			Very Coarse			
Soil Particle Size Divisions	Clay	Silt			Sand			Gravel			Cobbles	Boulders		
		Fine	Medium	Coarse	Fine	Medium	Coarse	Fine	Medium	Coarse				
mm	0.002	0.006	0.02	0.06	0.2	0.6	2	6	20	60	200	600	2000	

Diameter or Spacing

Relative Density of Granular Soils	% / Blows	Very Loose	15 / 4	Loose	35 / 10	Medium Dense	65 / 30	Dense	85 / 50	Very Dense	Relative Density / N Values

Plasticity Descriptions						
	Field Estimate	Lean	Intermediate	Fat	Very Fat	Extra Fat
	Laboratory Term	Low	Intermediate	High	Very High	Extra High
Liquid Limit, %	20	35	50	70	90	Liquid Limit, %

PROPOSED TEXTURAL CLASSIFICATION OF CARBONATES

Depositional texture recognisable					Depositional texture not recognisable
Containing Micrite matrix			Grain supported – lacking micrite matrix	Original components bound together	
Matrix supported		Grain supported			
Less than 10% grains	More than 10% grains				
Micritic Limestone	Micritic – Oolitic, Skeletal, Shelly, or Detrital Limestone	Oolitic, Skeletal, Shelly, or Detrital –micritic Limestone	Oolitic, Skeletal, Shelly, or Detrital Limestone	Algal, Coralline, etc. Limestone	Crystalline Limestone

figures 2.3.1 d t/m f
engineering geological classification of carbonate rocks
(Burnett & Epps 1979)

WEATHERING CLASSIFICATION

Soil Mass			Rock Mass		
Diagnostic Features	Term	Grade Symbol	Grade Symbol	Term	Diagnostic Features
			W VI	Residual Soil	Rock is discoloured and completely changed to a soil in which original rock fabric is completely destroyed.
Soil discoloured and totally altered, with no trace of original structures.	Completely Weathered	W V	W V	Completely Weathered	Rock is discoloured and changed to a soil but original fabric is mainly preserved. Occasional small corestones.
Soil mainly altered with occasional small lithorelics of original soil. Little or no trace of original structures.	Highly Weathered	W IV	W IV	Highly Weathered	Rock is discoloured; discontinuities may be open and surfaces discoloured. Original rock fabric near discontinuities may be altered and penetrate deeply inwards but corestones are still present.
Soil composed of large discoloured lithorelics or original soil separated by altered material. Alteration penetrates inwards from discontinuities.	Moderately Weathered	W III	W III	Moderately Weathered	Rock is discoloured; discontinuities may be open and will have discoloured surfaces with alteration starting to penetrate inwards. Intact rock noticeably weaker than fresh rock.
Material composed of angular blocks of fresh soil which may or may not be discoloured. Some alteration starting to penetrate inwards from discontinuities separating blocks.	Slightly Weathered	W II	W II	Slightly Weathered	Rock may be slightly discoloured, particularly adjacent to discontinuities, which may be open and will have slightly discoloured surfaces. Rock not noticeably weaker than fresh rock.
			W IA	Faintly Weathered	Weathering limited to the surfaces of major discontinuities.
Parent soil shows no discolouration or loss of strength. Discontinuities usually tight and not discoloured.	Fresh	W I	W IA	Fresh	Parent rock shows no discolouration or loss of strength. Discontinuities usually tight and not discoloured.

DIAGNOSIS OF CARBONATE TYPES WITH DILUTE HYDROCHLORIC ACID

(Test comprises immersing rock chips about $\frac{1}{2}$ in dia × $\frac{1}{8}$ in thick in cold dilute acid)

Rock Type	Reaction with cold dilute HCL (1:7·10)
Limestone	Violent effervescence; frothy audible reaction; small chips will bob about and tend to float on the surface
Dolomitic Limestone	Brisk, quiet effervescence; small chips skid about on the bottom of the container and rise slightly off the bottom; there is a continuous stream of CO_2 through the acid.
Calcitic Dolomite	Mild emission of CO_2 beads; small specimens may vibrate, but tend to stay in one place.
Dolomite	No effervescence; no immediate reaction; slow formation of CO_2 beads on the surface of the rock; reaction slowly accelerates until a thin stream of beads rises to the surface, especially when heated.

Grade	Brief description	Approximate range of E (kg/sq.cm)	Bearing pressure Causing 'yield' (kg/sq.cm)	Creep properties
V	Structureless remoulded chalk containing lumps of intact chalk	<5000	<2	Exhibits significant creep
IV	Friable to rubbly chalk with open joints often infilled with soft remoulded chalk	5000-10 000	2-4	Exhibits significant creep
III	Medium to hard rubbly to blocky chalk with closely spaced slightly open joints	10 000-20 000	4-6	For pressures not exceeding 4 kg/sq. cm creep is small and terminates in a few months
II	Medium hard to hard chalk with widely-spaced, tight joints	20 000-50 000	10	Negligible creep for pressures of at least 4 kg/sq. cm
I	Hard brittle chalk with widely-spaced, tight joints	>50 000	>10	Negligible creep for pressures of at least 4 kg/sq. cm.

figure 2.3.4 (Dearman 1981) Correlation between engineering geoligical grade and mechanical properties of chalk at Mundford, England.

3 Sampling of Limestone

In order to be able to examine a wide range in mechanical and other properties it seemed most efficient to sample limestones from the various geological formations present in Europe. At the same time the relation between geological age and strength promised to be interesting. Accordingly samples were taken ranging from the limestone beds of the Silurian upto the Cretaceous calcarenites.

3.1 Sample Selection

During April 1987 twelve types of limestones were sampled from quarries in the U.K. ,Belgium and The Netherlands. Because for testing purposes solid fresh and homogeneous material was needed, large blocks of each type of limestone were selected from the highest quality zones in the quarries. Directly after this the blocks were wrapped in polyethylene bags in order to prevent the samples from drying out. In the case of the 'red marble' from Belgium it was not possible to acquire fresh material. Later in this report the test results indicate that the rock was moderately weathered.

Nearly all of the quarries in the U.K. used explosives to fragment the rockmass, while in Belgium and in Southern Limburg the limestone was cut with diamond wire or saws. Therefore it is possible that the blasting has induced fine cracks or extended preexisting cracks, which could influence the test results.

3.2 Sample Description

The description of the limestones was done following the IAEG report (1981) for engineering geological mapping (Appendix A.2). Furthermore the limestones are identified with local name, origin and geological age. The twelve samples were :

Sample 01 : The Magnesian Limestone from Yorkshire is of Permian age. It is described as a yellowish white medium grained fresh weak calcisiltite.

Sample 02 : The Chalk from near Hull is of Upper Cretaceous age, it is described as a pale white fine grained thinly laminated fresh weak calcisiltite.

Sample 03 : The Lower Oolite Limestone from Lincolnshire is of Jurassic age. It is described as a dark grey medium grained slightly weathered strong

limestone.

Sample 04 - The Upper Oolitic Limestone, also known as Corallian Limestone, from Yorkshire is of Jurassic age. It is described as a light grey medium grained fresh strong limestone.

Sample 05 - The Wenlock Limestone from Shropshire is of Silurian age. It is described as a light pinkish white coarse crystalline fossiliferous fresh strong limestone.

Sample 06 - Wooldale Limestone from Derbyshire is of Carboniferous age (Visean). It is described as a dark grayish black medium grained calcite veined fresh very strong limestone.

Sample 07 - Vinalmont Limestone, also known as Maassteen, from Belgium is of Carboniferous age (Visean). It is described as a light grey medium grained fresh very strong limestone.

Sample 08 - The Muschelkalk also known as Wellenkalk or wavy limestone from Gelderland is of Triassic age. It is described as a light whitish green fine grained thinly bedded fresh moderately strong micritic calcilutite.

Sample 09 - Belgian Fossil Limestone also known as Petit Granit, from the Dinant area in Belgium is of Carboniferous age (Tournaisian). It is described as a light grey medium grained fresh very strong limestone.

Sample 10 - Red Reef Marble from South Belgium is of Upper Devonian age (Frasnian). It is described as a whitish red fine crystalline fossiliferous moderately weathered strong limestone.

Sample 11 - Grey Marble from East Belgium is of Middle Devonian age (Givetian). It is described as a dark blackish grey medium size crystalline fossiliferous slightly weathered very strong limestone.

Sample 12 - Marl from South Limburg is of Upper Cretaceous age (Maastrichtian). It is described as a light yellowish beige medium grained fresh weak calcarenite.

An extensive engineering geological description of the rock

ENGINEERING GEOLOGICAL DESCRIPTION OF LIMESTONE
(According to I.A.E.G. Report for Description of Rocks)

CODES	AGE	ORIGIN	LOCATION	NAME	COORDIN. LONG./LAT.	GRAIN SIZE
SL01	PERMIAN	NEWTHORPE YORKSHIRE	NEWTHORPE QUARRY	MAGNESIAN LIMESTONE	W 1.17.. N 53.42..	MEDIUM
SL02	CRETACEOUS	ELSHAM YORKSHIRE	SINGLETON BIRCH QUARRY	UPPER CHALK	W 0.17.. N 53.32..	MEDIUM
SL03	JURASSIC	BRIGG LINCOLNSHIRE	LINDSEY QUARRY	LOWER OOLITE LST.	W 0.32.. N 53.24..	FINE
SL04	JURASSIC	PICKERING YORKSHIRE	HARGREAVES QUARRY	UPPER OOLITE LST.	W 0.47.. N 54.12..	COARSE
SL05	SILURIAN	MUCH WENLOCK WALES	SHADWELL QUARRY	WENLOCK LST.	W 2.34.. N 53.09..	MEDIUM
SL06	CARBONIFEROUS	BUXTON	TARMAC QUARRY	WOOLDALE LST.	W 1.53.. N 53.09..	MEDIUM
SL07	CARBONIFEROUS	VINALMONT	HAINAULT CARRIERE	VINALMONT LST.	O 4.32.. N 50.07..	MEDIUM
SL08	TRIASSIC	WINTERSWIJK GELDERLAND	ANKERSMIT GROEVE	MUSCHELKALK	O 5.55.. N 51.08..	FINE
SL09	CARBONIFEROUS	DENEE	MGP	TOURNASIAN LST.C3	O 4.45.. N 50.19..	FINE
SL10	DEVONIAN	NEUVILLE	NEUVILLE CARRIERE	MARBRE ROUGE	O 4.32.. N 50.07..	FINE
SL11	DEVONIAN	AYWAILLE	V/D WILDENBERG	MARBRE NOIR	O 5.41.. N 50.27..	FINE
SL12	CRETACEOUS	SIBBE LIMBURG	MERGELBOUW V/D KLEIN	MERGEL	O 5.49.. N 50.49..	MEDIUM

CODES	STRENGTH	JOINT SPACING	JOINT APERTURE	BEDDING	CEMENTATION	COLOUR
SL01	WEAK	MOD. WIDE	NARROW	VERY THICK	POORLY	LYW
SL02	MOD. WEAK	VERY WIDE	MEDIUM	VERY THICK	MODERATELY	LPW
SL03	STRONG	VERY WIDE	MEDIUM	VERY THICK	WELL	DBG
SL04	STRONG	VERY WIDE	OPEN	MEDIUM THICK	WELL	LYG
SL05	MOD. STRONG	MOD. WIDE	MEDIUM	MEDIUM THICK	WELL	LGW
SL06	STRONG	MOD. WIDE	OPEN	VERY THICK	MODERATELY	DGB
SL07	VERY STRONG	VERY WIDE	NARROW	VERY THICK	WELL	DB1G
SL08	MOD. WEAK	MOD. WIDE	MEDIUM	MEDIUM THICK	WELL	LBGr
SL09	VERY STRONG	VERY WIDE	NARROW	VERY THICK	WELL	LWG
SL10	STRONG	VERY WIDE	NARROW	VERY THICK	WELL	MWR
SL11	VERY STRONG	VERY WIDE	NARROW	VERY THICK	WELL	DGB
SL12	WEAK	VERY WIDE	NARROW	MEDIUM THICK	FRIABLE	LYB

CODES	WEATHERING	BEDDING TYPE	TEXTURE	ORIGINAL COMPONENTS	OTHER COMPONENTS
SL01	F	PARALLEL	GRANULAR	OOLITES	DOLOMITE
SL02	F	UNDULATING	GRANULAR	FORAMINIFERAE	FLINTS
SL03	S-M	PARALLEL	GRANULAR	PELLETS & MOLLUSCS	
SL04	S	PARALLEL	GRANULAR	OOLITES	SHELLS
SL05	S-M	UNDULATING	CRYSTALLINE	CORAL ORGANISMS	CALCITE CRYSTALS
SL06	S-M	PARALLEL	GRANULAR	CRINOIDS	CALCITE VEINS
SL07	F	PARALLEL	GRANULAR	OOLITES	MOLLUSCS
SL08	S	PARALLEL	GRANULAR	MUDS	PYRITE
SL09	F	PARALLEL	GRANULAR	CRINOIDS	CALCITE VEINS
SL10	M	UNDULATING	CRYSTALLINE	CORAL ORGANISMS	BRACHIOPODS
SL11	S	UNDULATING	CRYSTALLINE	CORAL ORGANISMS	BRACHIOPODS
SL12	F	PARALLEL	GRANULAR	PELLETS & SHELLS	FLINTS

FIGURE 3.2.1

masses from which the samples were taken is listed in fig. 3.2.1 .

3.3 Preparation of Specimens

A total of 300 cylindrical specimens were drilled for testing using core drilling bits. The number of test specimens of each limestone, subjected to one test, was six at maximum, provided the testing procedures required this. All samples were cored normal to the bedding and cored from a single block except for the Lower Oolite (SL03), the Wooldale Limestone (SL06) and the Muschelkalk (SL08). Diameters were 50, 40 and 30 mm with an maximum deviation of 0.1 % departure from the length axis.

With regard to the strength tests, 50 mm cores were taken from the weak limestones ; Magnesian Limestone (SL01), Upper Chalk (SL02), Muschelkak (SL08) and Limburgian Marl (SL12). From the stronger limestones 40 mm specimens were cored, in order to ensure that the failure load did not exceed the maximum permissive load of the load frame. After coring surface grinding was applied to the 40 mm specimens for parallel planes.The 50 mm specimens could not endure such treatment without serious damage, due to their weakness. Finally the specimens were protected from deterioration by placing them in small airtight polyethylene bags.

Specimen failure during preparation sometimes occurred along cracks and calcite veins, as not uncommonly happens. This was especially the case with the calcite veined specimen of the Carboniferous Limestone SL06. A very sensitive sample to pre-testing failure was the Muschelkalk (SL08), due to its relatively high clay content and its thinly laminated bedding.

Tolerances on the dimensions of the cylindrical specimens were generally within the conditions defined in the procedures of the ASTM (American Society of Testing Materials) or the ISRM (International Society of Rock Mechanics).

quarries from which the samples were taken is listed in fig. 3.2.

3.3 Preparation of Specimens

A total of 700 cylindrical specimens were drilled for testing using core drilling bits. The number of test specimens of each limestone, subjected to one test, was six at maximum, provided the testing procedures required this. All samples were cored normal to the bedding and cored from a single block, except for the Lower Oolite (S107), the Woodale Limestone (S105) and the Mucheikalk (S108). Diameters were 50, 40 and 30 mm with a maximum deviation of 0.2 % departure from the length axis.

With regard to the strength tests, 30 mm specimens were taken from the weak limestones : Magnesian Limestone (S104), Upper Chalk (S102), Muschelkalk (S108) and Limburgian Marl (S112). From the stronger limestones 40 mm specimens were cored, in order to ensure that the failure load did not exceed the maximum capacity of the load frame. After coring surface grinding was applied to the 40 mm specimens for parallel planes. The 30 mm specimens could not endure much treatment without serious damage, due to their weakness. Finally the specimens were protected from deterioration by placing them in small airtight polythene bags.

Specimen failure during preparation sometimes occurred along cracks and calcite veins, as not uncommonly happens. This was especially the case with the calcite veined specimen of the Carboniferous limestone S106. A very sensitive sample to pre-testing failure was the Muschelkalk (S108), due to its relatively high clay content and thin laminated bedding.

Tolerances on the dimensions of the cylindrical specimens were generally within the conditions defined in the procedures of the ASTM (American Society of Testing Materials) or the ISRM (International Society of Rock Mechanics).

4 Testing Techniques

Most tests were undertaken following ASTM or ISRM testing techniques. The sections following describe the most important features of the test methods and testing apparatus. The mechanical tests were performed on specimens at a moisture content measured after preparation of these test specimens. This is the moisture content given in table 4.11.4 . Mechanical tests were performed normal to the bedding except in the case of the tensile strength. The tensile strength had to be tested parallel to the bedding because of the testing method. Hence a bedding description is necessary.

4.1 Water Content and Density
ISRM suggested Method No. 2

The test was performed on three specimens with a diameter of 30 mm and a length/diameter ratio of 1:1 . The tests involve determination of mass under field conditions as well as after drying in an oven at 105 degrees centigrade. The average mass of the cores was 50 grams. The accuracy to which the mass was recorded is + 0.005 grams and the dimensions of the cores were measured to the nearest 0.05 mm.

4.2 Porosity
Method of Kobe

The test was undertaken following the method of Kobe with a "Ruska" universal porositymeter (appendix B.1). Oven dried cores of 30 mm diameter length/diameter ratio 1:1 were submerged in the pyknometer and their volume was measured without and with an internal pressure of 30 Psi (=206.8 KPa). The dimensions of the cores were measured to the nearest 0.05 mm and the accuracy of the volume measurements was + 0,005 ml .

4.3 Permeability

The permeability measurements were performed with a liquid-permeameter for the Limburgian Marl (SL02) cores and with a "Ruska" gaspermeameter for the other cores (appendix B.2). The liquid-permeameter uses water to determine the flowrate and is suitable for rather permeable media, such as this Limburgian Marl. The permeability using this apparatus is calculated following the formula:

4 Testing Techniques

Most tests were undertaken following ASTM or ISRM testing techniques. The sections following describe the most important features of the test methods and testing apparatus. The mechanical tests were performed on specimens at a moisture content measured after preparation of these test specimens. This is the moisture content given in table 4.11.4 . Mechanical tests were performed normal to the bedding except in the case of the tensile strength. The tensile strength had to be tested parallel to the bedding because of the testing method. Hence a bedding description is necessary.

4.1 Water Content and Density
ISRM suggested Method No. 2

The test was performed on three specimens with a diameter of 30 mm and a length\diameter ratio of 1:1 . The tests involve determination of mass under field conditions as well as after drying in an oven at 105 degrees centigrade. The average mass of the cores was 50 grams. The accuracy to which the mass was recorded is + 0.005 grams and the dimensions of the cores were measured to the nearest 0.05 mm.

4.2 Porosity
Method of Kobe

The test was undertaken following the method of Kobe with a "Ruska" universal porositymeter (appendix B.1). Oven dried cores of 30 mm diameter length\diameter ratio 1:1 were submerged in the pyknometer and their volume was measured without and with an internal pressure of 30 Psi (=206.8 KPa). The dimensions of the cores were measured to the nearest 0.05 mm and the accuracy of the volume measurements was + 0.005 ml .

4.3 Permeability

The permeability measurements were performed with a liquid-permeameter for the Limburgian Marl (S102) cores and with a "Ruska" gaspermeameter for the other cores (appendix B.2). The liquid-permeameter uses water to determine the flowrate and is suitable for rather permeable media, such as this Limburgian Marl. The permeability using this apparatus is calculated following the formula:

$$K = \frac{m\ L\ V}{A\ dP\ t}$$

where m = viscosity (Cp) ; m_{water} = 1 Cp (Cp = centi poise)
L = length of the sample (mm)
V = volume passed (cc)
A = area normal to the flow (mm)
dP = difference in pressure (KPa)
t = time interval (sec)

The gaspermeameter allows for natural gas under a certain pressure to flow through the specimen in small quantities, hence the principle is the same as for the liquidpermeameter. This apparatus measures in the range of 10^{-3} Darcy.

The specimen of 30 mm diameter and length/diameter ratio of 1:1 were oven dried and their permeability was measured with a deviation of approximately 20 % due to turbulence and gas solution in the water.

4.4 Tensile strength
ASTM standard D 3967-81

The tensile strength was determined with an indirect method known as the Brazilian Tensile Strength test (BTS test). In the procedure of this test discs of with a 50 mm diameter and 25 mm thickness are split by vertical loading through a diameter.

In the Wykeham-Farrance 100 kN strain guided loading frame platens were connected to LVDT (Linear Variable Differential Transducers) displacement transducers. The LVDT's used are electromechanical transformers with a range of + 1 mm. The load was transmitted by a 50 kN load transducer. Through an 12 bits A/D converter displacements and load were digitized and recorded for every 0.001 mm vertical deformation. The displacement rate of the loading frame was 0.1 mm/min.

4.5 Unconfined Double Shear Test

This test determines the direct shear strength of intact rock as suggested by T.R. Stacey (1980).The test frame was developed by the section of Engineering Geology of the Technical University of Delft. The method involves punching a steel block trough a rock disc of 50 mm diameter and a Thickness of 10 mm .Two predetermined shear planes show when the failure occurs. Loading should be applied at a rate of 15 kN/min.

The shear test apparatus was placed in the ELE point load testing frame. The Unconfined Shear Strength was calculated with

the formula :

$$USS = \frac{P}{T * (L_1 + L_2)}$$

USS = Unconfined Shear Strength (MPa)
P = failure load (kN)
L_1&L_2 = length's of the shear planes (mm)
T = disc thickness (mm)

Because no clear planes developed the measurement of the shear planes in some cases had to be estimated. The accuracy of the length measurement was + 0.05 mm, while the load gauges deviated approximately 1 kN.

4.6 Unconfined Compressive Strength, Elastic-modulus and Poisson's ratio
ASTM D 2938-79, ASTM 3148-80

The Unconfined Compressive Strength (UCS) was determined using a 700 kN closed loop servo controlled load frame (see appendix B.3) for the 40 mm length cores and the WF 100 kN load frame for the 50 mm length cores. The length diameter ratio of the test specimens was 2:1 . The rate of loading was adapted so that the time in which the sample failed was 5 to 10 minutes. The exact loading rate range was 5.6 - 11.9 MPa/min.

Using LVDT transducers the vertical displacements were twice measured in opposite directions. The lateral displacements were four times measured at angles of 90 degrees. The measurement interval was fixed at 0.001 mm vertical deformation. This implied that for every 0.001 mm vertical deformation data were stored in the computer. Together with the signal from the load transducers they were digitized and converted to mean values for the proper stress-strain relations which were recorded on floppy disk.

Then from the deformation curves the elastic moduli were calculated with a tangent method at 50 % of the failure stress or, if the slope at 50 % of the failure stress was not representative, the average was token at the point of inflexion. At the same point the Poisson's ratio's were calculated, dividing the lateral strain by the vertical strain.

4.7 Ultra Sonic Velocity
ISRM suggested method No. 4

This index test was undertaken on the specimens prepared for the UCS using a CCT 4 ultra sonic velocity concrete tester. Pulses are generated by a 10 MHz oscillator and passed through the sample. Travel times are measured continuously in microseconds. To exclude the signal from other media a contact fluid is applied to both ends of the core.

4.8 Slake Durability
ISRM suggested document 2 part 2

The slake durability test is a combination of abrasion and slaking performed on 10 lumps of the sample. The limestone lumps are agitated by revolving them in a cylindrical mesh drum in cycles of 10 minutes, immersed in water. Following this the retained material in the drum is oven dried at 105 degrees centigrade and weighed. The Slake Durability Index is then calculated from the formula given below:

$$Id_2 = \frac{W_3}{W_1} * 100\ \%$$

were : Id_2 = slake durability index
W_3 = weight after the second cycle
W_1 = weight before first cycle

The accuracy of the balance measurements + 0.005 grams.

4.9 X-Ray Fluorescence

The percentages CaCO and MgO were determined with the X-Ray fluorescence technique from the Rontgen Laboratory of the Department of Mining and Petroleum Engineering (appendix B.4).

Sample preparation was performed by crushing representative core specimen to maximum diameter of 0.02 mm using a disc-crusher. Next the crushed sample was mixed and divided into equal portions.

The analyses were conducted on glass pearls (0.5 g sample + 5.0 g $Li_2B_4O_7$). Thus the pearls were compared with standard samples of the same matrix. With the aid of a linear regression method the percentages were calculated. Thereupon corrections for inter-element effects and weighing inaccuracy were applied. The total error of the calculated values is no more than 0.5 % .

4.10 Carbonate Resistance Index (CRI)

This test was developed by the author with the purpose to give an indication of the relative solubility rate of the carbonate rocks. The test may be considered valid only for those limestones, consisting for the major part of calcium and/or magnesium carbonate and in which no other significant in acid soluble minerals occur.

The test involves the submerging of a dried and weighed test specimen (the one used was cylindrical) in a 1.0 N hydrochloric acid. The specimen remains in 150 ml of this solution for exact 5 minutes were after the specimen is oven dried and weighed. The CRI is calculated with the following formula :

$$CRI = \frac{\text{Loss of weight}}{\text{Original weight}} * \frac{\text{Surface area of the specimen}}{\text{Surface area of a sphere with the same volume}} * (CO_3\text{-correction})$$

when applied to a cylindrical specimen the CR-Index is :

$$CRI = \frac{(W_1 - W_2)}{W_1} \cdot \frac{(2.\pi.R_d + 2.\pi.R_d.D)}{(4.\pi.R_s)} \cdot \frac{10000}{\%CO_3}$$

were : W_1 = dry weight before testing
W_2 = dry weight after testing
R_d = diameter of the cilinder
R_s = diameter of imaginary sphere of the same content
D = thickness of the cilinder
$\% CO_3$ = total amount of carbonate material

R_s is calculated from the formula : $R_s = \sqrt[3]{\{ 3/4.R_d.D \}}$

The temperature at which the test was performed was 22 degrees centigrade. For each test a new volume of acid is required. The measurement accuracy is + 0.05 mm. for length's and + 0.005 gram for weight.

4.11 Presentation of the Test Results

The complete record of all calculated test results is given in tables 4.11.2 - 4.11.4 . In these tables the above mentioned parameters are indicated for the twelve limestone samples. To simplify the presentation codes for the samples and abbreviations for the parameters, which are explained at the top of the table, are used (table 4.11.1). The accuracies are conform the limitations of the performed tests.

4.12 Microscope Study

The main aim of the microscope study was the identification of features related to engineering properties. As mentioned in chapter 2 the important contaminant minerals, besides carbonates, can be quartz, both detrital and silica quartz, and clay minerals such as bentonite and illite. Small amounts of carbonaceous fines cause the grey colour in the limestones. From physical point of view the grain sizes and the hardnesses of the various minerals form a point of investigation. The cuttability and the abrasive capacity are engineering parameters directly related to these factors.

From the limestone samples 12 thin sections have been examined under a transmitted light polarizing microscope. With the use of density diagrams the percentages of non-carbonate minerals have been estimated. The determination of grain sizes was done following the linear intercept method ; here the average intercept length has been multiplied by a correction factor of 1.5 as suggested in DIN 22021 (1985).

The data are summarized in table 4.12.1 where also the origin of the components is given. If the rock consists of particles and matrix, the grain size of both is indicated.

LEGEND for TEST RESULTS

TYPE OF TEST :

UCS = Unconfined Compressive Strength (MPa)
BTS = Brazilian Tensile Strength (MPa)
USS = Unconfined Shear Strength (MPa)
E-Modulus = Deformation Constant (GPa)
Poisson's Ratio = Lateral/Vertical Strain
Velocity = Ultra Sonic Velocity (m/s)
Porosity = Effective Porosity (%)
Permeab. = Permeability (mDarcy)
N.M.Cont = Natural Moisture Content (%)
Dry Density = Dry density (Tons/M^3)
Nat. Density = Natural Density (Tons/M^3)
CR-Index = Carbonate Resistence Index
Id2 =Slake Durability Index
MgCO3 %'= Magnesium Carbonate % (Dolomite)
CaCO3 % = Calcium Carbonate %
XRF ANALYSIS = X-Ray Diffraction

TYPE OF LIMESTONE :

SL01 = Magnesian Limestone
SL02 = Upper Chalk
SL03 = Lower Oolite
SL04 = Upper Oolite
SL05 = Wenlock Limestone
SL06 = Carboniferous Limestone
SL07 = Maassteen (Crinoid Lst.)
SL08 = Muschelkalk
SL09 = Belgian Fossil Limestone
SL10 = Red Marble
SL11 = Grey Marble
SL12 = Limbargian Marl

STATISTIC CODES (see table 5.1.1)

Nx = Number of test results
[S.D.] = Standard Deviation
Avg. = Average Value
* for median average values of tested sets
+ for mean average values of tested sets

SAMPLE CODES (see tables 4.11.1-3)

For Example SL03.2.1 means :

SL = Sample
03 = Third sample type
.2 = Second test series
.1 = First specimen

table 4.11.1

table 4.11.2

SAMPLE CODES	U.C.S. MPa	E-MODULUS GPa	POISSON RATIO	VELOCITY M/S	SAMPLE CODES	BTS MPa	STRAIN 10^-3 mm	SAMPLE CODES	USS MPa
SL01.1.1	11.69	2.88	.45	2421	SL01.2.1	1.38	175.42	SL01.3.1	7.92
SL01.1.2	10.18	4.22	.30	2509	SL01.2.2	2.41	223.02	SL01.3.2	7.76
SL01.1.3	13.23	5.35	.19	2612	SL01.2.3	2.15	163.08	SL01.3.3	4.47
SL01.1.4	13.73	4.71	.31	2604	SL01.2.4	1.03	161.50	SL01.3.4	5.21
SL01.1.5	15.29	5.27	.13	2603	SL01.2.5	2.22	3.91	SL01.3.5	4.45
SL01.1.6	12.68	4.24	.68	2750	SL01.2.6	2.18	197.87	SL01.3.6	7.02
SL02.1.1	24.89	10.90	.16	4297	SL02.2.1	3.23	158.44	SL02.3.1	13.78
SL02.1.2	13.48	8.91	.15	4197	SL02.2.2	2.38	345.21	SL02.3.2	11.27
SL02.1.3	26.73	10.99	.25	4233	SL02.2.3	3.37	186.65	SL02.3.3	16.57
SL02.1.4	19.98	9.33	.11	4111	SL02.2.4	1.53	151.61	SL02.3.4	14.17
SL02.1.5	24.63	13.39	.36	4416	SL02.2.5	3.43	167.96	SL02.3.5	9.80
SL02.1.6	25.27	13.39	.37	4057	SL02.2.6	3.74	157.10	SL02.3.6	13.34
SL03.1.1	96.07	40.35	.33	5570	SL03.2.1	6.87	154.54	SL03.3.1	22.04
SL03.1.2	86.75	39.89	.31	5594	SL03.2.2	5.64	127.32	SL03.3.2	20.91
SL03.1.3	115.79	38.49	.33	5575	SL03.2.3	6.72	96.56	SL03.3.3	25.14
SL03.1.4	92.67	40.20	.27	5525	SL03.2.4	6.05	95.46	SL03.3.4	22.65
SL03.1.5	116.47	41.19	.29	5564	SL03.2.5	6.21	103.89	SL03.3.5	14.45
SL03.1.6	95.00	42.47	.31	5534	SL03.2.6	5.93	82.03	SL03.3.6	15.26
SL04.1.1	138.52	37.37	.32	5319	SL04.2.1	5.62	135.25	SL04.3.1	21.61
SL04.1.2	117.25	30.96	.27	4990	SL04.2.2	6.08	186.09	SL04.3.2	20.26
SL04.1.3	125.80	31.16	.29	5103	SL04.2.3	6.88	135.86	SL04.3.3	16.31
SL04.1.4	80.72	29.86	.37	5025	SL04.2.4	6.81	110.10	SL04.3.4	19.80
SL04.1.5				5252	SL04.2.5	7.41	113.16	SL04.3.5	17.22
SL04.1.6	122.59	32.92	.31	5236	SL04.2.6	8.47	142.60	SL04.3.6	22.62
SL05.1.1	81.02	62.42	.33	5534	SL05.2.1	6.10	59.20	SL05.3.1	21.52
SL05.1.2	71.40	62.57	.33	5536	SL05.2.2	5.05	58.72	SL05.3.2	21.72
SL05.1.3	74.99	57.74	.39	5308	SL05.2.3	6.59	70.07	SL05.3.3	19.26
SL05.1.4	75.48	62.93	.36	5571	SL05.2.4	5.43	56.88	SL05.3.4	10.39
SL05.1.5	72.08	63.16	.36	5525	SL05.2.5	6.37	66.04	SL05.3.5	26.78
SL05.1.6	78.10	64.56	.39	5881	SL05.2.6	6.42	64.58	SL05.3.6	20.36
SL06.1.1				6277	SL06.2.1	9.31	90.33	SL06.3.1	22.33
SL06.1.2	107.83	64.92	.32	6455	SL06.2.2	7.51	72.63	SL06.3.2	19.88
SL06.1.3	56.83	62.38	.30	6372	SL06.2.3	9.53	84.96	SL06.3.3	24.40
SL06.1.4	86.07	62.62	.30	6404	SL06.2.4	7.59	65.06	SL06.3.4	22.64
SL06.1.5	170.87	64.94	.35	6285	SL06.2.5	8.01	80.08	SL06.3.5	30.26
SL06.1.6					SL06.2.6	4.53		SL06.3.6	24.70

table 4.11.3

SAMPLE CODES	U.C.S. MPa	E-MODULUS GPa	POISSON RATIO	VELOCITY M/S	SAMPLE CODES	BTS MPa	STRAIN 10^-3 mm	SAMPLE CODES	USS MPa
SL07.1.1	195.06	70.09	.32	6569	SL07.2.1	6.57	61.17	SL07.3.1	32.70
SL07.1.2	185.83	69.94	.31	6526	SL07.2.2	7.90	83.84	SL07.3.2	24.36
SL07.1.3	190.78	70.18	.31	6562	SL07.2.3	8.14	75.81	SL07.3.3	24.57
SL07.1.4	191.85	70.83	.30	6569	SL07.2.4	7.70	76.66	SL07.3.4	25.41
SL07.1.5	194.67	70.37	.32	6559	SL07.2.5	6.91	73.12	SL07.3.5	22.79
SL07.1.6	184.37	70.61	.32	6536	SL07.2.6	6.84	74.71	SL07.3.6	--------
SL08.1.1	83.81	17.16	.37	6136	SL08.2.1	5.22	119.02	SL08.3.1	21.60
SL08.1.2	51.10	12.20	.32	4141	SL08.2.2	7.39	145.26	SL08.3.2	19.85
SL08.1.3	37.61	11.81	.70	4103	SL08.2.3	6.49	134.40	SL08.3.3	19.46
SL08.1.4	66.58	15.81	.44	4132	SL08.2.4	4.20	226.07	SL08.3.4	20.44
SL08.1.5	39.29	13.17	.19	4212	SL08.2.5	5.84	151.00	SL08.3.5	13.97
SL08.1.6	66.21	16.11	.27	4128	SL08.2.6	5.59	136.35	SL08.3.6	18.76
SL09.1.1	148.82	69.18	.29	6439	SL09.2.1	9.63	96.44	SL09.3.1	20.64
SL09.1.2	159.51	70.80	.34	6445	SL09.2.2	6.34	86.55	SL09.3.2	19.88
SL09.1.3	153.00	69.29	.32	6445	SL09.2.3	9.71	92.16	SL09.3.3	21.65
SL09.1.4	159.99	69.83	.34	6468	SL09.2.4	8.75	89.48	SL09.3.4	22.13
SL09.1.5	158.63	69.72	.35	6432	SL09.2.5	6.20	93.63	SL09.3.5	22.79
SL09.1.6	162.52	70.72	.35	6413	SL09.2.6	9.50	105.35	SL09.3.6	22.69
SL10.1.1	96.07	51.40	.22	6006	SL10.2.1	6.59	177.60	SL10.3.1	28.81
SL10.1.2	80.53	52.55	.34	6104	SL10.2.2	7.05	96.56	SL10.3.2	21.52
SL10.1.3	86.55	57.66	.27	6166	SL10.2.3	5.65	104.25	SL10.3.3	34.66
SL10.1.4	107.15	54.22	.28	6153	SL10.2.4	6.46	152.59	SL10.3.4	26.99
SL10.1.5	61.10	55.46	.37	6196	SL10.2.5	7.11	81.79	SL10.3.5	29.67
SL10.1.6	105.20	59.42	.32	6210	SL10.2.6	5.01	75.93	SL10.3.6	29.55
SL11.1.1	141.34	68.46	.32	6155	SL11.2.1	9.42	95.33	SL11.3.1	20.77
SL11.1.2	160.96	67.52	.29	6226	SL11.2.2	8.65	86.91	SL11.3.2	24.44
SL11.1.3	156.01	62.10	.30	6206	SL11.2.3	8.39	78.98	SL11.3.3	20.93
SL11.1.4	156.01	62.36	.30	6097	SL11.2.4	7.83	89.36	SL11.3.4	20.49
SL11.1.5	178.45	66.77	.34	6212	SL11.2.5	9.75	94.36	SL11.3.5	18.15
SL11.1.6	152.12	76.58	.34	6200	SL11.2.6	10.47	101.20	SL11.3.6	21.85
SL12.1.1	3.54	1.24	.22	1755	SL12.2.1	.41	430.78	SL12.3.1	1.07
SL12.1.2	3.72	1.29	.25	1746	SL12.2.2	.41	467.65	SL12.3.2	.68
SL12.1.3	4.11	1.17	.29	1741	SL12.2.3	.40	425.70	SL12.3.3	.59
SL12.1.4	3.46	1.25	.25	1792	SL12.2.4	.38	505.16	SL12.3.4	.94
SL12.1.5	2.86	1.01	.19	1772	SL12.2.5	.33	384.03	SL12.3.5	.69
SL12.1.6	3.41	1.28	.30	1790	SL12.2.6	.37	363.16	SL12.3.6	1.01

table 4.11.4

CODE SAMPLE	POROSITY (%)	PERMEABILITY m Darcy	DRY DENSITY (TON/M3)	NAT. DENSITY (TON/M3)	M.N.CONT. (%)	CR-INDEX	SLAKE DURABILITY Id2	XRF-ANALYSIS
SL01.4.1	38.16	2.46	1.75	2.11	17.38	154.3	80.91	CaCO3%-62.18
SL01.4.2	37.93	2.60	1.76	2.11	16.78	163.1		MgCO3%-37.92
SL01.4.3	37.81	3.57	1.77	2.13	16.95			
SL02.4.1	14.97	0	2.30	2.41	4.75	70.6	98.03	CaCO3%-97.60
SL02.4.2	16.59	0	2.25	2.38	5.26	75.0		MgCO3%- 0.90
SL02.4.3	15.53	0	2.28	2.40	5.23			
SL03.4.1	5.41	0	2.57	2.61	1.60	86.1	98.78	CaCO3%-92.66
SL03.4.2	2.71	0	2.59	2.63	1.36	85.5		MgCO3%- 1.19
SL03.4.3	3.27	0	2.58	2.62	1.50			
SL04.4.1	2.12	0	2.53	2.58	2.07	75.7	99.65	CaCO3%-83.64
SL04.4.2	2.09	0	2.55	2.59	1.65	80.6		MgCO3%- 0.99
SL04.4.3	1.79	0	2.51	2.57	2.11			
SL05.4.1	1.11	0	2.68	2.68	.02	79.3	98.86	CaCO3%-97.41
SL05.4.2	1.14	0	2.68	2.68	.04	82.1		MgCO3%- 1.10
SL05.4.3	.98	0	2.68	2.68	.02			
SL06.4.1	.60	0	2.67	2.67	.19	75.0	98.11	CaCO3%-98.40
SL06.4.2	.49	0	2.68	2.68	.13	78.7		MgCO3%- 1.13
SL06.4.3	.61	0	2.67	2.68	.21			
SL07.4.1	.37	0	2.69	2.69	.05	88.8	99.32	CaCO3%-99.37
SL07.4.2	.70	0	2.68	2.68	.09	91.1		MgCO3%- 0.74
SL07.4.3	.66	0	2.68	2.69	.09			
SL08.4.1	6.13	0	2.56	2.58	.69	108.6	96.31	CaCO3%-82.01
SL08.4.2	4.02	0	2.55	2.57	.64	113.6		MgCO3%- 4.29
SL08.4.3	6.10	0	2.54	2.56	.79			
SL09.4.1	.88	0	2.67	2.67	.02	78.2	99.38	CaCO3%-97.13
SL09.4.2	1.04	0	2.66	2.66	.03	78.8		MgCO3%- 1.51
SL09.4.3	.99	0	2.67	2.67	.05			
SL10.4.1	.64	0	2.69	2.69	.07	75.9	98.99	CaCO3%-91.00
SL10.4.2	.63	0	2.69	2.69	.13	78.4		MgCO3%- 2.00
SL10.4.3	.49	0	2.69	2.70	.05			
SL11.4.1	.84	0	2.68	2.69	.19	75.5	99.48	CaCO3%-96.71
SL11.4.2	.76	0	2.68	2.69	.15	77.2		MgCO3%- 1.99
SL11.4.3	.78	0	2.68	2.68	.16			
SL12.4.1	50.15	4600	1.34	1.72	22.20	258.0	71.41	CaCO3%-96.64
SL12.4.2	50.02	5500	1.34	1.71	21.98	266.6		MgCO3%- 1.70
SL12.4.3	49.97	5400	1.33	1.71	21.97			

MICROSCOPE STUDY OF THIN SECTIONS

SAMPLE CODES	GRAINSIZE mm		QUARTZ (%)	FELDSPAR (%)	**ARG.FINES (%)	CARBON	SHAPE OF PART./CRYST.	TYPE OF COMPONENT	ABRASIVE CAPACITY
SL01	.13	Particle					Rounded	Oolitic	0
	.001	Matrix							
SL02	.07	Particle	+		+		Rounded	Skeletal	1
	.002	Matrix							
SL03	.80	Particle	++	+		+	Sub Rounded	Pellets	2
	.07	Matrix							
SL04	.09	Particle			00	+	Sub Rounded	Sketetal + Muds	1
	.002	Matrix							
SL05	4.80	Crystals		+			Irregular	Skeletal (Reefoidal)	1
SL06	.09	Particle *Crys.cem.				+	Rounded	Skeletal	1
SL07	.48	Particle *Crys.cem.				+	Rounded	Skeletal (Crinoidal)	2
SL08	.01	Particle *Crys.cem.			00		Sub Angular	Muds	1
SL09	.60	Particle *Crys.cem.	+			+	Sub Angular	Oolitic + Fossils	2
SL10	.01	Crystals	+	+			Angular	Skeletal (Reefoidal)	2
SL11	.08	Crystals		+		+	Angular	Skeletal (Reefoidal)	2
SL12	.12	Particle					Rounded	Pellets	0
	.01	Matrix							

LEGEND OF MICROSCOPE DATA

MODAL VOLUMES OF MINERALS :

00 = 6-10 %
0 = 3-6 %
++ = 1-3 %
+ = < 1 %

ABRASIVE CAPACITY :

F = Quartz % * Grainsize * BTS * 10

CUTTABILITY :

Ratio (UCS/BTS)

TYPE OF LIMESTONE :

SL01 = Magnesian Limestone
SL02 = Upper Chalk
SL03 = Lower Oolite
SL04 = Upper Oolite
SL05 = Wenlock Limestone
SL06 = Carboniferous Limestone
SL07 = Maassteen (Crinoid Lst.)
SL08 = Muschelkalk
SL09 = Belgian Fossil Limestone
SL10 = Red Marble
SL11 = Grey Marble
SL12 = Limbargian Marl

* = Crystalline Cement
**= Argillaceous Fines

table 4.12.1

5 Evaluation of test results

In order to be able to rely upon the information about the test results, the strength's and weaknesses of the various data must be assessed. This can be done with the help of statistics and a knowledge of the limestones in relation to their properties. When the test parameters are also compared it is possible say something about the degree of correlation.

5.1 Statistical Analysis

Distributions of the performed tests have certain characteristics such as their midpoint; measures indicating their spread; and measures of symmetry of the distribution. These characteristics are known as parameters if they describe the population of a limestone, and statistics if they refer to sets of limestone test data. In the following sections the statistics are used to estimate the parameters of the parent population, which is represented by the single block, and to test hypotheses about these populations.

The most obvious of a data set is some type of average value. Two of the important ones are the mean and the median; the mean representing the sum of the data divided by the number of data; and the median being the value, which at ranking in height takes the most middlemost value. To decide which average renders the most realistic value for the limestone properties concerned, the character of the frequency distribution is of importance. In a normal distribution, which is symmetric, the highest frequency coincides with the mean and the median. Since in this case the mean uses the values of all the data, and is demonstrated to be closer to the population mean than any other average, it is the most useful estimator. If however the distribution is strongly asymmetric the median may render more information about the population of limestone properties, because it is not so sensitive to single values with a large deviation. In strength properties the median value tends to be higher than the mean value. This is caused due to the fact that local weak planes in the block of limestone result in low test values, which are by no means representative for the rock material.

A set of data consists of all the values related to one test parameter and to one type of limestone (table 4.11.1). To test the hypothesis whether a data set is normal or not, and whether the mean value should be used or not, only the sets of 6 data can be subjected to such a normality test. Concerning the sets with less data, their number is too small to predict their distribution. Hence only a mean value can be calculated.

i	x(i)	$(x(i) - \bar{x})/s$	$t_i = \hat{F}(x(i))$	$(t_i - \frac{2i-1}{2n})^2$
1	1,34	-1,581	0,0569	0,00005
2	1,38	-1,186	0,1178	0,00104
3	1,41	-0,889	0,1870	0,00397
4	1,47	-0,296	0,3836	0,00113
5	1,49	-0,099	0,4606	0,00011
6	1,53	0,296	0,6164	0,00441
7	1,56	0,593	0,7234	0,00539
8	1,57	0,692	0,7555	0,00003
9	1,59	0,889	0,8130	0,00137
10	1,66	1,581	0,9431	0,00005
$W^2 = 0,01755 + \frac{1}{120} = 0,02588$				0,01755

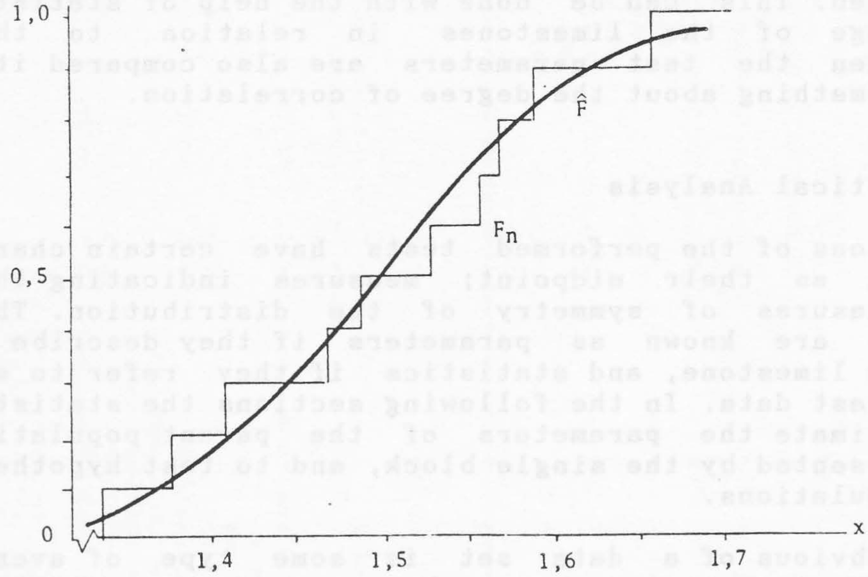


figure 5..1.1 the cumulative frequency distribution of a data set (xi) (van Soest 1983)

In case of a small number of data per set the most suitable test for normality is the one characterized as the empirical distribution function F_n (appendix C.1), which estimates the real distribution F. With this method it is possible to check the cumulative frequency distribution for normality with a certain unreliability (fig. 5.1.1). If the integrated quadratic difference between F_n and F is lower than a critical value, the distribution of the data set gives no cause for the population not to be normally distributed. This critical value is defined by the unreliability and the number of data in the set. If however the difference is higher than the normality of the data set is rejected and nothing can be said about the distribution of the population. In that event the median value is then taken as a representative average.

A measurement of the spread in the distributions is given by the calculation of the standard deviation for every set containing more than 2 data.

After application of the normality test it proved that 86 % of the data sets was normal distributed with a 10 % unreliability and 14 % of the data were not normal distributed. Hence in table 5.1.1 the average values are marked with an (*) are median values of negative tested data sets and those marked with a (+) are mean values of positive tested data sets. Behind them the averages, standard deviations and the number of data are given.

In case of the porosity of the Lower Oolite limestone (SL03) the difference between the three values was so high that it seemed not reasonable to define mean and deviation here.

5.2 Remarks on the average values

The UCS shows a wide range of values, which may be considered are representative for limestones with relative high moisture contents, in specific the weak limestones. An overview of all the stress vs. strain curves is given in figures 5.2.1-5.2.3, each plot containing 4-6 specimen of the same type. In figure 5.2.4 the relation of UCS vs. Geological age proves that not always the strength does increase with time. Four types (Permian limestone SL01, Silurian limestone SL05, Carboniferous limestone SL06 and Devonian limestone SL10) show deviating behaviour, which may be the result of external influences such as the relaxation of tectonic stresses or weathering processes.

The highest E-moduli are approximately 70 GPa and are therefore concurring to the expectation that pure calcite has the highest value, namely 85.0 GPa (Belikov 1967). The type of failure is for the stronger limestones generally an axial multi fracture, whereas for the weak ones mainly conical shaped end segments are formed along single shear planes. From figures 5.2.5

- 5.2.7 to typical E-moduli are viewed for all the samples.

The Poisson ratio's vary from 0.23 to 0.34 which is in accordance with the mentioned limestone ranges in the literature (Lama & Vutukuri 1978).

The ultra sonic velocities are can be related with the velocity of calcite. The quality of the limestone can be indexed by means of a ratio (Fourmaintraux 1976) :

$$IQ\ \% = \frac{V_{sample}}{V_{calcite}} * 100\ \% \quad \text{and } V_{calcite} = 6600\ m/s$$

Experiments have established that the IQ is affected by pores and fissures. Typical values for strong limestones range from 6000 to 6500 m/s .

The brazilian tensile strength shows only for the "Maas-steen" (SL07) an unexpected low value. The reason is unknown. From the stress vs. strain plots in fig. 5.2.8 - 5.2.10 it is seen that the stability of the curve decreases with increasing strain. The reason is the inaccuracy of the load transducer. The weak Limburgian Marl shows an enormous frequency, which is due to the large amount of strain measurements at low stress.

The measured porosity is an effective porosity, hence permeable limestones, such as the Limburgian Marl (SL12) and the Magnesian Limestone (SL01), will approach the total porosities to a higher degree than the nearly impermeable ones.

The zero permeability values of the stronger limestones indicates that nothing could be measured. The general permeabilities of these limestones should be, according to the literature (Brace 1978) between 10^{-5} and 10^{-13} m/s.

The slake durability can be rated with the classification of Gamble (1971) Concerning the data the lowest durability is then rated as "medium durability" (table 5.2.1).

groupname	% retained after two cycles
very high durability	> 98
high durability	95-98
medium high durability	85-95
medium durability	60-85
low durability	30-60
very low durability	< 30

table 5.2.1 Gamble's slake durability classification

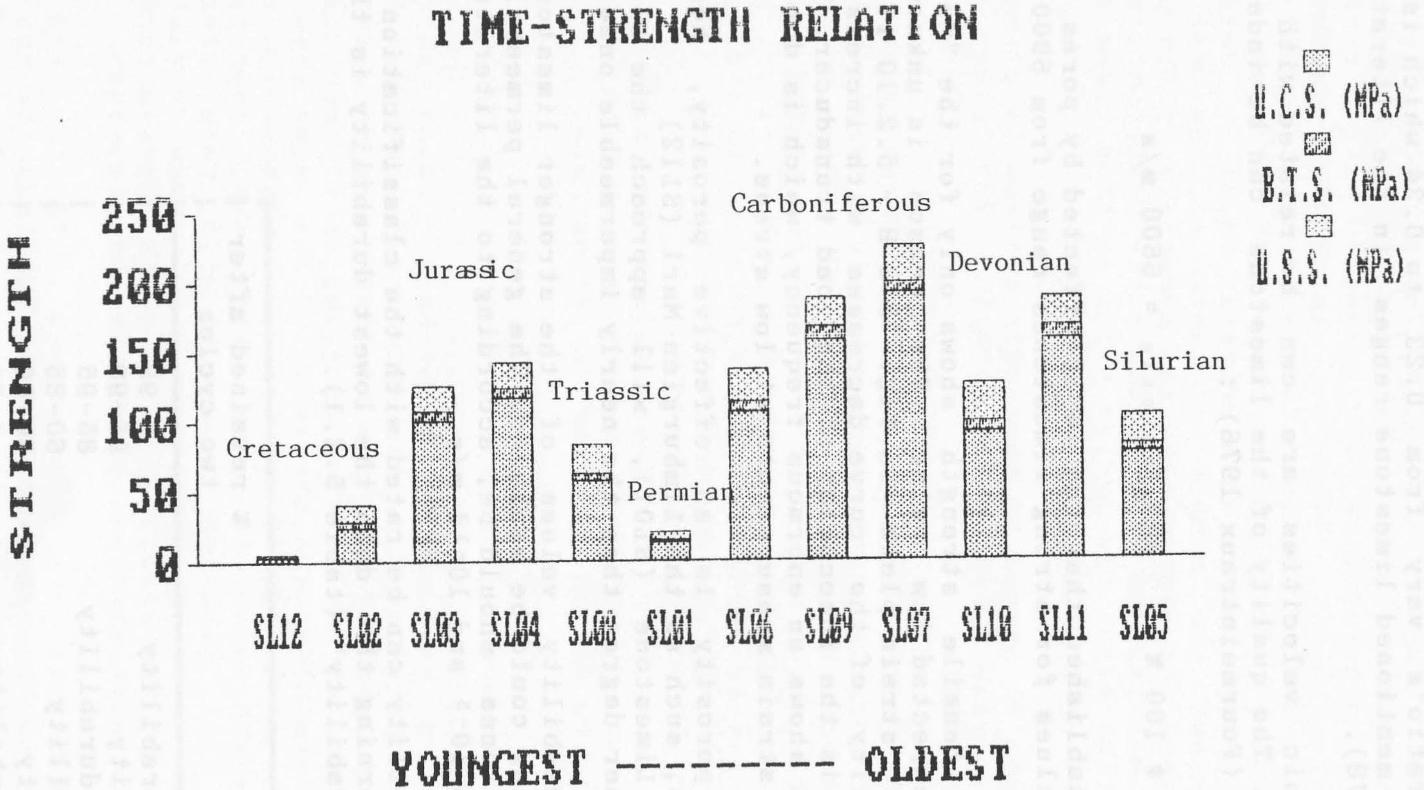


figure 5.2.4 The time-strength relation for 12 types of limestone with increasing age from left to right

The dry densities are all lower than the absolute density of pure calcium carbonate; specific gravity of $CaCO_3$ is ~ 2.71 (Handbook of Chemistry and Physics 1982).The differences in dry density are in the first place explained by pores and fissures and secondly by the contaminant minerals of the samples, with different specific gravities; $MgCO_3$ (magnesium) has a specific gravity of ~ 2.95 . This causes the gravity of the Magnesian Limestone (SL02) to be slightly higher than normal.

From the X-ray diffraction it is apparent that not all the sampled limestones are indeed pure limestones; the Magnesian Limestone (SL01), the Upper Oolite Limestone (SL04) and the Muschelkalk (SL08) have a $CaCO_3$ content between 50 % and 90 %, and thus actually have to be named "impure limestones" following the geological classification of Leighton & Pendexter.

The lowest value of the CR-Index is estimated to be in the range of 65-70 (fig. 5.3.2). Deviating values of the Carbonate Resistance Index are the Upper Chalk (SL02) and the "Maassteen" (SL07). It is found from the results that the solubility is reated to the effecive porosity of the rock.

5.3 Correlation of Parameters

When the parameters are mutually compared two types of functions are suggested from the correlation of the plots ; linear and logarithmic functions. If the correlation coefficient for such a function is greater than 0.8 it is assumed that the parameters are related. In the following sections correlations are made between the most important parameters.

Generally there are three groups distinguished by the sort of parameters compared; the mechanical parameters, like UCS, BTS, E-modulus and the physical parameters like porosity, density sonic velocity and moisture content.

In the first group the mechanical parameters are compared with each other, and in figure 5.3.1 linear correlations are evident; If the UCS increases the BTS and E-modulus increase proportionally.

In the second group mechanical parameters are correlated with physical ones (fig. 5.3.2). It shows that these relations have a strong tendency towards logarithmic functions, because their correlation coefficient may be as high as 0.96 .
The logarithmic functions have asymptotes at X and Y values.
For example the sensitivity of UCS is the highest for very low porosity values and therefore the relation has a vertical asymptote. It is confirmed in the literature (Dearman 1982) that this is true (fig. 5.3.3) for dolerites.

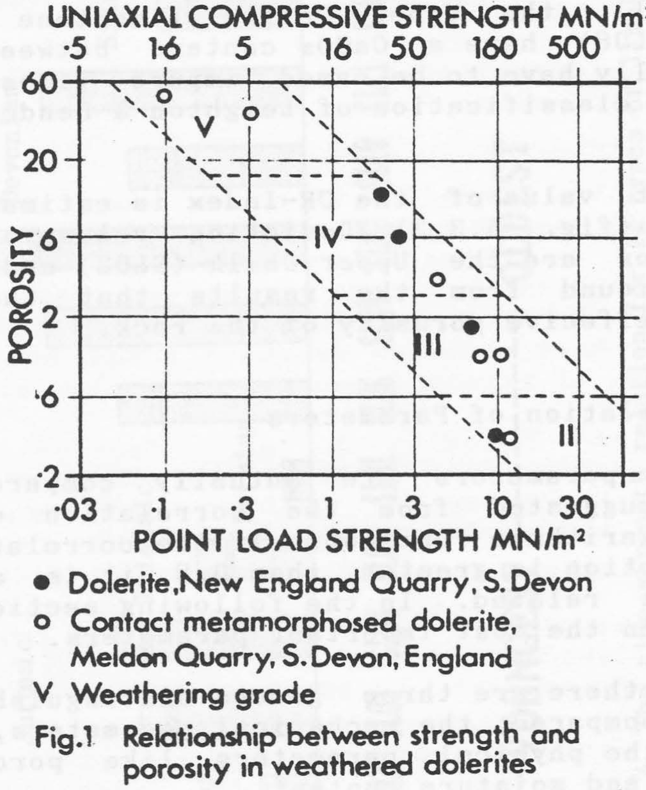


figure 5.3.3 The relation between Porosity and UCS (Dearman 1982)

The third group regards physical vs. physical parameters, such as dry density vs. porosity (fig. 5.3.4). For this example a linear correlation is almost absolute. When reviewing the literature it was found that this is correct (Goodman 1980) for the relation porosity vs. dry density :

$$\gamma_{dry} = \gamma_{w} . G . (1-n)$$

were γ_{dry} = dry density
γ_{w} = wet density
G = specific gravity
n = porosity

The other correlations in this group exhibit the same linearity.

Finally the correlation of grain sizes with mechanical and physical properties did not exist for the sample data. Correlation coefficients were between -0.5 and 0.5 .

Figure 5.2.3 The relation between Porosity and IS (Dearman 1982)

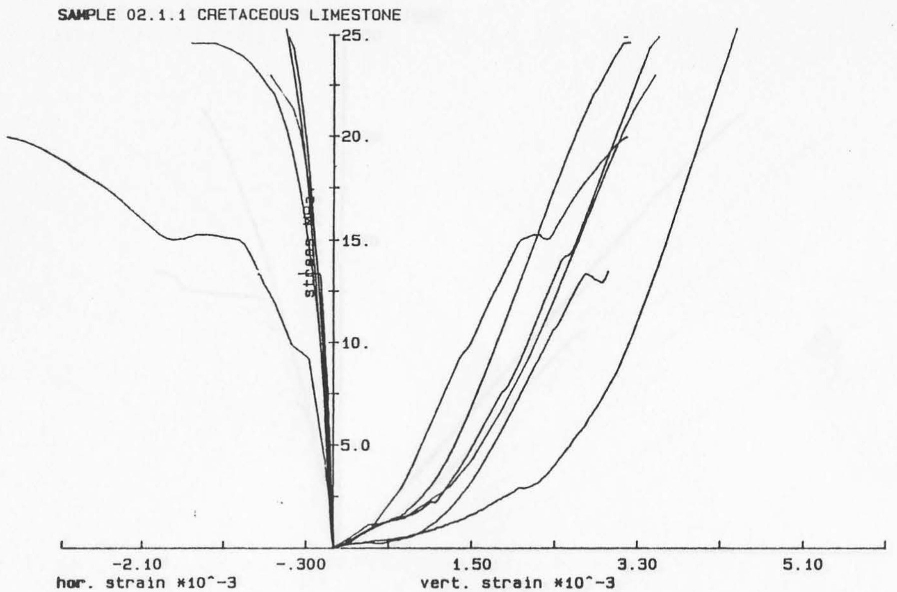
CODE SAMPLE	U.C.S. (MPa) Avg.	[S.D.]	Nx	E-MODULUS (GPa) Avg.	[S.D.]	Nx	POISSON RATIO Avg.	[S.D.]	Nx	SONIC VEL. (M/S) Avg.	[S.D.]	Nx
SL01	12.82 +	[1.75]	6	4.48 *	[.91]	6	.31 *	[.20]	6	2580 +	[110]	6
SL02	24.76 *	[4.97]	6	11.15 +	[1.92]	6	.23 +	[.11]	6	4198 +	[117]	6
SL03	100.46 +	[12.56]	6	40.15 +	[1.42]	6	.31 +	[.02]	6	5560 +	[26]	6
SL04	116.98	[21.73]	5	32.45	[2.96]	5	.31	[.03]	5	5169 +	[123]	6
SL05	75.51 +	[3.63]	6	63.13 +	[.85]	6	.34 +	[.02]	6	5535 *	[184]	6
SL06	105.40	[48.40]	4	63.72	[1.41]	4	.32	[.02]	4	6358 +	[77]	6
SL07	190.43 +	[4.46]	6	70.34 +	[.34]	6	.31 +	[.01]	6	6553 +	[18]	6
SL08	57.43 +	[17.99]	6	14.27 +	[2.20]	6	.35 *	[.19]	6	4137 *	[814]	6
SL09	157.08 +	[5.12]	6	69.92 +	[.69]	6	.33 +	[.02]	6	6440 +	[18]	6
SL10	91.31 *	[17.30]	6	55.12 +	[3.04]	6	.29 +	[.05]	6	6139 +	[75]	6
SL11	157.48 +	[12.21]	6	67.23 +	[5.28]	6	.32 +	[.02]	6	6183 +	[48]	6
SL12	3.52 +	[.41]	6	1.21 +	[.11]	6	.25 +	[.04]	6	1766 +	[22]	6

CODE SAMPLE	B.T.S. (MPa) Avg.	[S.D.]	Nx	U.S.S. (MPa) Avg.	[S.D.]	Nx	POROSITY (%) Avg.	[S.D.]	Nx	PERMEAB. (mDarcy) Avg.	[S.D.]	Nx	SLAKE DURABILITY INDEX
SL01	2.17 *	[.55]	6	6.14 +	[1.6]	6	37.97	[.18]	3	2.88	[.60]	3	80.91
SL02	2.95 +	[.83]	6	13.16 +	[2.4]	6	15.70	[.82]	3	0		3	98.03
SL03	6.24 +	[.47]	6	20.08 +	[4.3]	6				0		3	98.78
SL04	6.88 +	[1.00]	6	19.64 +	[2.5]	6	2.00	[.18]	3	0		3	99.65
SL05	6.18 +	[.46]	6	20.94 *	[5.4]	6	1.08	[.09]	3	0		3	98.86
SL06	7.75 +	[1.80]	6	24.04 +	[3.5]	6	.57	[.07]	3	0		3	98.11
SL07	7.34 +	[.65]	6	25.97	[3.9]	5	.68	[.18]	3	0		3	99.32
SL08	5.79 +	[1.09]	6	19.66 *	[2.7]	6	5.42	[1.21]	3	0		3	96.31
SL09	9.13 *	[1.65]	6	21.63 +	[1.2]	6	.97	[.08]	3	0		3	99.38
SL10	6.31 +	[.83]	6	28.53 +	[4.3]	6	.59	[.08]	3	0		3	98.99
SL11	9.09 +	[.97]	6	21.11 +	[2.1]	6	.79	[.04]	3	0		3	99.48
SL12	.38 +	[.03]	6	.83 +	[.2]	6	50.05	[.09]	3	5450		2	71.41

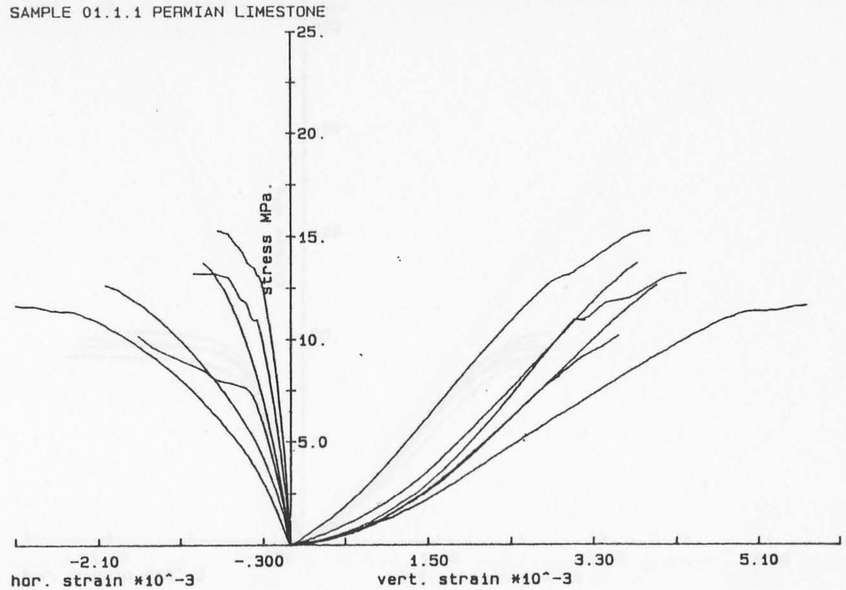
CODE SAMPLE	MOIST.CONT (%) Avg.	[S.D.]	Nx	WET DENSITY (TON/M3) Avg.	[S.D.]	Nx	DRY DENSITY (TON/M3) Avg.	[S.D.]	Nx	CaCO3 (%)	MgCO3 (%)	CR-INDEX Avg. of 2
SL01	17.04	[.31]	3	2.12	[.01]	3	1.76	[.01]	3	62.18	37.92	158.7
SL02	5.15	[.29]	3	2.40	[.02]	3	2.28	[.02]	3	97.60	.90	72.8
SL03	1.48	[.12]	3	2.62	[.01]	3	2.58	[.02]	3	92.66	1.19	85.8
SL04	1.94	[.25]	3	2.58	[.01]	3	2.53	[.02]	3	83.64	.99	78.2
SL05	.03	[.01]	3	2.68	[.00]	3	2.68	[.00]	3	97.41	1.10	80.7
SL06	.18	[.04]	3	2.68	[.00]	3	2.67	[.00]	3	98.40	1.13	76.9
SL07	.77	[.02]	3	2.69	[.01]	3	2.68	[.01]	3	99.37	.74	90.0
SL08	.70	[.08]	3	2.57	[.01]	3	2.55	[.01]	3	82.01	4.29	111.1
SL09	.03	[.02]	3	2.67	[.01]	3	2.66	[.01]	3	97.13	1.51	78.5
SL10	.09	[.04]	3	2.69	[.00]	3	2.69	[.00]	3	91.00	2.00	77.2
SL11	.17	[.02]	3	2.69	[.00]	3	2.68	[.00]	3	96.71	1.99	76.4
SL12	22.05	[.13]	3	1.71	[.01]	3	1.34	[.00]	3	96.64	1.70	262.3

table 5.1.1

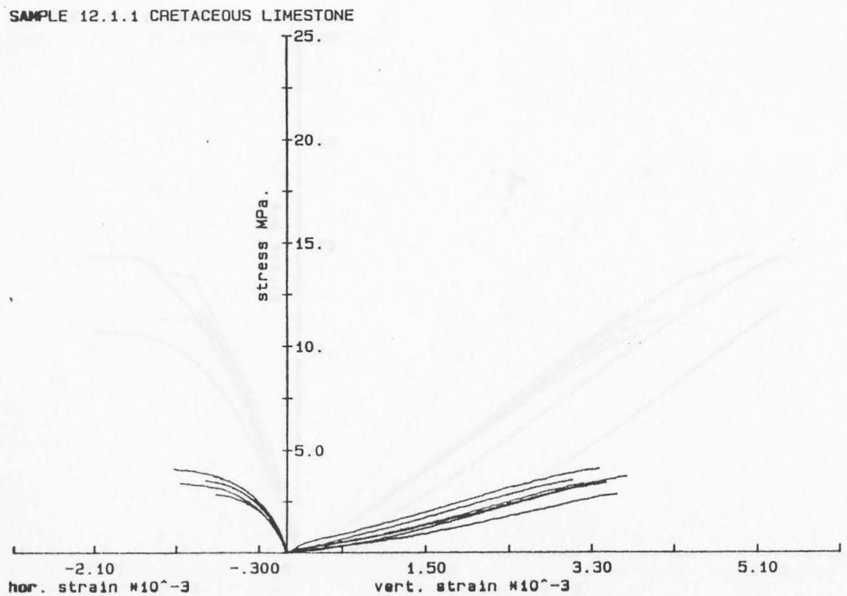
tafigure 5.2.1



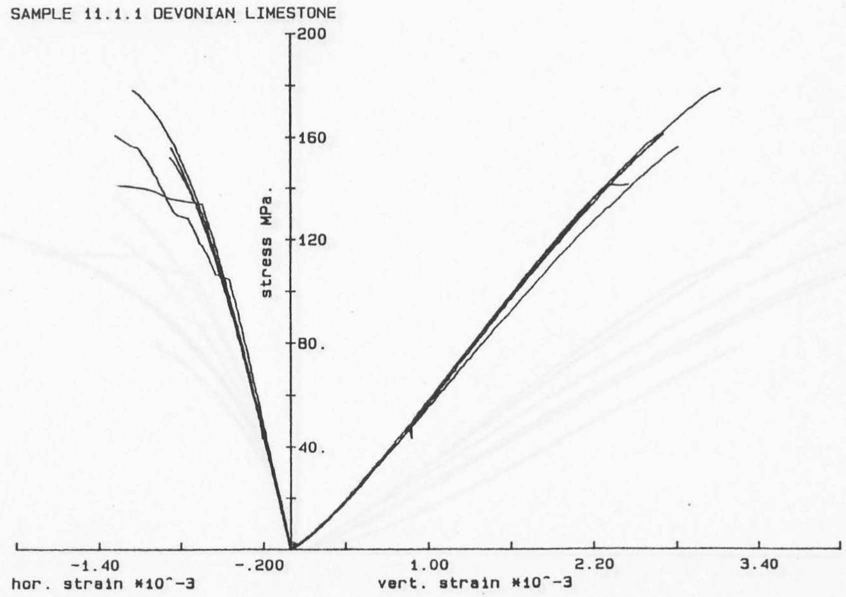
Laboratory Engineering Geology Delft University of Technology



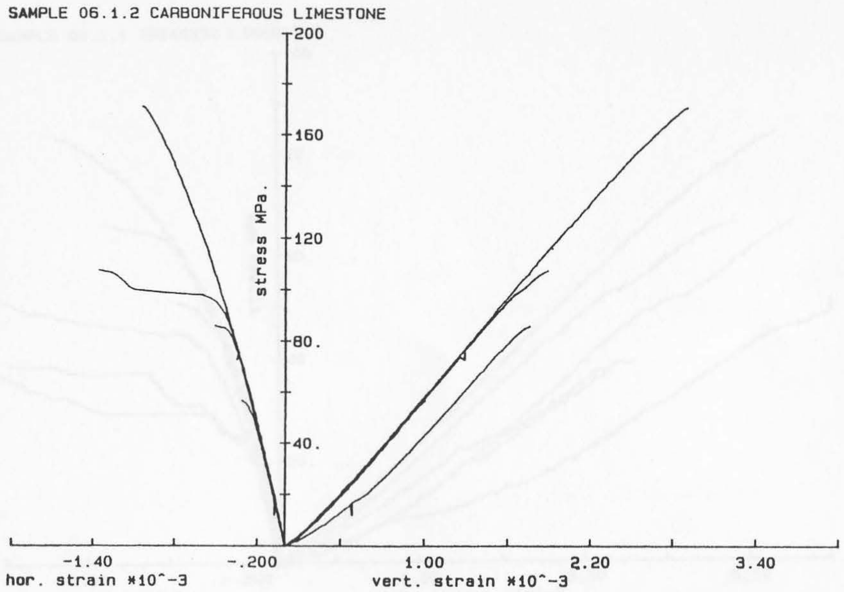
Laboratory Engineering Geology Delft University of Technology



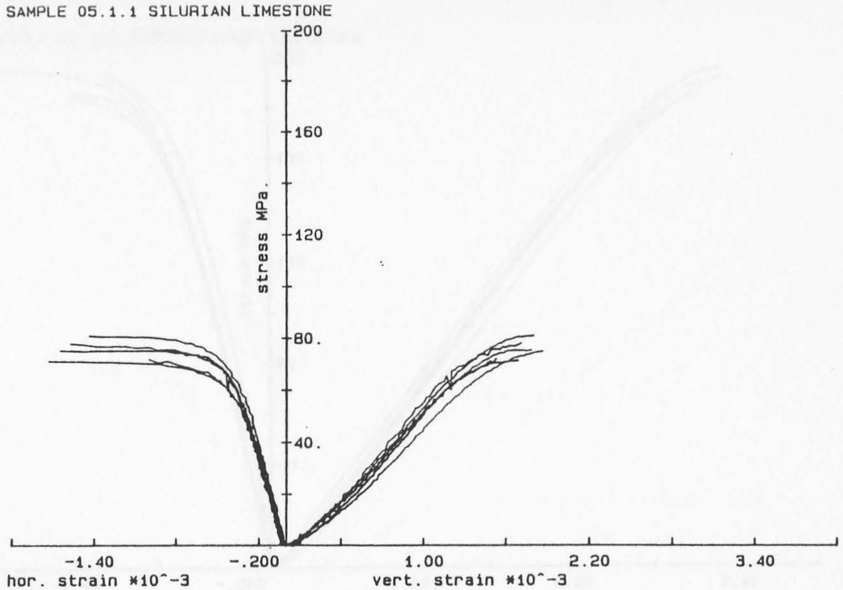
Laboratory Engineering Geology Delft University of Technology



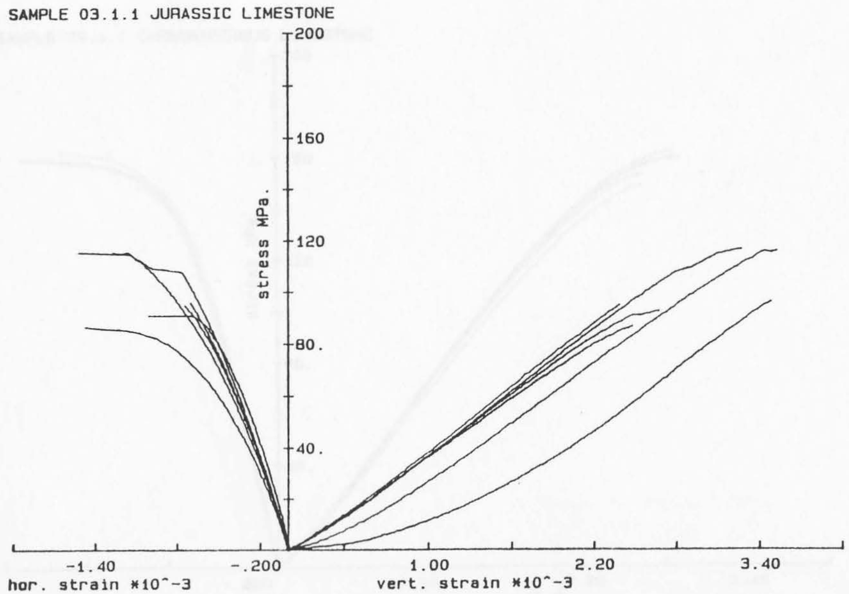
Laboratory Engineering Geology Delft University of Technology



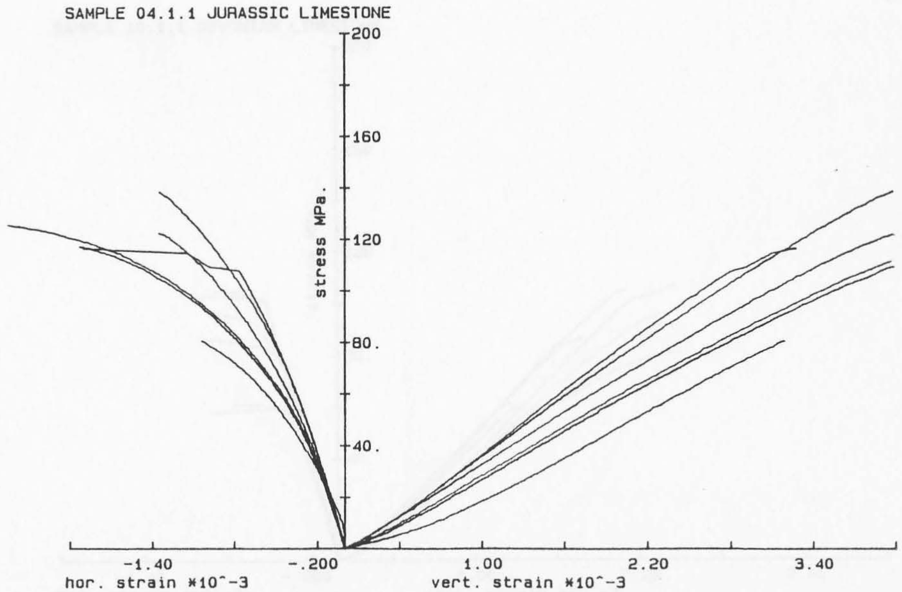
Laboratory Engineering Geology Delft University of Technology



Laboratory Engineering Geology Delft University of Technology



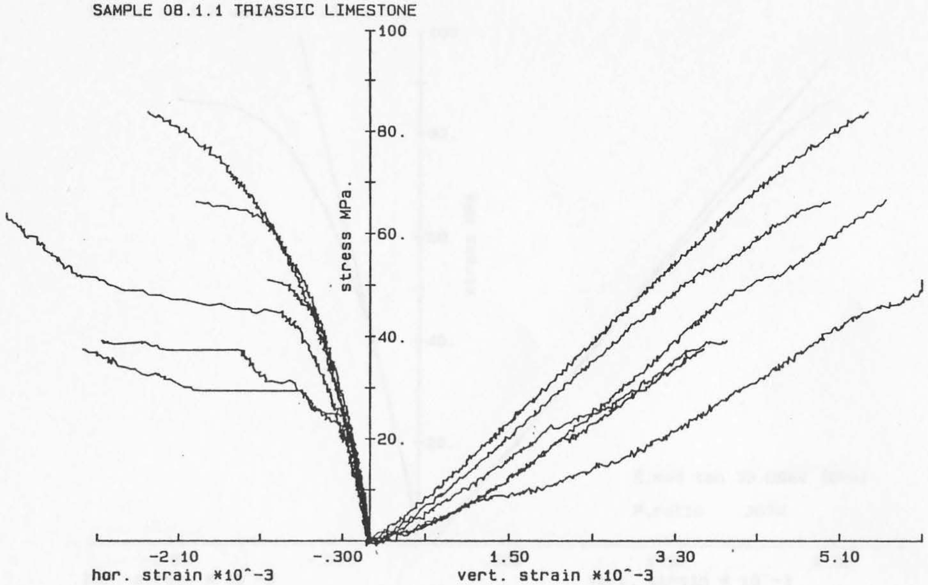
Laboratory Engineering Geology Delft University of Technology



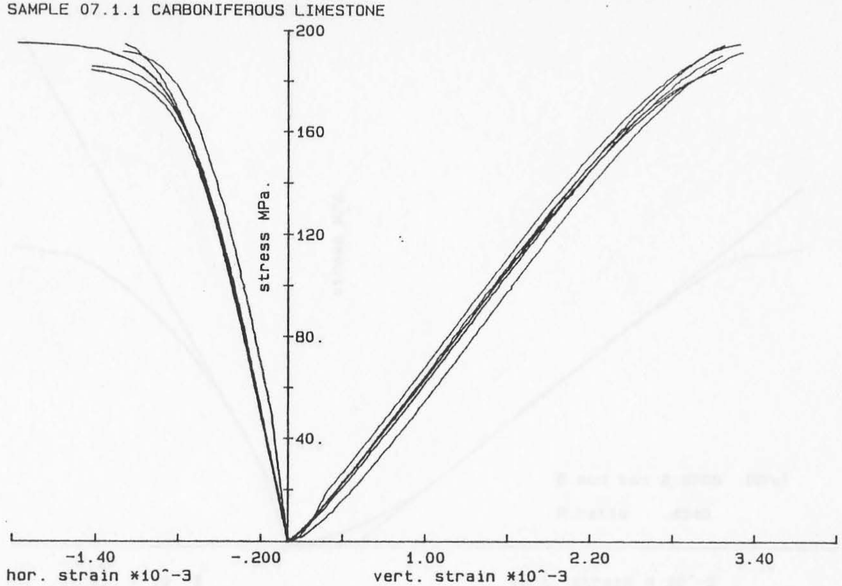
Laboratory Engineering Geology Delft University of Technology

figure 5.2.2

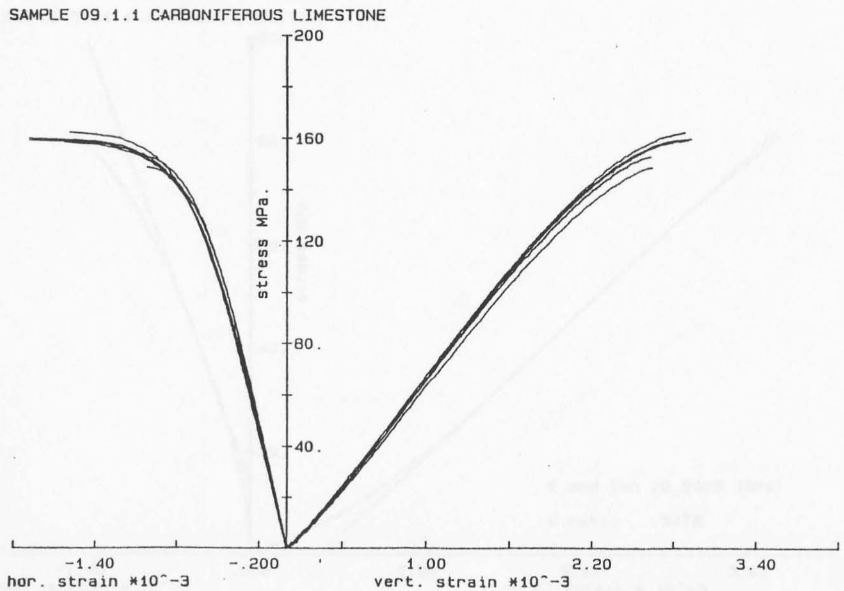
figure 5.2.3



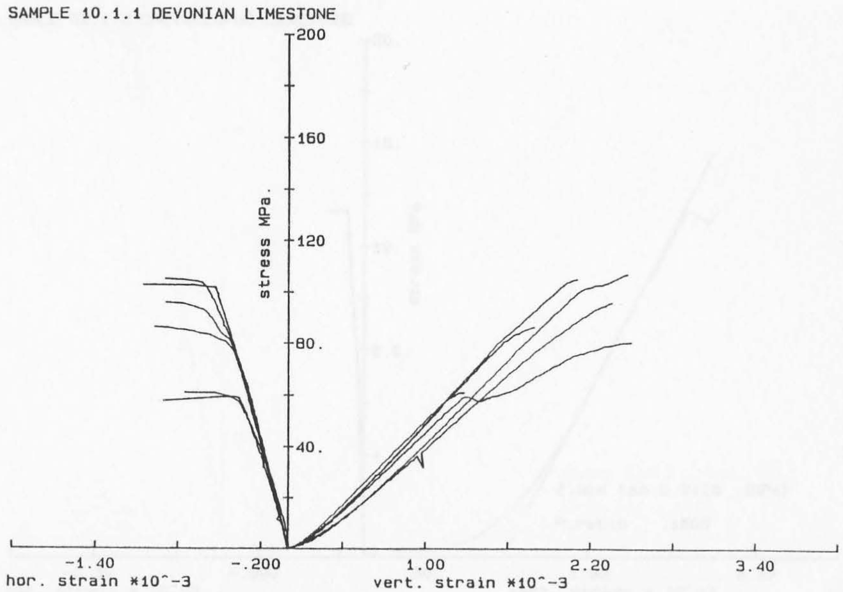
Laboratory Engineering Geology Delft University of Technology



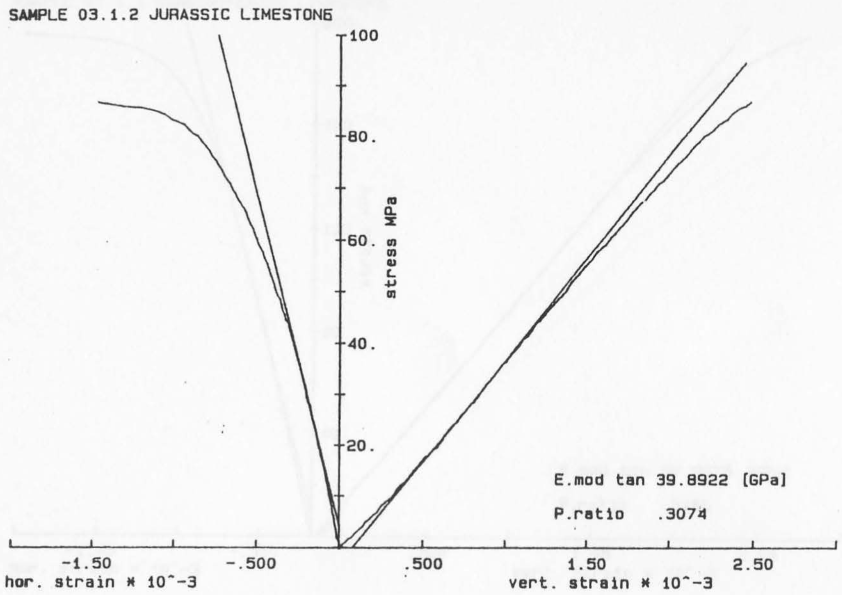
Laboratory Engineering Geology Delft University of Technology



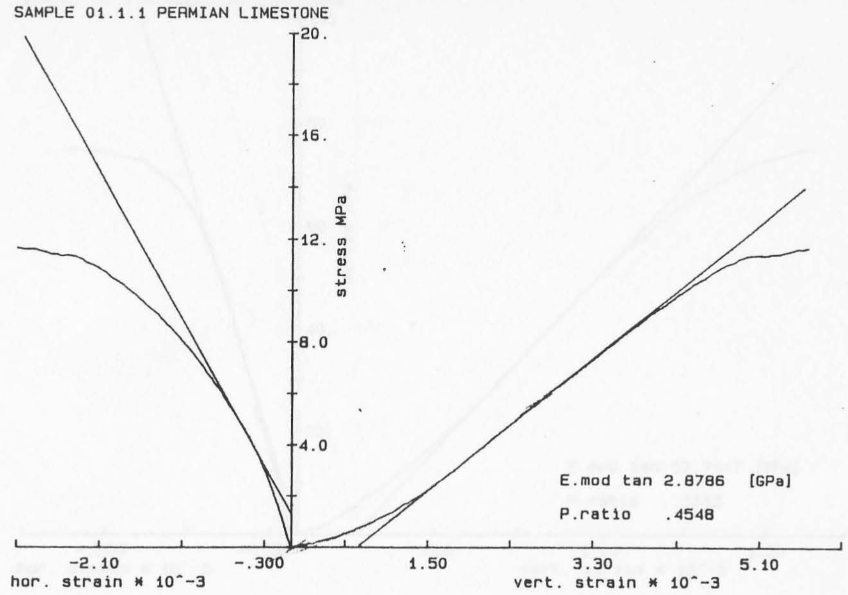
Laboratory Engineering Geology Delft University of Technology



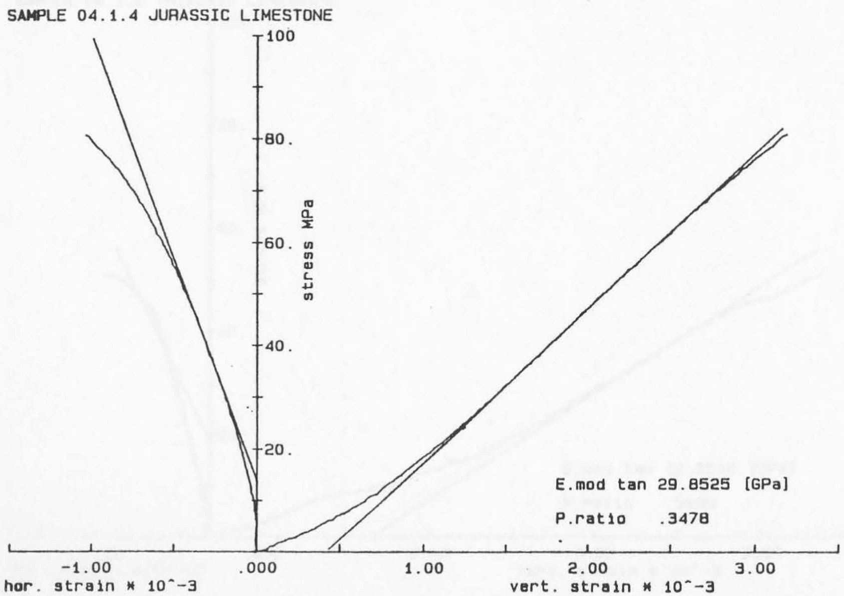
Laboratory Engineering Geology Delft University of Technology



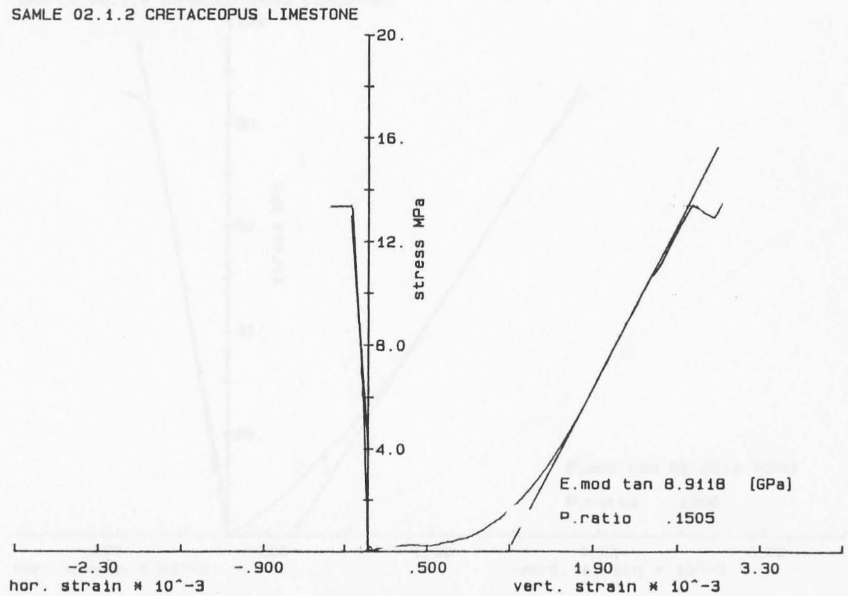
Laboratory Engineering Geology Delft University of Technology



Laboratory Engeneering Geology Delft University of Technology

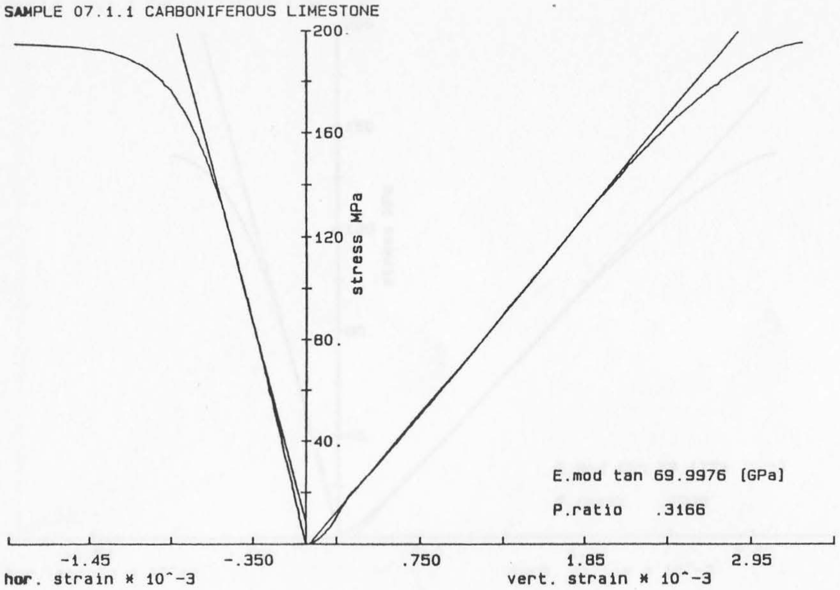


Laboratory Engineering Geology Delft University of Technology

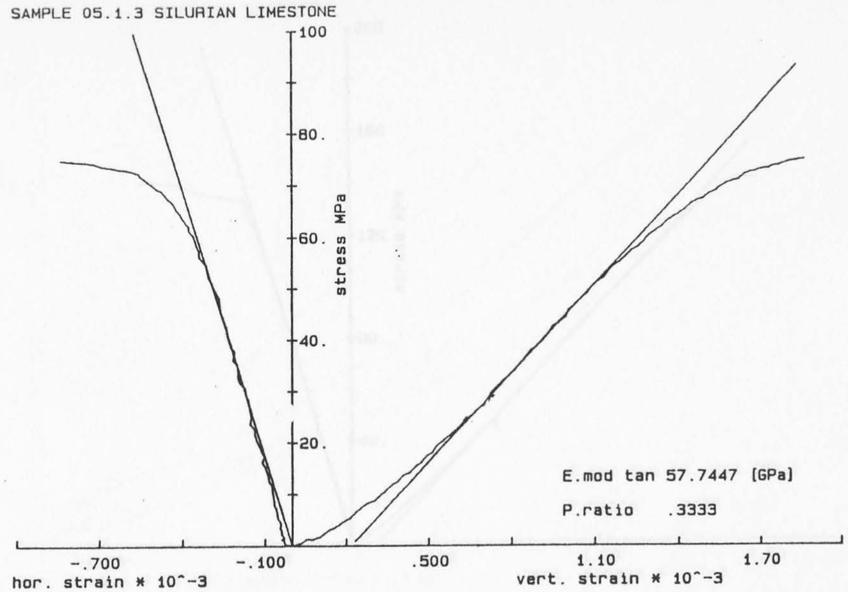


Laboratory Engeneering Geology Delft University of Technology

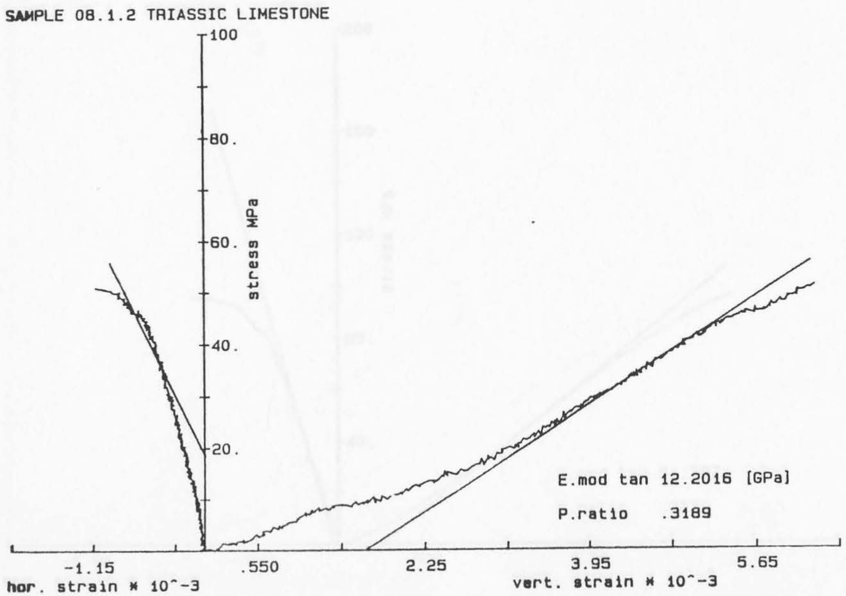
figure 5.2.5



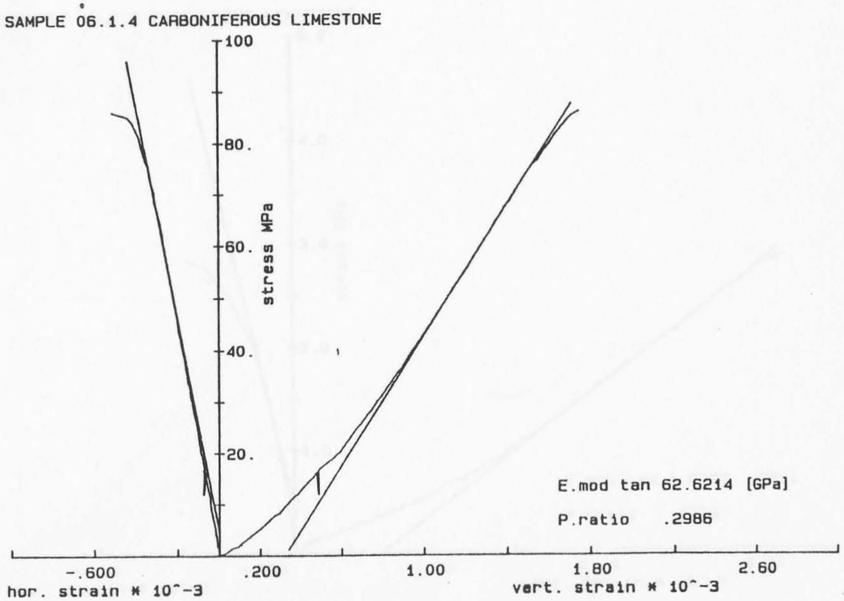
Laboratory Engeneering Geology Delft University of Technology



Laboratory Engineering Geology Delft University of Technology



Laboratory Engineering Geology Delft University of Technology



Laboratory Engineering Geology Delft University of Technology

figure 5.2.6

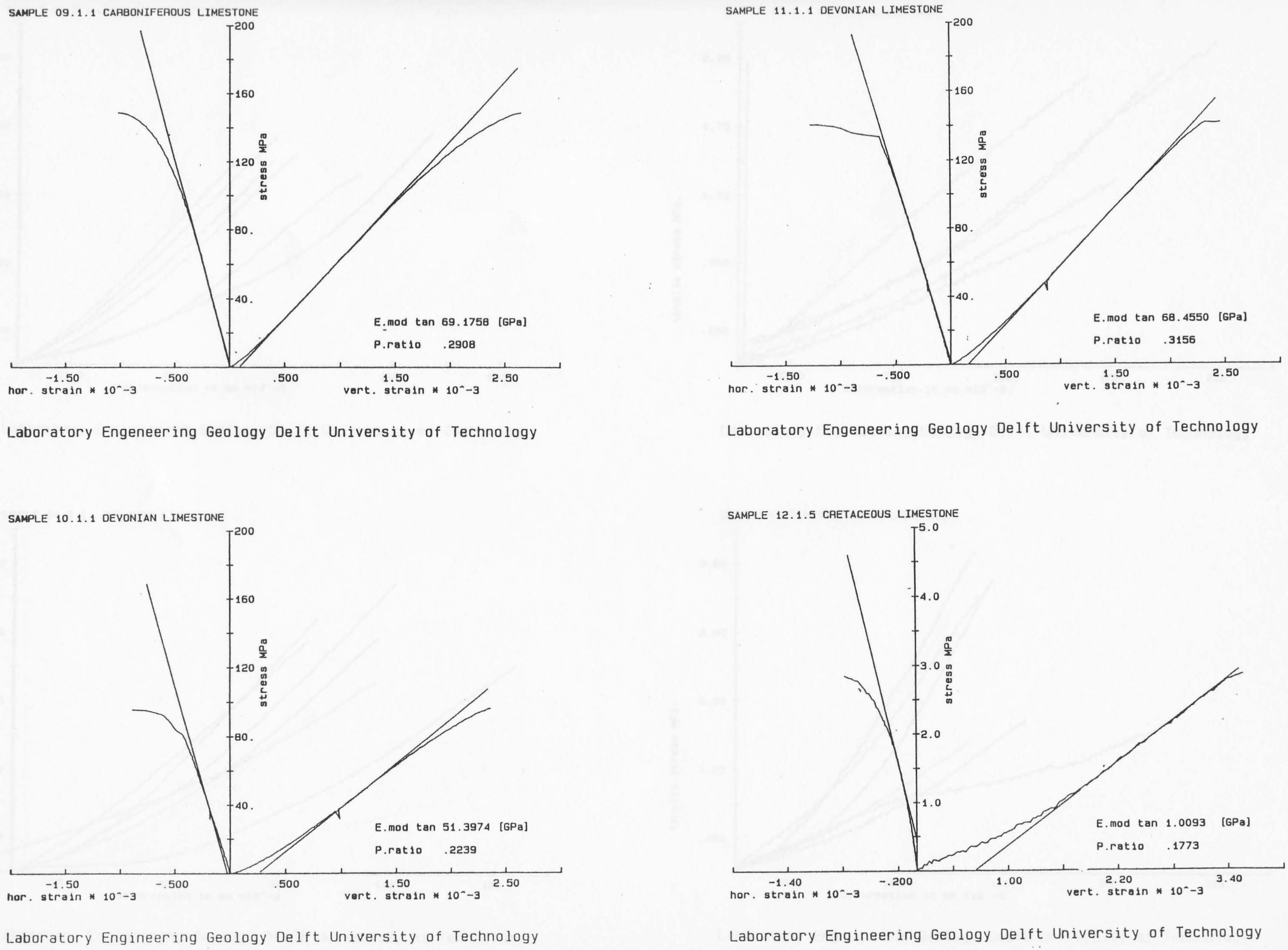
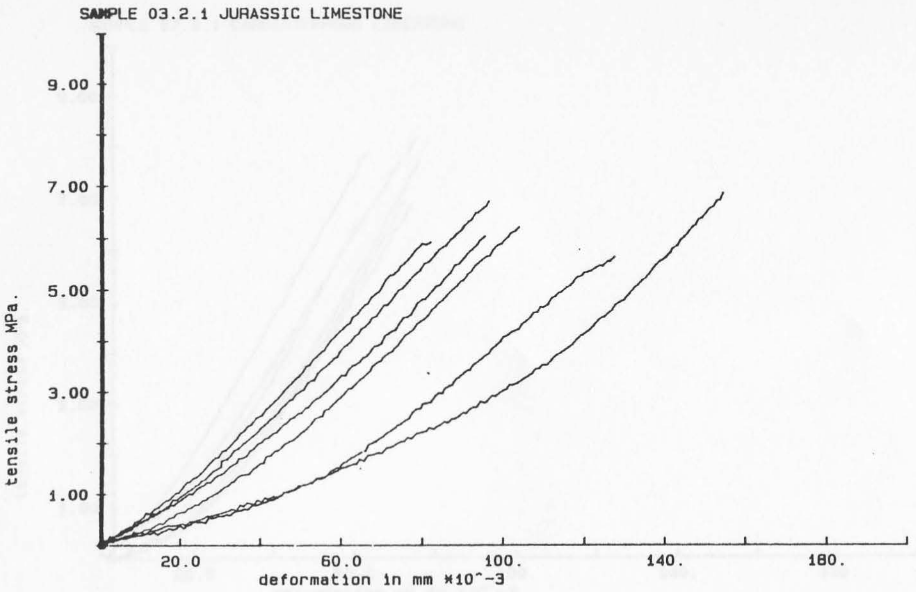
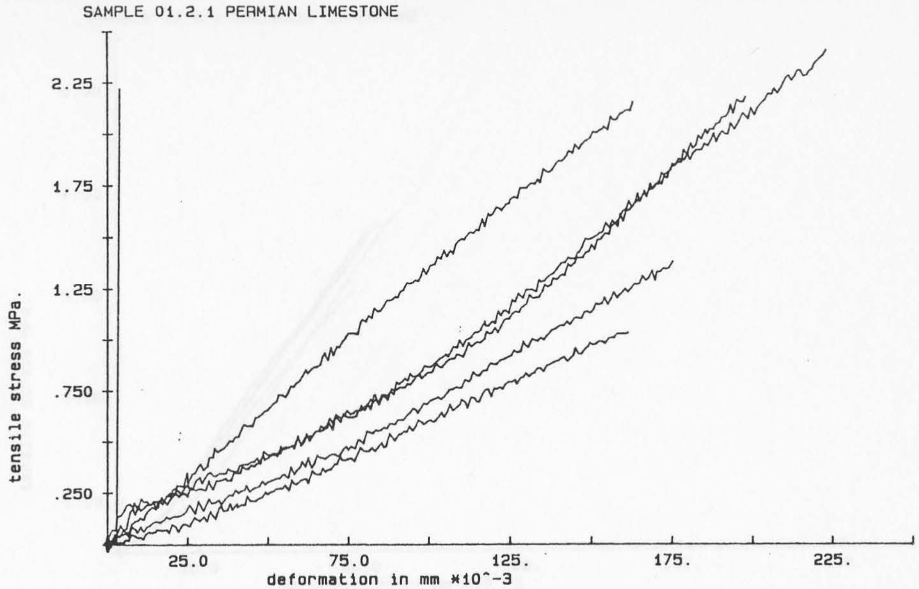

SAMPLE 09.1.1 CARBONIFEROUS LIMESTONE
200
160
120
80.
40.
stress MPa
E.mod tan 69.1758 [GPa]
P.ratio .2908
-1.50
-.500
.500
1.50
2.50
hor. strain * 10^-3
vert. strain * 10^-3
Laboratory Engeneering Geology Delft University of Technology
SAMPLE 11.1.1 DEVONIAN LIMESTONE
200
160
120
80.
40.
stress MPa
E.mod tan 68.4550 [GPa]
P.ratio .3156
-1.50
-.500
.500
1.50
2.50
hor. strain * 10^-3
vert. strain * 10^-3
Laboratory Engeneering Geology Delft University of Technology
SAMPLE 10.1.1 DEVONIAN LIMESTONE
200
160
120
80.
40.
stress MPa
E.mod tan 51.3974 [GPa]
P.ratio .2239
-1.50
-.500
.500
1.50
2.50
hor. strain * 10^-3
vert. strain * 10^-3
Laboratory Engineering Geology Delft University of Technology
SAMPLE 12.1.5 CRETACEOUS LIMESTONE
5.0
4.0
3.0
2.0
1.0
stress MPa
E.mod tan 1.0093 [GPa]
P.ratio .1773
-1.40
-.200
1.00
2.20
3.40
hor. strain * 10^-3
vert. strain * 10^-3
Laboratory Engineering Geology Delft University of Technology

figure 5.2.7

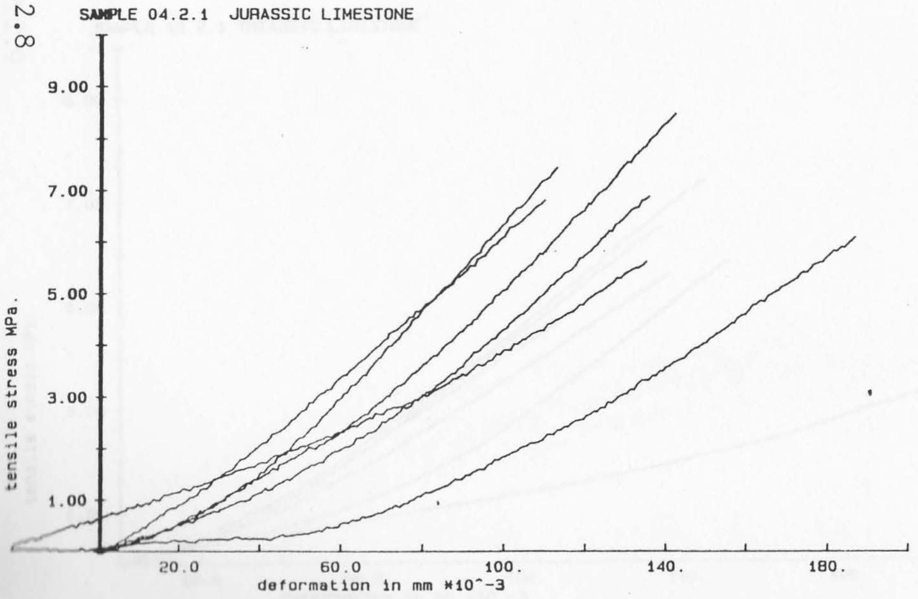
figure 5.2.8



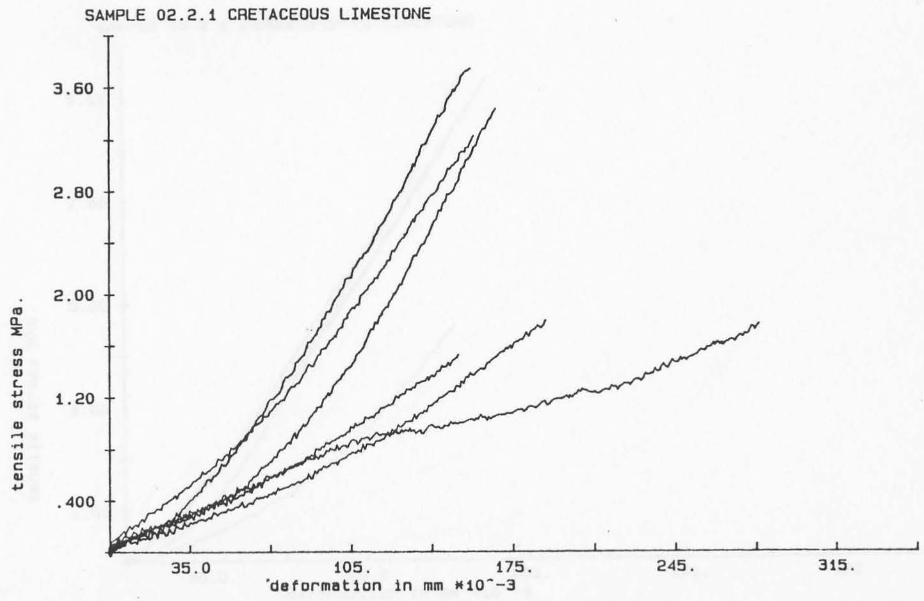
Laboratory Engineering Geology Delft University of Technology



Laboratory Engineering Geology Delft University of Technology

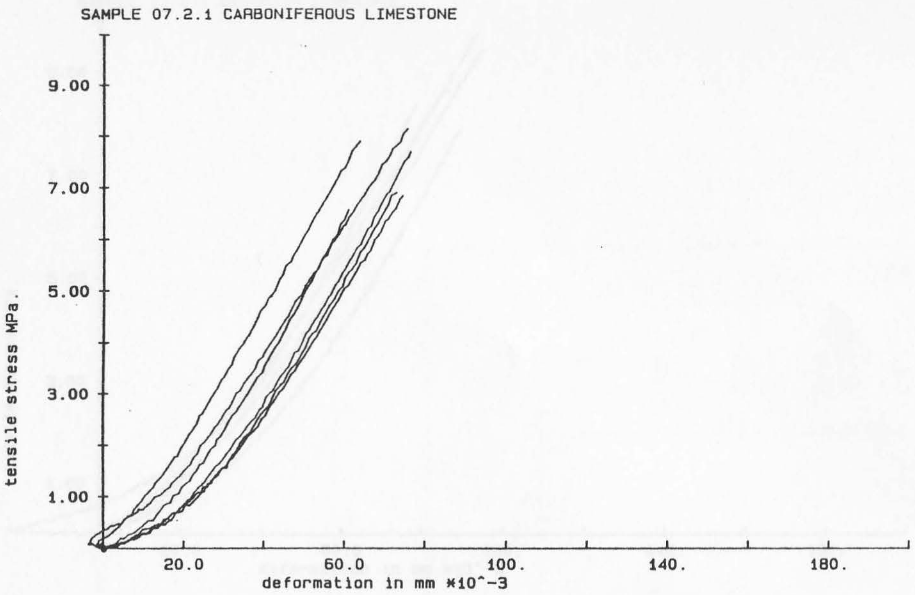


Laboratory Engineering Geology Delft University of Technology

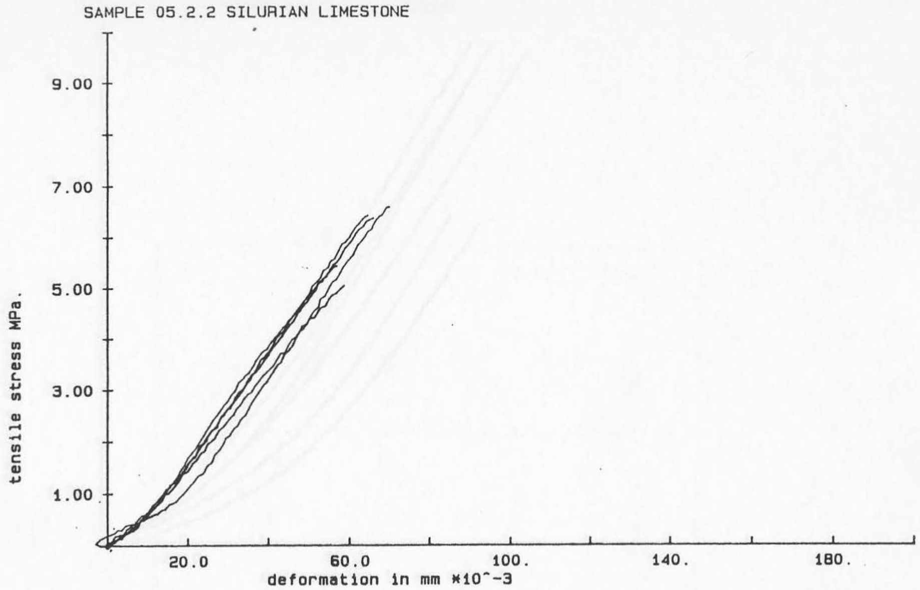


Laboratory Engineering Geology Delft University of Technology

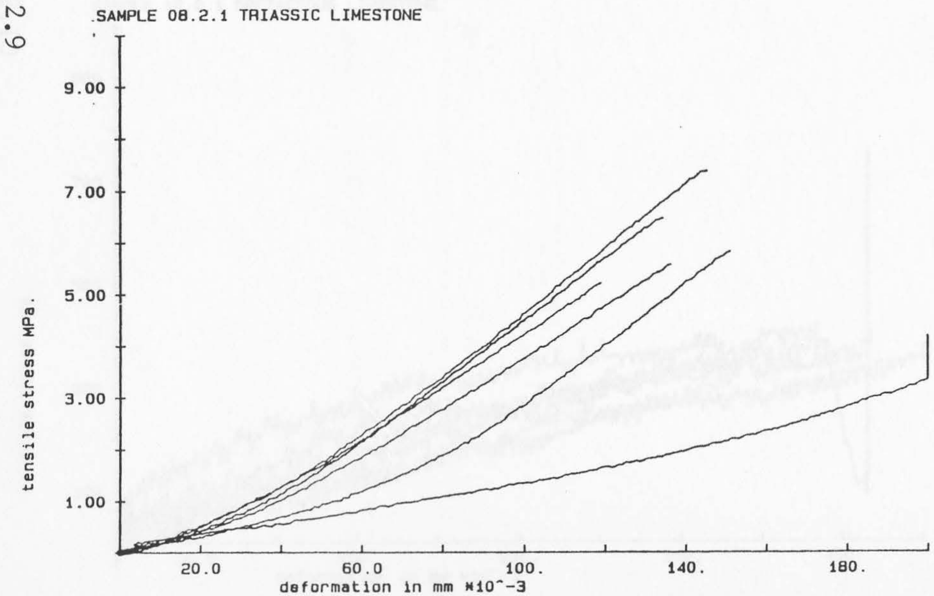
figure 5.2.9



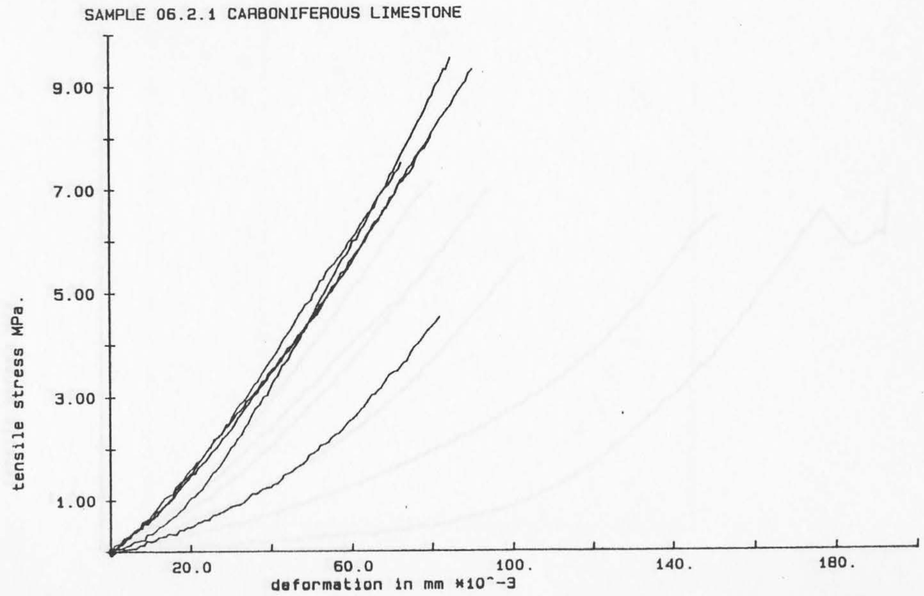
Laboratory Engineering Geology Delft University of Technology



Laboratory Engineering Geology Delft University of Technology

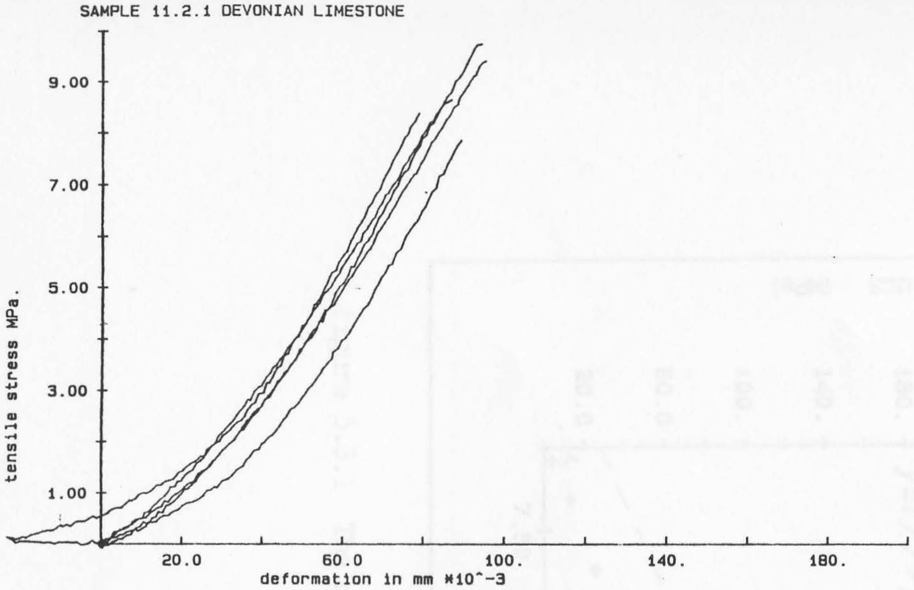


Laboratory Engineering Geology Delft University of Technology

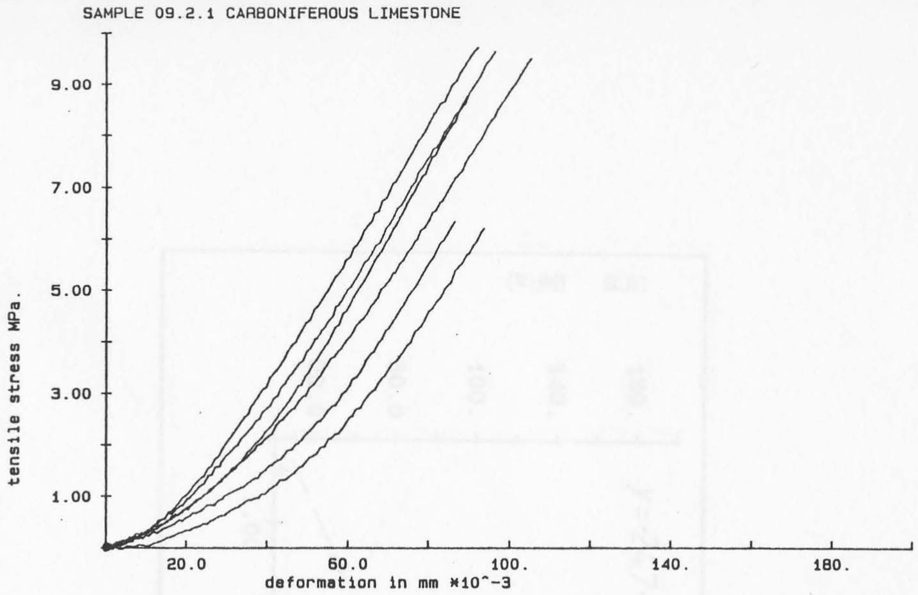


Laboratory Engineering Geology Delft University of Technology

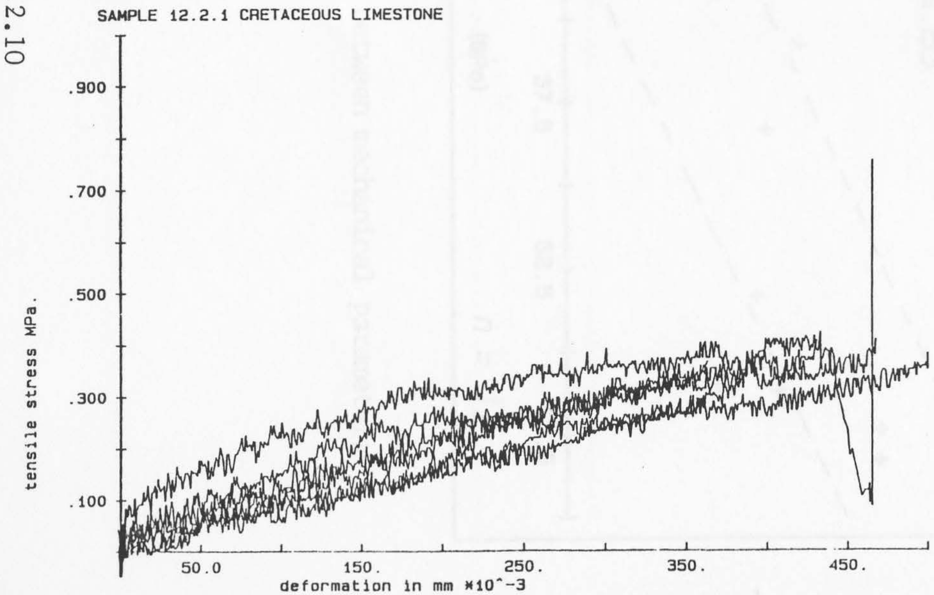
figure 5.2.10



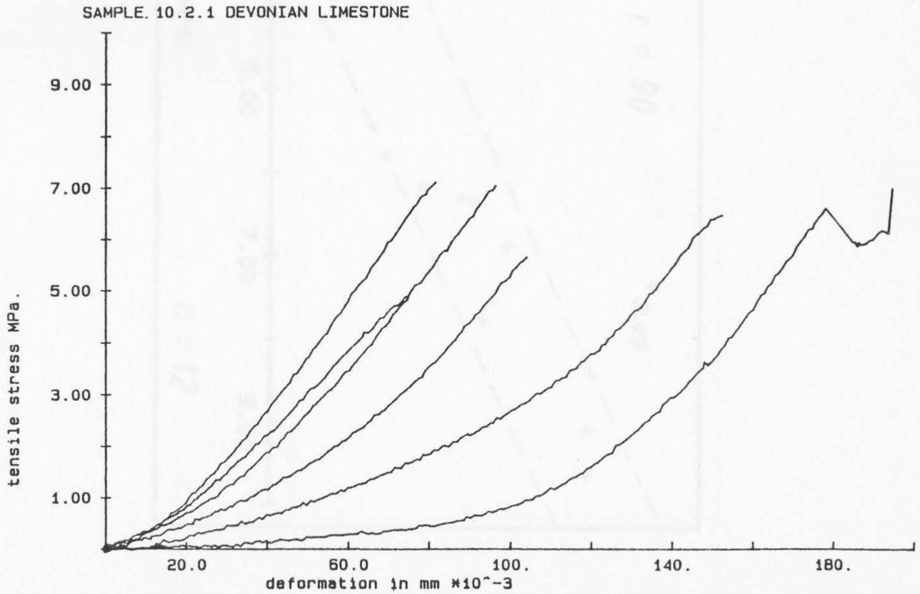
Laboratory Engineering Geology Delft University of Technology



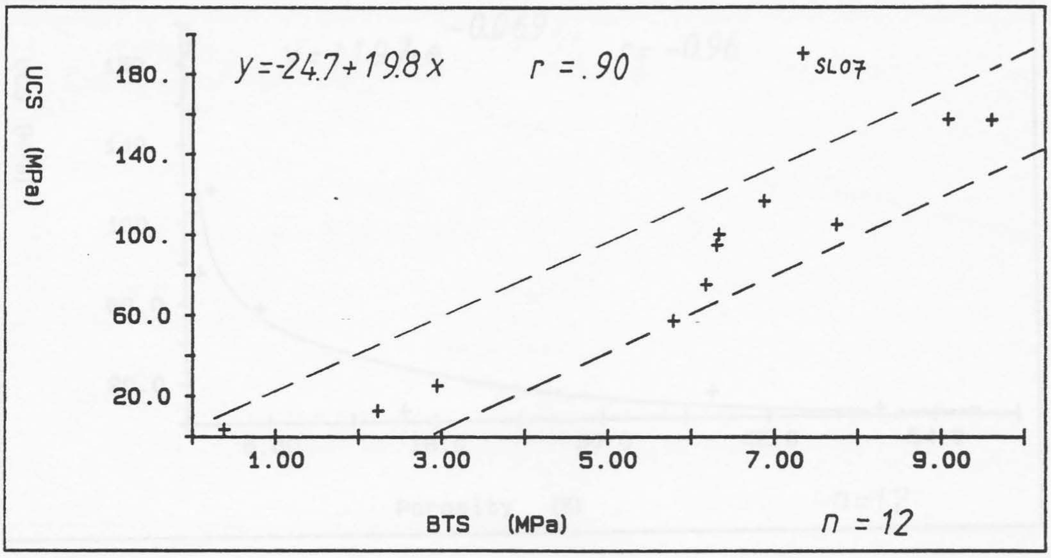
Laboratory Engineering Geology Delft University of Technology



Laboratory Engineering Geology Delft University of Technology



Laboratory Engineering Geology Delft University of Technology



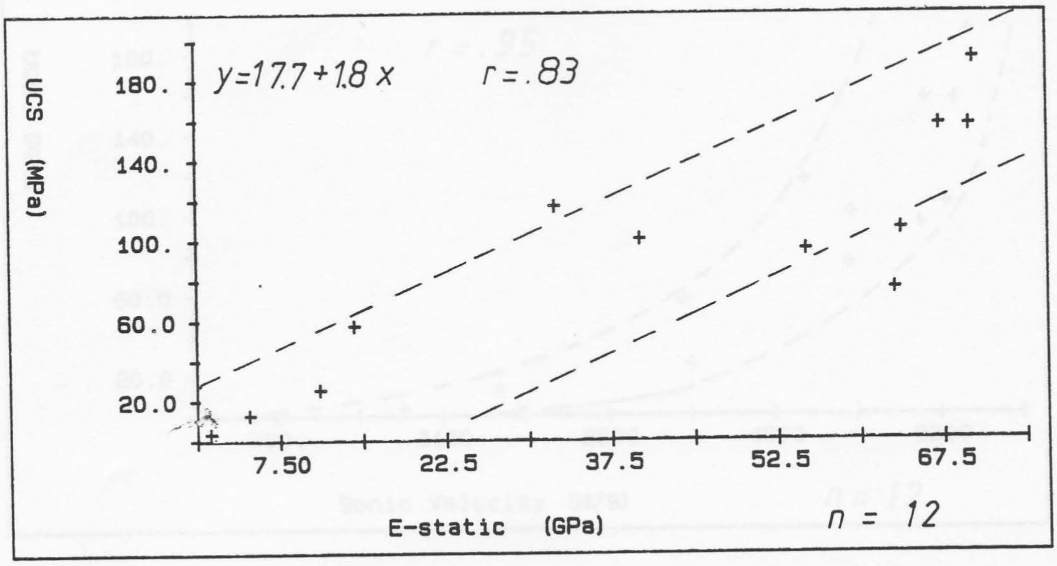
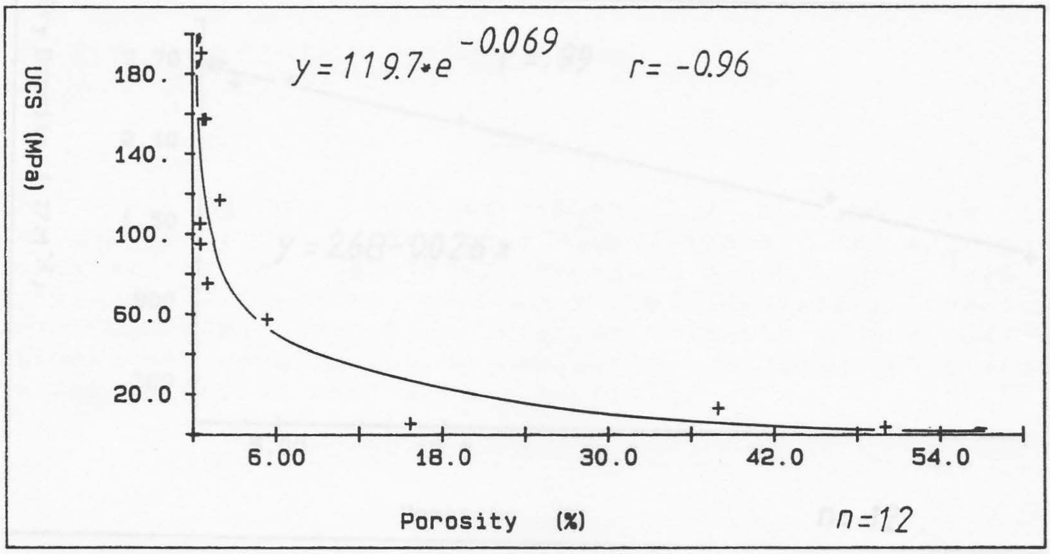


figure 5.3.1 The correlation between mechanical parameters



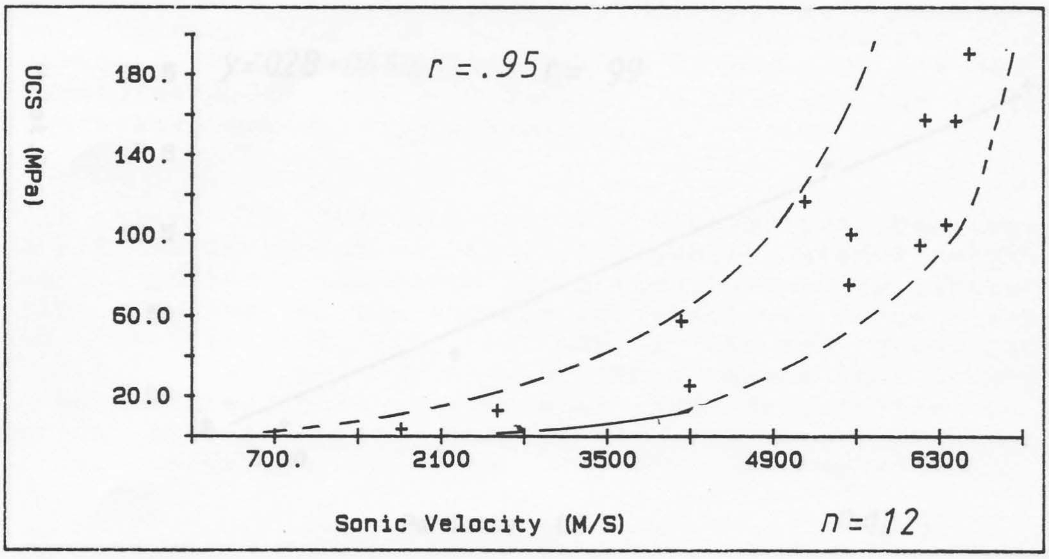
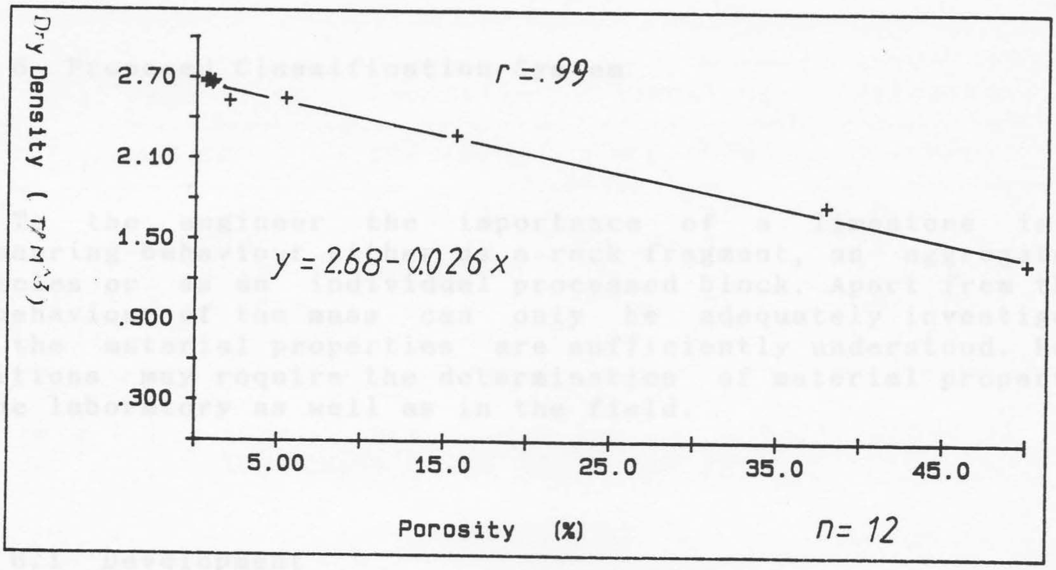


figure 5.3.2 The correlation between physical and mechanical parameters



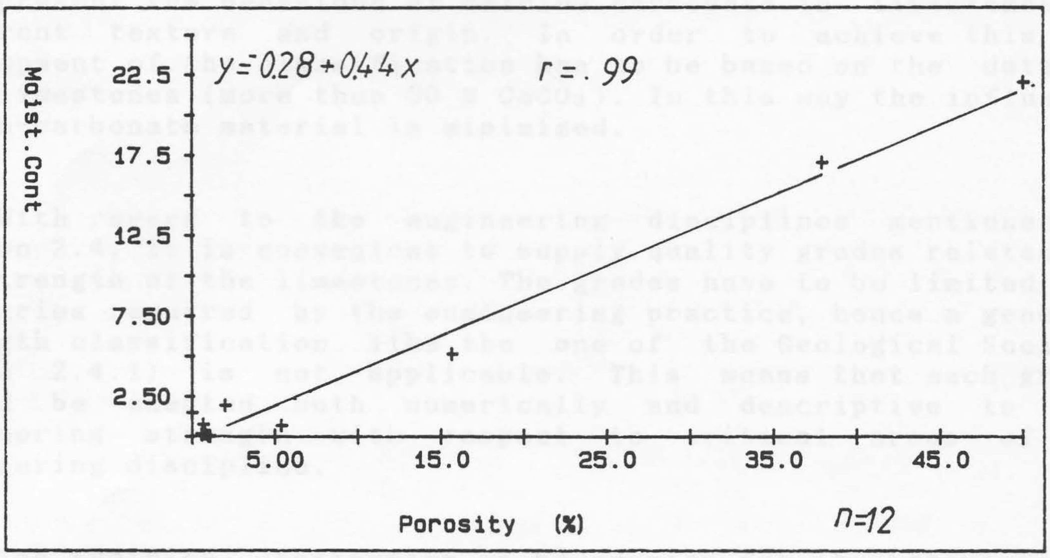


figure 5.3.4 The correlation between physical parameters

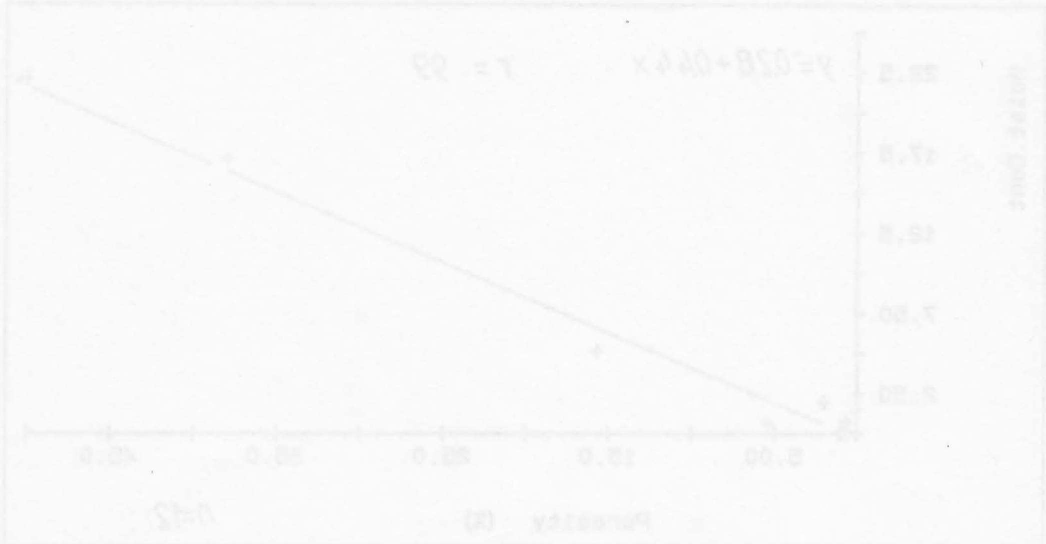


figure 3.3.4. The correlation between physical parameters

6 Proposed Classification System

To the engineer the importance of a limestone is its engineering behaviour either as a rock fragment, an aggregate of particles or as an individual processed block. Apart from this, the behaviour of the mass can only be adequately investigated when the material properties are sufficiently understood. Hence conditions may require the determination of material properties in the laboratory as well as in the field.

6.1 Development

As concluded in section 2.4 a useful classification system for limestones should include the properties strength, density and grainsize of the intact rock. The relation between such properties may then form a fundamental basis for an empirical classification system. Nevertheless the essence of such a system must present the behaviour of calcium carbonate in limestones of different texture and origin. In order to achieve this the development of the classification has to be based on the data of pure limestones (more than 90 % $CaCO_3$). In this way the influence of non-carbonate material is minimized.

With regard to the engineering disciplines mentioned in section 2.4, it is convenient to supply quality grades related to the strength of the limestones. The grades have to be limited by boundaries required by the engineering practice, hence a general strength classification like the one of the Geological Society (table 2.4.1) is not applicable. This means that each grade should be adapted both numerically and descriptive to the engineering strength with respect to critical areas of the engineering discipline.

The empirical distinction of boundaries for the behaviour of rock material has been derived from the literature and if necessary modified to limestone circumstances. Below the four engineering disciplines are supplied with quality grades for Unconfined Compressive Strength (table 6.1.1).

Quality Grade	Excavation	Foundation	Tunneling	Aggregates
	UCS (MPa)	UCS (MPa)	UCS (MPa)	UCS (MPa)
I	> 100	0- 3	1- 25	0- 12
II	50 -100	3-10	25- 50	12- 25
III	12.5- 50	10-40	50-100	25- 38
IV	2.5- 12.5	40-80	100-200	38- 55
V	0- 2.5	> 80	> 200	> 55

table 6.1.1 Approximate ranges for the quality grade of limestones based on intact rock.

Source of ranges : Excavation : Franklin (1971)
Foundation : CP for foundations (1972), Q30 (1984)
Tunneling : Bieniawski (1979)
Aggregates : ASTM C 33 (1979)

Additionally from the literature the following information was derived for limestone properties and procedures as a guidance to engineering practice (table 6.1.2).

Quality Grade	Excavation	Foundation	Tunnelling	Aggregates
	Method of removal	Safe Bearing Capacity (MPa)	Rate of Excavation m^3/h per hp	Nature of optimal concrete
I	blast(fragment)	0-0.2	> 0.16	---
II	blast(fracture)	0.2-0.4	0.12-0.16	light
III	blast(loosen)	0.4-0.8	0.06-0.12	normal
IV	rip	0.8-2.0	0.03-0.06	normal
V	shovel	> 2.0	< 0.03	heavy

table 6.1.2 presumed values and descriptions of limestone qualities for engineering disciplines, under the assumption that unweathered and unfractured rock is involved.

To develop the classification system as described, the

exact relation of UCS versus Dry Density for pure limestone is a starting point (fig. 6.1.1). At certain angles to this e-power curve lines of equal CR-Index form the boundaries between the quality grades. These lines can be derived from the variation in the correlations between Dry Density and CR-Index, and UCS and CR-Index (fig. 6.1.2). The intervals at a constant CR-Index for UCS and Dry Density render three (x,y) pairs on the UCS-Dry Density plot. Through these three points the best fit represents the boundary (fig. 6.1.3).To incorporate the quality degrees in the diagram the intersecting points of the boundaries and the UCS-Dry Density curve are token at the restricting strength's for each engineering discipline (fig. 6.1.4).

6.2 Mode of Operation (figure 6.2.1)

After selection of the required engineering discipline a descriptive classification renders a code based on the properties texture and grainsize. Additionally information about deformation modulus, abrasivity and cuttability could be supplied. Knowing the UCS and Dry Density of the limestone the quality grade can be determined. Finally, together with the descriptive classification code, the quality grade presents a measure of the engineering behaviour.

The application of this classification in the field can be realized with the help of light weight equipment; the Schmidt hammer for the UCS values; Hydrochloric acid (1.0 N) for the $CaCO_3$ content and the CR-Index; a lens for texture and grain size; a balance and a 100 ml cylinder and a small oven to measure the Dry Density .The volume of the limestone lump is then measured by the difference in the water height, when the lump is submerged.

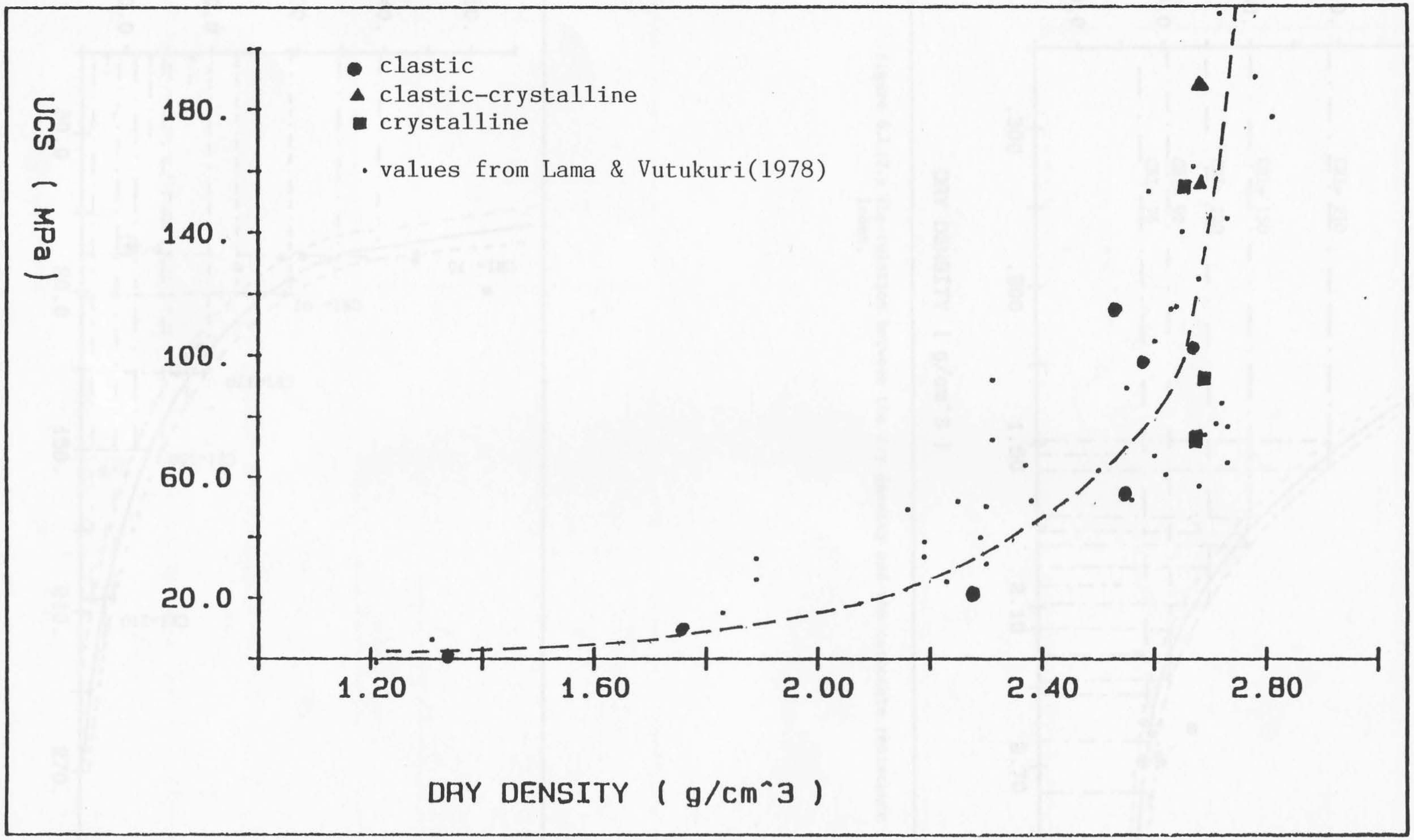


figure 6.1.1 The relation between dry density and strength for limestones.

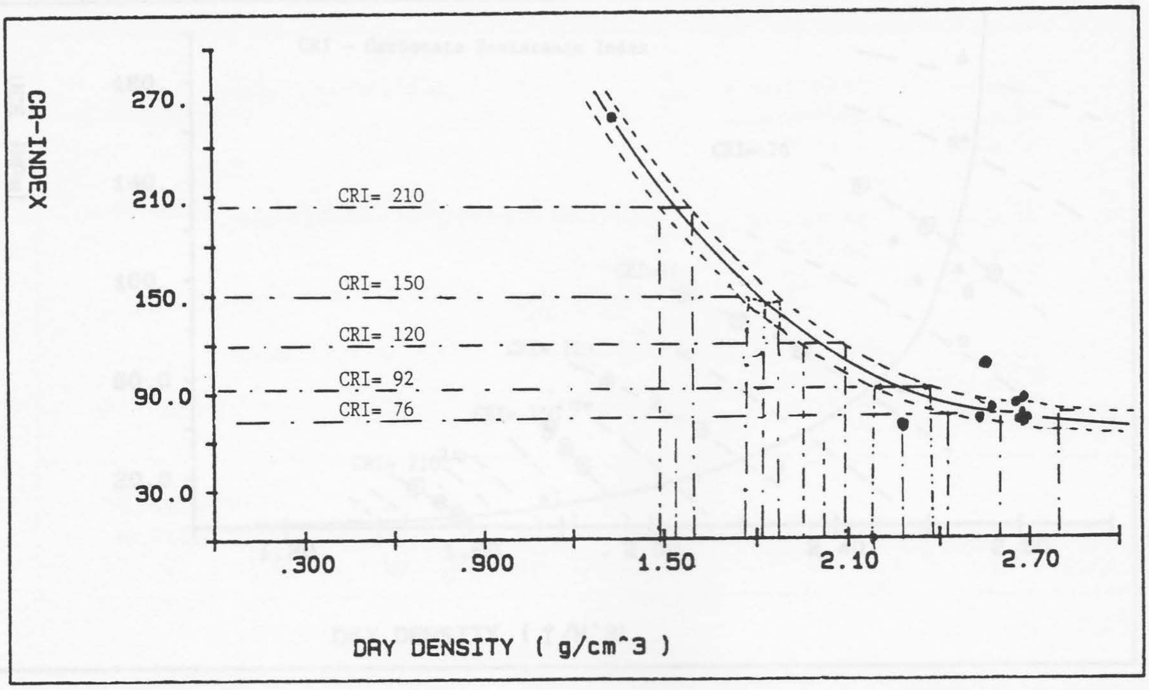


figure 6.1.2.a The relation between the dry density and the carbonate resistance Index.

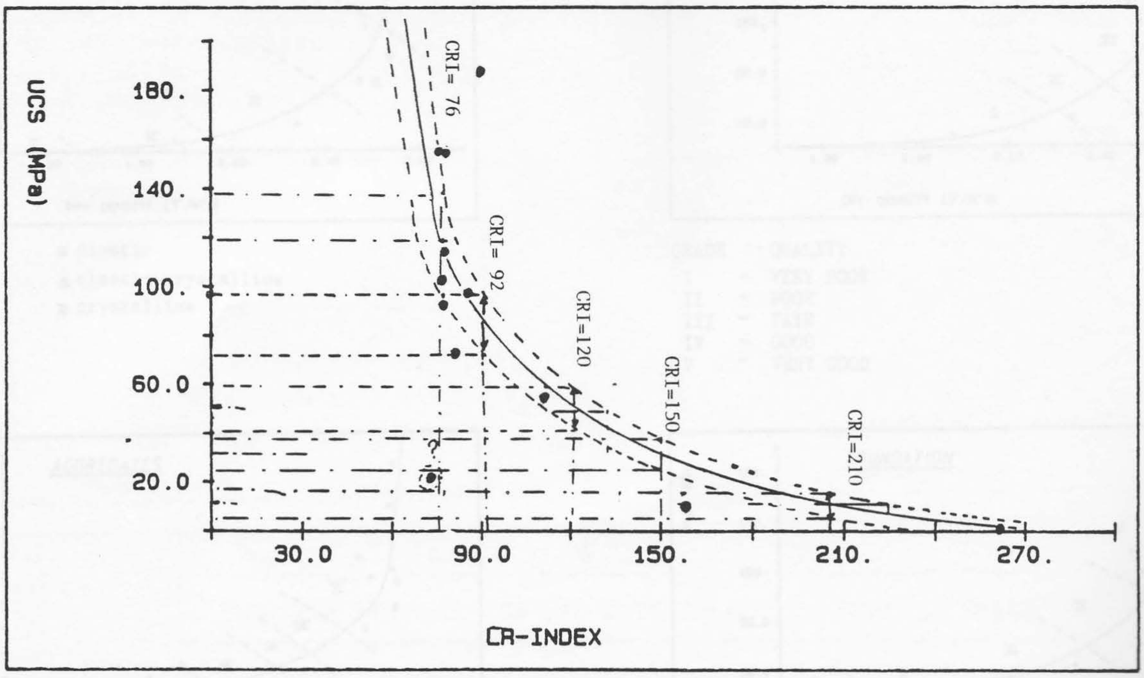


figure 6.1.2.b The relation between the unconfined compressive strength and the carbonate resistance index.

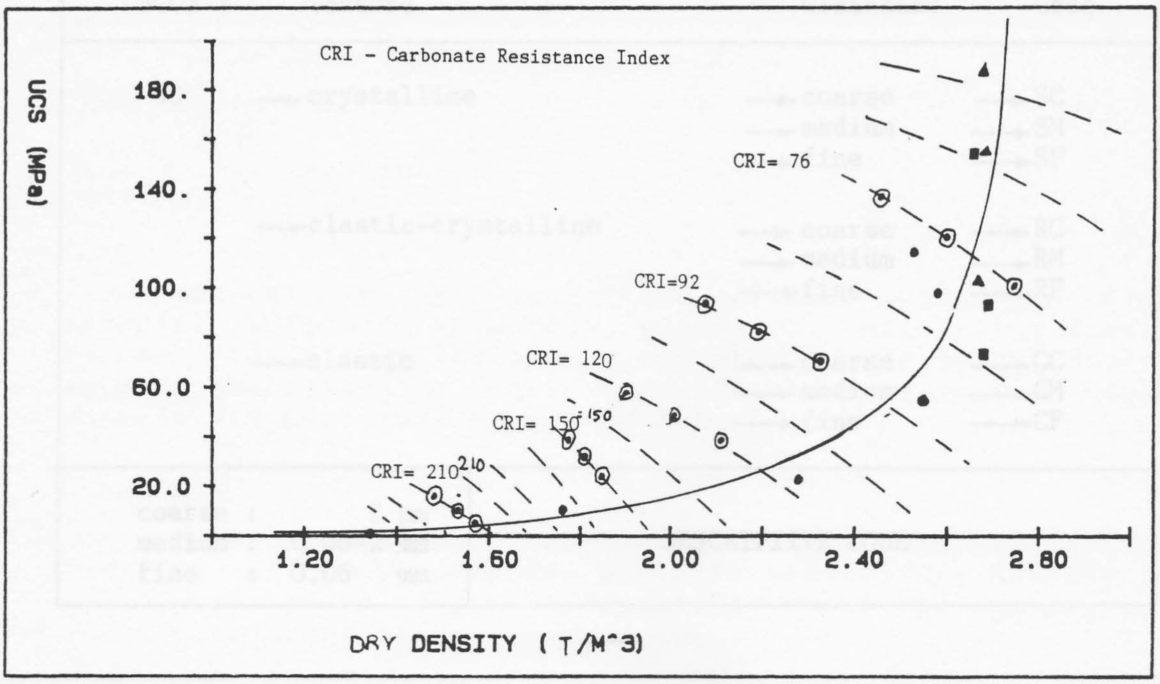


figure 6.1.3 Boundaries of constant CRI incorporated fot the UCS-Dry Density relation.

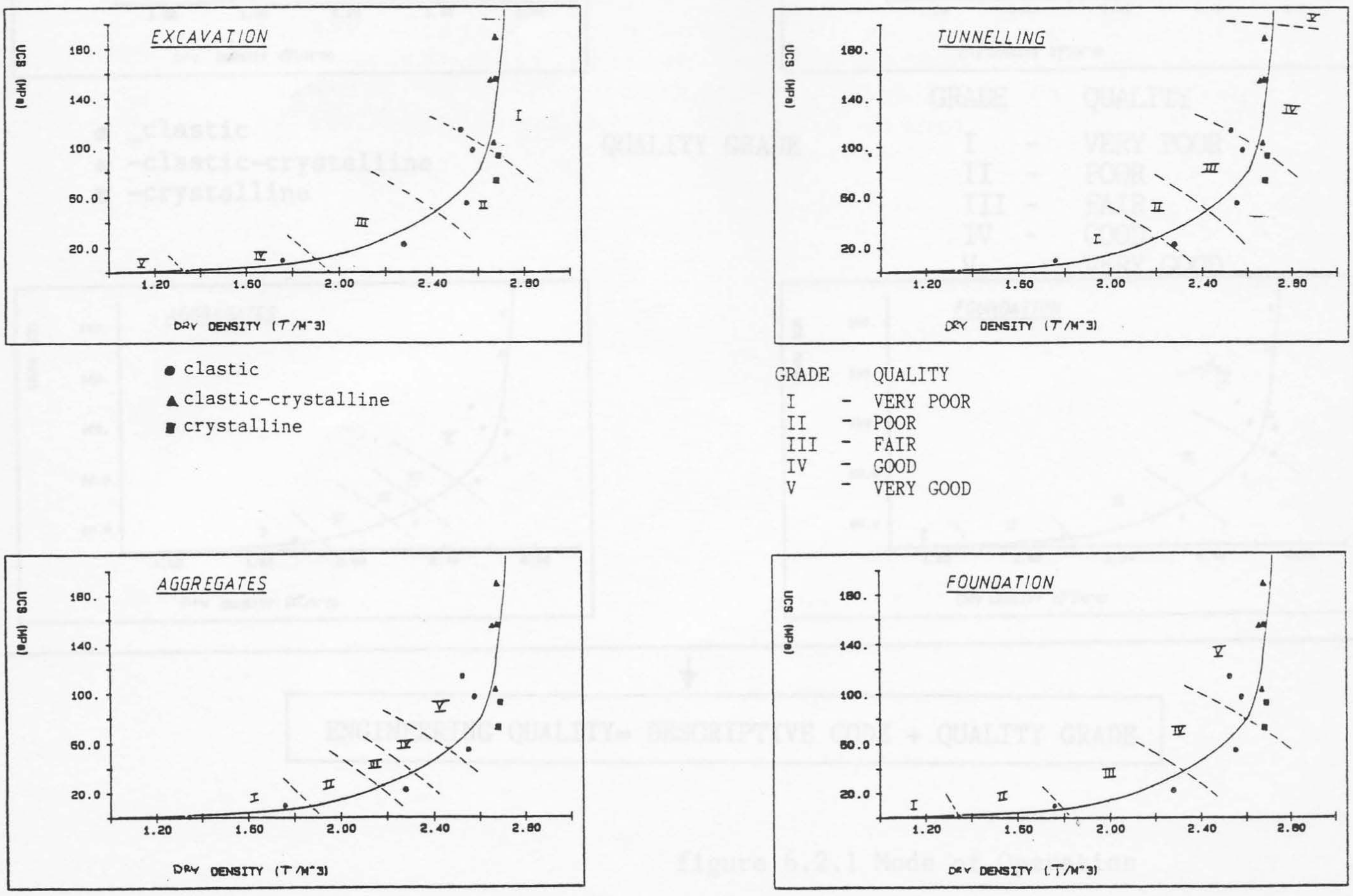


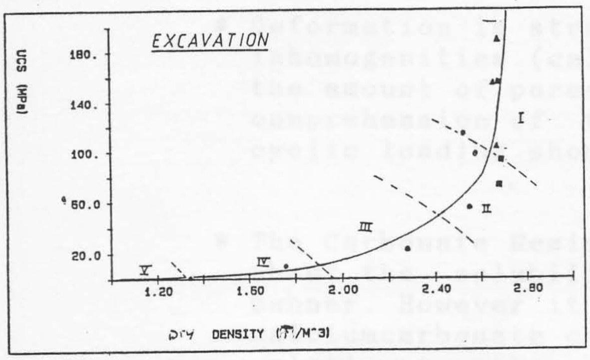
figure 6.1.4 Quality degrees for limestone material in engineering disciplines.

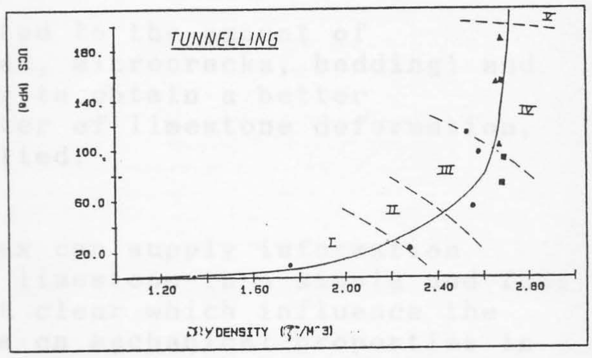
Classification of Limestone material for engineering purposes

CaCO3 %	Texture	Grainsize	Code
90	→ crystalline	→ coarse	→ SC
		→ medium	→ SM
		→ fine	→ SF
	→ clastic-crystalline	→ coarse	→ RC
		→ medium	→ RM
		→ fine	→ RF
	→ clastic	→ coarse	→ CC
		→ medium	→ CM
		→ fine	→ CF

coarse : 2 mm
medium : 0.06-2 mm
fine : 0.06 mm

DESCRIPTIVE CODE

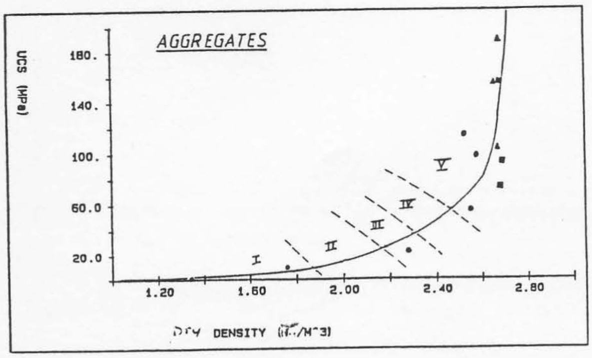


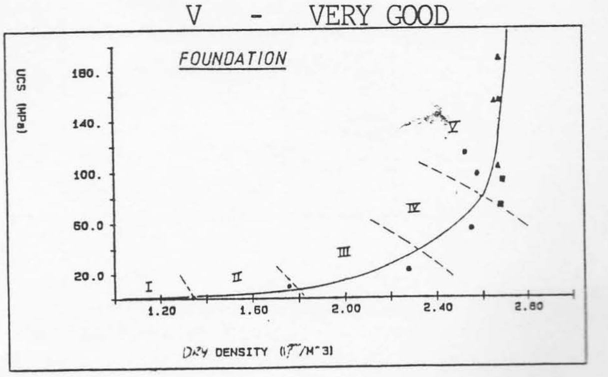


● _clastic
▲ -clastic-crystalline
■ -crystalline

QUALITY GRADE

GRADE		QUALITY
I	-	VERY POOR
II	-	POOR
III	-	FAIR
IV	-	GOOD
V	-	VERY GOOD





↓

ENGINEERING QUALITY= DESCRIPTIVE CODE + QUALITY GRADE

figure 6.2.1 Mode of Operation

7 Recommendations

The engineering geological classification of limestone material is founded upon requirements of engineering disciplines on one side and on geological features on the other. Having this in mind the following conclusions can be based on the results of experiments performed on intact material :

* From the empirical determined relation between the Unconfined Compressive Strength and the Dry Density it is possible to derive information about the engineering quality of limestone material.

* Deformation is strongly related to the amount of inhomogenities (calcite veins, microcracks, bedding) and the amount of pores. In order to obtain a better comprehension of the character of limestone deformation, cyclic loading should be applied.

* The Carbonate Resistance Index can supply information about the solubility of the limestone in a simple and fast manner. However it is not yet clear which influence the calciumcarbonate content has on mechanical properties in relation to other constituents. Hence impure carbonates cannot be classified in the same manner.

(Name of company)	SAMPLE DESCRIPTION SHEET	LOGGED BY	HOLE/PIT
		DATE	LOCATION
		SHEET of	GROUND LEVEL

ROCK		Sample 1	Sample 2	Sample 3	Sample 4	SOIL	
	SAMPLE REF NO	1	2	3	4	SAMPLE REF NO	
	DEPTH m.	27.50	3.25	4.75	6.83	DEPTH m.	
COLOUR	Hue	Pale	Dark		Pale	Hue	COLOUR
	Value	Yellow		Brown	Green	Value	
	Chroma	Brown	Grey	Cream	Grey	Chroma	
GRN SIZE	V Fine < .002mm		✓		Slight	Indurated	COMPACTION
	Fine .002–.06	✓				Non Cemented	
	Med .06–2			Calcite		Poorly Cemented	
	Coarse 2–60	✓				Mod Cemented	
	V Coarse > 60					Well Cemented	
GRN. TEXTR	Xalline / Granular	✓				V Dense / Hard	STRENGTH
	Amorphous				✓	Dense / Stiff	
	Porous / Rough		✓	✓	✓	Med Dnse / Firm	
	Smooth / Glassy					Loose / Soft	
BEDDING	V Thick > 2m	✓				V Loose / V Soft	
	Med 2–.02			✓		Homogeneous	STRUCTURE
	V Thin < .02		✓			Layered	
JOINTS	V Wide > 2m	✓			✓	Fissured	
	Mod 2–.02		✓		✓	Laminated	
	Close < .02				S	Weathering FSMHCR	
CEMENTED	Well			✓		Rounded	PARTICLE SHPE
	Mod	Calcite				Irregular	
	Poorly					Flakey	
	Friable / Non		✓			Angular	
Weathering FSMHCR		F	H			Elongated	
STRENGTH	V Weak					Glassy	PARTICLE TEXT
	Weak		✓	✓		Smooth	
	Mod Weak					Granular	
	Mod Strong	✓				Rough / Crust	
	Strong					Xalline	
	V Strong					Honeycombed	
NAME	Detrital / Shelly	1				Well Graded	GRADING & NAME
	Oolitic / Pisolitic					Gap Graded	
	Coral / Algal					Uniform Graded	
	Micritic / Xalline	2	1	✓		Poorly Graded	
	Clayey / Silty / Sandy	✓				Clean	
	Cicreous / Dlomitic	✓	✓		✓	Clayey / Silty	
	Lmestne / Dlomite	✓		Qtz.		Sandy / Grvelly	
	Claystne / Shale		✓			Lean / Intrmd / Fat	
	Sltstne / Sandstne			✓		Detrital / Xalline	
						Shelly / Coral	
				✓ ✓ 50,50	✓	Qtz / Calc / Dol	
					✓	Clay / Silt	
						Sand / Gravel	
	With Some		Silt	Trc.Clay		With Some	
Remarks		Occas. 5mm ϕ Clay Filled Cavities			Occas. 10cm ϕ Round Clayst. Nods.	Remarks	

Fig. 6. A suggested standardised sample description sheet

Appendix A.1 Suggested sample description sheet for carbonate rocks (Burnett & Epps 1979)

Appendix A.2 The description of rocks for engineering purposes -material (IAEG 1981)

3. Description of Rocks für Engineering Purposes

Description of rock involves the following steps:

(i) Determination of the fundamental rock name: the 'lithological rock name';

(ii) Description of the properties of the rock material;

(iii) Description of additional properties necessary to describe the features of the rock mass.

The properties of the rock mass are controlled partly by the properties of the rock material, but in many rock masses structural features substantially control the engineering properties. Such features include structures and discontinuities such as joints and bedding plane partings, and the distribution of rock and soil materials in the weathering profile.

The three steps listed above provide a 'descriptive rock name' from which engineering properties may more readily be inferred than from a 'lithological rock name'.

3.1 The Descriptive Rock Name

In a rock description the main characteristics should be given in the following order:

- Rock name
  - Supplementary petrographic properties
- Rock material properties
  - Colour
  - Texture
    - Grain size
    - Other textural features and fabric
  - State of weathering
    - State of alteration
  - Strength
- Rock Mass Properties
  - Structure
  - Discontinuities
  - Weathering profile

The descriptive scheme has been modified from that recommended in Anon. (1972b) The main differences are in the treatment of state of weathering and the weathering profile, and an expansion in the description of structure. Structural aspects have been dealt with more thoroughly by Anon. (1977) and also in I.S.R.M. (1977).

3.1.1 The Lithological Name: The lithological rock name is of primary importance because it indicates the genetic rock group and provides basic information on mineral composition and grain size. Supplementary petrographic properties may be used where necessary to qualify the rock name, signifying for example a relative abundance of a particular mineral — biotite granite — or indicating minor admixtures of other lithological types. These supplementary features may be extremely useful as a means of discriminating between different rocks that have the same lithological name. Minor constituents may also have an important effect on the mechanical and physical properties of rocks, and should be carefully considered.

The rock name is selected from the classification tables (Table 1) and these are the only rock names that are recommended for use. In arriving at a name for a rock, there is no substitute either for geological knowledge or for an aid to identification that is reliable and easy to apply.

LIGHTNESS	CHROMA	HUE
Light	pinkish	pink
Dark	reddish	red
	yellowish	yellow
	brownish	brown
	greenish	green
	bluish	blue
		white
	greyish	grey
		black

Table 2: Terms for lightness, chroma and hue which may be used in combination for colour description

3.2 Description of Rock Material

3.2.1 Colour: Rock colour can be quantitatively evaluated using, for example, the Rock Color Chart published by the Geological Society of America (Anon. 1963). As an alternative it is recommended that the following simple system (Anon. 1972b), which serves to limit the subjectivity of an estimation, should be used. One term is selected, as required, from each column (Table 2), and combined as a colour assessment.

Examples of use are: light yellowish brown, dark reddish brown, dark brown, etc. If necessary colour differences can be emphasized separately by the use of terms such as spotted, dappled, mottled, streaked, for example light yellowish brown spotted with dark brown.

3.2.2 Texture: Of the textural elements used for description and classification, the most important is grain size which, for the predominant size of grain, can be classified semiquantitatively. From Table 1 the relations between rock names and grain sizes can be understood. It will be recalled that the class boundaries have been fixed at limits of grain size grades adopted for engineering soils, that is the boundaries between clay, silt and sand sizes that are justified and determined by the differences in the physical behaviour of those soils (Glossop and Skempton, 1945).

Because grain size considerably affects the physical properties of a rock it should always be indicated directly in the rock description rather than relying on the grain size implication in the rock name.

It is usually sufficient to estimate grain size by eye, which may be aided by a hand lens in the case of fine-grained and amorphous rocks. The limit of unaided vision is approximately 0.06 mm.

Many other aspects of rock texture may be used to amplify the description, such as:

3.2.2.1 *Relative grain size:* for example uniform, non-uniform, porphyritic

3.2.2.2 *Grain shape:* may be described by reference to the general form of the particles, their angularity which indicates the degree of rounding at edges and corners, and their surface characteristics (Table 3).

FORM	equidimensional
	flat
	elongated
	flat and elongated
	irregular
ANGULARITY	angular
	subangular
	subrounded
	rounded
SURFACE CHARACTERISTICS	rough
	smooth

Table 3: Terms used in the description of grain shape

3.2.2.3 *Fabric:* the spatial arrangement of grains in the rock may show a preferred orientation or lack of it, and may produce patterns by non-uniform arrangements of grains, crystals and groundmass.

3.2.2.4 *Porosity:* the size, shape, orientation of pore or void spaces should be described.

3.2.3 State of Weathering: Description of the state of weathering of rock material is of particular importance in describing engineering rocks because weathering has profound effects on the physical and mechanical properties of rock material. In any description there needs to be a statement whether or not the rock material is considered to be either in a fresh state or is weathered. Weathering effects may be described in terms of discoloration, chemical decomposition or physical disintegration.

The extent of particular weathering effects may be sub-divided using such qualifying terms, for example 'highly decomposed', 'extremely discoloured', 'slightly disintegrated', as will aid the description of the material being examined. These descriptive qualifying terms may be quantified if necessary by estimation from drill core or in the natural exposure (Table 4).

TERM	DEGREE OF CHANGE (per cent)
Fresh	0
Slightly	Over 0 - 10
Moderately	10 - 35
Highly	35 - 75
Extremely	Over 75

Table 4: Terms for the description of the degree of weathering of rock material

Depending on the character and distribution of the weathering changes, and the extent to which a rigid rock framework is retained, the weathered rock material may assume the characteristics of an engineering soil at an early stage.

Extremely weathered rock material will almost certainly be an engineering soil, and may be classed as a residual soil if the original rock fabric has collapsed or changed so as to remove most traces of the original fabric.

Examples of use are: fresh rock; slightly decomposed; moderately disintegrated; highly discoloured. Usually combinations occur: highly disintegrated and moderately decomposed, etc.

3.2.4 State of Alteration: The terms used for weathering of rock material may be used where appropriate as in many instances the effects of alteration may not be easily distinguishable from those brought about by weathering. Wherever possible common terms should be used, e. g. slightly kaolinised, highly mineralised; the terms may be quantified using the scale in Table 4.

3.2.5 Strength: The uniaxial compression test gives a reliable indication of the strength of rock material, although the test results are dependent on the moisture content of the specimen, any anisotropy in the material, and the test procedure adopted. A scale of strength is given in Table 5.

As an alternative method of strength testing for use in the field, the point load test (Broch and Franklin, 1972; ISRM, 1977) is recommended. Provided that individual test results are normalised to a standard specimen thickness of 50 mm, and the recommended test procedures

3.3 Description of Rock Material

3.3.1 Colour: Rock colour can be quantitatively evaluated using, for example, the Rock Color Chart published by the Geological Society of America (Anon., 1963). As an alternative it is recommended that the following simple system (Anon., 1972a), which serves to limit the subjectivity of an estimation, should be used. One term is selected, as required, from each column (Table 2), and combined as a colour statement.

Examples of use are: light yellowish brown, dark reddish brown, dark brown, etc. If necessary colour differences can be emphasized separately by the use of terms such as spotted, dappled, mottled, streaked, for example light yellowish brown mottled with dark brown.

3.3.2 Texture: Of the textural elements used for description and classification, the most important is grain size which, for the predominant size of grain, can be classified semiquantitatively. From Table 1 the relations between rock names and grain sizes can be understood. It will be recalled that the class boundaries have been fixed at limits of grain size grades adopted for engineering soils, that is the boundaries between clay, silt and sand sizes that are justified and determined by the differences in the physical behaviour of those soils (Glossop and Skempton, 1945).

Because grain size considerably affects the physical properties of a rock it should always be indicated directly in the rock description rather than relying on the grain size implication in the rock name.

It is usually sufficient to estimate grain size by eye, which may be aided by a hand lens in the case of fine-grained and amorphous rocks. The limit of unaided vision is approximately 0.06 mm.

Many other aspects of rock texture may be used to amplify the description, such as:

3.3.2.1 Relative grain size for example uniform, non-uniform, porphyritic

3.3.2.2 Grain shape: may be described by reference to the general form of the particles, their angularity which indicates the degree of rounding of edges and corners, and their surface characteristics (Table 3).

FORM	equidimensional
	flat
	elongated
	flat and elongated
	irregular
ANGULARITY	angular
	subangular
	subrounded
	rounded
SURFACE CHARACTERISTICS	rough
	smooth

Table 3. Terms used in the description of grain shape

3.3.2.3 Fabric: the spatial arrangement of grains in the rock may show a preferred orientation or lack of it, and may produce planarity by non-uniform arrangements of grains, crystals and groundmass.

3.3.2.4 Porosity: the size, shape, orientation of pore or void spaces should be described.

3.3.3 State of Weathering: Description of the state of weathering of rock material is of particular importance in describing engineering rocks because weathering has profound effects on the physical and mechanical properties of rock material. In any description there needs to be a statement whether or not the rock material is considered to be similar to a fresh state or is weathered. Weathering effects may be described in terms of discolouration, chemical decomposition or physical disintegration.

The extent of particular weathering effects may be sub-divided using such qualifying terms, for example "highly decomposed", "extremely discoloured", "slightly disintegrated", as will aid the description of the material being examined. These descriptive qualifying terms may be quantified if necessary by reference from this concept of the standard alphabet (Table 4).

TERM	DEGREE OF CHANGE (per cent)
Fresh	0
Slightly	Over 0 – 10
Moderately	10 – 35
Highly	35 – 75
Extremely	Over 75

Table 4. Terms for the description of the degree of weathering of rock material

Depending on the character and distribution of the weathering changes, and the extent to which a rigid rock framework is retained, the weathered rock material may exhibit the characteristics of an engineering soil at an early stage.

Extremely weathered rock material will usually be classed as an engineering soil, and may be classed as a residual soil if the original rock fabric has collapsed or changed so as to remove most traces of the original fabric.

Examples of use are: fresh rock; slightly decomposed; moderately disintegrated; highly discoloured. Usually combinations occur: highly disintegrated and moderately decomposed, etc.

3.3.4 State of Alteration: The terms used for weathering of rock material may be used where appropriate as in many instances the effects of alteration may not be easily distinguishable from those brought about by weathering. Wherever possible common terms should be used, e.g. slightly kaolinised, highly mineralised; the terms may be quantified using the scale in Table 4.

3.3.5 Strength: The uniaxial compression test gives a reliable indication of the strength of rock material, although the test results are dependent on the moisture content of the specimen, its orientation to the structure, and the test procedure adopted. A scale of strength is given in Table 5.

As an alternative method of strength testing for use in the field, the point load test (Broch and Franklin, 1972; ISRM, 1973) is recommended. Provided that individual test results are normalised to a standard specimen size, and the test can be used in the recommended test procedures

TERM	COMPRESSIVE STRENGTH (MPa)
Weak	1.5*- 15
Moderately strong	15 - 50+
Strong	50 - 120
Very strong	120 - 230
Extremely strong	Over 230

*Rocks with a strength under 1.25 MPa are, as a rule, hard soils and should be tested accordingly

+Soft rocks are weaker than 50 MPa; strong rocks are stronger than 50 MPa

Table 5: A scale of strength for dry rock material

are followed, this test provides a good estimate of unconfined compressive strength. The relation:

$$UCS = 25\ PLS$$

where UCS is the unconfined compressive strength and PLS is the point load strength, has been demonstrated repeatedly and can be accepted as a reasonably reliable approximation.

The piston-press test, devised by Srejner, Petrova and Jakusev (1958) and described by Matula (1969), is a quick method of determining the strength and deformation properties of rock materials. Test values show a very close correlation with the results of the standard unconfined compressive strength performed on cubes of rock.

DETRITAL SEDIMENTARY					CHEMICAL/ ORGANIC	GENETIC GROUP	
BEDDED						Usual Structure	
Grains of rock, quartz, feldspar and clay minerals			At least 50% of grains are of carbonate		Salts, carbonates, silica, carbonaceous	Composition	
RUDACEOUS	Grains are of rock fragments		LIMESTONE (undifferentiated)		SALINE ROCKS Halite Anhydrite Gypsum	Very coarse-grained	PREDOMINANT GRAIN SIZE (mm)
	Rounded grains: CONGLOMERATE Angular grains: BRECCIA			Calci-rudite			60
						Coarse-grained	2
AREN-ACEOUS	Grains are mainly mineral fragments SANDSTONE Grains are mainly mineral fragments			Calc-arenite	CALCAREOUS ROCKS LIMESTONE	Medium-grained	0.06
ARGILLACEOUS or LUTACEOUS	MUDSTONE SHALE: fissile mudstone	SILTSTONE 50% fine-grained particles	Marlstone	Calci-siltite	DOLOMITE	Fine-grained	0.002
				CHALK			
		Claystone 50% very fine grained particles		Calci-lutite	SILICEOUS ROCKS	Very fine-grained	
					Chert Flint CARBONACEOUS ROCKS LIGNITE COAL	GLASSY AMORPHOUS	

Table 1: Classification of rock types: sedimentary

Appendix B.1 Porosity Determination with the "Ruska" Universal Porositymeter following the method of Kobe

Apparatus

The universal porositymeter consists of; a mercury pump; with on top the pyknometer barrel, which can be opened to insert a specimen; above the barrel a needle valve, which is used to close the barrel when pressure builds up; and two manometers, one for high pressure and one for low pressure.

Principle

The porosity measurement with the method of Kobe enables us to determine the porosity of a small kernel in a faster way. The method of Kobe is based on Boyle's law, which says that under a constant temperature, the product of pressure and volume of an ideal gas is also constant. If two reference volumes are taken at 40cc and at 30cc, which are then compressed to 30 Psi. From Boyle's law it follows that :

$$40.P_a = V_f.P_r \qquad 30.P_a = V_e.P_r \quad \Rightarrow \quad \frac{P_r}{P_r - P_a} = \frac{10}{10 - V_e - V_f} \qquad (1)$$

The volume of the material (V_g) is calculated from :

$$P_a.(V_f - V_g) = P_r.(V_f' - V_g)$$

$$\Rightarrow V_g = \frac{P_r}{P_r - P_a}.(V_f' - V_f) \qquad (2)$$

were P_a = the atmospheric pressure
P_r = Pressure at 30 Psi.
V_r = reference volume of uncompressed air
V_f = volume of 40cc air after compression
V_f' = volume of 40cc air and kernel after compression
V_e = volume of 30cc air after compression

when equation (1) is substituted in equation (2) one finds :

$$V_g = \frac{10}{10 - V_e - V_f} \cdot (V_f' - V_f) \qquad (3)$$

the porosity is then calculated from : $$\Phi = 1 - \frac{V_g}{V_b} \qquad (4)$$

V_b = bulk volume

Appendix B.2 Permeability measurement

Liquid permeameter

the liquid permeameter is an apparatus which uses pressurized water to create a flow through the specimen. the specimen, water saturated and placed in a holder, is after a few seconds submitted to a constant flow. At this time the increase of he weight of the out flowing water with time is measured. Based on Darcy's law for laminar flow, the weight per unit time is then recalculated to volume, and the permeability follows from the formula :

$$K = \frac{m \cdot V \cdot L}{A \cdot dP \cdot t}$$

Gas permeameter

The gas permeameter uses pressurized gas to determine the permeability of the specimen in three different ranges of sensitivity. The instrument includes; a thermometer; a flowrate meter; a manometer; and a pressure regulating valve. The kernel is placed in the holder surrounded by a rubber mantle to exclude gas leakage at the sides of the kernel. When gas under 1 atm. pressure is guided through the kernel, the permeability can be calculated according to Darcy from :

$$K = \frac{m \cdot Q \cdot L}{A \cdot P}$$

were m = viscosity (Cp)
m water = 1 Cp
m gas = 0.0176 Cp at 23° C
K = permeability (Darcy)

Q = average value of flow rate (cl/sec)
P = pressure difference in atmosphere
L = length of kernel (cm)
A = square area of kernel (cm^2)
V = volume of out flow (cc)
t = time (sec)

Appendix B.3 Unconfined Compressive Strength Determination

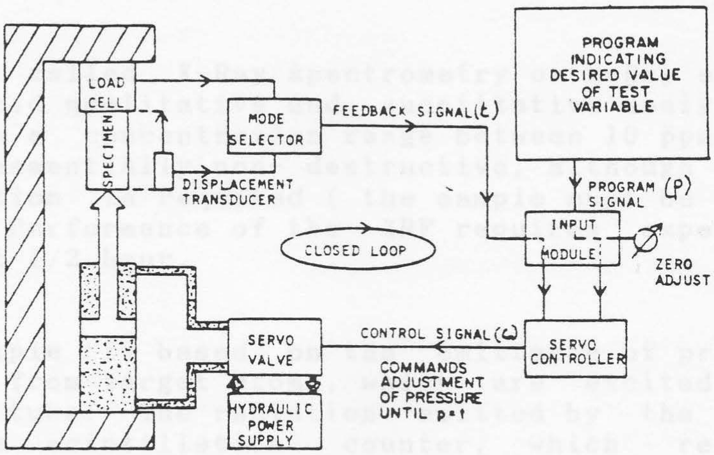


figure B.3.1 Closed Loop Servo Controlled System

For calibration of the 700 kN loading frame a steel core specimen, of elastic modulus 210 GPa, is tested. In figure B.3.1 the measured value is approximately 200 GPa. In the calculation program of the computer a correction factor for the deformation of the 30 mm of the bottom plate, which is also measured by the LVDT's, is accounted for.

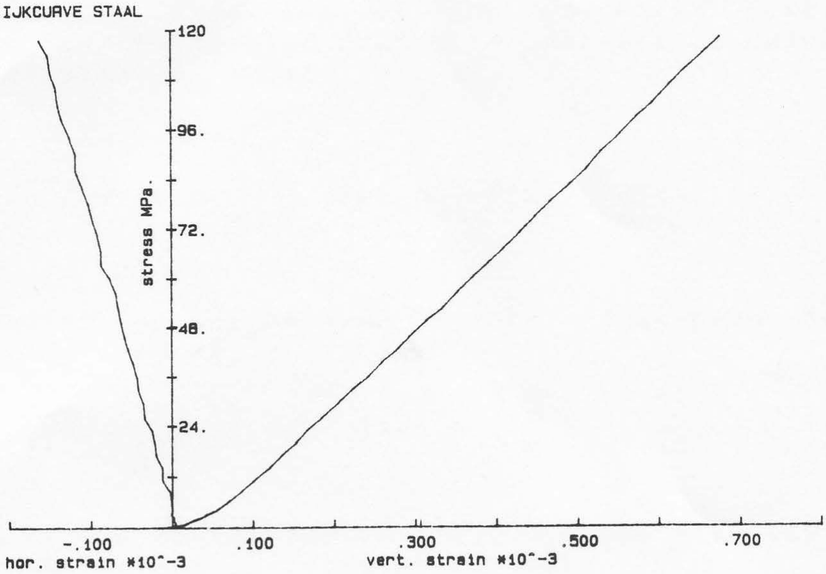


figure B.3.2 Calibration Curve of Steel

Appendix B.4 X-Ray Fluorescence Analysis

XRF (also called X-Ray spectrometry or X-Ray emission) can be used for rapid qualitative and quantitative analysis of over 80 elements in a concentration range between 10 ppm and 100 % . The method is essentially non- destructive, although some form of sample preparation is required (the sample must be submitted in powder form). Performance of the XRF requires expert knowledge and takes about 1/2 hour.

The principle is based on the emittance of primary X-rays (fluorescence) from target atoms, which are excited by a beam from an X-ray tube. The radiation emitted by the atom is then absorbed by a scintillation counter, which registers the intensities for the different elements. The height and amount of these signals, after amplifying, are then proportional to the quantity and quality of the sample. They can be recorded as the number of pulses per unit time.

Appendix C.1 Test for Normality

The empirical distribution function analysis is a technique, which does not require very large numbers of data to render information about the normality of a set. Regarding random sampled values, $x_1, x_2, x_3, \ldots\ldots x_n$, the empirical distribution function can be determined as:

$$F_n(x) = \frac{k}{n} \qquad \text{if } k \text{ measurements} < x$$

This function is nothing more than the frequency quotient of an event " X < x " as a function of x, based on n measured values. Ofcourse the empirical distribution function represents the unknown population distribution. As an approximate of this distribution function the sample set average x* and the sample set standard deviation s* can be calculated and the adapted normal distribution function as well.

$$F(x) = \Pr\{\, u < \frac{x - x*}{s*} \,\} \qquad \text{with } u \text{ standard normal}$$

F represents the unknown population under the condition that the random sampling set comes from a normal distributed population with m and o unknown. A large deviation between F_n and F will result in the rejection of the suspected normality. As a deviation the integrated quadratic difference between F_n and F will be considered, namely

$$W = n.\int_{-\infty}^{\infty} \{F_n(x) - F(x)\} \; dF(x)$$

This integral can be, because F_n is a stepped function (fig. C.1.1), redefined as,

$$W = \sum_{i=1}^{n} t_i - \frac{1}{n}.\sum_{i=1}^{n}(2i - 1)t_i + \left(\frac{n}{3}\right) = \frac{1}{12n} + \sum_{i=1}^{n}\left(t_i - \frac{2i - 1}{2n}\right)$$

in which $t_i = F\,(x(i))$ for i= 1,2,...,n and x(1),x(2),...,x(n) arranges the values in increasing height.

The critical value is given by *,

$$\frac{0.104}{1 + (1/2n)}$$ if the unreliability a = 0.10

$$\frac{0.126}{1 + (1/2n)}$$ if the unreliability a = 0.05

$$\frac{0.178}{1 + (1/2n)}$$ if the unreliability a = 0.01

*) Biometrica Tables for statisticians, Vol. 2, Cambridge University Press (1972), table 54 .

880638