Prediction of the compressive strength of concrete made by recycled coarse aggregate derived from selective demolition

CIE5060-09

Mouhannad Aladib

TU Delft Delft University of Technology

M. Sc. Thesis

Prediction of the compressive strength of concrete made by recycled coarse aggregate derived from selective demolition

By

Mouhannad Aladib

In partial fulfilment of the requirement to obtain the degree of

Master of Science

In Structural Engineering

At the Delft University of Technology

Student number: 4530926

Research committee:

Prof. Dr. Peter Rem (Chair)	Engineering Structures, Resources & Recycling
Dr. Francesco Di Maio	Engineering Structures, Resources & Recycling
Ir. Ali Vahidi	Engineering Structures, Resources & Recycling
Ir. Cor Kasbergen	Engineering Structures, Pavement Engineering

Preface

It gives me immense pleasure to reflect upon my transformative journey at the Delft University of Technology, where I have spent two years pursuing education, acquiring both theoretical and practical knowledge, engaging with initiative-taking students, and attending lectures and workshops conducted by the most excellent teachers. As I write this preface, I realize that my educational expedition has now reached its conclusion.

This research work represents the culmination of my efforts over the past nine months, undertaken as a partial fulfilment for the degree of Master of Science in Structural Engineering at the Delft University of Technology. The experiments for this study were conducted at the concrete and recycling-lab housed within the Department of Engineering Structures, Faculty of Civil Engineering at the university.

My passion for sustainability and recycling concrete rubble grew exponentially after leaving my home country, Syria. The devastating Syrian war caused extensive destruction across the nation, and as a Syrian civil engineer, I bear a deep sense of responsibility to contribute to the reconstruction efforts in our country. My personal experiences, combined with the scientific knowledge I have acquired in concrete waste recycling, hold great significance in the post-war context.

I would like to express my heartfelt gratitude to Ron Mulder from Dyckerhoff for his invaluable assistance in developing the concrete mix. His guidance and expertise in bridging the gap between research and practical application have been instrumental in formulating a viable mixing procedure suitable for large-scale projects. I deeply appreciate his supervision and consultancy, which have played a significant role in shaping my research.

I am deeply grateful to my mother, my lovely wife, siblings, and loved ones for their unwavering sup-port during my fulfilling study abroad journey. Their constant presence, encouragement, and determination have been invaluable in helping me overcome challenges. Special thanks to Hans Schrijner, Dr Yongli Wu, and Shaniel Chotkan for their exceptional supervision.

I extend my sincere appreciation to my committee members, particularly Ali, my daily supervisor, who has been a reliable source of answers, advice, and friendship. I am also grate-ful to Prof. Dr Peter Rem, Dr Francesco Di Maio, and Ir. Cor Kasbergen for their guidance throughout this journey. Lastly, I want to express my heartfelt gratitude to my classmates for making this educational experience enjoyable and memorable.

I present this thesis with great pleasure, hoping it contributes to sustainable practices in structural engineering and aids in post-war reconstruction efforts. May it inspire future research and encourage the adoption of sustainable solutions in the field.

Abstract

The utilization of Recycled Coarse Aggregate (RCA) in concrete has gained significant traction due to its environmental and economic advantages. However, ensuring the quality of RCA poses challenges as it is influenced by various unpredictable factors including the high water absorption of RCA, ineffective recycling processes, and the presence of contaminants. The existing body of research on the influence of RCA on the Compressive Strength (CS) of concrete has yielded inconsistent findings, and limited knowledge exists regarding the specific combination of parameters that enable effective control over CS. To address this gap, the present study aims to identify the essential parameters that contribute to controlling CS in concrete through the development of a predictive model. By investigating these crucial parameters, this research intends to extent current knowledge on optimizing the use of RCA in concrete.

To investigate the impact of the crucial parameters on the CS of concrete when utilizing RCA, a series of experiments were conducted. The RCA was obtained through the selective demolition recycling technique. The content of RCA was divided through manual separation into unbound stones, Low-Quality Recycled Aggregate (LQRA), and contaminants. LQRA is composed of residual mortar and stones with mortar attached to their surface. The experiments included physical properties tests and optimization of the concrete mix designs. Additionally, relevant literature was consulted to identify the parameters that would serve as variables in constructing the predictive model. Through analysis via response surface methodology, a predictive model was developed to assess the impact of these critical parameters on the CS of concrete.

The experimental findings confirmed the statistical significance of the predictive model in assessing the impact of critical parameters on the CS of concrete. The level of LQRA was found to have a negative impact on the quality of RCA. The water-to-cement ratio was identified as a significant factor affecting the CS of concrete, with lower ratios yielding higher CS. When using RCA with high LQRA content (up to 65% of the total weight of RCA) as a substitute for natural coarse aggregate, higher replacement ratios resulted in lower CS.

In order to further validate the predictive model, Artificial Neural Network (ANN) modelling was incorporated as a non-linear method of assessing the relationship between the variables and the output, which is the CS. The high R^2 values obtained from the ANN model demonstrated the robust alignment between the model and the data, strengthening its reliability. The integration of a Pareto chart and model-fitting regression gives a better physical understanding of the results of the predictive model by identifying influential terms and reducing complexity. The resulting model improves interpretability and predictive accuracy. The analyses emphasize the significance of integrating ANN and the Pareto chart approach in enhancing model validation and simplification.

These findings offer valuable insights into the parameters that are crucial to the CS of concrete which consists of RCA. By implementing the procedures that assess the quality of RCA, sustainable construction practices can be promoted, and the wider application of RCA can be facilitated on an industrial scale.

Table of Contents

Table of figures:

List of abbreviations:

AA: Artificial Aggregate

ADR: Advanced Dry Recovery

AM: Adhered Mortar

ANN: Artificial Neural Network

ARD: Absolute Relative Deviation

ARM: Adhered and Residual Mortar

BFS: Blast Furnace Slag

BRA: Brick Recycled Aggregate

C2CA: Concrete to Cement Aggregate

CCD: Central Composite Design

CDW: Construction and Demolition Waste

CEIP: Circular Economy Implementation Program

CS: Compressive Strength

DOE: Design Of Experiment

EOL: End-Of-Life

FA: Fly Ash

LAAT: Los Angeles Abrasion Test

LQRA: The combination of RCA types R^2 and R^3

LSP: Limestone Powder

MC: Mortar Content

MRA: Mixed Recycled Aggregate

NCA: Natural Coarse Aggregate

RAC: Recycled Aggregate Concrete

RCA: Recycled Coarse Aggregate

RSM: Response Surface Methodology

SCM: Supplementary Cementitious Material

SF: Silica Fume

SG: Specific Gravity

SP: Superplasticizers

WA: Water Absorption

1. Introduction

1.1 Background

Over the past century, the building industry has played a crucial role in improving economic and human well-being. However, the building industry activities are the primary carbon dioxide source. Besides, material production leads to large consumption of natural resources which causes unrecoverable harm to the environment (Abd Rashid & Yusoff, 2015).

Construction and Demolition Waste (CDW) forms the most significant portion of the solid waste produced in the world (Menegaki & Damigos, 2018). In the European Union alone, 450 million tons of CDW are generated; from a qualitative point of view, these volumes are the biggest compared to agricultural and mining activities (Müller, 2012). The majority of CDW is concrete. Concrete is one of the most widely used materials in the building industry; the yearly consumption rate of concrete is about $1m^3$ per individual human being (Meyer, 2004). Concrete consists of up to 80% of natural aggregate (Verian et al., 2018); therefore, concrete production is responsible for the main consumption of natural stone supplies. Intensive extraction of Natural Coarse Aggregate (NCA) can result in environmental instability, for instance, disturbing riverbanks' water levels, reducing the water quality, and affecting wildlife and biodiversity (Marinković et al., 2010).

A previous study developed the "3R strategy" approach by categorizing waste management into three management actions: reduce, reuse, and recycle (Haupt et al., 2017). The significance of 3R lies in lowering dumped waste, preserving natural assets, and lowering the effect of greenhouse gasses. In the present study, the focus is on the recycling level. Encouraging the recycling of waste leads to a sustainable and circular construction market.

Crushed concrete rubble generated from demolished concrete structures is used to produce recycled concrete aggregate. Concrete rubble recycling reduces the emission of Co2. Besides, it contains potentially sustainable waste that could be reused in making new concrete mixtures. However, the debris may contain high proportions of hazardous matters. Therefore, the contaminated material is dangerous for the environment and therefore cannot be used for structural applications.

The Delft University of Technology is one of the leading universities in Europe in developing recycling techniques that turn solid waste into a building material that can potentially be used for different applications (Gebremariam et al., 2020). The advanced selective demolition technique is currently the most circular approach compared to conventional and partial-selective demolition methods, due to the reclamation of components, minimization of contaminants, and the reduction in adverse environmental effects (Zhang et al., 2022).

Earlier studies have investigated the impact of Recycled Coarse Aggregate (RCA) on the mechanical properties of concrete. A study conducted by Etxeberria and colleagues (2007) looked into the mechanical behaviour of concrete with 100% RCA. The research observed a reduction of 25% of the CS compared to the reference mixture. Adding extra cement to the concrete mixture could overcome this reduction. This suggestion is not environmentally friendly from a sustainable point of view. To understand the significant difference in the mechanical properties between conventional concrete and Recycled Aggregate Concrete (RAC), it is essential to investigate the quality of RCA. In practice, RCA can contain various contaminations, such as brick, wood, gypsum, and Adhered and Residual Mortar (ARM), that can impact its mechanical behaviour, depending on the source, environmental conditions, and composition of parent concrete. To improve the quality of RCA, the contamination level has to be reduced. For example, wood can become an unstable material when subjected to freeze-and-thaw cycles (Lotfi et al., 2015). Brick has a similar density to natural stone; thus, it can complicate the separation process. ARM has a high Water Absorption (WA) due to its porous structure and relatively low density. In addition, RCA contains Adhered Mortar (AM). The AM cannot be easily removed from the surface, and this often leads to the degradation of the properties of new concrete. This study aims to investigate the impact of these impurities on the quality of RCA and thereby the mechanical behavior of concrete made with RCA.

1.2 Problem statement

The Circular Economy Implementation Program (CEIP) emphasizes the importance of reducing the use of natural resources and recommends reducing the use of NCA by 50% in 2030 and 100% in 2050; thereby contributing to the reduction of carbon emissions (de Boer et al., 2021). To reach this goal, alternative materials must be introduced. It is widely acknowledged that RCA derived from CDW is an excellent example of a material that can replace NCA in building applications (Suhendro, 2014).

At the time of the planning and design of this research, the Dutch recommendation for the use of RCA (CUR-Recommendation 112) sets the upper limit of the replacement ratio to 30% (Gonçalves & Brito, 2010). Many obstacles impede the use of percentage ratios higher than 30%. The obstacles faced in the practical implementation of RCA in concrete can be summarized as follows:

1. **Presence of contamination:** contaminants are always present in RCA. The percentage of contaminants depends on the source of RCA and the efficiency of the recycling techniques. These impurities might consist of materials that can disqualify their use in structural concrete. In addition, the presence of contaminants makes it difficult to maintain a consistent quality of RAC.

2. **Defining the parameters affecting the RCA quality:** crushed concrete derived from CDW usually has low quality compared to NA, due to contamination, ARM, and the parent concrete conditions. However, when studying the current knowledge on RCA, it is pretty challenging to find a quantitative approach that gives a baseline on how to define the RCA quality in RAC (Zhang et al., 2020).

3. **Inconsistent mechanical behavior of RAC:** numerous studies have been investigating the performance of RCA during the past 25 years (Tam et al., 2018). Research showed that mix designs with 50% RCA give the highest compressive strength (CS) compared to mixtures with 25%, 75%, and 100% RCA (Li, 2004). Another study stated that the higher the RCA content, the lower the CS (Deng, 2005). According to a previous study, no reduction of the CS is noticed for mixtures incorporating RCA between 30% and 100% (Xiao et al., 2012).

4. **The practical implementation of RCA**: The use of RCA in practice faces challenges related to grading curves and water content control. In practice, sieving aggregate to achieve specific grading curves is not feasible, as concrete ready-mix plants typically accept RCA as they are. Additionally, controlling the water content of RCA is difficult, leading to potential issues with workability and rejection of concrete.

This implies that the current knowledge gap potentially hinders reaching the goals of the CEIP. Building contractors might be more motivated to apply RCA in construction when its quality and mechanical behaviour can be better defined and predicted. This would especially be the case when the quality of RCA and mechanical behaviour of RCA exceed the current expectations. Therefore, to decide what needs to be done to enable the use of RCA in structural concrete, it is essential to classify the quality indicators for the use of RCA, keep the contamination levels at the lowest, and identify the critical parameters that can predict the mechanical performance of RAC.

It should be noted that at the time of the write-up of this research, the Dutch recommendation has been updated (CROW-CUR recommendation 127:2021) and now RCA can replace NCA up to 100% without adaptation of the constructive calculation rules.

1.3 Project description

1.3.1 Concrete to Cement & Aggregate (C2CA) technology

End-Of-Life (EOL) concrete forms up to 80% of the CDW (Gebremariam et al., 2020), which accounts for up to 33% of the total solid waste flows in Europe. Recycling EOL concrete contributes to reducing CO_2 emissions associated with building industry activities. EOL concrete flows are divided into cement and top-class aggregate. The Concrete To Cement Aggregate technology (C2CA) developed the world's first mobile factory for circular concrete (Di Maio, 2012).

The main goal of the C2CA technology is to provide a systematic and cost-effective approach to reusing EOL concrete. The technology is employed to make RCA with minimum contamination levels and mechanical improvement of the substances on-site. The layout of closing the loop cycle can be seen in figure 1.1.

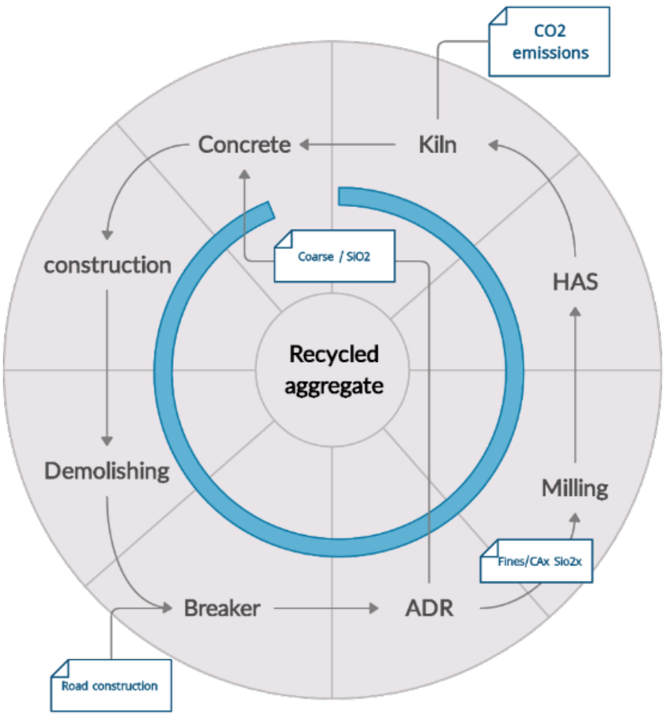


Figure 1.1: Closing the loop cycle.

In-situ recycling of concrete rubble is the major goal of the C2CA technology. To achieve this goal, a recent low-cost treatment technique is developed in the resources and recycling lab at TU Delft. The classification technology is known as Advanced Dry Recovery (ADR) (Gebremariam et al., 2020). This technology is applied to eliminate fines and small contaminations. The installation of the ADR is shown in Figure 1.2.

Figure 1.2: ADR installation (Lotfi et al., 2017).

Using the kinetic energy principle generated by the rotor, the water bond between fractions is broken. Therefore the particles of different sizes can be separated. Crushed aggregate produced by ADR is the RCA utilized in this study. The ADR process is explained as follows:

1. The EOL concrete waste (0-16mm) is fed to ADR installation.
2. The rotor hits the aggregate; they disperse at different velocities and distances based on the kinetic energy they possess. Hence, they end up on various conveyors.
3. While the wet fine fractions (0-1mm) are transported to their respective storage, the coarse fractions are further passed through the air sifter, where lighter aggregate attached to the surface of RCA is further separated from the coarse fractions.
4. Finally, the air sifter separates RCA (4-16mm) products on one side, and fine fractions (0-4mm) along with other contaminants such as wood, plastic, and glass on the other side of the product stream.

1.4 Research relevance

This study expands the existing knowledge of the utilization of RCA in concrete, focusing on controlling the quality of RCA and providing improved recipes that can optimize the mechanical performance of RAC. Accordingly, the use of RAC in structural concrete can be feasible, and limitations regarding the use of RCA in high replacement ratios can be overcome.

To increase the confidence and reliability of the potential of RCA, the collected information is critically evaluated for use in academic research. The key points that illustrate the significance of this study are outlined below:

- **Scarcity of natural resources:** rapid industrialization has led to a growing demand for primary aggregate and considerable danger to the environment. In addition, the consumption of finite resources leads to large energy consumption and CO2 emissions. In the building industry, the overwhelming amount of GHG emissions and consumption of raw resources are no longer tolerable (Hong et al., 2015). Recycling CDW into building materials can substantially lower energy consumption, reduce CO2 emissions, and lower the pressure on natural resources.

- **Research vs. practice:** theoretical research is mainly performed on a lab scale; pre-treatments such as eliminating the ARM or improving the surface of RCA are typically used to enhance the quality of RCA. The RCA in the lab is mainly treated or uncontaminated. In addition, the results of the pre-treatment techniques of RCA are inconsistent. They do not deliver firm conclusions on how to utilize them in controlling the mechanical performance of RAC. However, in reality, RCA coming from CDW contains various contaminations and cannot be certified. Besides, RCA must be used without any modifications on a large scale due to economic and technical restrictions. As a result, RCA is not used in high-grade structural applications. According to a local concrete ready-mix plant, the mixing procedure, storage conditions, and adequate quality characterization of RCA must be similar to make a reasonable comparison between lab- and industry-scale conditions (Pietersen et al., 1998).

- **Marketing demand:** the market uptake of RCA in the construction industry is quite restricted. Since incorporating RCA in ratios higher than 30% gives inconsistent results and uncertainties to the mechanical properties of concrete, the Dutch standard, at the time of performing the research, allows only up to 30% maximum replacement of NCA. To encourage higher replacement ratios of RCA, several aspects must be considered; increase the cost of using NCA by including the environmental impact in the form of additional tax, assign new legislation, and less strict recommendations concerning the employment of RCA.

- **Quality gradation of RCA:** strict control and monitoring protocols are key in producing consistent quality aggregate. However, the properties of RCA depend on the properties of parent concrete, which is generally untraceable. Therefore, the focus must be on identifying the critical aspects that define the quality of RA. Preliminary studies on the composition of RCA can provide a better understanding of why RCA performs less than NCA concerning mechanical properties. Most studies propose treatment techniques that enhance the performance of RCA. However, these approaches are either not applicable on a large scale or not cost-effective. Categorizing RCA based on their composition makes it possible to maximize their use for their proper applications. Besides, it also helps future clients to select the category suitable for their needs.

1.5 Research objectives and questions.

This research aims to develop a predictive model for the CS of RAC in which the effects of contaminants (among others) in the CDW are accounted for. The knowledge gap is that experimental results regarding the CS of RAC are not clarified by logical reasoning. Studies claim that contaminants and cement particles in RCA are the main factors leading to the decrease in CS (Ulloa et al., 2013). The objectives of this research are as follows:

- Investigating the quality of RCA, based on its content and physical properties
- Examining the impact of various parameters on the CS of RAC.

- Developing a predictive model for the CS of RAC based on Response Surface Methodology (RSM).
- Recommending criteria for the use of RCA

The following research questions are defined from the objectives and answered to satisfy those:

1. What are the main parameters that affect the fresh and hardened properties of RAC and can help characterize RCA?
2. What is the impact of common contaminants on the CS of RAC?
3. What is the relationship between the critical parameters, including contaminants, which allows the prediction of the CS of RAC?
4. What are the quantitative criteria which can classify the RCA for its use in RAC?

1.6 Methodology

To maintain a structured approach, the methodology for answering the research questions was split up into three phases. The workflow of the methodology is depicted in figure 1.3.

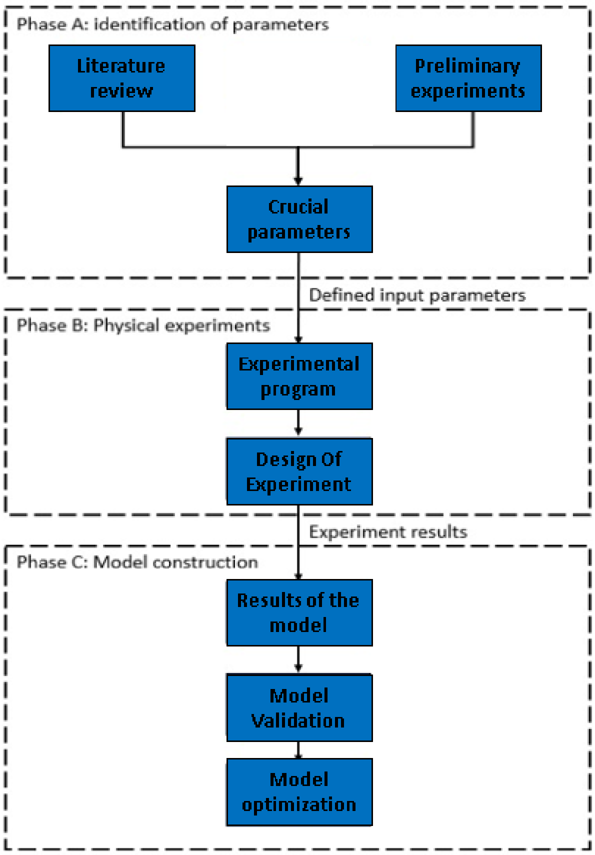


Figure 1.3: Workflow followed to obtain the research objectives defined in the research.

In phase A, parameters were defined that can potentially define the quality of RCA and predict the CS of RAC. The parameters were identified through three main sources of information. The first source consisted of a literature review. Articles were examined in which the quality of RCA was emphasized and in which it was explained in what manner the CS of RAC can be determined by other parameters. The second source of information consisted of a database in which the CS of conventional concrete was calculated against different parameters. It is assumed that the main parameters contributing to the CS of concrete also mainly contribute to the CS of RAC. The data analysis allowed the construction of heat maps and scatter plots to identify the correlations between the CS and the various parameters. The third source consisted of the results of preliminary experiments. The preliminary experiments investigated the relationship between the composition and physical properties of RCA with the CS of RAC. Phase A is concluded with an explicit amount of parameters which are the most critical ones contributing to the CS of RAC. Based on the results of the literature review, preliminary experiments, and data analysis, the first question was answered.

In phase B, which is defined as the experimental program, experiments were performed in which the physical properties of RCA were measured. In this experimental program, a specific amount of concrete sampled was constructed, of which the variables defined in Phase A were measured as well. After this, the CS was measured. This led to a database in which the numerical values of the input variables were associated with the numerical values of the CS. For the details regarding the physical experiments, one can refer to Chapter 3.

In phase C, the predictive model was constructed using the Design of Experiments (DOE) methodology. It is a systematic approach to engineering problem-solving that determines the interactive effects of variables that impact the output results of the experiments. RSM is considered one of the best approaches among existing methods in DOE (Dahmoune et al., 2015). It is a collection of empirical and analytical methods in which a response is described by a set of variables. figure 1.4 shows a flowchart describing the RSM process. The method requires a table in which the exact values of input variables are associated with the exact values of the output variable, which in this case is the CS. The database which was constructed in Phase B was utilized for constructing this predictive model. The predictive model results consist of Analysis of Variance (ANOVA) tables and contour plots. ANOVA tables contain information about how the model is fitted and the sensitivity of each chosen variable. Optimization of the model results shows where the maximum values of the CS are located and which values of the input variables are associated with these maxima.

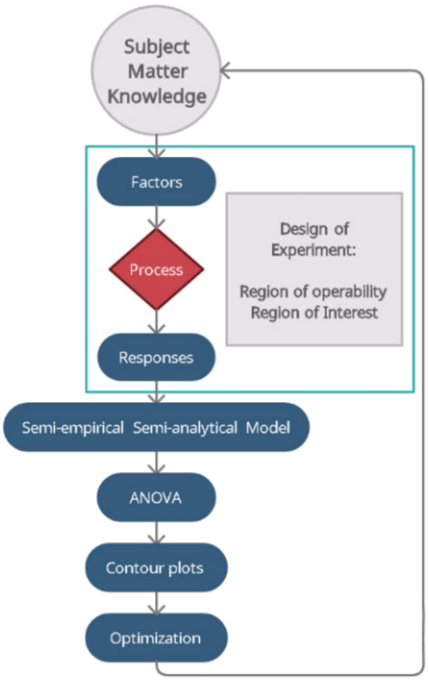


Figure 1.4: Flowchart describing the RSM process.

The predictive model underwent a validation process by comparing its results with several model control points. Validation was assessed by measuring the Absolute Relative Deviation (ARD). The model was deemed valid if the ARD values fell within a 10% range of the predictive model results (Alyamac et al., 2017). To further enhance the validation, Artificial Neural Network (ANN) analysis was employed.

The research findings, including guide values for labeling RCA and determining its suitability for various applications, are presented in a table. These results directly address the fourth research question and offer valuable insights for the practical implementation of RCA.

1.7 Research scope and constraints

This research investigates the impact of different parameters on the mechanical properties of RAC using RCA derived from CDW. The study also focuses on understanding the potential of utilizing RCA by defining the physical properties and composition of RCA, thereby achieving a clear quality gradation of RCA. The RCA used in the research was obtained from an ADR installation in July 2020. Data analysis is conducted using available academic repositories, primarily consisting of data sets for concrete made with NA.

For all the mixes studied in the research, cement type III (CEM III 42.5 N LH/SR) is Blast Furnace Slag (BFS) cement CEM III, which is a largely applied type for structural applications in the Netherlands. Mixture designs are made for environmental class XC3 and strength class C30/37. Using environmental class XC3 and strength class C30/37 implies no air contamination larger than 4%. These classes are widely used in the construction industry. Besides, additives such as Fly Ash (FA) and superplasticizers such as water-reducing agents are chosen based on the consultation of concrete experts in the building industry.

1.8 Thesis outline

Chapter 2 provides a comprehensive evaluation of recent studies focusing on the properties of RCA and the performance of RAC. The findings and results offer a clear understanding of the current research challenges, highlighting key factors that influence the mechanical behavior of RAC. In Chapter 3, the experimental procedure is detailed, covering the materials used and the casting activities conducted. Chapter 4 presents the results of the experiments and the corresponding modelling aspects. This chapter explores the impact of incorporating RCA in significant proportions and examines the consequences of contamination on the modelling outcomes. Chapter 5 showcases the results of preliminary experiments and the predictive model. In Chapter 6, a comprehensive discussion of the results is provided, including the optimization of the model based on validation methods. Lastly, Chapter 7 presents conclusions, recommendations, and alternative approaches for further exploration.

2. Literature Review

The content of this chapter addresses the main differences between research and practice in making concrete from RA. Besides, it describes the main aspects that define the quality of RCA. In addition, the impact of the contributing factors to the mechanical properties of RAC is investigated.

Results of published papers and studies regarding the quality of RCA and the mechanical properties of RAC are critically evaluated to give a clear insight into the main characteristics regarding the performance of RCA.

2.1 Construction and Demolition Waste (CDW)

CDW produced from building activities makes up 30% of the total generated waste in the EU. It consists of mineral materials and a smaller quantity of additional elements as its contents vary depending on the source and recycling process (Pellegrino et al., 2016). According to a previous study, assessing the potential of CDW means characterizing the components of the waste, which is an essential step in understanding its properties and composition before using it to attain structural purposes. The study showed that produced RCA does not affect the magnitude of the CS of RAC when similar crushing and processing methods are used (Butler et al., 2013).

2.1.1 Application of Recycled Coarse Aggregate (RCA), (Research vs. practice)

RCA obtained from CDW is known for its high variation in physical properties such as WA and density, unlike NA. Therefore, its application in structural concrete is limited. The following aspects illustrate the main differences between how RCA is used on a lab scale and its application in practice.

1. **Grading curves**: when comparing research to practice, there are some differences regarding the grading of aggregate. In research, the aggregate replacement ratio is typically defined and distributed equally over commercial fractions. Moreover, in most published papers, similar grading distribution and curves are used for standard concrete mixtures containing NCA (Müller, 1998). In practice, sieving is not a practical solution since in ready-mix plants, as long as the aggregate conforms to the grading standards, they are accepted as they are. Additionally, there are logistical complications regarding including RCA in the different fraction distributions. These constraints are generally related to land availability and use because of the high cost of the square meter of land. Furthermore, large spaces are required to distribute the different RCA across different commercial fractions, which is not feasible in most treatment plants. To facilitate the use of RCA in practice, the concrete production company should establish a target grading curve for the concrete mix, in which the properties of the concrete mix fulfill the requirements of the specific project being undertaken by the company. This grading curve should then serve as a reference for the aggregate-producing company to ensure that the grading curve of RCA complies with the requirements of the concrete production company.

2. **The water content of RCA:** the actual moisture content of aggregate is essential in determining the amount of water needed to ensure the unchanged mix proportioning in the

mix design (Silva et al., 2014). As previously mentioned, there are several obstacles related to controlling the water content of RCA. In practice, it is quite difficult to control the water content of RCA over time, unlike in lab conditions, where it is possible to calculate the compensation water precisely. In scientific terms, it is preferable to control the WA of RCA during mixing than using saturated aggregate. When RCA is initially saturated, its pores will be filled with water. It may lead to micro bleeding near the surface if it is overly saturated, resulting in an imperfect interface between the RCA and the new mortar. In the case of water compensation methods, the RCA will absorb water during mixing. Suppose the RCA has cement attached to the surface. In that case, the compensation water will fill in some pores and eventually lead to a better interface. However, there is a preference for using the RCA in natural moisture state in practice. From a practical point of view, it is easier to control the saturation of RCA than to precisely determine the absorbed water (Tošić et al., 2021). However, the water content cannot be appropriately measured when applying a water compensation approach. After mixing and during transport, water will be absorbed and concrete will lose workability and this may lead to unacceptable workability and rejection of concrete. To compensate for this effect, it is preferable to use a superplasticizers. Superplasticizers can maintain workability during transport time (1-2 hours) (Nkinamubanzi et al., 2016). The company should get information regarding the moisture content of the delivered aggregate, and the moisture content should remain constant. The most practical, efficient, and cost-effective method of measuring the moisture content of aggregate is the use of rapid moisture and moisture content meters.

2.2 Quality of Recycled Coarse Aggregate (RCA)

The main difference between NCA and RCA is that the latter consists of unbound stones, ARM, and various contamination levels. The presence of ARM and contaminants mainly affect the physical properties which directly impact the mechanical properties of RAC. Many aspects related to the quality of RCA are considered as follows:

1. **Quality of original material:** the mechanical behavior of RCA is mainly related to the weakest link, the cement paste. Two studies (Silva et al., 2014; Medina et al., 2014) used different techniques such as aggregate crushing value, LA abrasion, and aggregate impact value to evaluate the mechanical properties of RCA. The results showed that the increase in CS is associated with improving fragmentation resistance. Medina and colleagues (2014) showed that the natural stone has a higher crushing value than mixed RA.

2. **Recycling process:** it is generally known that the treatment method and recycling process of RCA may cause cracks in the Adhered Mortar (AM) and the interfacial transition zone between the aggregate and the AM, and therefore a reduction in the resistance to fragmentation. Besides, the treatment procedure plays a crucial role in determining the proportions of the components of the RCA, which also impacts the mechanical performance (Silva et al., 2014).

3. **Heterogeneity**: the concrete made of RCA shows uncertain behavior of this aggregate due to degradation of the RCA quality where mortar paste and contaminants are still attached to the surface (Etxeberria et al., 2007). Compared to the NA, RCA is weaker and prone to more deformation. Besides, RCA is known for its unfavorable geometry and

heterogeneous composition. The weakness and deformability have direct implications on concrete behavior. Moreover, it directly affects the fresh properties of concrete, such as the slump and consistency. Three fractions of the same resource are given in figure 2.1.

Figure 2.1: Different fractions of RCA

4. **Water Absorption:** WA of NCA is a fundamental property, and it depends mainly on the geological nature and source. While RCA depends on the cement matrix attached to the surface or percentage of RCA types 2 and 3 (further explained in Chapter 3). The significant WA of RA, in general, has a considerable consequence on the loss of concrete's workability and also affects the concrete CS. Many researchers have proposed different techniques to compensate for the high WA during mixing or before it. A study showed that two-stage mixing could mitigate the high WA of RCA (Tam et al., 2005). However, these techniques are costly and not suitable for large-scale practical applications. Introducing a new approach that minimizes the cost and is practically feasible can facilitate the utilization of RCA in practical applications.

5. **Porosity:** the high porosity affects the RCA quality on a microstructure level, see figure 2.2. The old mortar contains cracks and pores, which directly change the WA and density of hardened concrete (Silva et al., 2014). From a durability point of view, carbonation, freeze-and-thaw, and chloride penetration resistance are strongly related to the porosity of RAC, which is directly affected by the porosity of RA. FA, a mineral admixture, is a typical material used to decrease the effect of chloride penetration and densify the structure of RAC. In general, the mix design proportioning impacts the RCA durability; the higher the content of RCA, the less resistance of RAC to carbonation, fluid penetration, and freeze-and-thaw cycles (Otsuki et al., 2003).

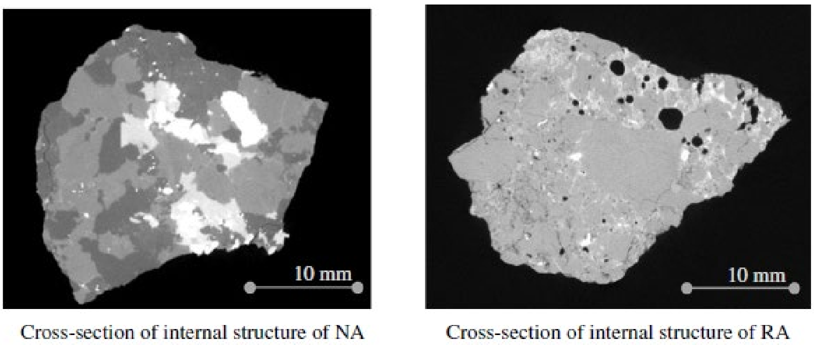


Figure 2.2: NCA vs RCA (Silva, R et al. 2014)

6. **Contamination level**: RCA is mainly made of unbound stones. However, depending on the efficiency of the treatment process and the source of RCA, the type of contaminants can be different. The level of various contaminants in RCA contributes to the CS, especially in high-grade practices. An example of a typical RCA content according to EN 933-11 is shown in figure 2.3. To characterize the effect of contamination levels such as wood, gypsum, chloride, and brick, the effect of each material must be examined separately. Gypsum increases the content of sulphates, which raises the internal deterioration of RAC. Chloride in RCA can increase the risk of Chloride penetration, which eventually impacts the durability of RAC (Tovar-Rodríguez et al., 2013).

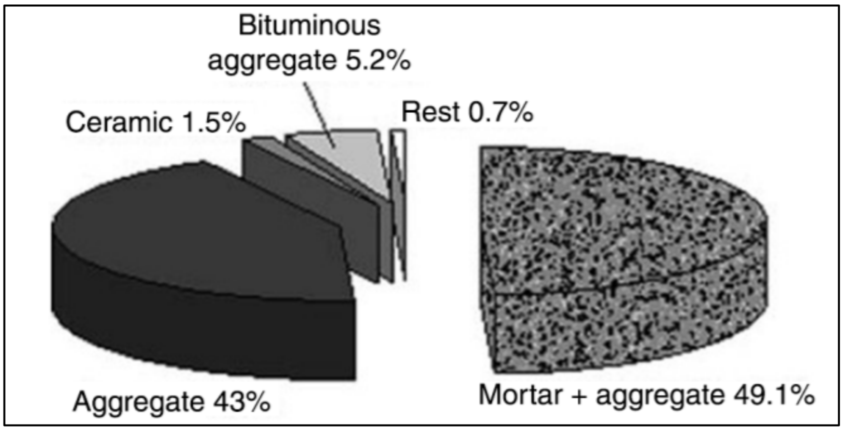


Figure 2.3: Components of RCA (Etxeberria et al., 2007).

7. **Mix design**: RCA must fulfil minimum requirements to reach high-quality concrete. Primarily chemical and mechanical properties indicated by European standards. As a rule of thumb, excellent quality RCA contains less than 5% masonry substances such as brick, minimum quantities of contamination, and the over-dried density is comparable to NA's. Besides, WA must be controlled (Pellegrino et al., 2016). The design of RAC is typically done by replacing NCA with RCA. For replacement ratios less than 30%, the overall performance of ordinary concrete made with RCA is not affected. However, when concrete mixes are designed with higher replacement ratios (up to 100%) of RCA, especially with certain constraints related to durability aspects, for instance, environmental exposure conditions and high strength classes, considerable losses regarding the mechanical and durability may occur.

8. **Pre-treatment techniques of RCA:** RCA's low quality is why its use in a structural application is limited; high WA, porosity, and low density are the main factors that in-

fluence the performance of RCA in a concrete mix. To get an insight into how treatment techniques differ, Shaban and colleagues evaluated the treatment techniques and weighed the advantages and disadvantages against each other. The focus was mainly on reducing the WA and improving the CS of RAC (Shaban et al., 2019). All treatment techniques are performed under laboratory conditions. The various techniques are compared and listed in the following table.

Table 2.1: Comparison between different treatment techniques (Shaban et al., 2019).

Treatment techniques	% Improvement in WA of RCA	% Improvement in CS at 28 days	Economic, environmental, and practicality aspects
Traditional heating	up to 10%	-	• Increase energy consumption • Time-consuming • Inconvenient on a large scale
Microwave heating	up to 33%	up to 27%	• Time-consuming • Inconvenient on a large scale
Mechanical treatment	up to 50%	up to 39%	• Need special devices • Increase energy consumption • Increase Co_2 emission
Thermal-mechanical treatment	up to 55%	up to 18%	• Increase energy consumption • Time-consuming • Increase CO_2 emission • Need to dispose of fine particles
Water cleaning treatment	-	up to 7%	• Time-consuming • Need to dispose of more wastewater
Chemical treatment (Pre-soaking in acid)	up to 19%	up to 19%	• High cost • Increased chloride and sulphate contents • Need to dispose of waste acids
Chemical-mechanical and thermal treatment	up to 50%	up to 23%	• Cost-intensive • Increase energy consumption • Increase CO2 emission • Need to dispose of waste acid and fine aggregate

Treatment techniques	% Improvement in WA of RCA	% Improvement in CS at 28 days	Economic, environmental, and practicality aspects
Polymer treatment	up to 74%	up to 11%	• Cost-intensive • Time-consuming • Need to dispose of waste solution • Inconvenient on a large scale
Calcium carbonate bio deposition	up to 21%	up to 40%	• Cost-intensive • Time-consuming • Inconvenient on a large scale
Pozzolanic materials	up to 50%	up to 23%	• Time-consuming
Carbonation	up to 22%	up to 20%	• Time-consuming • Need special devices • Inconvenient for reinforced concrete
Sodium silicate solution	up to 39%	up to 29%	• Cost-intensive • Increase the risk of alkali-silica reaction

2.3 Mechanical Properties of Recycled Aggregate Concrete (RAC)

2.3.1 Compressive Strength (CS) and the contributing factors

The mechanical strength of concrete is commonly determined by its CS. The contributing factors to the CS of RAC must be defined to obtain the CS for which the RAC is designed. The key factors are discussed as follows:

- Water to Cement ratio

A previous study has investigated the effect of the W/C ratio on the CS of concrete incorporating 100% RCA (Deng, 2005). The study found that the CS of RAC strongly relates to the W/C ratio. For mixtures with a W/C ratio above 0.57, the CS decreases as the W/C ratio increases. However, When the W/C ratio is lower than 0.57, the CS increases with the W/C ratio.

Another study conducted more detailed research into this relationship by examining the link between the W/C ratio of mixtures with varying RCA percentages and the 28-day CS (Li, 2004). The results are shown in figure 2.4.

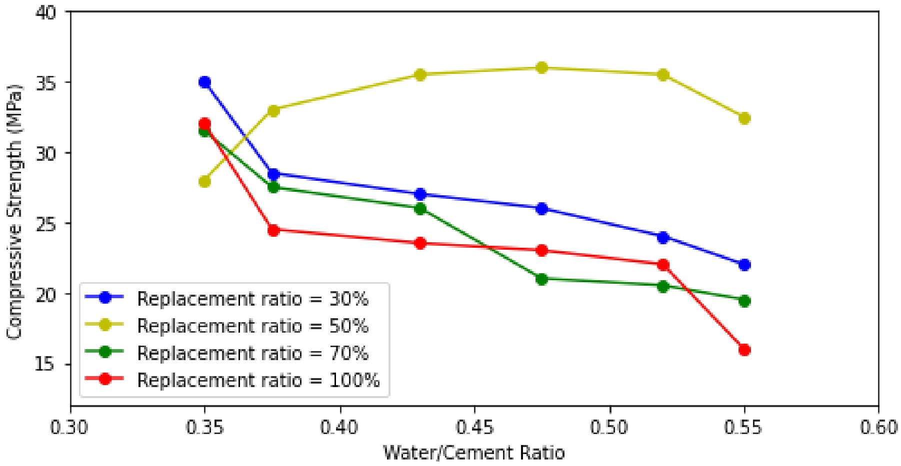


Figure 2.4: W/C ratio vs CS (Li, 2004, Deng, 2005).

It can be observed that the CS decreases with the increase of W/C ratio for 30%, 70%, and 100% of RCA. However, for 50% of RCA, the CS increases for W/C ratios up to 0.47. Beyond this value, the CS decreases.

As can be seen from the results, there is some type of linear relationship between the 30%, 70, and 100% replacement ratios of RCA and CS. While for 50% RCA, the relationship is non-linear. It can be noticed that no evident conclusions can be drawn regarding the effect of the W/C ratio on the CS of RAC when different ratios of RCA are used. Therefore, further studies are needed.

- RCA content

Many studies have looked into the effect of RCA on the CS of concrete. Various studies have conducted several experiments on the behavior of RCA in concrete. The results are shown in figure 2.5 (J. Xiao, Li, & Poon, 2012).

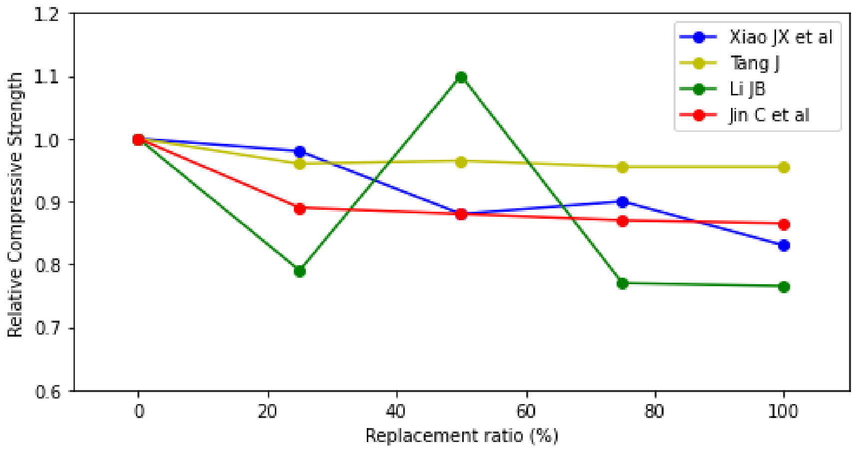


Figure 2.5: RCA percentage vs CS (J. Xiao, Li, & Poon, 2012).

It can be observed that in almost all cases the CS decreases with the increase of RCA proportions. For mixtures with 100% RCA, the reduction varies between 2% and 30%. The reduction of CS with the increase of the RCA content can be caused by different aspects, as previous studies argued. Another study related the reduction of the CS to the porosity of parent concrete and the weak interface bond between the aggregate and the matrix (Xiao et al., 2009).

It is essential to notice that the results are inconsistent. Therefore, no clear conclusions can be drawn, additional studies are needed.

- Brick as a contaminant

Enhancing the quality of RCA includes getting rid of contaminations. Organic contamination in RCA such as plastic, wood, foam, and brick must be minimized to limit the effect of different degradation mechanisms, for example, drying, wetting, and freeze-and-thaw.

Brick forms the highest percentage of contamination in RCA (Khalaf & DeVenny, 2005). Besides, it is mostly presented as a fraction in RCA (Debieb & Kenai, 2008). In addition, since it has a similar density as the ARM and coarse particles, it is more complicated to eliminate it during the separation process. In general, there is insufficient information regarding the effect of brick as a coarse fraction in concrete. The vast majority of the studies concerning applying crushed masonry aggregate focus on the mechanical behavior of concrete. Several studies have shown that employing crushed brick as a replacement of NCA leads to a reduction in the CS, (Debieb & Kenai, 2008; Khalaf & DeVenny, 2005). The reduction in CS varies from 10-35%, depending on the replacement percentage of brick.

In addition, other studies showed that mixtures including 5% of brick have barely lower CS compared to the reference mix of RAC with no contaminants (Jaskowska-Lemanska, 2019). Another study looked into the effect of incorporating 5% brick + 5% tile on mechanical behavior or RAC (Poon & Chan, 2007). The study showed that mixtures containing these impurities reduce the CS by 6% compared to mixtures without contaminants.

From a durability point of view, brick is a versatile building material with adequate load-carrying capacity. However, due to the high porosity of brick, further investigation is required concerning the water penetration and resistance to corrosion of reinforced concrete containing brick in relatively high percentages (Adamson et al., 2015).

- Supplementary Cementitious Material (SCM) in concrete mixtures

SCMs are known for their pozzolanic properties and can partly replace Portland cement. Nowadays, most concrete mixtures contain SCMs; they enhance the performance and properties of hardened and fresh concrete, namely durability and workability (Lothenbach et al., 2011). Including SCM in the concrete mix designs make it possible for concrete companies to adjust the mixture design to fit the demand and applications. Three different SCMs are discussed based on their application in RAC: FA, silica fume, and BFS.

- **Fly Ash (FA)**

FA is a waste product from burning coal in power plants; this by-product is known for its pozzolanic reaction when added to cement. FA reacts with Calcium Hydrate $Ca(OH)_2$ and results in C-S-H that ensures the strength of concrete. FA is used to slow down the hydration process; it functions as a retaining agent for free water more than Portland Cement (PC) and decreases water and superplasticizers' demand. A study has investigated the effect of the incorporation of FA in various ratios, 0,20,35 and 55% replacement of the cement content, on the CS of RAC (Kou & Poon, 2013). It found that as the replacement ratio of RCA increases, the short-term CS decreases. However, another study showed that incorporating RCA and FA by 30% and 20%, respectively, can increase CS compared to the conventional concrete mixture (Kurda et al, 2017). Besides, it confirmed that incorporating 100% of RCA has no adverse effect on the performance of RAC, see figure 2.6.

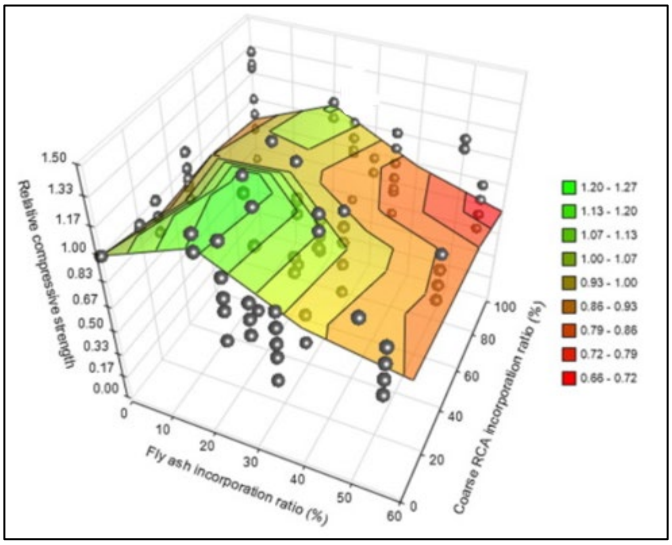


Figure 2.6: Fly ash and RCA impropriation vs CS (Kurda et al., 2017).

In terms of durability, FA as filler reacts with cement to produce more CHS, producing more CHS results in a stronger paste and improves the moisture from through the concrete, which leads to less permeability (Halstead, 1986).

- **Blast Furnace Slag (BFS)**

The introduction of BFS as a replacement material for PCs has been a widely used approach for many years. From a sustainable point of view, the utilization of BSF contributes to reducing CO2 emissions. A study conducted a state-of-the-art revision on the CS of RAC made of BFS cement. According to the results of 28- and 90 days of CS, incorporating BFS as PC replacement has a negligible effect on the CS for different W/C ratios. It showed that the replacement level of PC by BFS can have a slightly negative effect on the CS of concrete for 0.4 to 0.6 W/C ratios (Cabrera-Madrid et al., 2016). According to a previous study, mixture designs containing 50% replacement of PCs show excellent mechanical properties (Berndt, 2009). Moreover, alternative research explained that replacing 50% of PC with 20% FA, 25% slag, and 5% SF has a slightly positive effect on the mechanical properties of RAC (Limbachiya et al., 2012).

- **Silica Fume (SF)**

SF is one hundred times finer than cement, and it is known for its spherical shape. SF increases the packing density. It functions as a gap filler and makes very dense concrete, resulting in an impermeable structure and improving concrete's strength and physical durability. A study confirmed that incorporating silica fume in RAC slightly improves the concrete's CS due to SF's pozzolanic effect (Çakır & Sofyanlı, 2015). Moreover, it showed that a replacement ratio of 70% of NCA with RCA could lead to a marginal increase of the CS and that replacing up to 8% of PCs with SF enhances the CS of RAC.

- **Limestone**

Limestone Powder (LSP) is used in cement as a blended material. Its utilization as a replacement for PC lowers the environmental impact, and it is cost-effective due to the low energy production and CO2 footprint compared to Portland cement. Moreover, Concrete's fresh and hardened properties are enhanced when LSP is utilized. Regarding the hardened properties, the CS of concrete is affected by adding LSP. LSP functions as an inert filler. It fills the voids in the grain skeleton, creating a more effective grain stacking of the high-porous RA. Fewer pores mean higher CS. In addition, LSP acts as a catalyst for the hydration reaction between Portland cement clinker and water. The matrix of cement stone can be built up faster due to the fine fractions of LSP, activated as 'germs', which results in a slightly higher strength at the preliminary stages (Betoniek Standard, 2014). Furthermore, a study showed that using Limestone in combination with BFS cement enhances the CS of RCA. However, using Limestone in high volume can negatively affect its mechanical properties. Incorporating 60+7% of slag and limestone leads to no reduction of the CS (Majhi & Nayak, 2020).

- **Standard checks for the use of RCA (NEN 5905)**

Normally, recycling plants have to deal with CDW including various materials. In general, the content of RCA is not uniform. The content of RCA depends mainly on the construction processes used in each country. The selection of upper and lower limits for each specific component indicates the deviation from every country's regulations.

CDW typically consists of concrete, masonry aggregate, crushed glass, wood, etc. It is preferable to use RCA produced from concrete rubble for structural application since it contains the least amount of contamination (Cenci et al., 2021).

The NEN 5905 standard categorizes the components of RCA into an unbound aggregate (Ru), crushed concrete (Rc), crushed masonry aggregate (Rb), common contaminants (X), bituminous material (Ra), and floating material (FL). Table 2.2 shows the regulation and limits for each component of the RCA.

Table 2.2: Specifications of RCA composition in the Netherlands (Cenci et al., 2021).

Country	Standard/specialization	Ref	Class	Composition (%)					
				Rc+Ru	Rb	Rc	X	Ra	FL(cm3/kg)
Netherlands	CUR	1984	RCA	-	≤5	≥95	-	-	-
			BRA	-	≤65	≤20	-	-	-
	NEN 5905	2005	RCA	<100	≤5	-	≤1	-	≤0.1
			MRA	-	≤65	<20	≤1	-	≤0.1
	RAW	2005	MRA	≥50	≤50	≥45	≤1	≤5	-

2.4 Main findings of the literature review

The literature review regarding the quality of RCA and comparisons between research and practice support the purpose of this research; to understand the potential of RCA, it is preferable to investigate the performance of concrete made of RCA, rather than tracking down the origin of the primary structure since this information is mostly not obtainable (Tam et al., 2018). Besides, recycling companies must ensure uniform deliveries of RCA commercial fractions. The crushing, sieving, and screening processes have to be improved to produce particles with consistent shape, size, and level of contamination.

An underestimation approach is proposed to compensate for the high WA of RCA. This process might lead to workability losses. However, using superplasticizers in combination with increasing the mixing time will solve this problem. This approach is feasible and easy to adapt in ready-mix concrete plants.

The building industry is observable to question the reliability of incorporating RCA in a high ratio due to its low quality. To increase confidence and reliability in RCA, it is important to clear the uncertainties regarding the behavior of RCA and provide consistent quality and reliable results.

Regarding the industrial aspects, concrete companies must adjust their business models and probably the operations to enable incorporating RCA in high ratios. Besides, consistent data and results regarding the RAC performance must be obtained to put more pressure on the government to incorporate higher RCA ratios in the current standards.

Previous studies showed contradictory results regarding the effect of RCA content on the CS of concrete, as shown in the literature review. Studies stated that the difference in findings is mainly related to the qualitative aspects, including moisture content, the composition of RCA, specific gravity (SG), and parent concrete properties.

It can be concluded that to understand the behavior of RCA in a better way, it is essential to identify its composition. Using RCA derived from similar recycling processes and determining the level of contamination and ARM are crucial aspects of defining the quality of RCA. It has been shown that the innovative selective crushing method is cost-effective and proves its ability to minimize contaminants (Gebremariam et al., 2020). The study demonstrated that using selective demolition and autogenous milling reduces the number of contaminants and enhances RCA quality Besides, physical properties, ARM content, and WA of all tested RCA are predefined and categorized into different fractions. This process can help identify the impact of each aspect on the mechanical properties of RAC.

In terms of density, Silva and colleagues (2014) showed a reduction of only 5% of the total density when All NCA are replaced with RCA from different resources, which actively demonstrates that this effect may be neglected. Including pozzolanic material such as FA and BFS in specific percentages is considered a reasonable approach to improving RCA microstructure and reducing porosity. Besides, Using FA as a filler can densify the microstructure. Other treatment techniques are either cost-intensive or need special equipment. Therefore, these are not investigated in the research. Besides, in an industrial environment, it is not feasible to determine the density of RCA since it depends mainly on the source and nature of utilized RCA. Therefore, aggregate replacement by mass is implemented, and that changes the corresponding proportions of materials.

In summary, table 2.3 outlines the most important parameters that significantly influence the CS of concrete.

Table 2.3: An overview of the selected parameters

Parameter	Selection criteria
- **Water to Cement ratio**	The W/C ratio is a principal factor in determining the mechanical properties of concrete. As shown in the literature review, varying the W/C ratio can impact the workability and mechanical performance of RAC.
- **Recycled Coarse Aggregate replacement ratio.**	WA capacity of RCA impacts the strength of concrete since it affects the condition of the W/C ratio. Besides, when incorporating high percentages of RCA, mixtures become less workable and more porous, which leads to higher AC and large losses in the CS of RAC.
- **Fly Ash content**	FA densifies the structure, enhances the fresh properties of concrete, and reduces permeability. Besides, it is economical and environmentally friendly.

Parameter	Selection criteria
- **Adhered and Residual Mortar content**	ARM is present in the form of coarse and fine fractions, depending on the source and composition. Besides, it is known for its high porosity and low density, and therefore, the different percentages of ARM in RCA impact the quality and mechanical performance of RAC.
- **Brick content**	The current standards allow for a maximum of 5% of masonry aggregate as contamination in RCA, while other types of contaminants may not exceed 0.1%. Therefore, it is essential to examine the effect of varying the percentage of brick on the mechanical properties of RAC.

3. Experimental program

This chapter describes in detail the experimental schedule in which the process of examining the material properties of RCA, the concrete mixture designs, the optimization of the Particle Size Distribution (PSD) of RCA, and the casting procedure according to an industrial procedure performed on a lab scale. Lastly, the fresh and hardened RAC properties are presented.

3.1 Materials

In this research, the following materials are used:

Water: Water from the lab was utilized for casting.

Cement: Cement type CEM III/B 42.5 N LH/SR is used. It is a ground BFS-based cement widely utilized in the Netherlands.

Superplasticizers: VC 1550 con. 30% produced by SIKA is used as superplasticizers to reach the desired consistency of each mix. The superplasticizers specification is shown in Appendix A.

Brick: The brick used has a CS of 35 MPa. The additional technical information is shown in Appendix B.

Fly Ash: The additive used is stored in the casting lab silos. The specifications are attached in appendix C.

Recycled Coarse Aggregate: The RCA is produced from the ADR installation, fractions range: 4-16mm.

Natural Coarse Aggregate: The NCA aggregate, which is gravel, is taken from the aggregate silo in the TU Delft casting lab, fractions range: from 4-16 mm.

Natural Fine Aggregate: The NFA, which is river sand, is taken from the aggregate silo in the TU Delft casting lab, fractions range: from 0-4 mm.

3.2 The approach of the experimental program

The experimental part investigates the physical properties that enable the definition of the quality of RCA derived from selective demolition waste and their impact on the mechanical performance of concrete. In addition, the material utilized in making the RAC mix designs, including various amounts of additives and superplasticizers, are depicted. Trial mix designs are made to determine the optimized PSD of RCA. After that, the RAC design mixtures are determined and the casting procedure is described.

3.2.1 The physical properties of Recycled Coarse Aggregate (RCA)

The physical properties of RCA and NCA are investigated according to the Eurocode standards (EN 933-1 and EN 1097-6) for the PSD and WA respectively. WA is the main physical requirement in characterizing the quality of RCA according to the Eurocode NEN 5905 (Silva et al., 2014). There is a consensus amongst researchers that RCA has higher WA than NCA, which can be related to the porous structure of mortar attached to the surface of the aggregate. The higher content of AM gives higher WA. Another study claims that ARM forms 25%-65% (in volume percentage) of the total volume of RCA (Çakır & Sofyanlı, 2015). Besides, extensive analysis and studies showed that the maximum ARM levels on the RCA might not exceed 45% for structural applications (Betoniek Standard, 2014). The WA of RCA is considered one of the basic properties when designing the mixture of RAC.

3.2.2 Water absorption (WA) and Specific Gravity (SG) of Recycled Coarse Aggregate (RCA)

The standard procedure for determining the WA, according to NEN-EN 1097-6, is demonstrated in Appendix D (Müller, 1998). The results of the WA tests from RCA taken from different sources are presented in table 3.1.

Table 3.1: WA and SG of NCA and RCA.

Aggregate type	Source	Water Absorption (%)	Specific gravity
NCA	Heidelberg cement	1	2.7
RCA 4-16 mm	ADR (Almelo)	4.8	2.3
Artificial Aggregate	Lab TU Delft	9.2	1.9

Table 3.1 shows that there are differences in WA and SG of NCA compared to RCA. The composition of RCA needs to be further examined for its WA.

A previous research introduced by Fathifazl and colleges (2009) showed that the characteristics of RCA can be classified based on its content. It stated that RCA consists basically of two-type materials, unbound stone, NCA, and residual mortar (RM) bonded to it. Moreover, the physical performance is strongly related to the quantity and properties of RM.

In this study, a handpicking approach is used to divide the RCA content into distinct types of fractions. After manually organizing the content of RCA, the content was categorized into three types. Type one corresponds to high-quality RCA, primarily composed of unbound NCA. Type two comprises a significant proportion of mortar adhered to the surface of NCA, making it a medium-quality RCA. Type three primarily consists of RM, thus classified as Low-Quality RCA. Due to the difficulty in separating types two and three, they are considered together as a mixed type known as Low-Quality Recycled Aggregate (LQRA). The three types are shown in figure 3.1.

Figure 3.1: Different types of RCA fractions.

The WA and SG of each type are calculated independently. The results are shown in table 3.2.

Table 3.2: Water absorption and specific gravity test results.

Type NR	Source	Water Absorption (%)	Specific gravity
NCA	Heidelberg cement	1	2.7
RCA type R^1	ADR (Almelo)	1.7	2.6
RCA type R^2	ADR (Almelo)	4.9	2.2
RCA type R^3	ADR (Almelo)	7.9	1.8

As can be seen from the results, the higher the content of ARM, the higher the WA, and the lower the SG. Based on the results, it can be concluded that the approach of hand-picking is effective since the variation in WA and SG values are considerable.

3.2.3 Contamination level of Recycled Coarse Aggregate (RCA)

The contamination level of RCA can vary depending on the source and the processing methods. To identify the composition of RCA, the content RCA is separated by size and quality through a process known as sieving. The process involves passing the RCA through a series of sieves that are designed to separate the material based on its particle size. The sieving process is also used to remove larger contaminants that may be present in RCA. Once the material has been sieved and sorted, it is weighed and analyzed to determine its quality. The content of the RCA is shown in table 3.3.

Table 3.3: Size and quality distribution of RCA

Size range	Weight	RCA type R^1	RCA type R^2	RCA type R^3	Contaminants
4-8 mm	21.8%	8%	4.6%	8.7%	-
8-16 mm	69.5%	22.6%	33.6%	13.3%	-
>16 mm	8.7%	4.1%	3.2%	1.4%	-
All	100%	34.7%	41.4%	23.4%	0.5% (Brick= 0.4%)

The contaminants consist of wood, plastic, brick, gypsum, and foam. As can be seen in table 3.3, the contamination level was quite low. From the manual sorting procedure, which is based on visual inspection and a hand-picking approach, it can be seen that brick makes up the largest composition in size and weight. Therefore, more brick was added to the concrete mixtures to investigate its impact on the quality of RCA.

The experiments utilized RCA with an adjusted starting value of 40% for the percentage of LQRA. This adjusted value is slightly lower than the actual percentage of LQRA found in RCA obtained from the ADR installation, which is 65%. The purpose of reducing the initial percentage of LQRA in RCA is to allow for its manipulation as a variable in the predictive model.

3.2.4 Resistance to abrasion of Recycled Coarse Aggregate (RCA)

The Los Angeles Abrasion Test (LAAT) is a commonly used approach to check the abrasion resistance and toughness of aggregate against crushing. It is tested according to the EN 1097-2:2020 standards.

The principle works as follows; a total mass of 5000 g (W_1) of aggregate is placed in a rotating drum. Several steel balls are added depending on the size of the aggregate. After 500 revolutions are completed, the weight of the remaining aggregate is sieved on a 1.6 mm sieve. The sample preparation procedure is presented in appendix E. The quantity of the retained weight (W_2) is used in the following formula as follows:

$$LA_{loss}=(W_1-W_2/W_1)*100 \quad (1)$$

The results of the LAAT are displayed in table 3.4.

Table 3.4: LA abrasion test results.

Type RCA	Source	LA abrasion value (%)
RCA 4-8 mm	ADR (Almelo)	26
RCA 8-16 mm	ADR (Almelo)	24

Table 3.5 shows the maximum permissible values for different uses of aggregate.

Table 3.5: The maximum permitted LA abrasion values (Silva et al., 2014).

Type RCA	Source	LA abrasion value (%)
1	Granular Sub Base (G.S.B.)	Not specified in MORT%H
2	Base course W.B.M. (Water Bound Macadam)	40
3	Base course W.M.M. (Wet Mix Macadam)	40
4	Base course W.B.M. (Water Bound Macadam)	40
5	Base course W.B.M. (Water Bound Macadam)	40
6	Base course W.B.M. (Water Bound Macadam)	35
7	Surface course/ wearing source S.D.B.C	35
8	Surface course/ wearing source B C.	30
9	Cement concrete pavement	30

Based on the previous table, it can be concluded that the measured values of all samples lie below the upper limit.

3.2.5 Aggregate's crushing value

Aggregate's Crushing value investigates the resistance of an aggregate to crushing under progressively applied load. The results of the aggregate crushing value are measured by weight, which is expressed in percentage, of the crushed fractions when the aggregate is exposed to the gradually increasing load under regulated terms. The reference standard used is (IS: 2386-part 4-1963).

Apparatus for crushing test:

- Mould with base plate
- Tamping rode
- Cylindrical measure
- Weighting machine
- Sieves of specific aperture.
- Straight edge
- Compressive testing machine

Testing procedure:

- A representative sample of the aggregate is taken and thoroughly dried to remove any moisture content. The sample is then sieved through appropriate sieves to remove any dust or debris, ensuring a clean and uniform sample.
- The mass of the aggregate sample is determined using a precise weighing machine, and the weight is recorded accurately. This provided the initial weight (W_1) of the sample for further calculations.
- The cylindrical mould is filled with the aggregate sample in three layers, and each layer is compacted using a tamping rod. The tamping rod is applied with 25 strokes per layer, evenly distributed to achieve uniform compaction.
- Once the final layer is compacted, the top surface of the specimen is levelled using a straight edge to ensure a smooth and even surface.
- The mould is carefully removed from the compacted aggregate specimen, taking precautions to maintain the integrity of the specimen.
- The volume of the specimen is measured using a cylindrical measure, providing an accurate measurement for further calculations.
- The prepared specimen is placed in a compressive testing machine, and a gradually increasing compressive load is applied until failure occurred. The maximum load at failure is recorded, representing the crushing strength of the aggregate specimen.

The aggregate crushing value is calculated according to the following formula:

$$\frac{W2}{W1} x\ 100 = \text{the aggregate's crushing value} \quad (2)$$

Given:

W_2= the weight of the portion passing the 2.4 mm sieve.
W_1= the total wight of the sample.

The test results are presented in table 3.6.

Table 3.6: crushing aggregate value test results

Recycled Coarse Aggregate	Aggregate's rushing value (%)
ADR (Almelo)	25
RCA type R^1	18.9
RCA type R^2+R^3	29

3.3 Definition of the variables of the predictive model

In the experimental program, several parameters were defined to enable their use as variables in the predictive model. To investigate the influence of RCA as a variable alongside other factors affecting CS. of RAC, the composition of RCA was investigated.

The first variable represents the proportion of RCA used in the concrete mixture. By controlling and manipulating this percentage, the influence of RCA on the CS of concrete could be evaluated and incorporated into the predictive model.

The second variable considered was the percentage of LQRA in RCA. It quantifies the amount of RCA type R^2 and R^3 present in the RCA particles, as explained in sections

3.2.1 and 3.2.2. Quantifying the percentage of LQRA plays a crucial role in determining the quality of the RCA.

Another variable of interest was the percentage of FA used as an additive. FA is a by-product of coal combustion and is often incorporated as a supplementary cementitious material to enhance the performance of concrete. By varying the percentage of FA, the influence of this additive on the fresh and hardened properties of concrete will be studied and incorporated into the predictive model.

The W/C ratio, another critical variable, determines the amount of water used in proportion to the cement content in the concrete mixture. This ratio directly affects the workability and strength of the concrete. By controlling and adjusting the W/C ratio, its impact on the CS will be investigated and considered as a variable in the predictive model.

Lastly, the inclusion of brick as a contaminant was considered in the study. Amongst various types of contaminants, brick had the highest percentage. To evaluate the impact of brick on the CS, it was included as a variable in the predictive model.

By defining and analyzing these variables within the predictive model, their impact on the CS of concrete was examined. This comprehensive approach aimed to enhance the accuracy and reliability of the model in estimating the CS while considering the effects of these crucial variables.

To summarize, the list of chosen variables is as follows:

1. The percentage of Recycled Coarse Aggregate (RCA).
2. The percentage of Low-Quality Recycled Aggregate (LQRA).
3. The percentage of Fly ash (FA).
4. Water/cement ratio.
5. The percentage of brick.

Variables description:

The above variables were used in the predictive model. Each variable has a minimum, average, and maximum quantity, see table 3.7.

Table 3.7: design parameters quantities

Variable	Quantity		
	Minimum	Average	Maximum
RCA (%)	0	50	100
LQRA (%)	0	12.5	25
Brick (%)	0	0.5	1
FA (%)	0	10	20
W/C ratio	0.45	0.5	0.54

3.4 Mix designs

The concrete mixtures are designed according to the approach introduced by an earlier study (Kosmatka & Wilson, 2011). The approach is explained in Appendix F.

The composition of RAC reference recipes used in this study is listed in table 3.8.

Table 3.8: Mixture designs (kg/m3)

Recipe	NCA	RCA	NFA	cement	Water	SP (m/m)	WA%
Reference recipe:0% RCA	1000	0	833	368	122	0.38%	1
0% RCA and 25% LQRA	701	299	833	368	122	0.40%	2.3
0% RCA (24% LQRA), 1% brick	691	299	833	368	122	0.40%	2.4
50% RCA (40% LQRA)	450	550	817	368	123	0.38%	2.3
50% RCA (52.5% LQRA)	446	554	817	368	123	0.39%	2.6
50% RCA (65% LQRA)	442	558	817	368	123	0.40%	2.8
100% RCA (40% LQRA)	0	919	838	363	118	0.40%	3.8
100% RCA (52.5% LQRA)	0	919	838	363	118	0.40%	4.1
100% RCA (65% LQRA)	0	919	838	363	118	0.40%	4.3

The total number of utilized recipes is 32. All recipes are included in appendix G.

3.4.1 Mixing procedure

The casting procedure was carried out and controlled according to an industrial procedure performed on a lab scale at a local concrete plant.

The mixing process was performed as follows:

1. Sand and gravel are mixed for +/- 30 sec.
2. Cement is added carefully to the sand-gravel mixture. If this is done very fast, much cement may blow away.
3. The mix is diluted with a bit of water and mixed for +/- 15 sec.
4. Most of the (water + superplasticizers) is added to the cement mixture and mixed for +/- 20 sec
5. The remaining water is added and mixed for +/- 30 sec.

Then, if necessary, more water is added to reach the correct consistency (based on trail mixtures). The extra water must be weighed and reported. After carrying out all tests, it is time to pour the concrete into the moulds. The moulds are oiled and cleaned so it is easy to de-mould their casting. The moulds are filled and put on the vibration table. The moulds are vibrated for 45 seconds. After that, the cubes are filled up to 120% of the capacity and put again on the vibration table. Now, the cubes are ready to be labelled and covered with a plastic mat to protect them to preserve the water and avoid evaporation, see figure 3.2.

Figure 3.2: Concrete casted in moulds

The effectiveness of this mixing process has been observed and acknowledged by professionals for local concrete plants, who have employed it in various construction projects. The use of this established mixing process provides confidence in its reliability and suitability for achieving desired concrete properties.

3.5 Fresh properties of Recycled Aggregate Concrete (RAC)

Fresh properties such as consistency, AC, and volumetric weight were assessed. Fresh concrete properties are performed according to the Dutch standard ISO 1920-2:2016.

3.5.1 Fresh density

Equipment:

1) The container that is used to perform the fresh density test is clean and damp.
2) The container is placed on a level surface.
3) The container is weighted to determine its mass.
4) The internal height and diameter are measured.

The container is filled with a total of three equal layers. The concrete is compacted using a rod. Each layer gets 25 uniformly applied tamps. When tamping layers two and three, the base must not be stroked, no penetration of the lower layer. After applying the third layer, the concrete level is stroked by a rolling and sawing motion using the rod.

The following formula is used to determine the density of concrete:

$$D = \frac{\mathrm{m2} - \mathrm{m1}}{\mathrm{V}} \tag{3}$$

Where:

D: density of concrete (kg/m^3)
m1: mass of container (kg)
m2: mass of both container and concrete (kg)
V: volume of the container (m^3)

3.5.2 Air Content

The same procedure is mentioned in the fresh density test applied for the AC test. The test is performed according to ASTM C231/C231M10 (Kalhori & Ramezanianpour, 2021). A cover assembly and gasket are extra equipment needed for the test. After that, all three layers are applied and compacted, and the flange and rim of the container are cleaned. The cover assembly and gasket are cleaned. the cover assembly is placed on the container and clamps are used to securely lock the cover assembly to the container. Water is injected into one petcock until it emerges from the other side. Both petcocks are closed and the air bleeder valve is closed accordingly. Air is pumped into the pressure chamber until the index reaches the initial pressure line. The main air valve is opened and the air content can be read form the dial gauge on the cover assembly.

3.5.3 Consistency

Consistency is the ability of fresh concrete to flow. The consistency of concrete is controlled by the water added to the mix, FA content, and the dosage of SP. Table 10.1 of the NEN 8005 standard provides the recommended consistency classes and their corresponding measurement methods. The consistency classes range from "dry" (C0) to "very fluid" (F6). For example, the "dry" consistency class (C0) indicates a lower workability, while the "very fluid" consistency class (F6) signifies a higher fluidity of the concrete. The desired consistency class is F3. This means that the consistency values must lie between 42 to 48 cm.

Equipment:

1) Vibrator table
2) Metal cone
3) Standard rod

Procedure:

The slump test is carried out according to NEN-EN 123502:2009. After that the cone metal is removed, the electrical vibrator is turned on and the concrete starts to spread on the table. The vibrating goes on until the conical shape of concrete disappears and the concrete takes a cylindrical form. When the concrete reaches the cylindrical form the table is switched off. The diameter of the formed circle is measured and reported. The results of the fresh properties tests, including the consistency results, are presented in table 3.9.

Table 3.9: Fresh properties of RAC with W/C ratio = 0.45

Recipe	Fresh density (kg/m3)	Consistency (cm)	Air Content (%)
1) 0% RCA and 0% LQRA	2330	46	2
2) 0% RCA and 25% LQRA	2298	43	2.5
3) 0% RCA, 25% LQRA, 10% FA, and SP	2305	46	2.3
4) 100% RCA and 40% LQRA	2285	42	2.4
5) 100% RCA, 40% LQRA, 10% FA, and SP	2295	46	2.3
6) 100% RCA and 52.5% LQRA	2268	40	2.5

Recipe	Fresh density (kg/m3)	Consistency (cm)	Air Content (%)
7) 100% RCA, 52.5% LQRA, 10% FA, and SP	2275	44	2.4
8) 100% RCA and 65% LQRA	2241	38	2.7
9) 100% RCA, 65% LQRA, and 10% FA, and SP	2255	42	2.5

It can be observed that the AC increases with the increase in the content of LQRA. Besides, The fresh RAC density decreases with the increase in the percentage of RCA. In the cases of (6) 100% RCA and 52.5% LQRA and (8) 100% RCA with 65% LQRA, the consistency values are not within the plastic range (F3), which indicates that these recipes suffer from workability problems.

Table 3.10: Fresh properties of RAC with W/C ratio = 0.54

Recipe	Fresh density (kg/m3)	Consistency (cm)	Air Content (%)
6) 100% RCA and 52.5% LQRA	2245	44	2.6
8) 100% RCA and 65% LQRA	2228	42	2.8

The findings presented in table 3.10 indicate that mixtures with a W/C ratio of 0.54 can maintain satisfactory workability, even when 100% RCA with high LQRA content is used. These mixtures do not require the addition of FA or SP. However, it is important to note that the fresh density and AC of the concrete mixtures decreased.

The optimized RAC mixtures were designed by modifying FA content, dosage of SP, and the PSD of RCA to acquire high CS and desired fresh properties with RCA content up to 100%.

3.6 Hardened properties of Recycled Aggregate Concrete (RAC)

The structural behavior of RAC is influenced by properties such as the characteristic CS. This section discusses the procedure for making and testing the RAC samples on the CS.

3.6.1 Compressive strength (CS)

The CS is one of the most well-known methods to define the strength of a concrete mix. Great CS means HQ concrete. The CS is an essential parameter in providing information that characterizes the performance of concrete.

Procedure:

First, the equipment that is needed for the test:

1. Cube moulds of 150 mm size
2. Compression testing machine
3. An observation sheet to record the readings

After casting the concrete, the cube moulds are kept in a moisture room (95% relative humidity, temp= 20C) This ensures that the cubes are in good condition to keep curing until the test moment. On the day of testing, the needed amount of cubes is taken for the test.

Testing procedure:

After making sure that the cubes are dry, the cubes are centrally placed in the loading unit. The load shall be applied to the opposite side of the cubes as cast. The axis of the specimen should be carefully aligned with the center of the spherically stated plated. Then the load is applied with a speed of 13.5 kN per second till the cube breaks. The maximum load at which the specimen breaks are taken as the compressive load. The maximum load is the load that can be denoted on the observation sheet. Thirty-two mixes of RAC were tested under the CS, each mixture consists of three cubic samples. The samples were tested at the ages of 28 and 91 days. The results are presented in chapter 5.

3.6.2 Optimization of the Particle Size Distribution (PSD)

The PSD is evaluated by sieving through the standard openings from 16 - 4 mm. In this research, most recipes contain RCA. These particles are more angular and are less uniform in terms of shape and texture and thereby varying density and WA. To encounter the irregularity of the RCA particles, several trial mixtures with different PSD are made to ensure sufficient slump and consistency values.

To consider the incorporation of 0% to 100% RCA proportions. Trail mixtures had to be made to ensure the desired fresh properties of RAC for each mix design. Besides, performing trail mixtures showed that applying the same PSD for all designs does not deliver the required consistency class F3. Therefore, modifications had to be made to the PSD of several mixtures to guarantee acceptable fresh properties of RAC.

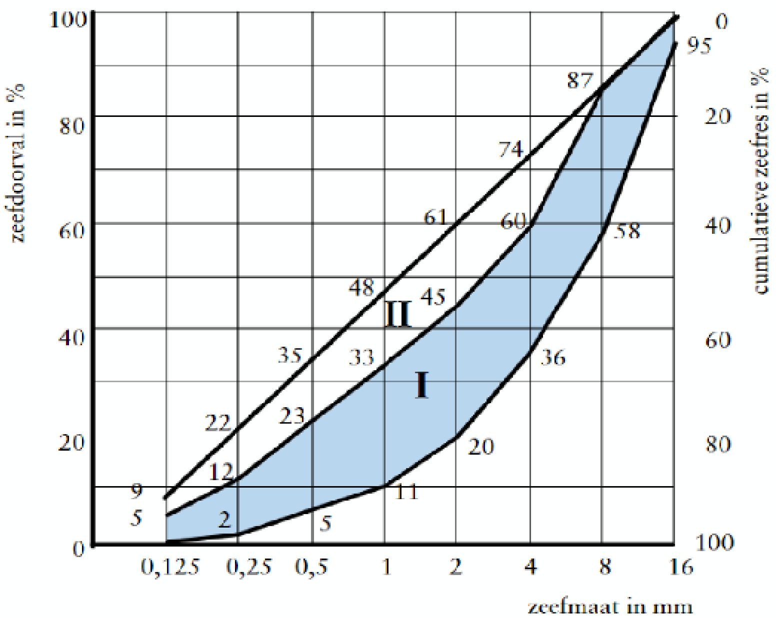


Figure 3.3: Zone I and zone II of the PSD (Kosmatka & Wilson, 2011).

The philosophy behind using Zone I and Zone II in figure 3.3 is rooted in the understanding of particle packing and its influence on the properties of the resulting concrete mixture.

Zone I, also known as the fine sand zone, represents the finer particles in the aggregate mixture. These particles have a smaller size and tend to fill the voids between the larger particles more effectively. In concrete, the fine particles in Zone I help to enhance the workability and cohesiveness of the mixture. They also contribute to increasing the surface area available for cement hydration, which promotes better bond formation and overall strength development.

Zone II, on the other hand, comprises the coarser particles in the aggregate mixture. These particles have a larger size and play a crucial role in providing stability and strength to the concrete. The coarse particles in Zone II help to provide interlocking and resistance against segregation. They also improve the overall mechanical properties of the concrete, such as CS.

RAC mixtures with varying content of RCA were investigated. Results have shown that mixtures with 100% RCA and 0.45 W/C ratio showed a significant decrease in workability compared to the reference mixture. Adjusting the PSD and including FA and superplasticisers positively affected the workability. However, mixtures with a W/C ratio of 0.54 and 100% RCA had satisfactory workability without any modifications. By considering the PSD and specifically focusing on Zone I, it is possible to optimize the packing of particles. The combination of fine particles from Zone I with mixtures containing high percentages of RCA creates a well-graded aggregate mixture that maximizes the packing density and minimizes voids. This results in a more dense and compact concrete matrix, which improves the overall strength and performance of the concrete.

Figure 3.4, figure 3.5, and figure 3.6 demonstrate the optimum PSD for mixtures incorporating 0%, 50%, and 100% RCA. Figure 3.7 shows a mixture with acceptable consistency.

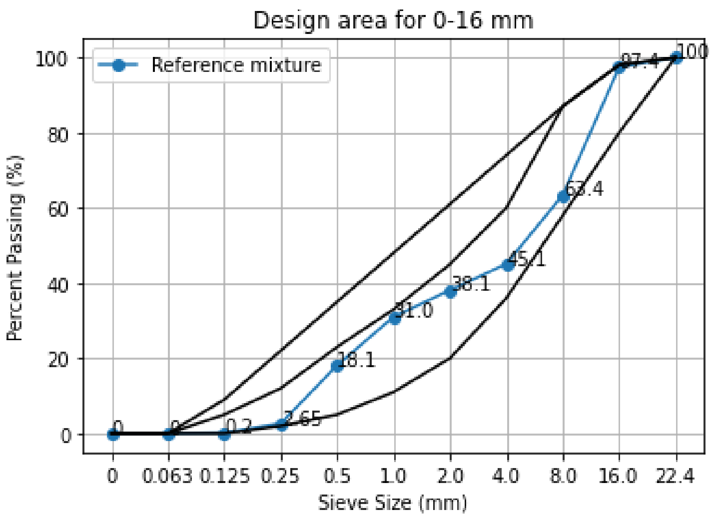


Figure 3.4: Optimum PSD of mixtures incorporating 0% RCA

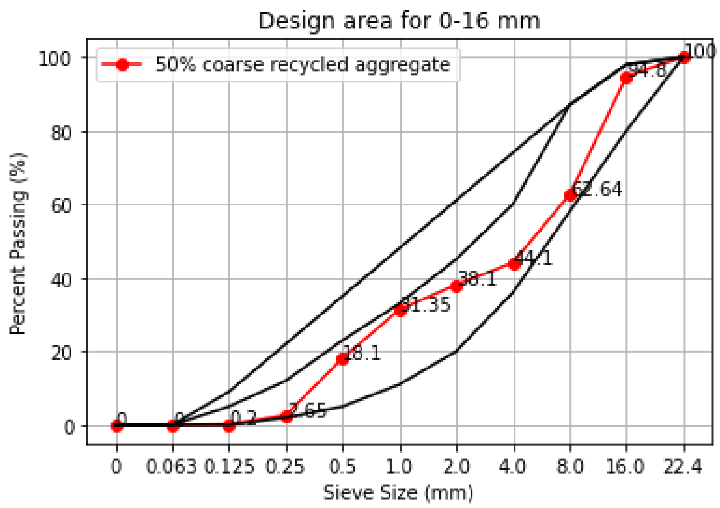


Figure 3.5: Optimum PSD of mixtures incorporating 50% RCA

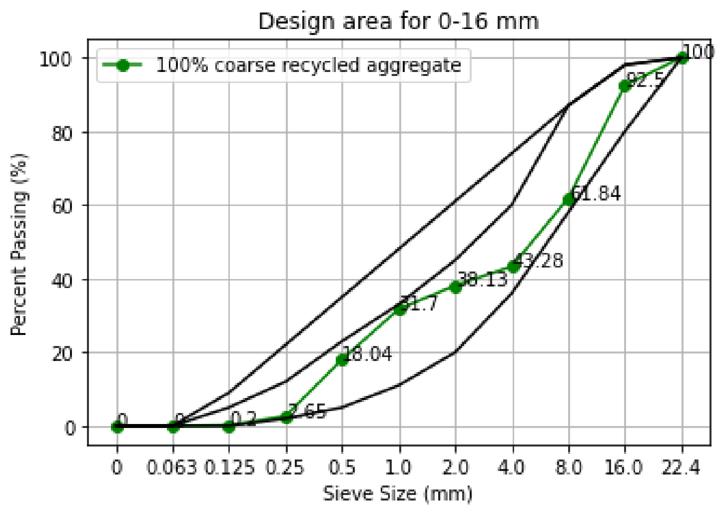


Figure 3.6: Optimum PSD of mixtures incorporating 100% RCA

Figure 3.7: Consistency of concrete made with 100% RCA.

4. Design Of Experiment (DOE)

This chapter looks in-depth into the applied approach in defining the relationships between the variables obtained from the literature review and preliminary experiments and their relation to the CS. The proposed approach should fit the objective, research questions, and prospective data used in this study.

4.1 General procedure for constructing the model

The statistical DOE method is a multivariate approach that aims to determine the relationship between factors affecting a process and the outputs of the process by varying the number of potentially influential factors simultaneously. DOE also helps identify the essential relations that may not be possible when experimenting with one parameter at once.

The general procedure of DOE is shown in figure 4.1.

Figure 4.1: General procedure of DOE

The process in each phase is described as follows:

Experimental design:

1. Defining research question/objective.
2. Identifying variables (independent and dependent).
3. Designing the experimental setup.
4. Determining experimental conditions.

Performing experiments:

1. Preparing and setting up the experiment.
2. Applying treatments to variables.
3. Collecting data through systematic observations.

Analyzing experimental observations:

1. Organizing data in a structured format.
2. Applying statistical/analytical methods for interpretation.
3. Drawing conclusions based on patterns, relationships, and significance.
4. Validating and interpreting results, considering bias and confounding factors.
5. Communicating findings effectively through summaries and presentations.

DOE has multiple approaches, Full and fractional factorial, RSM, and Taguchi. However, RSM is one of the most known methods for DOE.

Several studies have claimed that using RSM provides accurate results for various applications (Alyamac et al., 2017; Dahmoune et al., 2015; Güneyisi et al., 2014). Nevertheless, its use for studies regarding the mechanical properties of RAC is limited.

As mentioned previously in chapter 3, the relationship of the five variables to the CS of RAC was investigated. The applicability of RSM is illustrated in the following section.

4.1.1 Response Surface Methodology (RSM)

RSM is an old-fashioned technique that was introduced by George E. P. Box (Box et al., 1978). It was developed to understand the relationship between several explanatory variables and one or more responses. RSM collects statistical and mathematical methods that evaluate the correlation and relationships among different parameters and one or more responses (Dahmoune et al., 2015). Besides, it is used to construct a predictive model based on a limited number of experiments. The significance of this method for this research is explained in the following example.

When looking into two Full- or fractional factorial designs, it means one is searching for linear trends or possible interactions. Besides, Full- or fractional factorial designs check whether the chosen variables significantly impact the response and in what direction. In this study, five different variables have to be examined. These variables are chosen based on screening experiments and assessment of the existing literature, as conducted in Chapters 2 and 3. The literature review and the preliminary experiments show that all variables are significant. This means a more advanced approach is required to take into account all interactions between all variables and the response. RSM assumes that all variables are significant, which is the case for this study as concluded in chapter 2. Besides, RSM can be used to optimize the process, which means that desirable values of the response can be achieved by checking the possible combinations of the values of the parameters. RSM describes the response using the Taylor expansion curve. The equation has the following structure:

$$\text{Response} = A + B\cdot X_1 + C\cdot X_2 \cdots H\cdot X_1^2 + L\cdot X_2^2 + \cdots M\cdot X_1\cdot X_2 + N\cdot X_1\cdot X_3 + \cdots + e \quad (4)$$

Where:

X1: term for input variable one
X2: term for input variable two
.
.
$X1^2$: quadratic term for input variable one
$X2^2$: quadratic term for input variable two
.
.
X1·X2: Interaction between terms one and two
X1·X3: Interaction between terms one and three
.
.

One of the most applied designing tools of RSM is Central Composite Design (CCD).

4.2 Central Composite Design (CCD)

CCD consists of full factorial, or fractional designs with center, axial, and factorial points. The initiation of CCD is shown in figure 4.2.

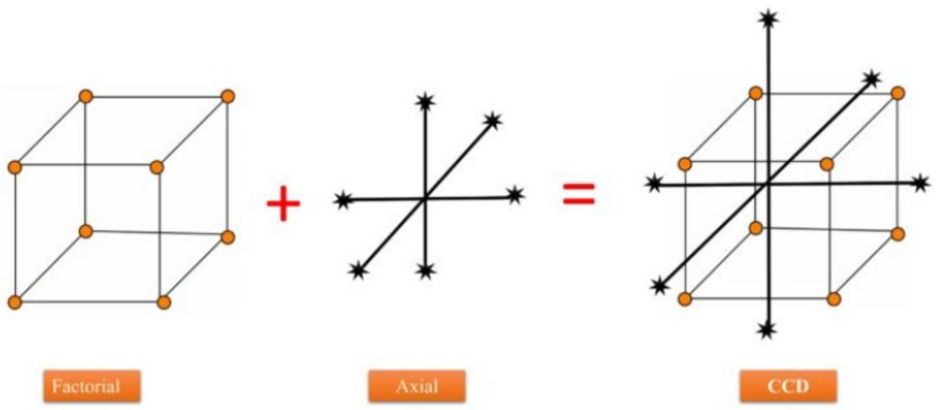


Figure 4.2: The Design space of CCD

The orange balls are the corners of a factorial design space and the exterior points are the star/axial points. It is important to note that the best predictions are within the orange balls of the design space. The axial points are used to get a reasonable estimation of the quadratic terms. However, it is not meant to make precise predictions at these spots. The center points are used to estimate the measurement noises and tie the blocks together, while star/axial points are meant to estimate the pure quadratic effects.

4.2.1 Full vs half factorial design

Full factorial design measures the response at all possible combinations of the factor levels. In contrast, the half-factorial design considers a specific subset of the runs of the full design. The second is an excellent option when the number of parameters is high, which is the case in this research. Table 4.1 displays the difference between design methods for CCD.

Table 4.1: RSM designs.

Available Response Surface Designs

Design		Continuous Factors								
		2	3	4	5	6	7	8	9	10
Central composite full	unblocked	13	20	31	52	90	152			
	blocked	14	20	30	54	90	160			
Central composite half	unblocked				32	53	88	154		
	blocked				33	54	90	160		
Central composite quarter	unblocked							90	156	
	blocked							90	160	
Central composite eighth	unblocked									158
	blocked									160
Box-Behnken	unblocked		15	27	46	54	62		130	170
	blocked			27	46	54	62		130	170

As seen from the previous table, the Central Composite Half is preferable since it saves time and effort (52 runs compared to 32). To compare Full to half factorial design methods, A previous study looked into both approaches (De Beer et al., 1996). It showed that using a half-fraction factorial design can work with interactive parameter effects on an Ion pair-based liquid chromatography system.

To conclude, the central composite half design provides a reasonable number of experiments that can be performed to cover all possible combinations of the variables and optimizes the variables and response. It starts with the two-level factorial design. Firstly, select all variables that can be turned out to be the most important according to the performed data analysis. These variables are set to reasonable ranges of minimums and maximums for each one. An inscribed design is a central composite face-centered design where the star points, which are the extremes, lie on the sides of the cube, and all data points are the same distance away from the center of the factorial space, see figure 4.3.

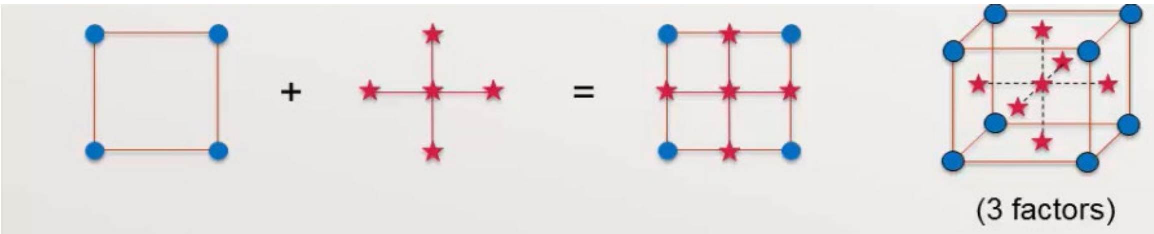


Figure 4.3: Central Composite Face-centred approach (Maran et al., 2017).

4.2.2 Concrete mix designs:

The number of experiments (N) required to construct the predictive model using CCD half design is derived from the equation stated below:

$$N = 2^{k-1} + 2k + c \qquad (5)$$

Where:

k: Number of input parameters

2^k: Factorial points

2k: Axial points

c: Number of experiments in the central points (Ghafari et al., 2014).

When considering all possible combinations of five variables, the total number of experiments would be quite large.

If each variable has 2 levels (maximum and minimum), there would be 2^5 = 32 possible combinations of the main effects. However, to account for all possible interactions, it is necessary to include the combinations of different levels for each variable, resulting in a larger number of experiments.

In the case of checking all possible combinations without reducing the number of experiments, all the possible combinations of the main effects and interaction terms should be considered. For five variables, this would result in a total of 2^5 = 32 main effects and 2^10 = 1,024 two-way interactions.

The total number of experiments needed to check all possible combinations would be 32 (main effects) + 1,024 (two-way interactions) = 1,056 experiments.

Conducting such a large number of experiments is not practical due to resource limitations. CCD can be used to reduce the number of experiments while still capturing the most important effects and interactions.

According to Equation (5), a CCD with five factors (k=5) is composed of a total of 32 experiments. These experiments are distributed as follows: 16 runs for the factorial points (2^4), 10 runs for the axial points (2x5), and one additional point as the center point with 6 replicates (c=6).

4.3 Utilizing Minitab for variable handling and response surface modelling

Minitab is a statistical software package that provides various tools and techniques for data analysis and modelling, including the use of RSM. When building a predictive model using RSM in Minitab, the software allows for the effective handling of variables to ensure accurate model development. Here's how Minitab deals with the variables in the context of RSM:

1. **Defining variables:** Minitab enables the user to define and input the variables used in the predictive model. This includes both the independent variables and the dependent variable (response). The user can specify the range and levels of the variables based on the experimental design.

2. **Design creation**: Minitab facilitates the creation of experimental designs that systematically explore the variable space. RSM typically employs designs such as CCD. Minitab generates the design matrix with appropriate combinations of factor levels based on the specified variable ranges.

3. **Model fitting**: Minitab allows users to fit response surface models to the data obtained from the designed experiments. The software utilizes regression analysis techniques to estimate the coefficients of the model equation, which represents the relationship between the response variable and the independent variables.

4. **Model diagnostics**: Minitab provides various statistical measures and graphical tools to assess the quality of the fitted model. These include ANOVA, lack-of-fit tests, normal probability plots, and residual analysis. These diagnostics help evaluate the adequacy and reliability of the predictive model.

5. **Response optimization**: Minitab offers optimization tools that allow users to find the optimal combination of factor levels that maximize or minimize the response variable. Users can set specific constraints or target values to guide the optimization process.

6. **Model validation**: Minitab facilitates the validation of the predictive model using additional data or by performing validation experiments. This step helps assess the model's generalizability and performance in predicting the response variable accurately.

Overall, Minitab provides a user-friendly interface and a comprehensive set of features to effectively handle variables, construct response surface models, and analyze the relationships between variables and responses using RSM.

In the process of utilizing Minitab for handling variables in the context of constructing a predictive model, it is essential to consider the nature of the input variables and their relationships with the response. In this thesis, the input variables are expressed in linear and quadratic functions, allowing for a comprehensive exploration of their effects on the response variable. The range of each variable is defined from its lowest to the highest value, and all possible combinations are executed within the same set of experiments.

By leveraging the capabilities of Minitab, the software provides the number of runs required to conduct the experimental design, ensuring that all necessary data points are collected to construct the predictive model accurately. The operational factors, represented by the input variables, are then utilized to develop a mathematical equation for the predictive model.

The suitability of the model for predicting the response is determined by the P-value. The P-value, with a threshold of $p < 0.05$, indicates that the proposed model fits the experimental data, and the independent variables have a significant effect on the response. This statistical significance demonstrates the importance and reliability of the predictive model at a 95% confidence level. R-squared represents the proportion of the variance in the response variable that can be explained by the independent variables included in the model. It ranges from 0% to 100%, where a value of 100% indicates that the model perfectly predicts the response and a value of 0% indicates that the model does not explain any of the variability in the response. A higher R-squared value indicates a better fit of the model to the data. However, it is important to note that R-squared alone does not determine the model's validity or the significance of the independent variables. The P-value helps determine the overall significance of the model and the individual significance of the independent variables.

Therefore, in addition to assessing the statistical significance of the model through the P-value and the R-squared value provides valuable information about the goodness-of-fit of the model and the proportion of variability in the response explained by the independent variables.

5. Results

This chapter describes the experimental results of the study. In the first part, the effect of WA and ARM on the CS is presented in the preliminary experiment's results. In the second part, data analysis of available data is performed to describe the effect of the W/C ratio and FA on the CS of conventional concrete. The third part explains the mix design optimization based on the fresh properties of RAC. The last part illustrates the predictive model results of 7-,28-, and 91-day CS.

5.1 Preliminary experiments

5.1.1 Effect of Water Absorption (WA) and Adhered and Residual Mortar (ARM) on the CS

The WA experiment is one of the criteria, which is usually used, to characterize the physical properties of RCA. Preliminary experiments were carried out to confirm or disprove the previous statement. The mixtures, used in the experiments, are composed of NCA, RCA type R^1, type R^2, type R^3, and AA. Besides, the WA percentages are also included. The final results are displayed in figure 5.1. The bars represent the CS results while the blue line shows the WA percentages.

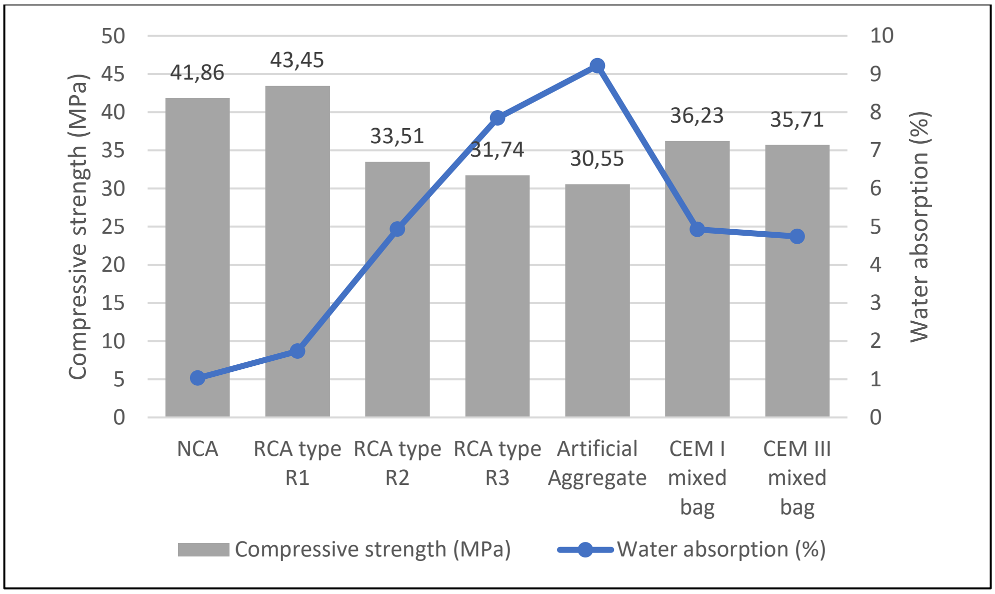


Figure 5.1 WA vs CS

As shown in figure 5.1, RCA type $R^2$and R^3, and AA have higher WA absorption compared to the reference recipe while RCA type R^1 has a comparable WA. Concrete made of RCA type R^1 gives the highest CS among all tests, which is 43.5 MPa. A Microscopic and Optical Shadow Effect Mode illustrations of particles from the reference recipe and RCA type R^1 are shown in figure 5.2.

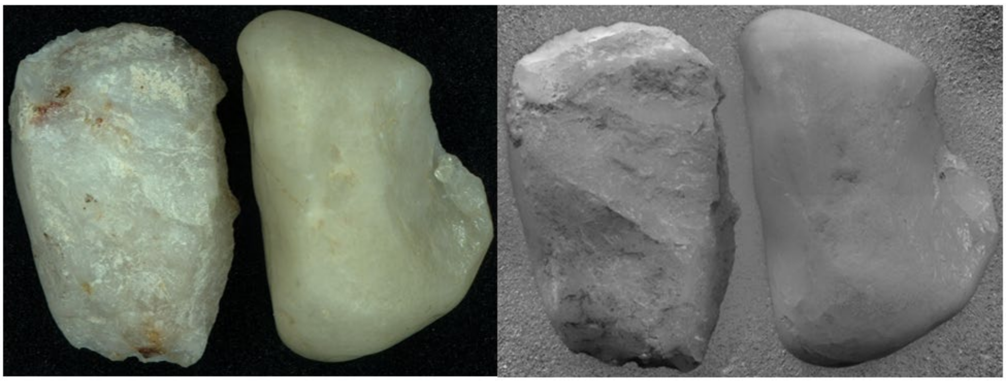


Figure 5.2: Microscopic and optical shadow effect mode image of RCA type R^1(Left) vs. NCA (right).

As seen in the figure, the RCA on the left exhibits a noticeably rougher surface texture in comparison to the NCA on the right. This difference in surface characteristics can be attributed to the fact that RCA has undergone a recycling process.

RCA type R^2 and type R^3 have comparable CS, 33 MPa and 31.7 MPa respectively. However, the WA percentages vary between 4.5% and 8%. These results show that the large variation in WA does not directly mean a lower CS. Besides, the CS of RCA type R^2 and type R^3 is reduced by 25% compared to the reference recipe, which indicated that the ARM content has a negative effect on the CS of RAC.

The CS of RCA from different resources (CEM I mixed bag, CEM III mixed bag), have similar CS and WA. The percentage of LQRA in RCA are 56%, 62%, and 64% respectively. AA shows similar results compared to RCA type R^3, 31.7 MPa and 30.6 MPa respectively.

5.1.2 Effect of fly ash (FA) and W/C ratio on the Compressive Strength (CS) of concrete

This section aims to utilize the data, which is included in appendix H, taken from the UCI Machine Learning repository to analyze the mechanical behaviour of concrete made with NCA. Besides, it sets the boundary conditions and guidelines for setting up the mixtures made of RCA.

The focus of this analysis is on exploratory data. The implemented approach makes it possible to investigate the possible relationships between data and employed variables, generate solutions for problems, and ultimately determine the quality of concrete.

The dataset consists of six instances with 350 attributes, demonstrating that five input parameters and one target variable are analyzed. The performed data analysis gives insights into how every variable affects other variables. To visualize the results, plot scatters are displayed to understand the more complex relationships between specific variables. Six input parameters and one output parameter are used. The input variables are represented as follows (all quantities are in kg/m^3): Cement type, FA, BFS, water, SP, and water-to-binder ratio (W/B ratio). The response parameter is the CS.

The Pearson correlation is a widely known method that checks the linear correlation between sets of data. The ratio between the covariance of two variables is determined using the Pearson correlation Heatmap. The results are shown in figure 5.3.

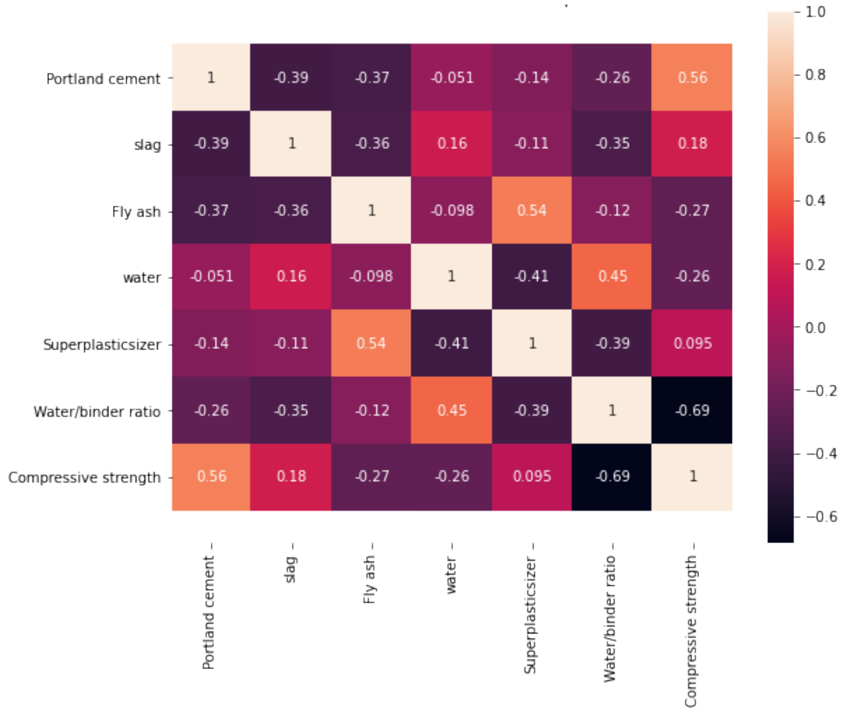


Figure 5.3: Feature Pearson Correlation Heatmap

From figure 5.3, the following observations are made:

1. There is a strong positive correlation between the cement content and the CS, indicating that increasing the cement content leads to an increase in CS.
2. BFS shows a slight positive correlation with CS, suggesting that incorporating BFS in concrete mixtures may contribute to a slight increase in CS.
3. There is a strong positive correlation between the FA content and the superplasticizers content. However, further information is required regarding the specific type of superplasticizers used and the WA characteristics of FA to provide a clearer understanding of this observation.
4. The W/B ratio exhibits a large negative correlation with CS, indicating that as the W/B ratio decreases, the CS of the concrete tends to increase.

These correlations give important insights into the data. It also helps to understand how different parameters affect each other and the response.

5.1.3 Adhered and Residual Mortar (ARM) content vs Compressive Strength (CS)

The determination of the quality of RCA is influenced by various factors, including the ARM content. Estimating the ARM content requires a careful examination of the physical properties of RCA. In chapter 3, the approach of handpicking is elucidated, providing insights into the process of assessing ARM content. Additionally, the results of WA and SG tests, which are indicative of the pore structure and density of the RCA, are presented in table 3.2 of chapter 3. These tests contribute to the understanding of the relationship between WA, SG, and the quality of the RCA.

The relationship between WA and SG of RCA is typically inverse. WA refers to the amount of water that can be absorbed by the aggregate, usually expressed as a percentage of the aggregate's weight. SG, on the other hand, represents the density or heaviness of the aggregate compared to the density of water.

In general, as the WA of RCA increases, the SG tends to decrease. This is because when aggregate materials have higher WA, it means they have more pores or voids within their structure. These pores can be filled with water, which adds to the overall weight of the aggregate, leading to a higher SG.

On the contrary, aggregate with lower WA has fewer internal pores and thus tends to have a higher SG. This indicates a denser and more compact structure, where the voids within the aggregate are minimal, resulting in a higher SG value.

Preliminary results were carried out to investigate the relationship between the WA and SG. A graphic illustration of the results is shown in figure 5.4. Linear regression was used to fit a line between all data points. In addition, other experiments were conducted to examine the impact of the presence of ARM in RCA on the CS of concrete. The results are shown in figure 5.5.

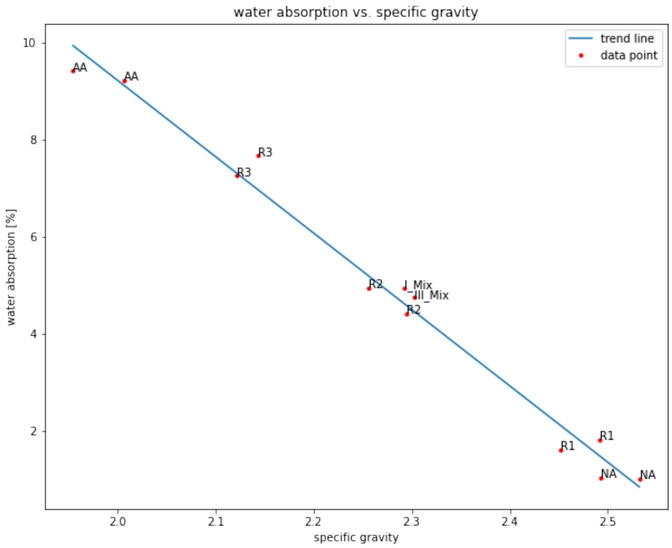


Figure 5.4: SG vs WA.

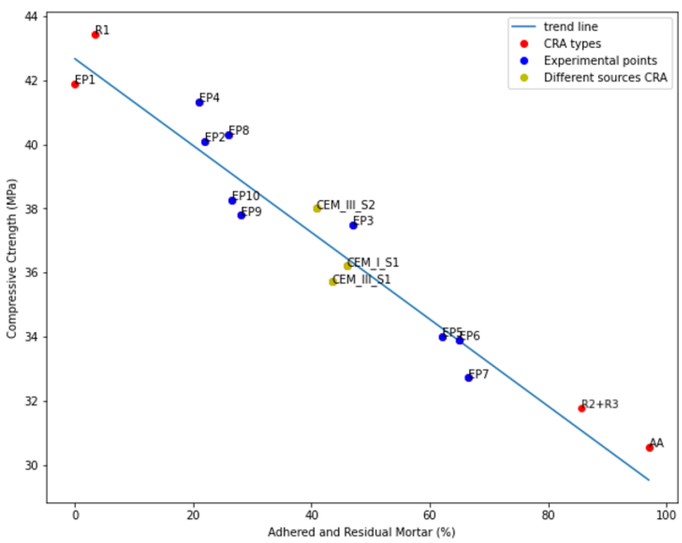


Figure 5.5: ARM vs CS

The red points in figure 5.5 represent the different fractions of RCA, the Blue points represent the experimental points used in building the predictive model, and the yellow points represent the RCA from different sources. R-squared (R^2) and Standard Error of the regression must be calculated to measure the goodness-of-fit. $R^2 = 0.95$. Based on the obtained results, it can be concluded that the model is a good fit for the data points.

To obtain a physical understanding of the relationship between WA and SG of RCA of the previous figures, a linear regression equation was developed. The derived formula provides a quantitative link between these two parameters.

$$WA[\%] = -18.29 * SG + 46.79 \quad (6)$$

To further analyze the percentage of ARM for different types of RCA, the densities of NCA and AA were used in conjunction with the formula. The density values of NCA and AA were 2.5 and 2.04, respectively. However, it should be noted that the WA and SG values of AA were only considered in the study experiments. The percentage of ARM in each RCA type was calculated using the following formula:

$$ARM[\%] = 1 - \frac{SG_{aggregate} - SG_{AA}}{SG_{NCA} - SG_{AA}} \quad (7)$$

Based on this calculation, the ARM percentages for RCA types R^1, R^2+R^3, AA, CEMIII_source1, CEMI_source2, and CEMIII_source3 were determined to be 3.32%, 85.2%, 100%, 43.52%, 46.02%, and 40.84%, respectively.

In the context of the CS of concrete, the percentage of ARM in RCA is more crucial than the WA. This is particularly evident when dealing with RCA which has a high percentage of brick. The presence of brick can lead to increased WA and, surprisingly, an enhancement in the CS of concrete.

The following sections present the results of CS tests conducted on concrete specimens at 7, 28, and 91 days, considering the effects of RCA, LQRA FA, W/C ratio, and brick. Analyzing the CS at these time intervals provides insights into the performance of concrete with these influencing variables. The utilized RCA has an initial LQRA percentage of 40% (WA = 4%).

5.2 Experimental results of the 7-day Compressive Strength (CS)

5.2.1 Effect of Recycled Coarse Aggregate content (RCA) and Low-Quality Recycled Aggregate (LQRA) on the Compressive Strength (CS).

-W/C ratio = 0.45

The plot illustrates that the higher the content of LQRA, the lower the CS for mixtures with varying percentages of RCA. Figure 5.6 shows that for mixtures with 0% RCA, the CS decreases by 9.3% with LQRA content varying from 0%-25% (WA from 1% to 2.7%). Similar behavior is observed for mixtures with 100% RCA (WA from 4% to 4.8%), the total reduction equals 6.7%.

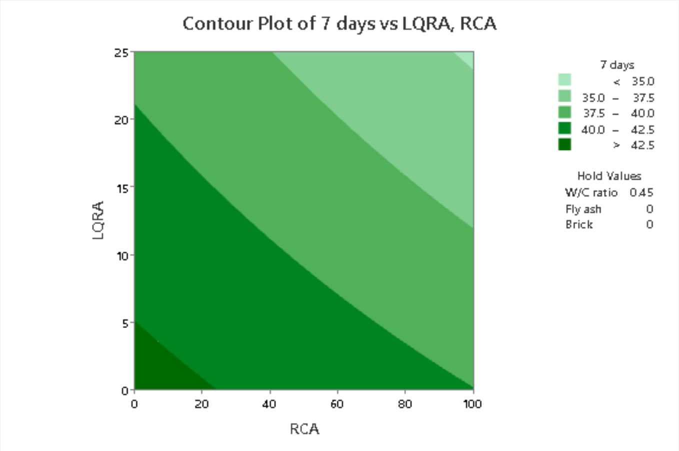


Figure 5.6: Contour plot RCA vs. LQRA

-W/C ratio = 0.54

The plot in figure 5.7 illustrates that as the LQRA content increases, the CS decreases in mixtures with varying percentages of RCA. For mixtures with 0% RCA, a decrease of 10.3% in CS is observed as the LQRA content increases from 0% to 25% (WA from 1% to 2.7%). A similar trend is observed in mixtures with 100% RCA (WA from 4% to 4.8%), resulting in a total decrease of 13.5%.

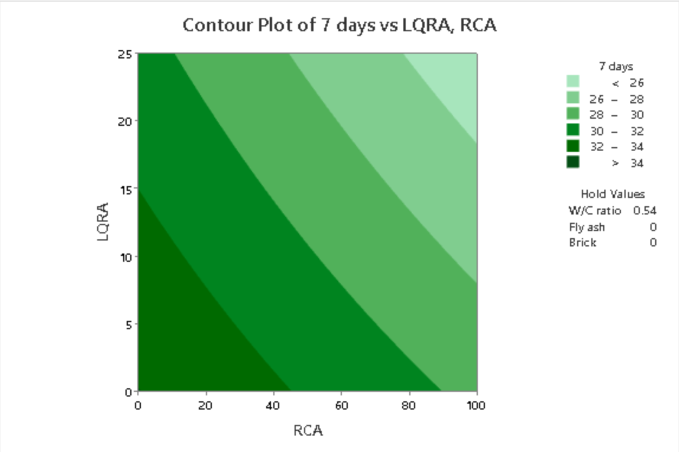


Figure 5.7: Contour plot RCA vs. LQRA

5.2.2 Effect of Recycled Coarse Aggregate (RCA) and Brick content on the Compressive Strength (CS).

-W/C ratio = 0.45

The results indicate that adding more brick to mixtures with varying percentages of RCA leads to a decrease in CS. In mixtures with 0% RCA, the CS drops by 5.1% as the brick content increases (WA from 1% to 1.2%). In mixtures with 100% RCA (WA from 4% to 4.2%), the decrease in CS is limited to 3%.

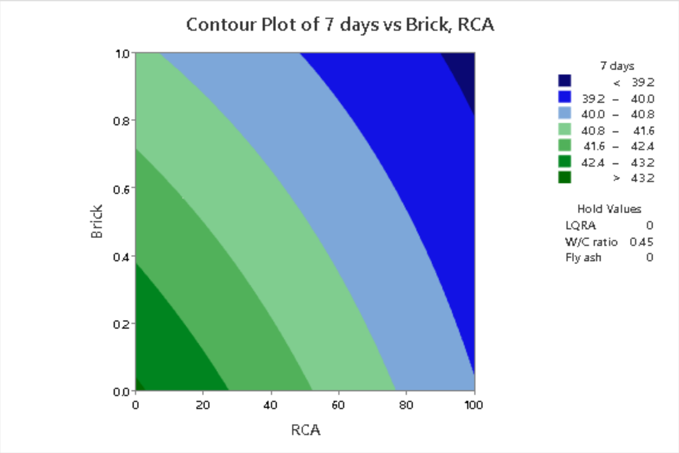


Figure 5.8: contour plots RCA vs. Brick

- W/C ratio = 0.54

The results suggest that for mixtures with 0% RCA (WA from 1% to 1.2%), the CS increases by 2% as the brick content increases. In mixtures with 100% RCA (WA from 4% to 4.2%), the increase in CS is limited to 5.7%.

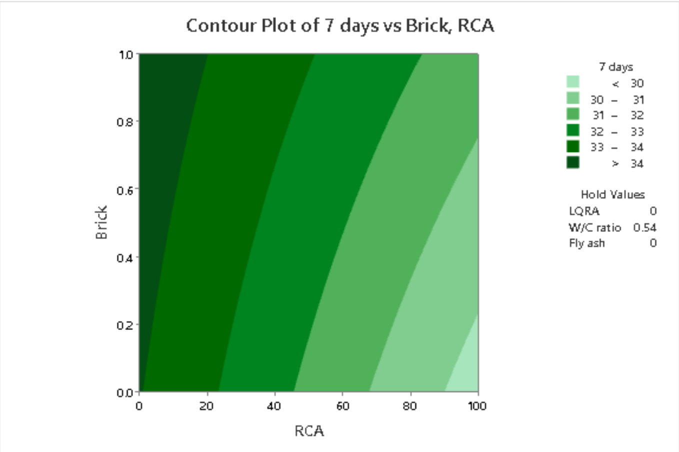


Figure 5.9: Contour plots RCA vs. Brick

5.3 Compressive Strength (CS) results of 28-day experiments

5.3.1 Effect of Recycled Coarse Aggregate content (RCA) and Low-Quality Recycled Aggregate (LQRA) on the Compressive Strength (CS).

-W/C ratio = 0.45

The plot illustrates that the higher the content of LQRA, the lower the CS for mixtures with varying percentages of RCA. Figure 5.10 shows that for mixtures with 0% RCA, the CS decreases by 9% with LQRA content from 0%-25% (WA from 1% to 2.7%). Similar behavouir is observed for mixtures with 100% RCA (WA from 4% to 4.8%), the total reduction equals 9.6%.

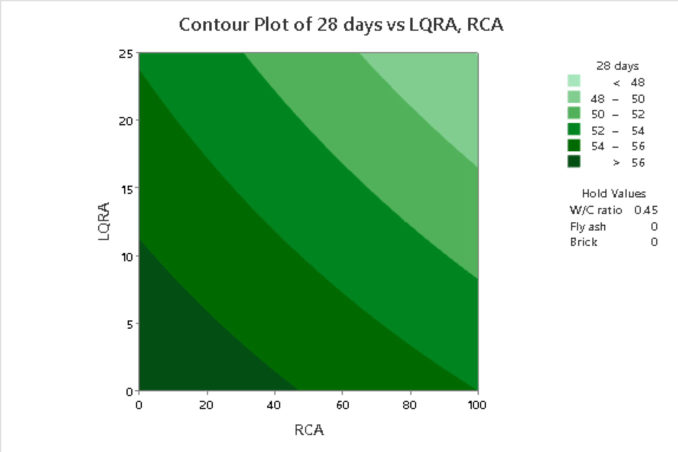


Figure 5.10: Contour plot RCA vs. LQRA

-W/C ratio = 0.54

The plot in figure 5.11 illustrates that as the LQRA content increases, the CS decreases in mixtures with varying percentages of RCA. For mixtures with 0% RCA, a decrease of 2.2% in CS is observed as the LQRA content increases from 0% to 25% (WA from 1% to 2.7%). A similar trend is observed in mixtures with 100% RCA (WA from 4% to 4.8%), resulting in a total decrease of 9.5%.

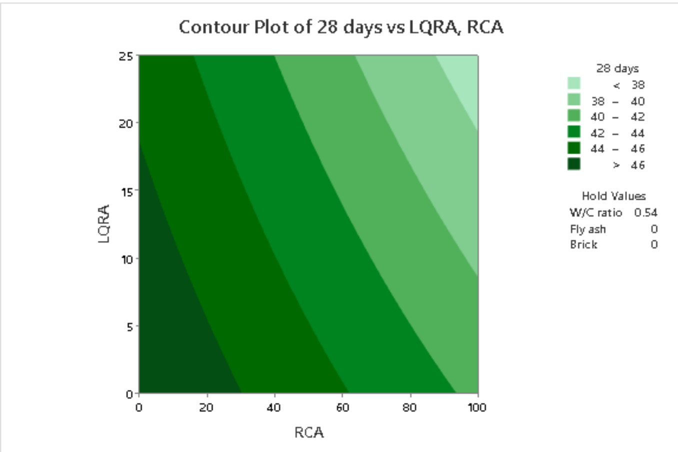


Figure 5.11: Contour plot RCA vs. LQRA

5.3.2 Effect of Recycled Coarse Aggregate (RCA) and Brick content on the Compressive Strength (CS).

-W/C ratio = 0.45

The results indicate that adding more brick to mixtures with varying percentages of RCA leads to a decrease in CS. In mixtures with 0% RCA (WA from 1% to 1.2%), the CS drops by 1.8% as the brick content increases. In mixtures with 100% RCA (WA from 4% to 4.2%), the decrease in CS is limited to 0.5%.

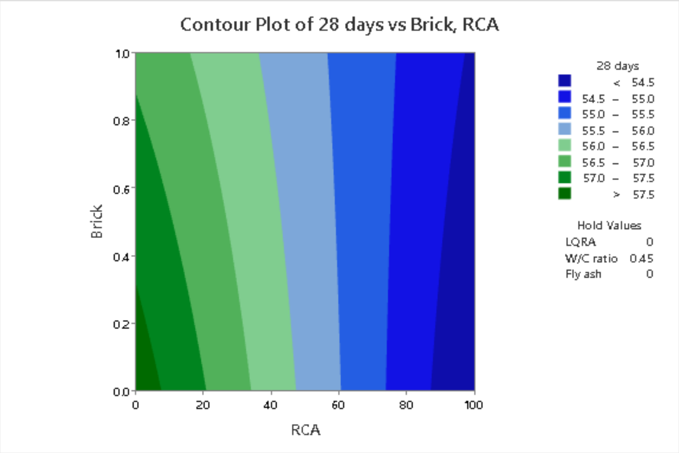


Figure 5.12: Contour plots RCA vs. Brick

- W/C ratio = 0.54

The results suggest that for mixtures with 0% RCA (WA from 1% to 1.2%), the CS slightly increases by 0.5% as the brick content increases. In mixtures with 100% RCA (WA from 4% to 4.2%), the increase in CS is limited to 2.3%.

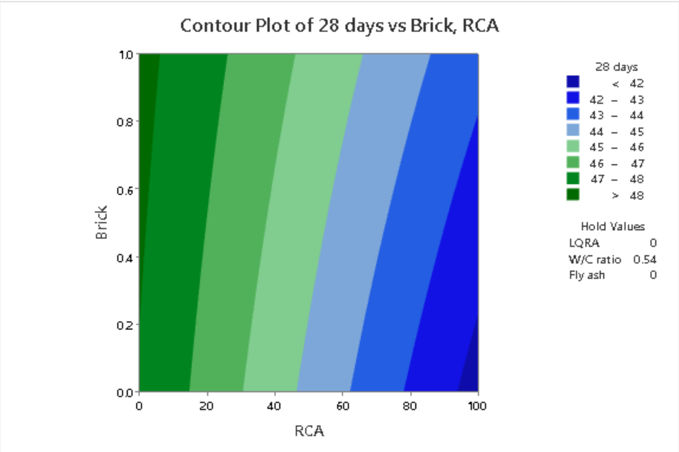


Figure 5.13: Contour plots RCA vs. Brick

5.4 Compressive Strength (CS) results of 91-day experiments

5.4.1 Effect of Recycled Coarse Aggregate content (RCA) and Low-Quality Recycled Aggregate (LQRA) on the Compressive Strength (CS).

-W/C ratio = 0.45

The plot illustrates that the higher the content of LQRA, the lower the CS for mixtures with 0% RCA. In addition, figure 5.14 shows that for mixtures with 0% RCA, the CS decreases by 5.5% for LQRA content from 0%-25% (WA from 1% to 2.7%). For mixtures with 100% RCA (WA from 4% to 4.8%), the LQRA contribution reduces the CS by 6.3%.

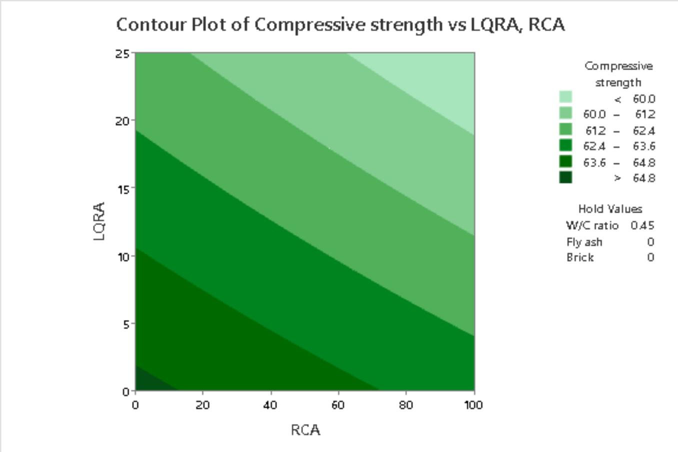


Figure 5.14: Contour plot RCA vs. LQRA

-W/C ratio = 0.54

Figure 5.15 shows that increasing the LQRA content in mixtures with varying percentages of RCA results in a decrease in CS. The CS decreases by 5.7% as the LQRA content increases in mixtures with 0% RCA, while the decrease is limited to 6.8% in mixtures with 100% RCA. In addition, as the content of LQRA increases (WA percentage changing from 1%-4.8%), the CS decreases regardless of the percentage of RCA.

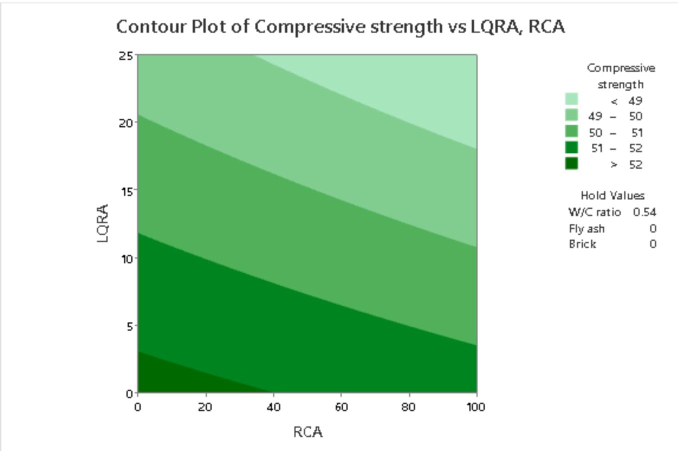


Figure 5.15: Contour plot RCA vs. LQRA

The findings indicate that as the W/C ratio increases, the CS remains relatively consistent for mixtures with varying percentages of RCA, provided that the content of LQRA remains constant.

5.4.2 Effect of Recycled Coarse Aggregate (RCA) and Brick content on the Compressive Strength (CS).

- W/C ratio = 0.45

The results indicate that adding more brick to mixtures with varying percentages of RCA does slightly impact the CS results. Moreover, an insignificant decrease in the CS is observed for mixtures with 0% RCA (WA from 1% to 1.2%). While for mixtures with 100% RCA (WA from 4% to 4.2%), a decrease of 2.4% is observed.

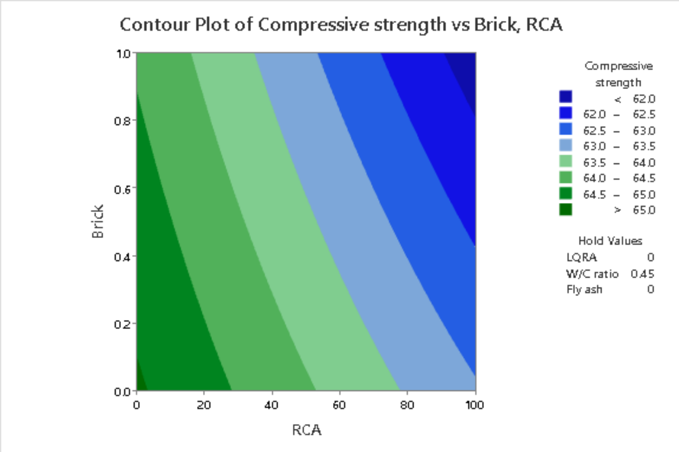


Figure 5.16: Contour plots RCA vs. Brick.

- W/C ratio = 0.54

The results suggest that for mixtures with 0% RCA (WA from 1% to 1.2%), the CS slightly increases as the brick content changes from 0% to 1%. However, in mixtures with 100% RCA (WA from 4% to 4.2%), the CS decreases by 1.2%.

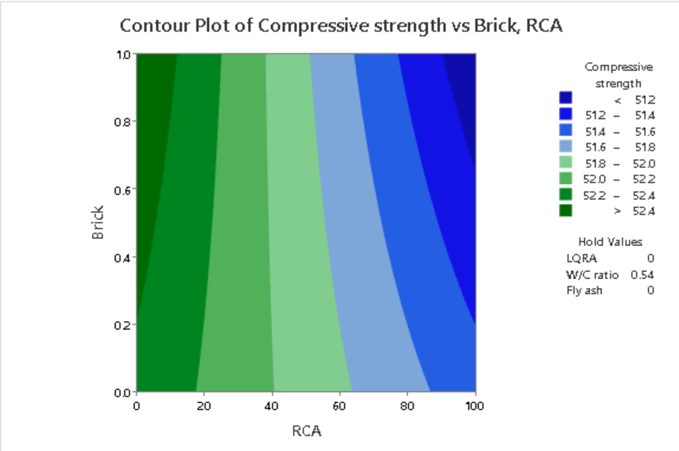


Figure 5.17: Contour plots RCA vs. Brick.

5.4.3 Effect of Recycled Coarse Aggregate (RCA) and Fly Ash (FA) on the Compressive Strength (CS).

- W/C ratio = 0.45

In the case of 0% RCA (WA= 1%), the results show that increasing the FA content from 0% to 20% increases the CS by 5.1%. For mixtures with 100% RCA (WA= 4%), the CS improves by 3.8%.

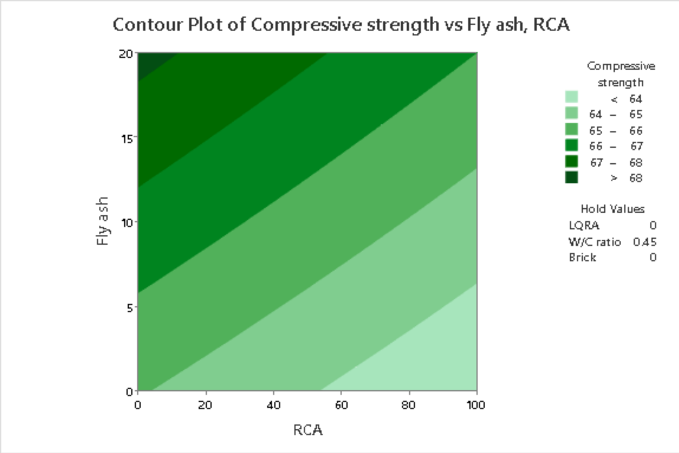


Figure 5.18: Contour plot RCA vs. FA.

- W/C ratio = 0.54

The results suggest that for mixtures with 0% RCA and 0% LQRA (WA from 1% to 2.7%), the CS increases by 5.5% as the FA content changes from 0% to 20%. In mixtures with 100% RCA (WA form 4% to 4.8%), the increase in CS is limited to 4.6%. Besides, increasing the content of FA has an overall positive impact on the CS of all tested mixtures regardless of the level of LQRA.

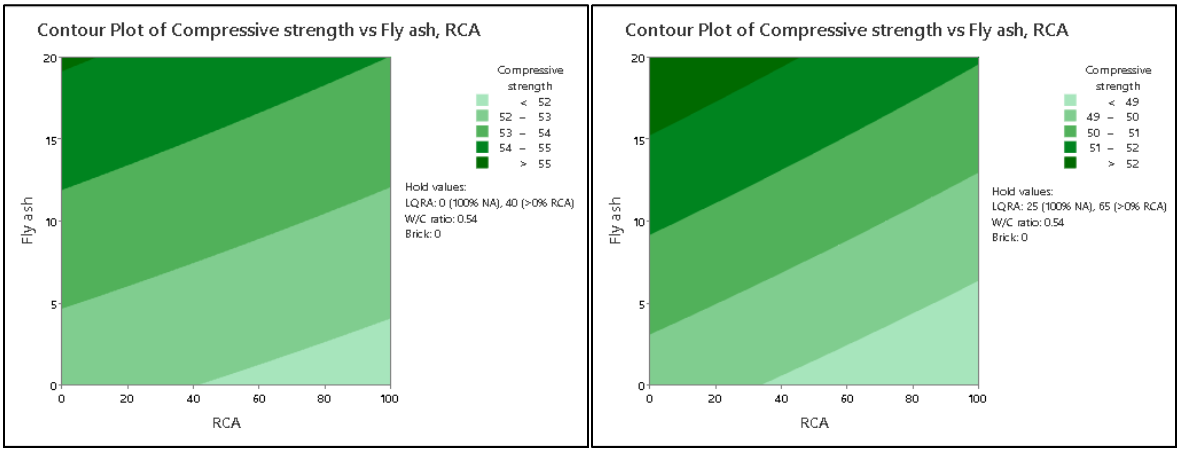


Figure 5.19: Contour plots RCA vs. FA.

5.4.4 Effect of Water Absorption (WA) on the Compressive Strength (CS)

- W/C ratio = 0.45

The results in figure 5.20 indicate that as the LQRA content increases, the CS decreases. Furthermore, when mixtures contain RCA, the CS is further reduced as the percentage of LQRA increases, as RCA has a higher WA compared to NA. Additionally, the results indicate that the lowest CS value recorded for the mixtures consisting of 100% RCA and 55% LQRA was 59 MPa.

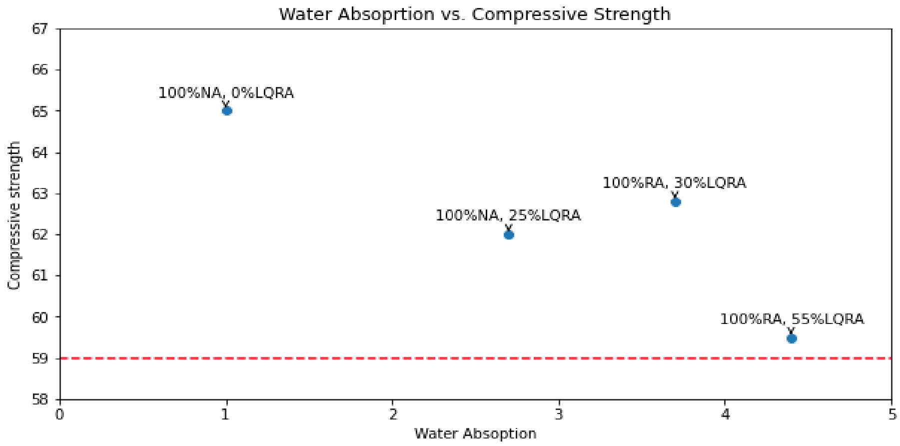


Figure 5.20: WA vs. CS, W/C= 0.45.

- W/C ratio = 0.49

The data presented in figure 5.21 shows that the lowest CS value calculated for the mixtures consisting of 100% RCA and 55% LQRA was 53.5 MPa. Moreover, the CS of mixtures is even more diminished with the inclusion of RCA, particularly as the proportion of LQRA grows.

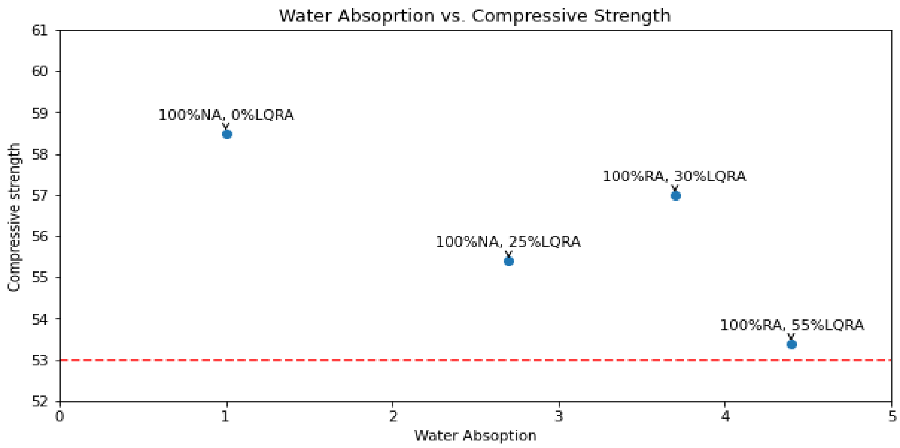


Figure 5.21: WA vs. CS, W/C= 0.49.

- W/C ratio = 0.54

The information displayed in figure 5.22 indicates a reduction in the CS as the amount of LQRA increases. The plot also shows that the mixtures composed of 100% RCA and 55% LQRA had the lowest CS value of 48 MPa.

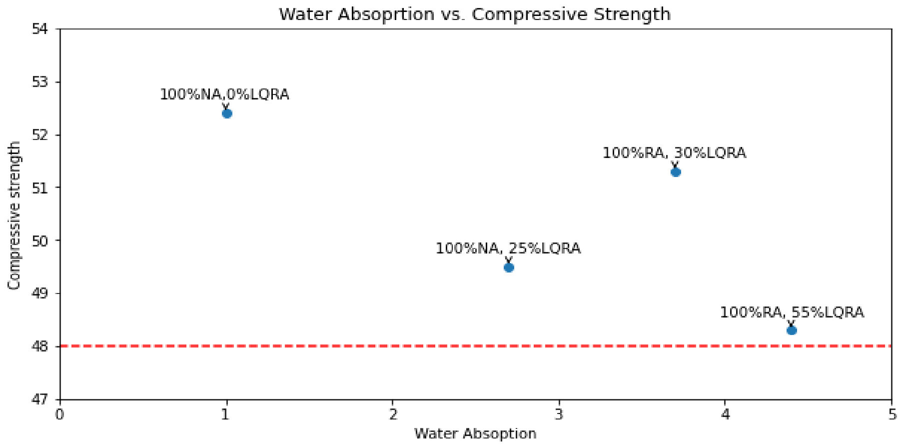


Figure 5.22: WA vs. CS, W/C= 0.54.

According to the results, a combination of 100% RCA and a maximum WA of 4.4% has a minimum CS of 59 MPa for a W/C ratio of 0.45. Additionally, mixtures consisting of 100% RCA and WA up to 4.4% display a minimum CS of 48 MPa for a W/C ratio of 0.54.

5.5 Predictive model

5.5.1 Analysis of Variance (ANOVA)

ANOVA is a commonly used statistical technique for assessing the impact of different variables on a measurable outcome. In this study, ANOVA was employed to assess the statistical significance of various variables on the CS of RAC. This approach was used to determine which variables have the greatest impact on the CS.

Table 5.1 displays the results of the ANOVA. The p-values of the RCA, FA, W/C ratio, brick, and LQRA content terms were found to be less than 0.05, indicating that these variables have a significant influence on the outcome. However, variables with p-values greater than 0.1 were deemed insignificant and eliminated from consideration. For instance, the interaction term of FA*RCA was found to be insignificant, as its p-value was 0.183. As a result, this term was excluded.

Table 5.1: ANOVA summary table.

Source	P-Value
Linear	
LQRA	0.000
W/C ratio	0.000
Fly Ash	0.000
RCA	0.000
Brick	0.000
2-Way Interaction	
LQRA*W/C ratio	0.006
LQRA*Fly Ash	0.012
LQRA*RCA	0.006
LQRA*Brick	0.000

Source	P-Value
W/C ratio*Fly Ash	0.034
W/C ratio*RCA	0.000
W/C ratio*Brick	0.000
Fly Ash*RCA	0.183
Fly Ash*Brick	0.003
RCA*Brick	0.003

5.5.2 Regression model

Based on the equation (4) from RSM in section 4.1.1 and the experimental results of CS tests with varying variables, a regression equation is formulated for CS prediction, as follows:

Compressive Strength = 128.66- 0.2568 LQRA- 141.32 W/C ratio+ 0.2698 FA - 0.0775 RCA - 5.00 Brick + 0.2633 LQRA*W/C ratio + 0.001065 LQRA*FA - 0.000237 LQRA*RCA + 0.03290 LQRA*Brick - 0.243 W/C ratio*FA+ 0.1275 W/C ratio*RCA + 9.69 W/C ratio*Brick- 0.03337 FA*Brick - 0.00673 RCA*Brick (8)

R^2, also known as the coefficient of determination, is a measure that explains the proportion of the variance in the dependent variable (response) that can be attributed to the independent variable(s) (predictor variable(s)). It represents the goodness of fit of a regression model. R^2(adj) expresses how many points/terms lie within the constructed regression line. R^2(pred) refers to the coefficient of determination for a predictive model. It represents the proportion of the variance in the dependent variable that can be predicted by the independent variable(s).Additionally, R^2(pred) helps assess how well the predictive model can explain or predict the outcome based on the input variables.

The results of R^2, R^2(adj), and R^2(pred) of the predictive model (equation (8))are shown in table 5.2. It is shown that all three values are high (i.e., >95%), indicating the model fits the data well.

Table 5.2: model summary

R-sq	R-sq(adj)	R-sq(pred)
99.9%	99.8%	96.5%

Table 5.3 presents the results of the CS tests conducted on the 32 mixture designs of RAC. In the subsequent sections, a thorough analysis and interpretation of the results is provided.

Table 5.3: Results of the CS of 32 mixture designs.

Node Nr	LQRA%	W/C ratio	FA%	RCA%	Brick%	CS (MPA)
1	12.5	0.54	10	50	0.5	51.67
2	12.5	0.495	10	50	1	57.26
3	0	0.495	10	50	0.5	58.90
4	0	0.45	20	0	0	68.30
5	25	0.54	20	0	0	52.80
6	0	0.45	20	100	1	64.15

Node Nr	LQRA%	W/C ratio	FA%	RCA%	Brick%	CS (MPA)
7	25	0.45	20	100	0	62.53
8	12.5	0.495	10	50	0.5	57.30
9	0	0.54	0	0	0	52.40
10	25	0.45	20	0	1	64.90
11	12.5	0.495	10	50	0.5	57.50
12	25	0.495	10	50	0.5	56.40
13	25	0.54	20	100	1	50.90
14	12.5	0.495	10	50	0.5	57.50
15	12.5	0.45	10	50	0.5	63.50
16	25	0.45	0	100	1	58.61
17	12.5	0.495	10	100	0.5	56.12
18	0	0.54	0	100	1	51.20
19	0	0.54	20	100	0	54.10
20	12.5	0.495	10	50	0	58.07
21	12.5	0.495	10	50	0.5	57.50
22	25	0.45	0	0	0	61.60
23	25	0.54	0	0	1	50.60
24	0	0.54	20	0	1	54.78
25	0	0.45	0	0	1	64.50
26	12.5	0.495	20	50	0.5	58.90
27	12.5	0.495	10	0	0.5	58.80
28	12.5	0.495	10	50	0.5	57.50
29	25	0.54	0	100	0	48.10
30	12.5	0.495	10	50	0.5	57.40
31	0	0.45	0	100	0	63.14
32	12.5	0.495	0	50	0.5	56.10

5.6 Validation and simplification of the predictive model

Ensuring the reliability and accuracy of a predictive model is of paramount importance in decision-making processes. In this section, we delve into the two primary parts of model validation and model simplification.

5.6.1 Validation using control points

Verifying the model includes picking random combinations of experimental trails from the model design space. The experiments are performed using these sets of values, and the results are compared to the predictive model results. Seven control design sets are selected as follows:

1) RCA%: 0 W/C ratio: 0.45, LQRA: 15, Brick: 1, FA:0.
2) RCA%: 15 W/C ratio: 0.54, LQRA: 12.5, Brick: 0.5, FA:20.
3) RCA%: 60 W/C ratio: 0.45, LQRA: 0, Brick: 0, FA:15.
4) RCA%: 50 W/C ratio: 0.50, LQRA: 20, Brick: 1, FA:10.
5) RCA%: 50 W/C ratio: 0.54, LQRA: 0, Brick: 0, FA:0.
6) RCA%: 100 W/C ratio: 0.45, LQRA: 0, Brick: 1, FA:5.

7) RCA%: 30 W/C ratio: 0.50, LQRA: 25, Brick: 1, FA:15.

The experimental results of the seven control design space sets are compared with the outcome of the predictive model (equation (8)). The ARD is calculated to validate the predictive model (Fatemi et al., 2006). The ARD formula is presented as follows:

$$ARD\ (\%) = \frac{Experimental - model}{Experimental} * 100 \tag{9}$$

The computed ARD values for the respective sets are 3.3%, 4%, 6.6%, 8%, 7.4%, 6.5%, and 5.5%.

5.6.2 Pareto chart

Because there are many terms in the predictive model (equation (8)), it is interesting to explore if the model can be simplified by mainly considering the key influential variables in the equation.

A Pareto chart is a visual representation of data that helps identify and prioritize the most significant variables or categories contributing to a particular outcome. The results are displayed in a bar graph. The bars represent the individual variables, arranged from left to right in decreasing order. This chart allows decision-makers to quickly identify the vital few variables that have the most substantial impact, enabling them to focus their resources and efforts on addressing these critical issues for maximum improvement or resolution.

A Pareto chart can be used to simplify the regression formula by identifying the key variables that have a substantial impact on the CS. This involves analyzing the predictive model, calculating the effects of the variables, ranking them, and creating a Pareto chart of the standardized effects. By setting a threshold and selecting the variables above that threshold, the model can be simplified to focus on the most influential variables. This simplification process helps in better understanding the key terms affecting the response and leads to a streamlined model that captures the most critical variables driving the outcome.

The results of the Pareto chart of the standardized effects are presented in figure 5.23.

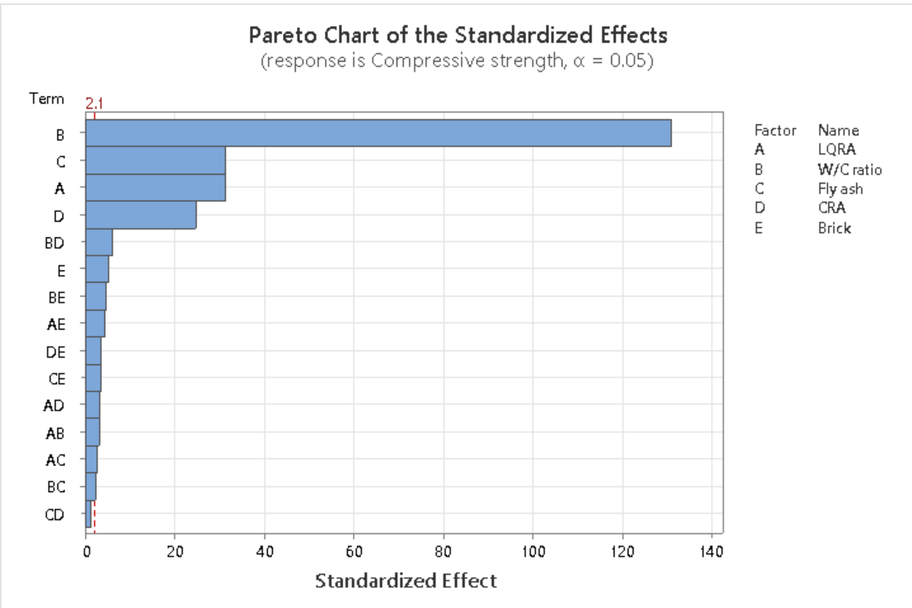


Figure 5.23: Pareto chart of the standardized effects

To understand the results of the Pareto chart, the following points should be considered:

1. **B standardized effect = 130:** this indicates that the effect of term B is the most significant or influential among all the terms represented in the chart. The value of 130 suggests that the effect of term B is relatively large compared to the other variables.

2. **C standardized effect = 30:** the standardized effect of term C is 30, which is smaller than the effect of term B. This means that term C has a lesser impact or influence compared to term B but still holds some significance.

3. **A standardized effect = 30:** similar to term C, factor A also has a standardized effect of 30. This implies that both terms A and C have the same level of impact or influence on the CS being measured.

4. **D standardized effect = 25:** term D has the smallest standardized effect among the variables mentioned. Although it has a lower impact compared to terms B, A, and C, it still contributes to the overall effect to some extent.

When analyzing the standardized effects, terms with a standardized effect of less than five are considered insignificant. These terms are considered insignificant because their impact does not significantly affect the outcome compared to other terms with larger standardized effects. By identifying and excluding these insignificant terms, attention can be directed toward the more influential terms that possess a significant impact on the outcome.

5.6.3 Simplification of the predictive model

Since the key influential variables are identified in section 5.6.2, the mathematical equation of CS prediction can be refined and simplified. This simplification process streamlines the formula and removes unnecessary terms, resulting in a more concise representation of the relationship between the input variables and CS. The simplified mathematical formula is as follows:

$$\textbf{Compressive Strength} = 122.89 - 0.11124\ \text{LQRA} - 129.23\ \text{W/C ratio} + 0.1395\ \text{FA} - 0.02203\ \text{RCA} \quad (10)$$

Equation (10) represents a predictive equation for estimating CS. The physical understanding behind each term can be broken down into the following:

1. **LQRA:** The coefficient (-0.11124) associated with LQRA in the formula represents the effect of LQRA on CS. A negative coefficient suggests that a higher proportion of LQRA might lead to a decrease in CS.

2. **W/C ratio:** The coefficient (-129.23) associated with the W/C ratio in the formula indicates that a higher W/C ratio has a negative impact on CS.

3. **FA:** The coefficient (0.1395) associated with FA in the formula suggests that an increase in FA content can have a positive impact on CS.

4. **RCA:** The coefficient (-0.02203) associated with RCA implies that an increase in the amount of RCA may have a slight negative impact on CS.

By plugging in specific values for the LQRA, W/C ratio, FA, and RCA variables into the formula, the equation provides an estimated value for CS. It is important to note that the formula provided may be specific to this particular study and should be interpreted within that context.

Verifying the simplified formula includes applying random combinations of experimental trails, as mentioned in section 5.6.1, and comparing the results with the original formula results. The comparison between the original formula and the simplified formula is shown in table 5.4. The differences between the two formulas are quite small (<2%), indicating the simplified formula has well captured the main characteristics of the CS prediction.

Table 5.4: ADR results of the simplified formula vs. original

Control points	CS original formula (MPa)	CS simplified formula (MPa)	ARD (%)
1	63.07	62.85	0.35
2	54.17	53.72	0.85
3	65.51	66.27	1.14
4	56.34	56.1	0.43
5	52.00	51.91	0.17
6	63.23	62.38	1.37
7	56.93	56.87	0.1

5.7 Validation using Artificial Neural Network (ANN)

5.7.1 Artificial Neural Network (ANN)

Because the linear regression models (e.g., equations (10)) are mainly obtained by fitting specific experimental data points, their robustness and generality may be limited. In this section, a predictive model based on non-linear ANN will be investigated. ANN has been successfully used in previous studies to predict the CS of concrete (Naderpour et al., 2018; Ni & Wang, 2000; Song et al., 2021).

ANN is a computational model inspired by the structure and functioning of the human brain. The structure of ANN is shown in figure 5.24. It consists of interconnected nodes, called neurons, organized in layers. Each neuron takes input values, applies weights to them, performs mathematical operations, and produces an output.

The development of the ANN model is data-driven, e.g., by training the model based on the actual dataset. In the developing process, ANN adjusts its weights and biases during training to minimize the difference between its predictions and the actual data. The trained ANN is then tested using separate data, and its performance is evaluated using statistical metrics such as R^2.

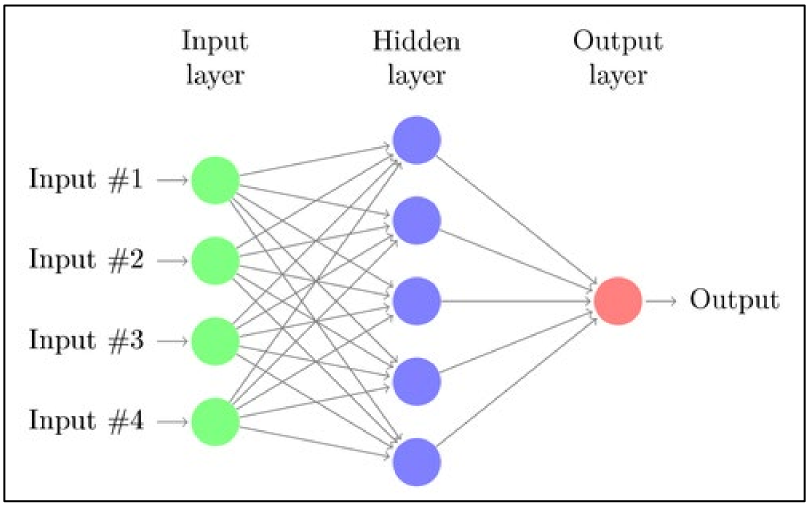


Figure 5.24: Flowchart ANN.

5.7.2 Development and evaluation of the ANN predictive model

To develop the predictive model of CS using ANN, one basic issue is how to determine the input variables. In previous sections, it has been known that the five variables (i.e., LQRA, W/C, FA, RCA, Brick) are the basic variables that may also have the most influences on CS. Here, to determine a suitable input layer of variables, four different input sets (shown in table 5.5) are tested for developing the model. Meanwhile, the impact of different numbers of hidden layers was also investigated, showing that a layer number of five led to a favourable result.

Table 5.5: Input data for ANN.

Input sets	Number of input variables N	Input variable set
Input-1	5	LQRA W/C FA RCA Brick
Input-2	4	LQRA W/C FA RCA
Input-3	3	W/C FA RCA
Input-4	3	LQRA W/C FA

The used dataset consists of 39 experimental data points, with 27 points for training, six points for validation, and six points for testing. Based on the four different input sets of variables, four different ANN models are developed. The results of the regression errors are shown in figure 5.25.

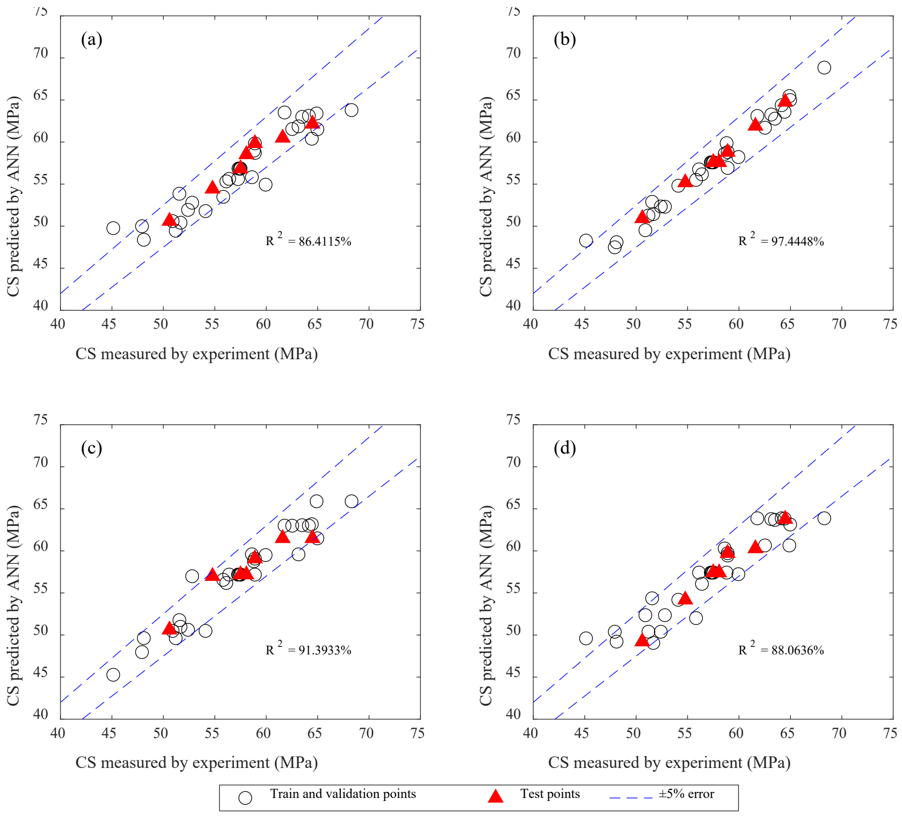


Figure 5.25: Regression errors of trained models based on 39 experimental data points: (a) Input-1, (b) Input-2, (c) Input-3, (d) Input-4.

As can be seen in figure 5.25, the ANN model gives an R^2 from 86% to 97%. Besides, the tested prediction of CS lies within ± 5% error. The mean ARD of the ANN predictions based on the four different inputs is presented in figure 5.26. For the considered variable range, the following is concluded:

1. Input-2 with the four variables (LQRA, W/C, FA, RCA) gives the best prediction (the lowest value of mean ARD), thus the four variables are important for evaluating the CS.
2. By comparison, the influence of brick percentage is less important; with this variable, the prediction accuracy decreases.

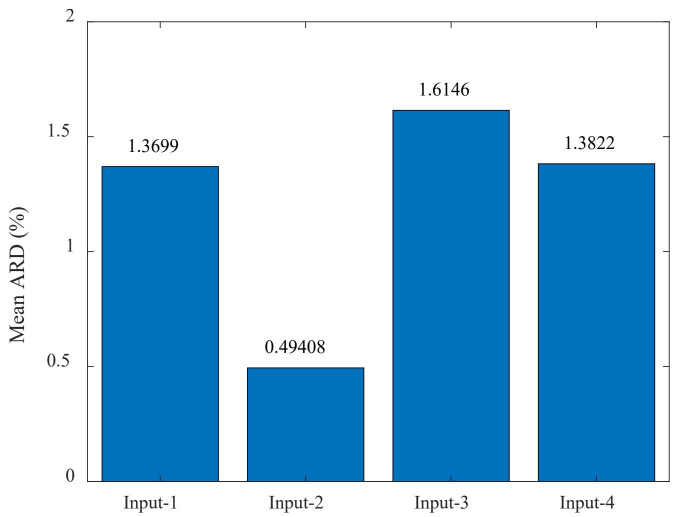


Figure 5.26: the mean ARD of the four inputs.

Overall, it is shown that a data-driven model by ANN can be developed to predict CS. After using different input sets of variables for training and testing, the results show that the ANN model, based on Input-2 with 4 variables (similar to the Pareto chart, i.e., W/C ratio, FA, LQRA, RCA), gives the lowest prediction error. Thus, this further supports that the four variables (i.e., W/C ratio, FA, LQRA, RCA) should be important for evaluating CS.

6. Discussion

In this chapter, the results of the previous chapter are interpreted and explanations of the outcomes are provided. The focus is on defining the quality of RCA through the results of the preliminary experiments, and the fresh and hardened properties of RAC. Moreover, the relationships between input parameters and the response of the predictive model are explained.

6.1 Fresh properties of Recycled Aggregate Concrete (RAC)

The results of the fresh properties are related to the following points:

1) **Superplasticizers dosage:** Superplasticizers dosage of 0.26%-0.30% of the cement mass was enough to reach the desired consistency for all the mixtures with RCA percentages up to 50%. However, for mixtures containing higher than 50% RCA, the dosage had to be increased to 0.4%. The obtained results are in line with the findings of a previous study conducted by Rahman and colleges (2009), the study demonstrated that the rough surface, irregularity, and high MC of RCA increase the friction between the fractions and decrease the workability of the RAC.

2) **FA filler effect:** Mixtures incorporating high percentages of FA (up to 20%) achieved the required consistency with the same superplasticizers content. These results are in line with the findings of a former study in which it was stated that the viscosity-modifying- property of FA improves the workability without modifying the superplasticizers dosage (Gesoğlu et al., 2012). Mixtures with low W/C ratios and high content of LQRA, up to 65%, have workability losses and high AC. Combining superplasticizers and FA improves the consistency and decreases the AC.

3) **Air content (AC):** The AC of RAC increases with increasing the incorporation of RCA. RCA fractions are more porous than NCA due to the presence of ARM and masonry aggregate such as brick. However, introducing FA as a filler decreased the AC considerably. The ball-bearing effect and spherical shape of the FA particles densify the structure of RAC and fill up vacant holes that might contain entrapped air (Ju et al., 2020).

4) **Research vs. practice:** The casting procedure, which was recommended by a local concrete mixing center, was proved to be applicable on a lab scale. The produced RAC achieved the desired workability for all mixtures. Overall, the insights gained from the study can inform and improve the practical applications of RAC.

6.2 Quality of Recycled Coarse Aggregate (RCA)

The findings showed that utilizing the same recycling technique to produce RCA resulted in a consistently negative correlation between the ARM content of RCA and CS. This was observed regardless of the parent concrete's composition and origin from which the RCA was obtained.

The results of the preliminary experiments indicated that the increase of WA of RCA is not directly related to the reduction of the CS of RAC, as can be observed in figure 5.1. In addition, the results showed that RCA type R^1, which consists of unbound stone, had a much higher WA compared to RCA type R^2 and R^3, which mainly consists of cement paste and small-sized aggregate. These results are in line with the fact that the microstructure of the old cement paste is porous due to partial carbonation (C. S. Poon et al., 2004). However, the results in this research are only applicable to RCA produced by selective demolition techniques.

6.2.1 Effect of Water Absorption (WA) on the Compressive Strength (CS) of Recycled Aggregate Concrete (RAC)

In general, WA has a negative impact on the CS of RAC. However, the effect of WA on the CS of RAC is a subject of ongoing research in the field of civil engineering (Tam et al., 2005). Nevertheless, results from the predictive model have shown that to mitigate the negative effects of WA, it is important to carefully select and prepare the RCA samples, utilize RCA generated from selective demolition waste, optimize the mix design, and produce a workable concrete mix. In addition, the use of chemical admixtures, such as superplasticizers, can also improve workability in concrete. The results of the CS of nodes in which the WA is the most critical are shown in table 6.1.

Table 6.1: The critical nodes of the predictive model

Recipe	FA (%)	RCA (%)	LQR (%)	Brick (%)	W/C	WA (%)	CS (MPa)
1	0	100	65	1	0.45	4.9	58.61
2	20	100	52.5	1	0.54	4.5	50.90
3	20	100	65	0	0.45	4.8	62.53
4	10	100	40	0.5	0.5	4.1	56.12
5	0	100	40	0	0.45	4	63.14

The table presented indicates that the CS of RAC does not go below 50.9 MPa for WA content up to 4.9%. The European Standard (EN 12620:2002+A1:2008) states that the maximum allowable WA for RCA is 7%. The results support this recommendation, given that the LQRA content used in the experiments did not exceed 65% of the total mass of the RCA.

When brick is present in the RCA, it introduces additional porosity and water-holding capacity, which can result in higher WA values. However, the ARM content has a more pronounced impact on the CS of the concrete. Excessive ARM plays a critical role in influencing the bonding between the aggregate and the cement matrix. If there is inadequate bond formation due to a high ARM content, the CS of the concrete may be compromised.

Therefore, when assessing the CS of concrete made with RCA, it is imperative to consider the percentage of ARM as it directly influences the strength properties.

6.3 Predictive model analysis

RSM was used to develop a predictive model of CS. The results of the predictive model are discussed in detail, highlighting the key variables, which are RCA, FA, LQRA, W/C ratio, and brick, that impact the outcome, the validity of the model, and the potential practical applications of the results.

According to the results in section 5.4, it is shown that the 91-day CS of RAC has linear and 2-way interactive relationships with input variables. In fact, at the age of 91-days, an overall reduction in CS of RAC was observed in mixes with varying content of RCA compared to mixtures containing NCA. These results are in line with the findings of a previous study (Ozbakkaloglu et al., 2018). In addition, varying the content of FA from 0% to 20%, enhances the CS of concrete regardless of the percentage of RCA, According to the findings of research that had looked into the impact of FA on the CS of RAC (Somna et al., 2012), incorporating FA as a replacement for cement in RAC led to an increase in CS compared to concrete without FA while maintaining the same W/C ratio.

Furthermore, it was observed that the W/C ratio exerted the most significant influence on the CS of RAC. As the W/C ratio increased, the CS of RAC decreased regardless of the LQRA content. Interestingly, the inclusion of up to 1% brick content in the RAC mixtures did not have a noticeable impact on the CS. This implies that incorporating RCA with brick content up to 1% does not significantly affect the CS of the concrete.

The obtained P-values, mentioned in table 5.1, indicate significant relationships and interactions between various variables in the study. Variables such as LQRA, W/C ratio, FA, and RCA, demonstrate strong statistical significance, highlighting their substantial impact on the CS of concrete. The results emphasize the importance of carefully considering and controlling these variables. Additionally, the significant interaction effects between LQRA and other variables underscore their combined influence. The findings provide valuable insights into the physical understanding of the data.

6.4 Model validation and simplification

6.4.1 Validation by evaluating ARD of control points

According to a previous study conducted by Al-Yamac et al. (2017), it was determined that the acceptable range of the ARD should not exceed 10% for a reliable control design. In line with this criterion, our experimental results for the seven control points revealed ARD values well within the acceptable range. These results indicate that the control design methodology employed in this study successfully meets the established criterion, demonstrating the reliability and effectiveness of the implemented approach.

The ARD values for the seven control points were calculated and evaluated. These control points represent specific conditions for which the predictive model is used to generate concrete mix designs. The experimental results revealed that all seven control points achieved ARD values well within the acceptable range, below the recommended threshold of 10%. This means that the predicted values from the control design methodology closely matched the actual values observed in the experiments.

The fact that the ARD values for all control points remained below the 10% threshold is a significant finding. It indicates that the control design methodology employed in this study successfully meets the established criterion and demonstrates the reliability and effectiveness of the implemented approach. The close agreement between the predicted and observed values suggests that the predictive model used in the control design process is accurate and capable of generating reliable results.

6.4.2 Simplification of the regression equation

The Pareto chart was used to provide valuable insights into the relative significance and impact of the most influential terms considered in the prediction of CS. The identified key influential terms from the Pareto chart help reduce the number of terms in a mathematical formula for predicting CS. The resulting adjusted/simplified formula included four key variables: LQRA, W/C ratio, FA, and RCA. The coefficients associated with each term provided insights into their impact on CS. Higher proportions of LQRA and FA had opposing effects, with LQRA decreasing CS and FA increasing it. Similarly, a higher W/C ratio negatively affected CS, while RCA had a slight negative impact.

The streamlined formula allows for estimating CS by inputting specific values for the variables. However, it is noted that the applicability of the model is specific to the study's dataset and context.

6.5 Prediction by Artificial Neural Network (ANN)

Due to its reliance on data fitting rather than a clear physical understanding, the linear regression model may lack applicability and robustness. Developing a physically meaningful model becomes challenging when considering linear trends and multiple variables, as demonstrated in sections 5.1-5.4. As an alternative, this study explores and tests a data-driven approach using Artificial Neural Networks (ANN) to create a predictive model for CS.

Based on 39 data points from the experiments, an ANN model for CS prediction is developed. From the results of the ANN prediction based on four different input sets of variables, it is shown that the ANN prediction based on the input set of the four variables, i.e., LQRA, W/C, FA, and RCA, yields the most accurate predictions. Conversely, the variable brick content shows less importance, and its inclusion in the model may even lead to a decrease in prediction accuracy. Therefore, within the considered variable ranges of this work, the four variables (i.e., LQRA, W/C, FA, and RCA) are deemed crucial for assessing CS, while the influence of brick is less important.

6.6 Main findings

The main findings of the study on the fresh properties of RAC show that the dosage of superplasticizers varies based on the percentage of RCA used. Besides, the inclusion of FA as a filler improved workability without modifying the superplasticizers dosage. The AC of RAC increased with higher RCA incorporation but decreased significantly with the addition of FA. The recommended casting procedure proved its applicability on a lab-scale, achieving the desired workability for all concrete mixtures.

The results of the predictive model show that as the content of LQRA increases, the CS decreases, regardless of the W/C ratio. According to existing research (Martín-Morales et al., 2011), an increase in the percentage of ARM in RAC led to a decrease in the resulting concrete's CS. In addition, controlling the content of LQRA for mixtures carrying various percentages of RCA have a substantial impact on the CS of RAC.

The amount of brick presented in RAC depends on various variables such as the source of the RCA and the recycling technique utilized to obtain the RCA. The content of brick in RCA produced from selective demolition techniques was measured for different patches of RCA available in the Stevin-lab in TU Delft. The results showed that the maximum measured percentage of brick was 0.4%. The percentage was increased to 1% to make it critical for purposes of analysis.

In addition, the results showed that adding a small percentage of brick, up to 1%, does not significantly affect the CS of RAC. In general, the addition of brick to a concrete mix may impact the CS. However, the norm (CUR 1984) limits the maximum permissible percentage of brick contamination in RCA to 5%. In brief, the CS of RAC is not reduced when the brick content is limited to 1%. These results are in line with the findings of previous research (Jaskowska-Lemanska, 2019), in which it was mentioned that RAC containing up to 5% brick has barely lower CS compared to the reference mix of RAC with no brick.

In previous research, the impact of various variables on the CS of RAC has been explored individually or in combination with two or three variables. However, the present study takes a step further by investigating the most critical variables collectively within a semi-empirical semi-analytical model. The findings of this study revealed that four out of the five variables examined had a significant influence on the CS of RAC. Interestingly, it was observed that the content of brick in RAC, even up to 1%, did not exhibit any noticeable negative impact on the CS. This extended analysis provides valuable insights into the combined effects of multiple variables on the CS of RAC.

Employing ANN to develop a predictive model of CS is shown to be feasible. By comparing different input sets of variables on ANN prediction, it shows that the ANN prediction based on the input of four variables (i.e., LQRA, W/C, FA, and RCA) gives the highest accuracy, with an R^2 value of about 97%. Besides, it also provides the reassurance of the finding about the significant impacts of the four variables (i.e., LQRA, W/C, FA, and RCA) in predicting and obtaining desired outcomes of CS.

7. Conclusions and recommendations

This research aimed to develop a semi-empirical semi-analytical model based on the RSM approach for predicting the CS of RAC. Besides, it characterizes the quality of RCA based on the content of LQRA, SG, and WA. In addition, the research showed that proposing an optimized RAC mix design with enhanced fresh and hardened properties provides reliable CS of RAC. Finally, the study provides quantitative criteria for RAC use based on the LQRA content, W/C ratio, and the RCA's replacement ratio.

The following conclusions are drawn based on the results of the research:

1) The physical properties of RCA produced by selective demolition techniques are mainly affected by the LQRA content.

Selective demolition techniques minimize the content of impurities such as brick, wood, and gypsum. However, ARM is still present in large percentages. The higher the LQRA content, the higher the WA and the lower the SG values.

2) The reduction in CS of RAC is directly related to the amount of LQRA in RCA.

By categorizing the RCA into distinct types and conducting individual experiments on each one, a fresh understanding can be gained regarding the impact of ARM content on CS. The results of the research indicate that, as a rule, CS decreases as ARM content increases.

3) Combining FA with superplasticizers enhances the fresh properties of RAC.

The utilization of both the superplasticizers and FA can effectively improve the fresh characteristics of RAC, especially in mixtures comprising entirely of RCA. The superplasticizers and FA combination facilitates the regulation of AC and consistency for low W/C ratios and high proportions of LQRA. These findings underscore the capability of superplasticizers and FA for enhancing the workability of RAC.

4) The W/C ratio, RCA percentage, LQRA content, and FA content are crucial parameters that provide reliable mechanical behavior of RAC.

Several key parameters were identified as crucial for achieving a consistent CS in RAC. By carefully controlling these parameters, it is possible to achieve a consistent CS in RAC, which is essential for ensuring its suitability for use in construction applications. These findings highlight the importance of considering multiple variables when designing and producing RAC and guide for improving the quality of this sustainable building material.

5) RCA containing up to 1% brick does not negatively impact the CS of RAC.

The results of the study suggest that incorporating up to 1% brick in RAC does not have a negative impact on its CS. This indicates that the presence of brick up to 1% does not compromise the overall performance of the resulting RAC.

6) Casting procedure (Research vs. practice).

Laboratory research emphasizes stringent control measures to ensure the quality and consistency of the casting procedure. Every aspect of the process is carefully monitored and controlled to achieve reliable results. In contrast, the casting procedure in practice faces challenges in replicating the same level of control due to the mass production of concrete. This highlights the importance of bridging the gap between research and practice.

In this study, the mixing procedure for RAC was optimized through the conduct of trial mixtures and the incorporation of recommendations from a local concrete mixing center. The implemented casting procedure was found to be effective, efficient, and suitable for both laboratory and industrial-scale production, resulting in the desired workability for all concrete mixtures.

These findings have significant implications for practical applications, as the successful implementation of RAC in large-scale construction projects can be enabled. By developing casting procedures that can be adapted to mass production conditions, the feasibility and potential benefits of utilizing RAC in the construction industry can be realized.

7) Simplification of the mathematical formula using Pareto chart and model fitting regression

The implementation of a Pareto chart and fitting a regression model has proven to be a highly effective approach for reducing the number of terms in a regression formula (8). By analyzing the relationship between various variables and the CS, the Pareto chart allows for the identification of significant terms while disregarding insignificant terms. This process of feature selection helps to streamline the predictive model and focus on the most influential variables that contribute to CS. The subsequent fitting of a regression model through the data points further refines the formula by capturing the essential relationships and minimizing unnecessary complexity. This approach not only improves the physical interpretability of the model but also enhances its predictive accuracy. By reducing the number of terms through the integration of a Pareto chart and regression modelling, the resulting mathematical formula provides a more concise and reliable tool for predicting CS.

8) CS prediction using ANN

The utilization of ANN as a predictive model of CS has proved to be highly effective. The compelling results obtained from the ANN analysis, characterized by high R^2 values (e.g., 97%), demonstrated a robust alignment between the model and the data. The high R^2 values may also indicate the model's accuracy in predicting desired outcomes. By incorporating the ANN alongside the RSM-based approach, the reliability and applicability of the predictive model were further strengthened. The comparisons of different input sets of variables for ANN prediction indicate the significant impacts of the four variables (i.e., W/C ratio, RCA percentage, LQRA content, and FA content) on CS, which may serve as a validation of the overall reliability and effectiveness of the obtained findings, e.g., the conclusion (4) listed above.

The research questions are answered considering the results, observations, and conclusions as mentioned earlier.

1. What are the main parameters that affect the fresh and hardened properties of RAC and can help characterize the RCA?

The quality of RCA is largely determined by consistent recycling techniques and controlling the ARM content. When producing RAC with 50% to 100% RCA, the critical parameters for controlling the consistency, AC, and volumetric weight of the fresh mixture are the dosage of superplasticizers and the content of FA. The hardened properties of RAC are mainly influenced by the W/C ratio, the replacement ratio of RCA, and the content of LQRA. These findings underscore the importance of considering different parameters in the design and production of RAC to guarantee its quality and performance.

2. What is the impact of common contaminants on the CS of RAC?

Maintaining the percentage of brick in RCA below 1% does not result in a negative impact on the CS of RAC. However, when the percentage of brick contaminants increases, it leads to an increase in AC and WA of the RCA, while decreasing the hardened density of the resulting RAC. These findings highlight the importance of minimizing the amount of brick in RCA to enable maintaining appropriate levels of AC of RAC and WA of RCA.

3. What is the relationship between the critical parameters, including contaminants, which allow for predicting the CS of RAC?

The WA percentage, which comes from the amount of LQRA and contaminants in RCA, as well as the W/C ratio and RCA replacement ratio, are the most important parameters in predicting the CS of RAC. Moreover, adding FA for mixtures containing high percentages of RCA has a positive impact on the CS of RAC.

4. What are the quantitative criteria which can classify the use of RCA in RAC?

The use of RCA in RAC can be classified based on the percentage of RCA used in the RAC mixture. Additionally, the content of LQRA in RCA is another quantitative criterion that influences the classification of RCA in RAC. The study suggests that a quantitative criterion of 40-65% of LQRA can provide sufficient CS for mixtures containing up to 100% RCA.

Future recommendations for obtaining reliable results regarding the mechanical performance of the RAC and quality of the RCA are shown as follows:

1) Characterizing the effect of different contaminants on the CS of RAC.

When present in high percentages, wood and gypsum might negatively affect the CS of RAC. wood due to its high WA, and gypsum can negatively affect the setting time and hardening of the concrete, leading to reduced CS. In addition, gypsum can also cause the concrete to shrink during the hardening process, resulting in cracking and other structural defects. Furthermore, the presence of chloride and sulfate can significantly impact reinforced concrete. Chloride may cause steel corrosion, while sulfate can cause deleterious expansion of hardened concrete through its reaction with hydration products.

2) Examining the mechanical performance of RAC made with RCA produced by different recycling techniques.

The literature review revealed that the composition of RCA can impact the CS of RAC and that the composition of RCA is influenced by the recycling and treatment process. Therefore, further research is needed to investigate the impact of different recycling and treatment methods on the composition and physical properties of RCA. By exploring these variables, it may be possible to develop more effective and sustainable approaches to RCA production and improve the quality and performance of RAC in construction applications.

3) Investigating the effect of the RCA on the durability of RAC.

The presence of ARM in RCA can lead to a high porosity, which may increase the permeability of RAC and the risk of damage from freeze-and-thaw cycles. As such, it is important to carefully consider these variables when evaluating the suitability of RAC for use in severe exposure conditions and structural applications. By taking a holistic approach and examining these aspects in detail, it may be possible to identify strategies for optimizing the durability of RAC.

4) Developing a practical method to automate the sorting process of the composition of RCA.

While the hand-picking approach used in this study was effective for lab-scale purposes, it is not practical for large-scale applications due to time constraints and the need for greater efficiency and amounts of RCA. As such, there is a need for more innovative methods for classifying RCA composition, such as automated separation processes. By developing new and more efficient methods for RCA separation, it may be possible to increase the scalability and practicality of RAC production.

8. References

Abd Rashid, A. F., & Yusoff, S. (2015). A review of life cycle assessment method for building industry. *Renewable and Sustainable Energy Reviews*, *45*, 244–248.

Adamson, M., Razmjoo, A., & Poursaee, A. (2015). Durability of concrete incorporating crushed brick as coarse aggregate. *Construction and Building Materials*, *94*, 426–432.

Alyamac, K. E., Ghafari, E., & Ince, R. (2017). Development of eco-efficient self-compacting concrete with waste marble powder using the response surface method. *Journal of Cleaner Production*, *144*, 192–202.

Berndt, M. L. (2009). Properties of sustainable concrete containing fly ash, slag and recycled concrete aggregate. *Construction and Building Materials*, *23*(7), 2606–2613.

Betoniek Standard. (2014). *Betoniek, platform voor technologie en uitvoering van beton*. https://www.betoniek.nl/artikel/16/8-kalksteen

Box, G. E., Hunter, W. H., & Hunter, S. (1978). *Statistics for experimenters* (Vol. 664). John Wiley and sons New York.

Butler, L., West, J. S., & Tighe, S. L. (2013). Effect of recycled concrete coarse aggregate from multiple sources on the hardened properties of concrete with equivalent compressive strength. *Construction and Building Materials*, *47*, 1292–1301.

Cabrera-Madrid, J. A., Escalante-García, J. I., & Castro-Borges, P. (2016). Compressive strength of concretes with blast furnace slag. Re-visited state-of-the-art. *Revista AL-CONPAT*, *6*(1), 64–83.

Çakır, Ö., & Sofyanlı, Ö. Ö. (2015). Influence of silica fume on mechanical and physical properties of recycled aggregate concrete. *HBRC Journal*, *11*(2), 157–166.

Cenci, C. S., Tadeu, A., De Brito, J., & Veiga, R. (2021). A brief framework of construction and demolition waste composition in Portugal within the European context. *Proceedings of the CEES*.

Dahmoune, F., Remini, H., Dairi, S., Aoun, O., Moussi, K., Bouaoudia-Madi, N., Adjeroud, N., Kadri, N., Lefsih, K., Boughani, L., Mouni, L., Nayak, B., & Madani, K. (2015). Ultrasound assisted extraction of phenolic compounds from P. lentiscus L. leaves: Comparative study of artificial neural network (ANN) versus degree of experiment for prediction ability of phenolic compounds recovery. *Industrial Crops and Products*, *77*, 251–261. https://doi.org/10.1016/j.indcrop.2015.08.062

De Beer, J. O., Vandenbroucke, C. V., Massart, D., & De Spiegeleer, B. M. (1996). Half-fraction and full factorial designs versus central composite design for retention modelling in reversed-phase ion-pair liquid chromatography. *Journal of Pharmaceutical and Biomedical Analysis*, *14*(5), 525–541.

de Boer, B. F., Rietveld, E., Rodrigues, J. F., & Tukker, A. (2021). Global environmental and socio-economic impacts of a transition to a circular economy in metal and electrical products: A Dutch case study. *Journal of Industrial Ecology*, *25*(5), 1264–1271.

Debieb, F., & Kenai, S. (2008). The use of coarse and fine crushed bricks as aggregate in concrete. *Construction and Building Materials*, *22*(5), 886–893.

Deng, X. H. (2005). Study on effect of compressive strength of recycled aggregate concrete with water cement ratio. *Concrete*, *2*, 46–48.

Di Maio, F. (2012). *Cement and clean aggregates from CDW: the C2CA project*. http://www.c2ca.eu/publications/news-item-2/

Etxeberria, M., Vázquez, E., Marí, A., & Barra, M. (2007). Influence of amount of recycled coarse aggregates and production process on properties of recycled aggregate concrete. *Cement and Concrete Research*, *37*(5), 735–742.

Fatemi, S., Varkani, M. K., Ranjbar, Z., & Bastani, S. (2006). Optimization of the water-based road-marking paint by experimental design, mixture method. *Progress in Organic Coatings*, *55*(4), 337–344.

Fathifazl, G., Abbas, A., Razaqpur, A. G., Isgor, O. B., Fournier, B., & Foo, S. (2009). New mixture proportioning method for concrete made with coarse recycled concrete aggregate. *Journal of Materials in Civil Engineering*, *21*(10), 601–611.

Gebremariam, A. T., Di Maio, F., Vahidi, A., & Rem, P. (2020). Innovative technologies for recycling End-of-Life concrete waste in the built environment. *Resources, Conservation and Recycling*, *163*, 104911.

Gesoğlu, M., Güneyisi, E., Kocabağ, M. E., Bayram, V., & Mermerdaş, K. (2012). Fresh and hardened characteristics of self compacting concretes made with combined use of marble powder, limestone filler, and fly ash. *Construction and Building Materials*, *37*, 160–170.

Ghafari, E., Costa, H., & Júlio, E. (2014). RSM-based model to predict the performance of self-compacting UHPC reinforced with hybrid steel micro-fibers. *Construction and Building Materials*, *66*, 375–383.

Gonçalves, P., & Brito, J. de. (2010). Recycled aggregate concrete (RAC)–comparative analysis of existing specifications. *Magazine of Concrete Research*, *62*(5), 339–346.

Güneyisi, E., Gesoğlu, M., Algın, Z., & Mermerdaş, K. (2014). Optimization of concrete mixture with hybrid blends of metakaolin and fly ash using response surface method. *Composites Part B: Engineering*, *60*, 707–715.

Halstead, W. J. (1986). Use of fly ash in concrete. *NCHRP Synthesis of Highway Practice*, *127*.

Haupt, M., Vadenbo, C., & Hellweg, S. (2017). Do we have the right performance indicators for the circular economy?: Insight into the Swiss waste management system. *Journal of Industrial Ecology*, *21*(3), 615–627.

Hong, J., Shen, G. Q., Feng, Y., Lau, W. S., & Mao, C. (2015). Greenhouse gas emissions during the construction phase of a building: A case study in China. *Journal of Cleaner Production*, *103*, 249–259.

Jaskowska-Lemanska, J. (2019). Impurities of recycled concrete aggregate-types, origin and influence on the concrete strength parameters. *IOP Conference Series: Materials Science and Engineering*, *603*(4), 042056.

Ju, M., Jeong, J.-G., Palou, M., & Park, K. (2020). Mechanical behavior of fine recycled concrete aggregate concrete with the mineral admixtures. *Materials*, *13*(10), 2264.

Kalhori, M., & Ramezanianpour, A. A. (2021). Innovative air entraining and air content measurement methods for roller compacted concrete in pavement applications. *Construction and Building Materials*, *279*, 122495.

Khalaf, F. M., & DeVenny, A. S. (2005). Properties of new and recycled clay brick aggregates for use in concrete. *Journal of Materials in Civil Engineering*, *17*(4), 456–464.

Kosmatka, S. H., & Wilson, M. L. (2011). Designing and proportioning concrete mixtures. *Design and Control of Concrete Mixtures, 15th Ed., Skokie, IL: Portland Cement Association*.

Kou, S.-C., & Poon, C.-S. (2013). Long-term mechanical and durability properties of recycled aggregate concrete prepared with the incorporation of fly ash. *Cement and Concrete Composites*, *37*, 12–19.

Kurda, R., de Brito, J., & Silvestre, J. D. (2017). Influence of recycled aggregates and high contents of fly ash on concrete fresh properties. *Cement and Concrete Composites*, *84*, 198–213.

Li, J. (2004). Study on mechanical behavior of recycled aggregate concrete. *Shanghai, Tongji University. Thesis, Master of Engineering*.

Limbachiya, M., Meddah, M. S., & Ouchagour, Y. (2012). Use of recycled concrete aggregate in fly-ash concrete. *Construction and Building Materials*, *27*(1), 439–449.

Lotfi, S., Di Maio, F., Xia, H., Serranti, S., Palmieri, R., & Bonifazi, G. (2015). Assessment of the contaminants level in recycled aggregates and alternative new technologies for contaminants recognition and removal. *EMABM 2015: Proceedings of the 15th Euroseminar on Microscopy Applied to Building Materials, Delft, The Netherlands, 17-19 June 2015*.

Lotfi, S., Rem, P., Di Maio, F., Teklay, A., Hu, M., van Roekel, E., & van der Stelt, H. (2017). Closing the loop of EOL concrete. *HISER International Conference: Advances in Recycling and Management of Construction and Demolition Waste*, 83–91.

Lothenbach, B., Scrivener, K., & Hooton, R. D. (2011). Supplementary cementitious materials. *Cement and Concrete Research*, *41*(12), 1244–1256.

Majhi, R. K., & Nayak, A. N. (2020). Production of sustainable concrete utilising high-volume blast furnace slag and recycled aggregate with lime activator. *Journal of Cleaner Production*, *255*, 120188.

Maran, J. P., Manikandan, S., Nivetha, C. V., & Dinesh, R. (2017). Ultrasound assisted extraction of bioactive compounds from Nephelium lappaceum L. fruit peel using central composite face centered response surface design. *Arabian Journal of Chemistry*, *10*, S1145–S1157.

Marinković, S., Radonjanin, V., Malešev, M., & Ignjatović, I. (2010). Comparative environmental assessment of natural and recycled aggregate concrete. *Waste Management*, *30*(11), 2255–2264.

Martín-Morales, M., Zamorano, M., Ruiz-Moyano, A., & Valverde-Espinosa, I. (2011). Characterization of recycled aggregates construction and demolition waste for concrete production following the Spanish Structural Concrete Code EHE-08. *Construction and Building Materials*, *25*(2), 742–748.

Medina, C., Zhu, W., Howind, T., de Rojas, M. I. S., & Frías, M. (2014). Influence of mixed recycled aggregate on the physical–mechanical properties of recycled concrete. *Journal of Cleaner Production*, *68*, 216–225.

Menegaki, M., & Damigos, D. (2018). A review on current situation and challenges of construction and demolition waste management. *Current Opinion in Green and Sustainable Chemistry*, *13*, 8–15.

Meyer, C. (2004). Concrete materials and sustainable development in the USA. *Structural Engineering International*, *14*(3), 203–207.

Müller, C. (1998). Requirements on concrete for future recycling. *Sustainable Construction: Use of Recycled Concrete Aggregate: Proceedings of the International Symposium Organised by the Concrete Technology Unit, University of Dundee and Held at the Department of Trade and Industry Conference Centre, London, UK on 11–12 November 1998*, 445–457.

Müller, C. (2012). Use of cement in concrete according to European standard EN 206-1. *HBRC Journal*, *8*(1), 1–7.

Naderpour, H., Rafiean, A. H., & Fakharian, P. (2018). Compressive strength prediction of environmentally friendly concrete using artificial neural networks. *Journal of Building Engineering*, *16*, 213–219.

Ni, H.-G., & Wang, J.-Z. (2000). Prediction of compressive strength of concrete by neural networks. *Cement and Concrete Research*, *30*(8), 1245–1250.

Nkinamubanzi, P.-C., Mantellato, S., & Flatt, R. J. (2016). Superplasticizers in practice. In *Science and technology of concrete admixtures* (pp. 353–377). Elsevier.

Otsuki, N., Miyazato, S., & Yodsudjai, W. (2003). Influence of recycled aggregate on interfacial transition zone, strength, chloride penetration and carbonation of concrete. *Journal of Materials in Civil Engineering*, *15*(5), 443–451.

Ozbakkaloglu, T., Gholampour, A., & Xie, T. (2018). Mechanical and durability properties of recycled aggregate concrete: Effect of recycled aggregate properties and content. *Journal of Materials in Civil Engineering*, *30*(2), 04017275.

Pellegrino, C., Faleschini, F., Pellegrino, C., & Faleschini, F. (2016). Recycled Aggregates for Concrete Production: State-of-the-Art. *Sustainability Improvements in the Concrete Industry: Use of Recycled Materials for Structural Concrete Production*, 5–34.

Pietersen, H. S., Fraay, A. L., & Hendriks, C. F. (1998). *Application of recycled aggregates in concrete–Experiences from the Netherlands*.

Poon, C. S., Shui, Z. H., & Lam, L. (2004). Effect of microstructure of ITZ on compressive strength of concrete prepared with recycled aggregates. *Construction and Building Materials*, *18*(6), 461–468.

Poon, C.-S., & Chan, D. (2007). Effects of contaminants on the properties of concrete paving blocks prepared with recycled concrete aggregates. *Construction and Building Materials*, *21*(1), 164–175.

Shaban, W. M., Yang, J., Su, H., Mo, K. H., Li, L., & Xie, J. (2019). Quality Improvement Techniques for Recycled Concrete Aggregate: A review. *Journal of Advanced Concrete Technology*, *17*(4), 151–167. https://doi.org/10.3151/jact.17.151

Silva, R. V., De Brito, J., & Dhir, R. K. (2014). Properties and composition of recycled aggregates from construction and demolition waste suitable for concrete production. *Construction and Building Materials*, *65*, 201–217.

Somna, R., Jaturapitakkul, C., Chalee, W., & Rattanachu, P. (2012). Effect of the water to binder ratio and ground fly ash on properties of recycled aggregate concrete. *Journal of Materials in Civil Engineering*, *24*(1), 16–22.

Song, H., Ahmad, A., Farooq, F., Ostrowski, K. A., Maślak, M., Czarnecki, S., & Aslam, F. (2021). Predicting the compressive strength of concrete with fly ash admixture using machine learning algorithms. *Construction and Building Materials*, *308*, 125021.

Suhendro, B. (2014). Toward green concrete for better sustainable environment. *Procedia Engineering*, *95*, 305–320.

Tam, V. W., Gao, X. F., & Tam, C. M. (2005). Microstructural analysis of recycled aggregate concrete produced from two-stage mixing approach. *Cement and Concrete Research*, *35*(6), 1195–1203.

Tam, V. W., Soomro, M., & Evangelista, A. C. J. (2018). A review of recycled aggregate in concrete applications (2000–2017). *Construction and Building Materials*, *172*, 272–292.

Tošić, N., Torrenti, J. M., Sedran, T., & Ignjatović, I. (2021). Toward a codified design of recycled aggregate concrete structures: Background for the new fib Model Code 2020 and Eurocode 2. *Structural Concrete*, *22*(5), 2916–2938.

Tovar-Rodríguez, G., Barra, M., Pialarissi, S., Aponte, D., & Vázquez, E. (2013). Expansion of mortars with gypsum contaminated fine recycled aggregates. *Construction and Building Materials*, *38*, 1211–1220.

Ulloa, V. A., García-Taengua, E., Pelufo, M.-J., Domingo, A., & Serna, P. (2013). New views on effect of recycled aggregates on concrete compressive strength. *ACI Mater. J*, *110*(6), 687–696.

Verian, K. P., Ashraf, W., & Cao, Y. (2018). Properties of recycled concrete aggregate and their influence in new concrete production. *Resources, Conservation and Recycling*, *133*, 30–49.

Xiao, J., Li, J., Sun, Z., & Hao, X. (2004). Study on compressive strength of recycled aggregate concrete. *Tongji Daxue Xuebao/Journal of Tongji University*, 1558–1561.

Xiao, J., Li, W., Fan, Y., & Huang, X. (2012). An overview of study on recycled aggregate concrete in China (1996–2011). *Construction and Building Materials*, *31*, 364–383.

Xiao, J., Li, W., & Poon, C. (2012). Recent studies on mechanical properties of recycled aggregate concrete in China—A review. *Science China Technological Sciences*, *55*(6), 1463–1480. https://doi.org/10.1007/s11431-012-4786-9

Xiao, J. Z., Liu, Q., Li, W. G., & Tam, V. (2009). On the micro-and meso-structure and failure mechanism of recycled concrete. *Journal of Qingdao Technological University*, *30*(4), 24–30.

Zhang, C., Hu, M., Di Maio, F., Sprecher, B., Yang, X., & Tukker, A. (2022). An overview of the waste hierarchy framework for analyzing the circularity in construction and demolition waste management in Europe. *Science of The Total Environment*, *803*, 149892. https://doi.org/10.1016/j.scitotenv.2021.149892

Zhang, C., Hu, M., Yang, X., Miranda-Xicotencatl, B., Sprecher, B., Di Maio, F., Zhong, X., & Tukker, A. (2020). Upgrading construction and demolition waste management from downcycling to recycling in the Netherlands. *Journal of Cleaner Production*, *266*, 121718.

9. Appendixes

Appendix A: Superplasticiser specification

TECHNISCHE FICHE
Sika® ViscoCrete®-1550 Con30%

SUPERPLASTIFICEERDER, STERK WATERREDUCEERDER, WATERDICHTINGSMIDDEL IN DE MASSA

NBN EN 934-2 BENOR 12/54

PRODUCTBESCHRIJVING

Sika® ViscoCrete®-1550 Con30% is een super plastificeerder, sterke water-reduceerder, waterdichtingsmiddel in de massa van de laatste generatie.

TOEPASSINGEN

Sika® ViscoCrete®-1550 Con30% wordt aanbevolen voor beton dat geproduceerd wordt in de betoncentrale.

Dankzij de zeer sterke watervermindering, de uitstekende vloeibaarheid gecombineerd met een sterke cohesie en dank zij de zelfverdichtende kenmerken, wordt Sika® ViscoCrete®-1550 Con30% toegepast bij de volgende beton types:

- zelfverdichtend beton (SCC),
- beton met zwak W/C gehalte,
- beton met hoge weerstand op lange termijn,
- beton met een lang rheologie behoud,
- waterdichtbeton.

Sika® ViscoCrete®-1550 Con30% kan gebruikt worden met andere hulpstoffen (ons raadplegen).

Wij bevelen Sika® ViscoCrete®-1550 Con30% niet aan voor de productie van gepolijst beton.

EIGENSCHAPPEN / VOORDELEN

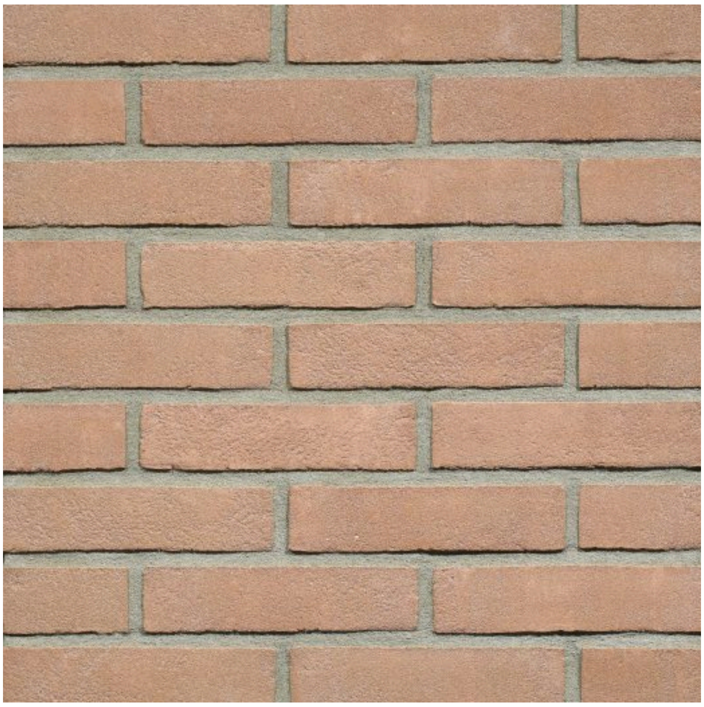
Sika® ViscoCrete®-1550 Con30% reageert door middel van verschillende mechanismen. Zijn actie bevindt zich op het absorberend oppervlak van de cementkorrel en de afscheiding van elk van deze korrels. Het beïnvloedt eveneens het hydratatie proces.

Dankzij deze eigenschappen, bekomt men volgende resultaten:

- zelfverdichtend gedrag,
- zeer sterke waterreduceerder,
- zeer grote vloeibaarheid,
- lang behoud van de rheologie,
- verhoogt sterk de waterdichtheid,
- vermindert de snelheid van de carbonatatie van beton.

Sika® ViscoCrete®-1550 Con30% bevat geen chloriden of andere producten die de corrosie van staal bevordert. Kan eveneens gebruikt worden zonder beperkingen wat betreft gewapend en voorgespannen beton.

Appendix B: Recycled Brick properties



Productnaam	**Euroa VB WF**
Productiemethode	**Vormbak**
Formaat	**Waalformaat**
Productielocatie	**Erlecom**
Artikelnummer	**11410700**
Toepassingsvoorwaarden	**Dient te worden verwerkt overeenkomstig de geldende richtlijnen van Wienerberger.**

Productinformatie

Afmetingen en toleranties (volgens EN 772-16 - EN 771-1)	
Gedeclareerde afmeting (L x B x H) in mm	+/- 211 x 101 x 50
Maattolerantie	T2
Maatspreiding	R1
Fysische eigenschappen (volgens EN 771-1)	
IW klasse	IW3
Initiële wateropneming	1 - 5 kg/m²*min
Vrijwillige wateropneming	20 massa %
Bruto droge volumieke massa	1600 kg/m³
Gehalte actieve oplosbare zouten	S2

Druksterkte (volgens EN 771-1)	
Gemiddelde druksterkte loodrecht op het legvlak	≥ 35 N/mm²
Vorstbestandheid (volgens EN 772-22)	
Klasse vorstbestendigheid	F2
Overige eigenschappen	
Gewicht per stuk	1.848 kg
Thermische geleiding, λ 10, droge steen	0,410 W/m*K
Brandreactie - klasse	A1
Vochtwerende behandeling	Nee

Informatie

Wienerberger - Verkoop Terca gevelbakstenen| T 088 - 118 55 00 | F 088 - 118 50 55 | verkoop.gevel@wienerberger.com
Productpagina: https://wienerberger.nl/11410700 Bezoek www.wienerberger.nl voor online services, downloads en referenties.

Appendix C: Fly Ash Specification

PRESTATIEVERKLARING
POEDERKOOLVLIEGAS VOLGENS NEN-EN 450-1 (cat. A)

EFA-Füller® MR 3 A-01102018

1. Unieke identificatiecode van het producttype

Poederkoolvliegas voor toepassing als type II vulstof in beton, mortel en grout, in overeenstemming met NEN EN 450-1: 2012

2. Type-, partij- of serienummer, dan wel een ander identificatiemiddel voor het bouwproduct, zoals voorgeschreven in artikel 11, lid 4:

Zie afleverdocument: productnaam, verladingsdatum, transportnummer

3. Beoogde gebruiken van het bouwproduct, overeenkomstig de toepasselijke geharmoniseerde technische specificatie, zoals door de fabrikant bepaald:

Toevoeging voor de productie van beton in overeenstemming met NEN EN 206-1, en voor gebruik in mortel en grout

4. Naam, geregistreerde handelsnaam of geregistreerd handelsmerk en contactadres van de fabrikant, zoals voorgeschreven in artikel 11, lid 5:

Uniper Benelux NV Coloradoweg 10 3199 LA Maasvlakte RT

5. Indien van toepassing, naam en contactadres van de gemachtigde wiens mandaat de in artikel 12, lid 2, vermelde taken bestrijkt:

Niet van toepassing

6. Het systeem of de systemen voor de beoordeling en verificatie van de prestatiebestendigheid van het bouwproduct, vermeld in bijlage V:

Systeem 1+

7. Activiteit van de aangemelde certificatie-instantie zoals vereist in de geharmoniseerde norm: Kiwa Nederland B.V., identificatienummer 0956, heeft onder systeem 1+ de volgende taken uitgevoerd:
   - de initiële inspectie van de productie-installatie en van de productiecontrole in de fabriek;
   - permanente bewaking, beoordeling en evaluatie van de productiecontrole in de fabriek;
   - steekproefsgewijze controle van monsters voordat het product in de handel wordt gebracht.

   en heeft hiervoor een certificaat van prestatiebestendigheid verstrekt met nr.: 0956-CPR-1306.

8. Indien de prestatieverklaring betrekking heeft op een bouwproduct waarvoor een Europese technische beoordeling is afgegeven:

Niet van toepassing

9. Aangegeven prestatie

Essentiële kenmerken	**Prestaties**	**Geharmoniseerde technische specificaties**
Gloeiverlies	≤ 5,0 % categorie A	NEN-EN 450-1:2012
Chloride (Cl)	≤ 0,10 %	
Sulfaatgehalte (SO_3)	≤ 3,0 %	
Vrij calciumoxide (CaO vrij)	≤ 1,5 % [1)]	
Reactief CaO (als totaal CaO)	≤ 10 %	
Reactief SiO_2	≥ 25 %	
Som van de gehalten SiO_2, Al_2O_3 and Fe_2O_3	≥ 70 %	
Totaal alkaliën (Na_2O-eq)	≤ 5,0 %	
Magnesiumoxide (MgO)	≤ 4,0 %	
Oplosbaar fosfaat (P_2O_5 oplosbaar)	≤ 100 mg/kg	
Totaal fosfaat (P_2O_5 totaal)	≤ 5,0 %	
Fijnheid > 45 micron	22 ± 10 % categorie N	
Activiteit index	Na 28 dagen: ≥ 75 % Na 90 dagen: ≥ 85 %	
Vormhoudendheid: expansie	≤ 10 mm [1)]	
Volumieke massa	2300 ± 200 kg /m^3	
Begin binding: verschil tussen een cementpasta en een cement/vlieg-as pasta	Maximaal twee maal de tijd nodig voor de begin binding van de 100 % (m/m) cementpasta	
Duurzaamheid	NPD [2)]	
Vrijkomen van gevaarlijke bestanddelen of vrijkomen van straling	NPD [3)]	

1) Indien CaO vrij ≤ 1,5% dan wordt aan de eis van vormhoudendheid voldaan. Indien CaO vrij > 1,5% dan wordt aan de eis van CaO vrij voldaan indien de vormhoudendheid ≤ 10 mm. (5.2.5 en 5.3.3 van NEN-EN 450-1:2012).

2) De samenstelling en prestatie van de vliegas is dusdanig dat met deze vliegas duurzaam beton (zie NEN-EN 206-1) geproduceerd kan worden.

3) Vliegas bevat geen componenten die, wanneer zij vrijkomen uit beton, risicovol zijn voor gezondheid, hygiëne en het milieu. Overeenkomstig artikel 31 van de REACH verordening is geen aanvullende informatie noodzakelijk. Het product is geregistreerd en heeft geen gevaareigenschappen volgens CLP.

10. De prestaties van het in de punten 1 en 2 omschreven product zijn conform de in punt 9 aangegeven prestaties.

Deze prestatieverklaring wordt verstrekt onder de exclusieve verantwoordelijkheid van de in punt 4 vermelde fabrikant:

Ondertekend voor en namens de fabrikant door:

Maasvlakte, 1-10-2018

K. Stam
Manager Q&P – Uniper Benelux NV

Appendix D: Determining the Specific Gravity (SG) and Water Absorption (WA) of Coarse Aggregate (CA)

Standard: NEN-EN 1097-6

Required material: Balance, Thermostatically controlled oven, glass vessel, coarse aggregate, dry soft absorbent cloths.

<table>
<tr><th rowspan="2" colspan="2">Description</th><th colspan="2">Sample number</th></tr>
<tr><th>I</th><th>II</th></tr>
<tr><td colspan="2">5. Weight of sample (g)
6. Wight of vessel + sample + water (g) A
7. Weight of vessel + water (g) B
8. Weight of Saturated & Surface Dry Sample (g) C
9. Weight of Dry oven sample (g) D
10. Specific Gravity = [D/[C-(A-B)]]
11. Apparent Specific Gravity = [D/D-[A-B)]]
12. Water Absorption, Percentage Dry Weight (%) = [C-D/D]x100</td><td></td><td></td></tr>
<tr><td rowspan="3">Average Value:</td><td>Specific Gravity</td><td colspan="2"></td></tr>
<tr><td>App. Specific Gravity</td><td colspan="2"></td></tr>
<tr><td>Water absorption</td><td colspan="2"></td></tr>
</table>

Procedure:

- Weigh 1 kg of coarse aggregate
- Sieve the sample to 4mm sieve to remove the fines
- Place the sieved sample into the glass vessel
- Partly fill the vessel with distilled water
- Keep aggregates immersed for about 24 hrs, so that they are completely saturated
- At the end of soaking period, entrapped air is removed by gently agitation
- The vessel is then overfilled with water. Cover the vessel place ground plain glass disc. Make sure that no air is trapped in the vessel.
- Take the weight of the vessel assembly (A)
- Drain the vessel and place the aggregates on a dry cloth to assure surface dry conditions
- Refill the vessel with distilled water and cover it with glass disc. Make sure no air is trapped in the vessel
- Weigh the vessel assembly (B)
- Now, take the weight of surface dry aggregates (C)
- Place the aggregates into a tray and place then into an oven at 110 C. after 24 hrs remove the tray and cool the aggregates in an air tight container.
- Take the weight of the cooled oven dry aggregates (D)
- Then Calculate the Specific Gravity, App. Specific Gravity and water of absorption

Specific gravity: The ratio of the mass of a unit volume of a material to the mass of the same volume of water at stated temperatures (dimensionless). i.e., It is the ratio of the weight of aggregate in air to the weight of equal volume of water displaced by saturated surface dry aggregate.

Apparent Specific Gravity: The ratio of the weight in air of a unit volume of the impermeable portion of aggregate at a stated temperature to the weight in air of an equal volume of gas-free distilled water at a stated temperature.

Water Absorption: The increase in the weight of aggregates due to water in the pores of the material, but not including water adhering to the outside surface of particles expressed as a percentage of the dry weight.

Water absorption as percentage dry weight (%)

Appendix E: Sample preparation LAAT

2. Sample preparation:

Two samples of 5 kg of sieved aggregate (8-16 mm) are dried in an oven at 110 degrees for 4 hours. After drying, the exact weight is measured, corresponding to the selected grading see table 9.1, and the number of steel balls is determined. The sample is then placed in the rolling drum with the specified number of balls and set to 500 revolutions.

Table 9.1: LA abrasion range classifications.

Range classification (mm)	Intermediate sieve size (mm)	Percentage passing intermediate sieve (%)	Number of balls	Mass of ball load (g)
to 6.3	5	30-40	7	2930-3100
to 8	6.3	60-70	8	3410-3540
3-10	8	30-40	9	3840-3980
to 11.2	10	60-70	10	4250-4420
11.2-16	14	60-70	11	5120-5300

Appendix F: Design specifications

Step 1: Material choice

The material used for making the concrete mixtures are specified as follows:

- Cement type CEM III/B 42.5 N LH/SR.
- Water
- RCA 4-16mm
- Natural sand 0-4 mm
- FA
- SP

Step 2: water to cement ratio specifications

The W/C ratio can be determined according to this formula:

$$fcube = a + \text{Nn} + \frac{b}{wcf} - c$$

The parameters a, b, and C can be taken for the Eurocode NEN 8005 table 9.2.

Table 9.2: Design parameters (Çopuroğlu, O 2020) (Kosmatka & Wilson, 2011).

Cement	a	b	c
ENCI CEM I and CEM II/B-V	0.85	33	62
ENCI CEM III/A	0.8	25	45
ENCI CEM III/B	0.75	18	30

For cement type CEM III/B, the values are:

N_n= 51(Cement strength after 28-days)
a= 0.75
b=18
c= 30
w/c= 0.45
F_{cube}= 48.3 MPa (cube strength after 28-days)

The curing conditions of the cubes match with the environmental class XC3. From the NEN 8005, the following additional requirements are stated:

- Maximum W/C permissible = 0.55
- minimum cement content = 300 kg/m^3
All mix designs satisfy the requirements of the Eurocode NEN 8005.

Step 3: Water and cement binder specifications:

The needed water can be determined based on the maximum fraction, diameter, and slump value, see table 9.3. The bigger the particle the more water it absorbs. For a maximum fraction size is 16mm and desired consistency is F3 (plastic), the needed water is 170. this means that the cement content equals: 170/0.45 = 378 kg.

Table 9.3: Design area vs consistency values (Çopuroğlu, O 2020) [40]

Grootste zeefmaat (mm)	8		11,2		16		22,4		31,5	
Ontwerpgebied / Consistentie	I	II	I	II	I	II	I	II	I	II
Aardvochtig (zetmaat ≤ 40 mm, verdichtingsmaat 1,26)	165	185	160	180	155	175	150	170	145	165
Half plastisch (zetmaat 50 t/m 90 mm)	180	200	175	195	170	190	165	185	160	180
Plastisch (zetmaat 100 t/m 150 mm)	195	215	190	210	185	205	180	200	175	195

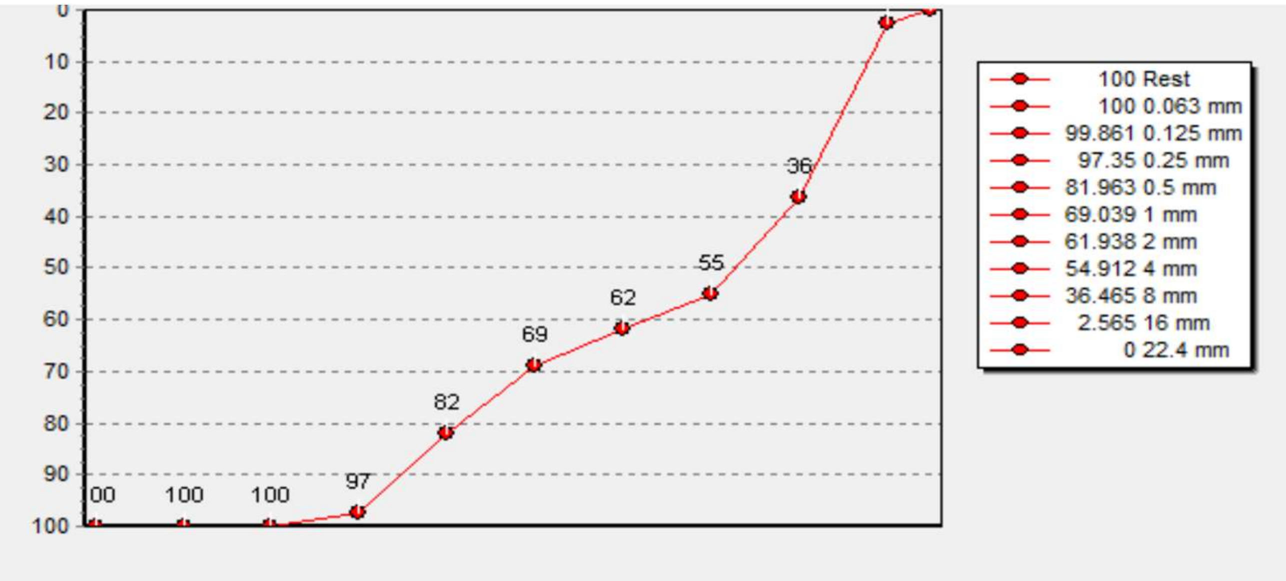
Appendix G: The list of utilized Recycled Aggregate Concrete (RAC) recipes

Recipe	11B

Water absorption of coarse aggregate	2,9%
stregth class	C30/37
Consistency	F4
Max Grain size	16
Water/cement ratio	0,54

Raw material	Description	Dosing mass
Cement	CEM III/B 42.5 N	321 kg
Fine fractions	Sand 0-4 mm	845 kg
Recycled aggregate	Gravel 4-22 mm	0 kg
Natural aggregate	Gravel 4-22 mm	1013 kg
Flyash	Vliegas EFA Füller MR-3 Cat A	0 kg
Superplasticizer	VC 1550 con. 30%	0,83 kg
Water	Tap water	129 kg
Air	-	20 L
Total	-	2308 kg

Sieving according to NEN 2560

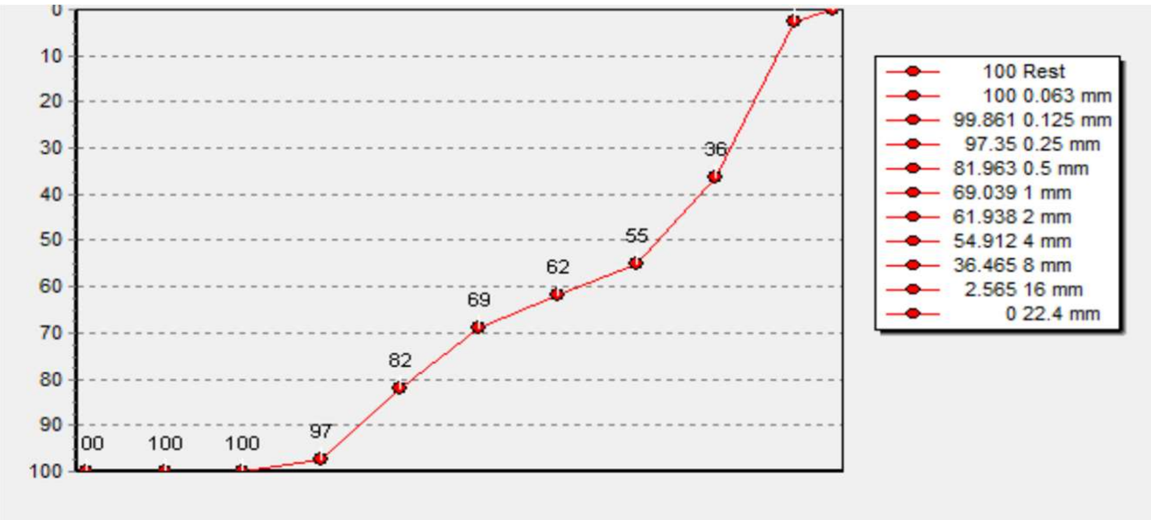


Recipe	1B

Water absorption of coarse aggregate	2,7%
stregth class	C30/37
Consistency	F4
Max Grain size	16
Water/cement ratio	0,45

Raw material	Description	Dosing mass
Cement	CEM III/B 42.5 N	368 kg
Fine fractions	Sand 0-4 mm	833 kg
Recycled aggregate	Gravel 4-22 mm	0 kg
Natural aggregate	Gravel 4-22 mm	1000 kg
Flyash	Vliegas EFA Füller MR-3 Cat A	0 kg
Superplasticizer	VC 1550 con. 30%	1,4 kg
Water	Tap water	122kg
Air	-	20 L
Total	-	2325 kg

Sieving according to NEN 2560

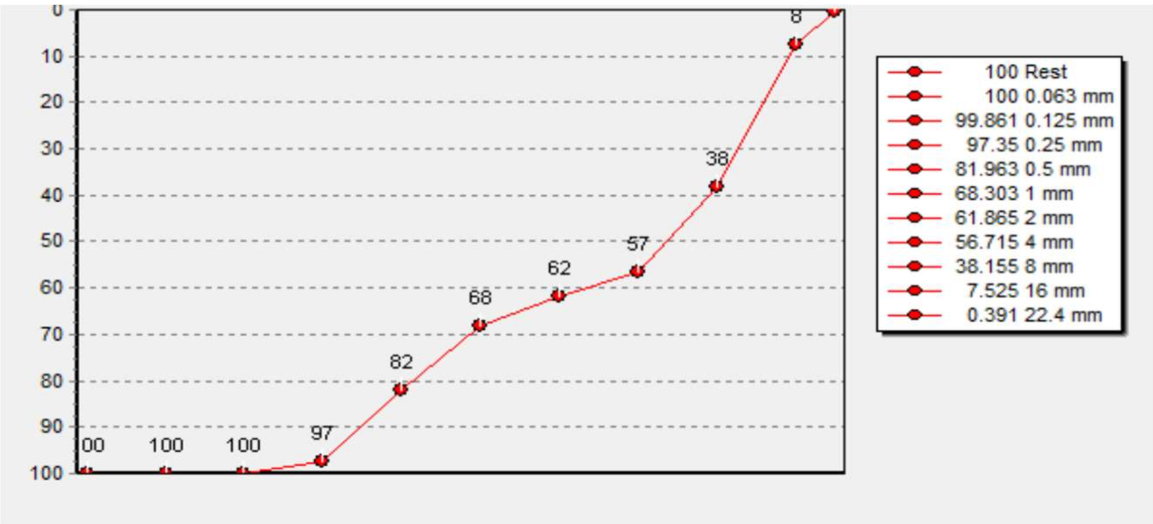


Recipe	14B

Water absorption of coarse aggregate	4,8%
stregth class	C30/37
Consistency	F4
Max Grain size	16
Water/cement ratio	0,54

Raw material	Description	Dosing mass
Cement	CEM III/B 42.5 N	317 kg
Fine fractions	Sand 0-4 mm	849 kg
Recycled aggregate	Gravel 4-22 mm	931 kg
Natural aggregate	Gravel 4-22 mm	0 kg
Flyash	Vliegas EFA Füller MR-3 Cat A	0 kg
Superplasticizer	VC 1550 con. 30%	0,82 kg
Water	Tap water	125 kg
Air	-	20 L
Total	-	2222 kg

Sieving according to NEN 2560

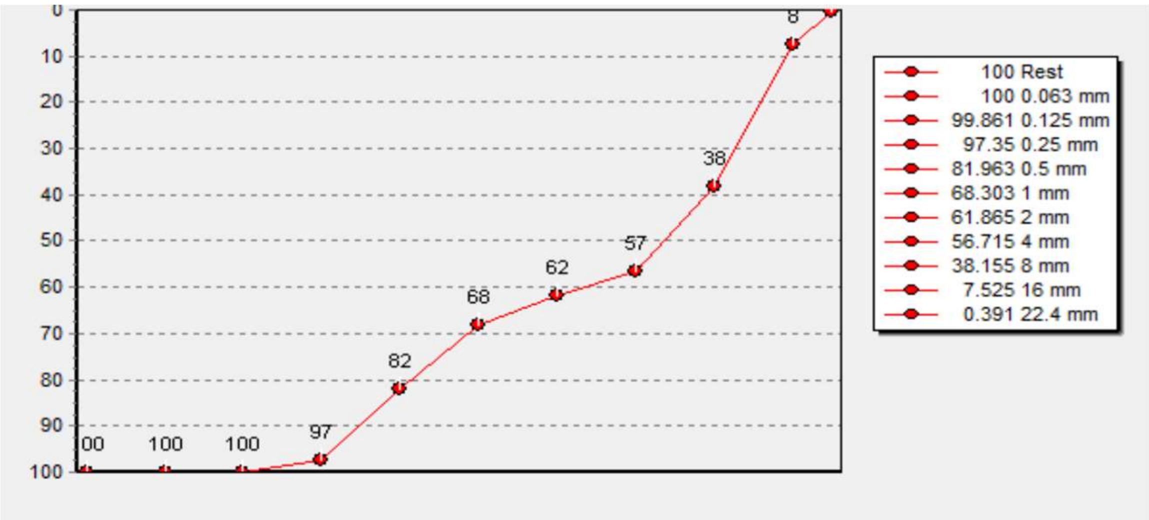


Recipe	14A

Brick content	1,0%
Water absorption of coarse aggregate	4,2%
stregth class	C30/37
Consistency	F4
Max Grain size	16
Water/cement ratio	0,54

Raw material	Description	Dosing mass
Cement	CEM III/B 42.5 N	317 kg
Fine fractions	Sand 0-4 mm	849 kg
Recycled aggregate	Gravel 4-22 mm	931 kg
Natural aggregate	Gravel 4-22 mm	0 kg
Flyash	Vliegas EFA Füller MR-3 Cat A	0 kg
Superplasticizer	VC 1550 con. 30%	0,82 kg
Water	Tap water	125 kg
Air	-	20 L
Total	-	2222 kg

Sieving according to NEN 2560

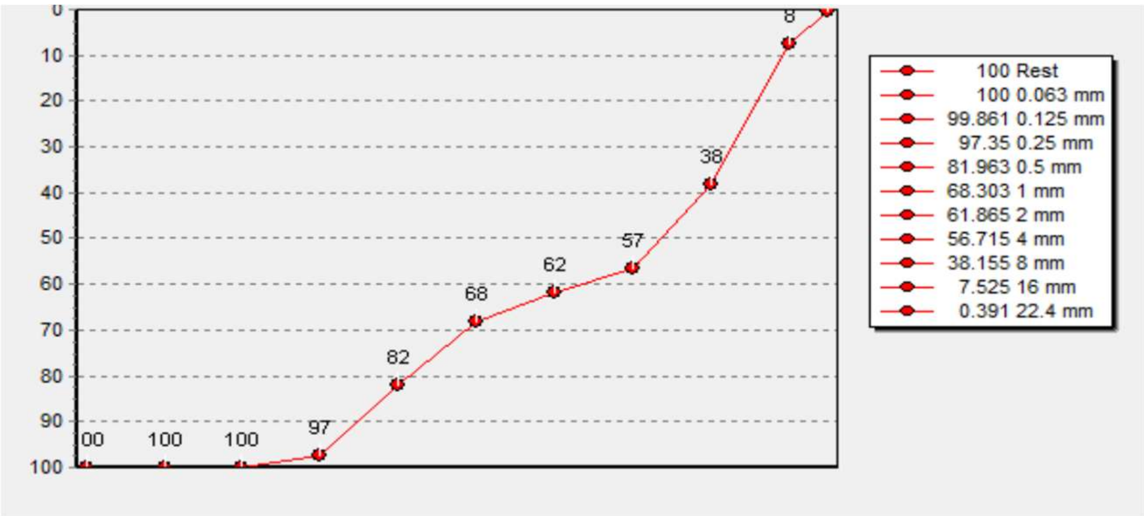


Recipe	5B

Water absorption of coarse aggregate	4,8%
stregth class	C30/37
Consistency	F4
Max Grain size	16
Water/cement ratio	0,45

Raw material	Description	Dosing mass
Cement	CEM III/B 42.5 N	363 kg
Fine fractions	Sand 0-4 mm	838 kg
Recycled aggregate	Gravel 4-22 mm	919 kg
Natural aggregate	Gravel 4-22 mm	0 kg
Flyash	Vliegas EFA Füller MR-3 Cat A	0 kg
Superplasticizer	VC 1550 con. 30%	1,45 kg
Water	Tap water	118 kg
Air	-	20 L
Total	-	2240 kg

Sieving according to NEN 2560

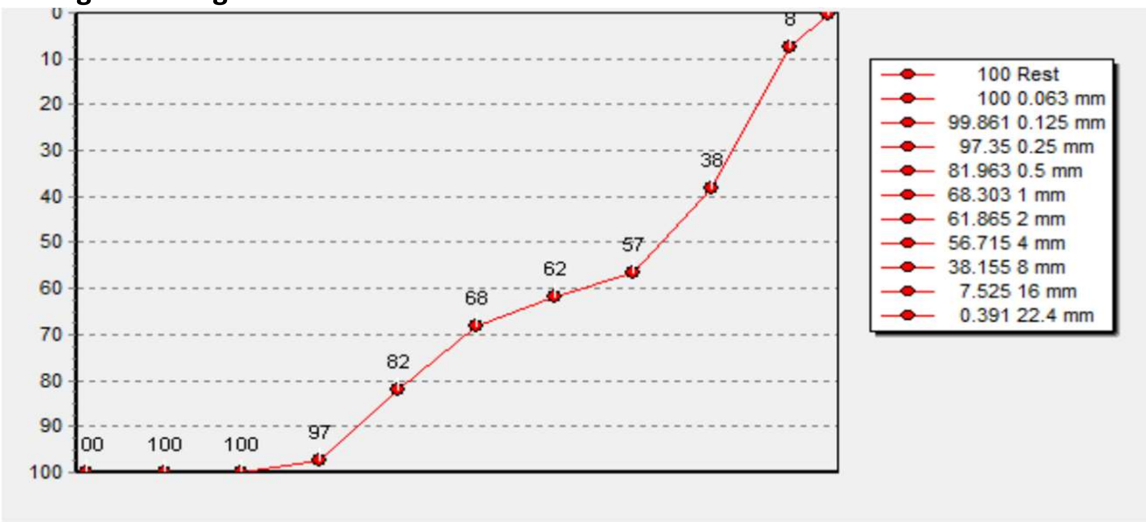


Recipe	15A

Water absorption of coarse aggregate	4%
stregth class	C30/37
Consistency	F4
Max Grain size	16
Water/cement ratio	0,54

Raw material	Description	Dosing mass
Cement	CEM III/B 42.5 N	309 kg
Fine fractions	Sand 0-4 mm	817 kg
Recycled aggregate	Gravel 4-22 mm	896 kg
Natural aggregate	Gravel 4-22 mm	0 kg
Flyash	Vliegas EFA Füller MR-3 Cat A	60 kg
Superplasticizer	VC 1550 con. 30%	0,74 kg
Water	Tap water	129 kg
Air	-	20 L
Total	-	2211 kg

Sieving according to NEN 2560

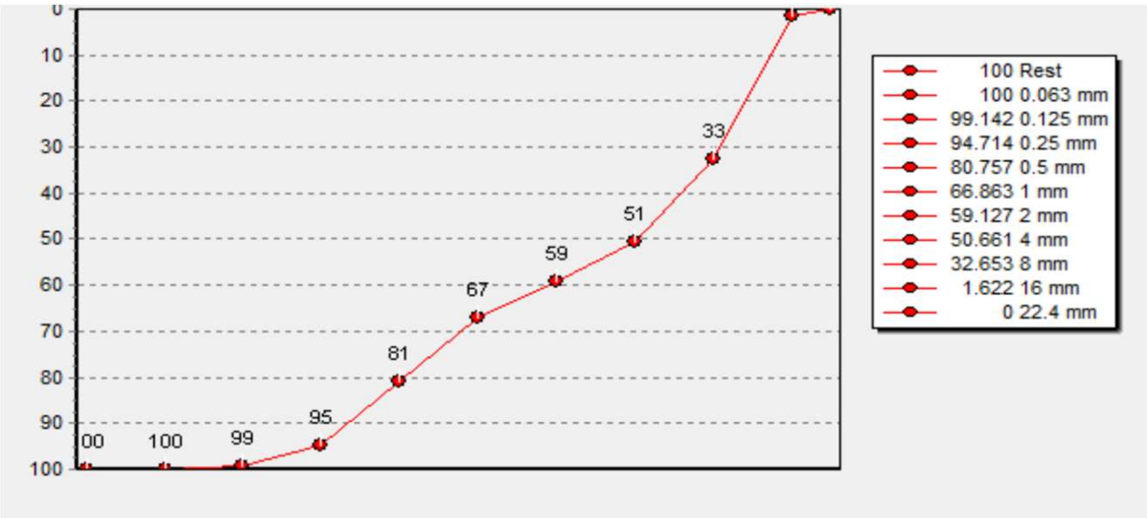


Recipe	12B

Water absorption of coarse aggregate	2,7%
stregth class	C30/37
Consistency	F4
Max Grain size	16
Water/cement ratio	0,54

Raw material	Description	Dosing mass
Cement	CEM III/B 42.5 N	313 kg
Fine fractions	Sand 0-4 mm	811 kg
Recycled aggregate	Gravel 4-22 mm	0 kg
Natural aggregate	Gravel 4-22 mm	972 kg
Flyash	Vliegas EFA Füller MR-3 Cat A	60 kg
Superplasticizer	VC 1550 con. 30%	0,75 kg
Water	Tap water	137 kg
Air	-	20 L
Total	-	2294 kg

Sieving according to NEN 2560

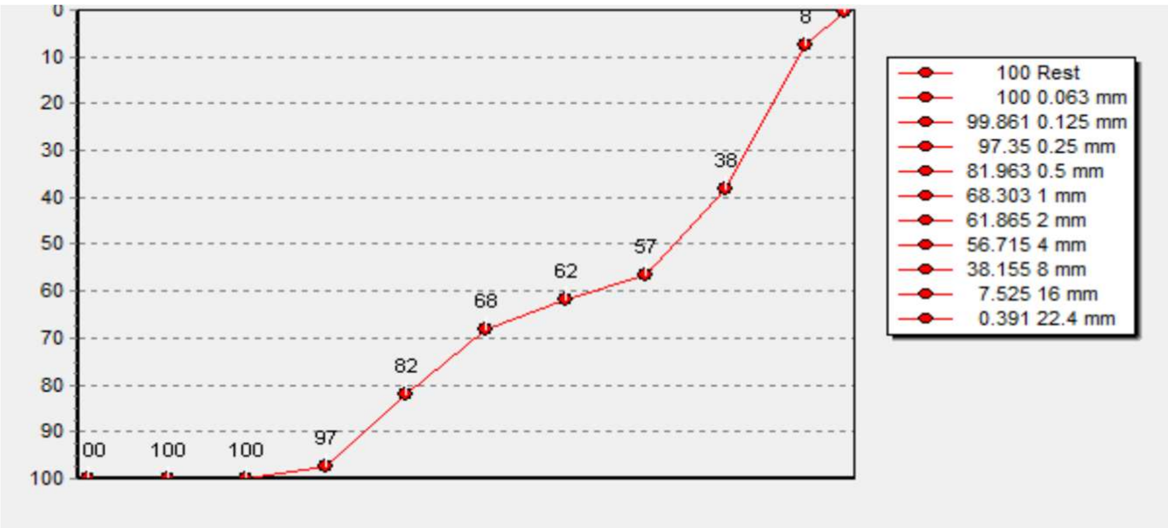


Recipe	5A

Brick content	1,0%
Water absorption of coarse aggregate	4,2%
stregth class	C30/37
Consistency	F4
Max Grain size	16
Water/cement ratio	0,45

Raw material	Description	Dosing mass
Cement	CEM III/B 42.5 N	362 kg
Fine fractions	Sand 0-4 mm	801 kg
Recycled aggregate	Gravel 4-22 mm	878 kg
Natural aggregate	Gravel 4-22 mm	0 kg
Flyash	Vliegas EFA Füller MR-3 Cat A	60 kg
Superplasticizer	VC 1550 con. 30%	1,23 kg
Water	Tap water	124 kg
Air	-	20 L
Total	-	2227 kg

Sieving according to NEN 2560

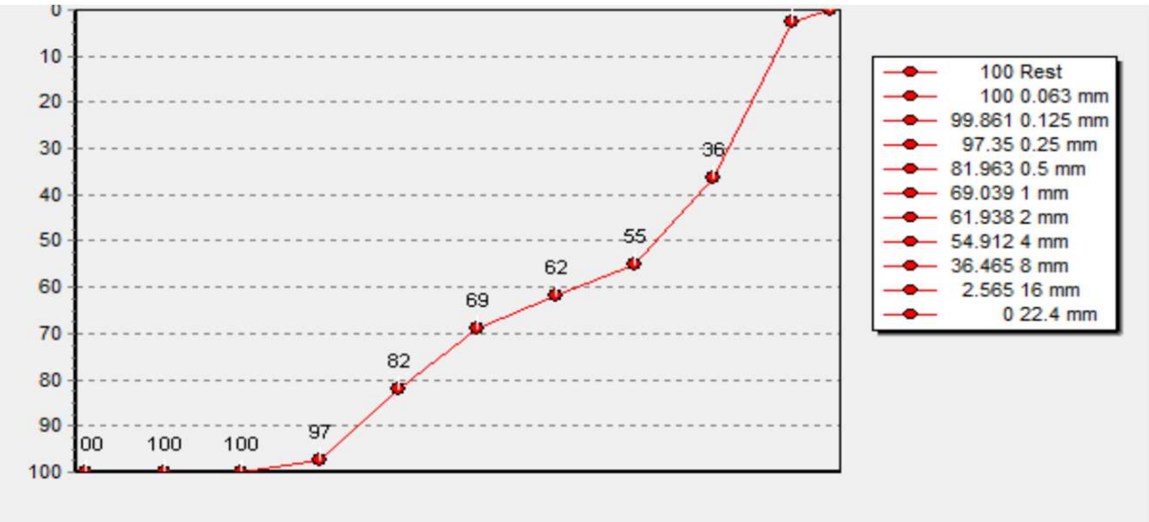


Recipe	2B

Brick content	1,0%
Water absorption of coarse aggregate	2,9%
stregth class	C30/37
Consistency	F4
Max Grain size	16
Water/cement ratio	0,45

Raw material	Description	Dosing mass
Cement	CEM III/B 42.5 N	362 kg
Fine fractions	Sand 0-4 mm	801 kg
Recycled aggregate	Gravel 4-22 mm	0 kg
Natural aggregate	Gravel 4-22 mm	960 kg
Flyash	Vliegas EFA Füller MR-3 Cat A	60 kg
Superplasticizer	VC 1550 con. 30%	1,35 kg
Water	Tap water	126 kg
Air	-	20 L
Total	-	2310 kg

Sieving according to NEN 2560

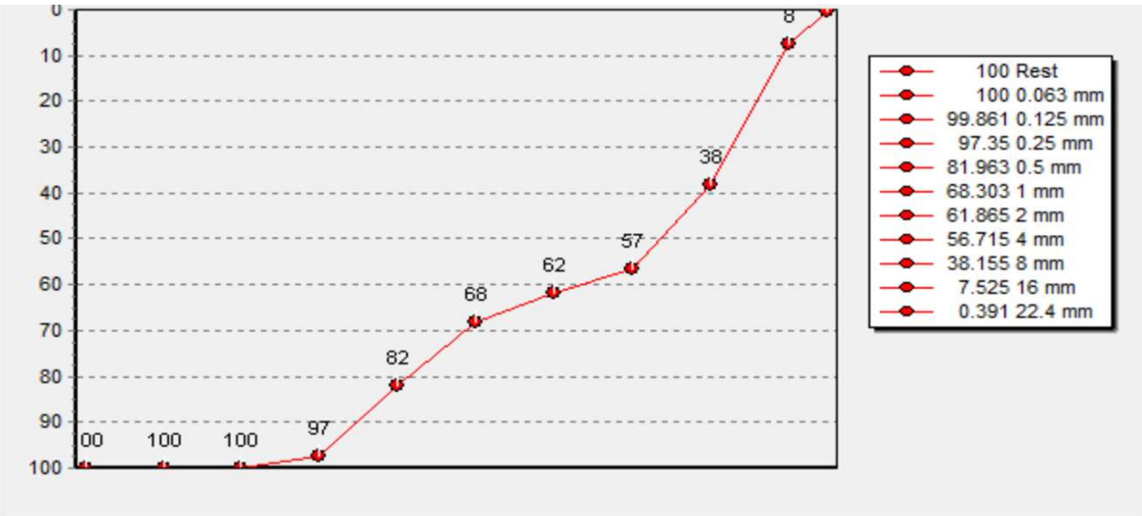


Recipe	15B

Brick content	1,0%
Water absorption of coarse aggregate	4,9%
stregth class	C30/37
Consistency	F4
Max Grain size	16
Water/cement ratio	0,54

Raw material	Description	Dosing mass
Cement	CEM III/B 42.5 N	309 kg
Fine fractions	Sand 0-4 mm	817 kg
Recycled aggregate	Gravel 4-22 mm	896 kg
Natural aggregate	Gravel 4-22 mm	0 kg
Flyash	Vliegas EFA Füller MR-3 Cat A	60 kg
Superplasticizer	VC 1550 con. 30%	0,74 kg
Water	Tap water	129 kg
Air	-	20 L
Total	-	2211 kg

Sieving according to NEN 2560

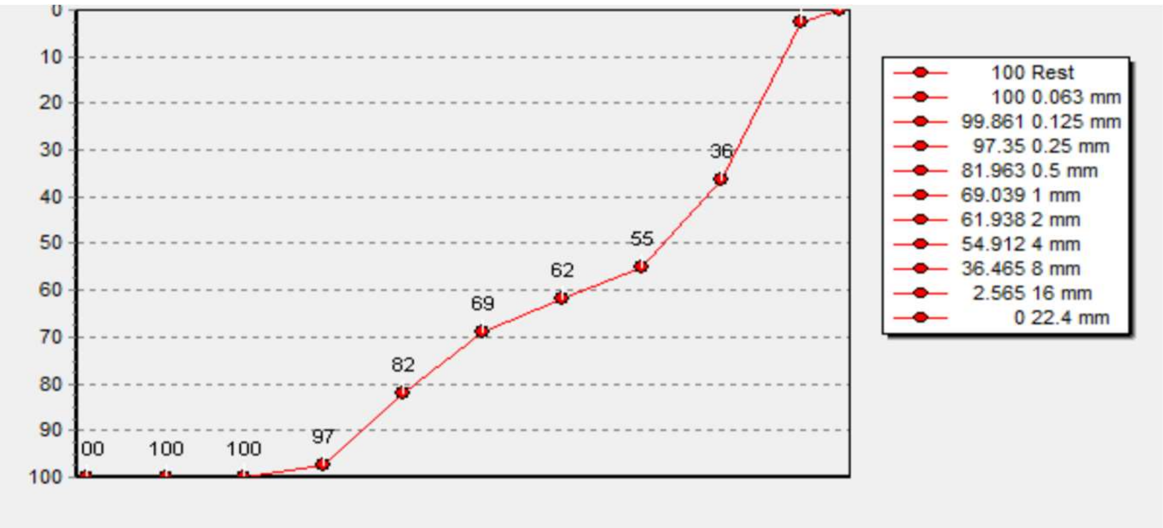


Recipe	6A

Brick content	0,5%
Water absorption of coarse aggregate	2%
stregth class	C30/37
Consistency	F4
Max Grain size	16
Water/cement ratio	0,49

Raw material	Description	Dosing mass
Cement	CEM III/B 42.5 N	346 kg
Fine fractions	Sand 0-4 mm	817 kg
Recycled aggregate	Gravel 4-22 mm	0 kg
Natural aggregate	Gravel 4-22 mm	980 kg
Flyash	Vliegas EFA Füller MR-3 Cat A	30 kg
Superplasticizer	VC 1550 con. 30%	0,92 kg
Water	Tap water	131 kg
Air	-	20 L
Total	-	2304 kg

Sieving according to NEN 2560

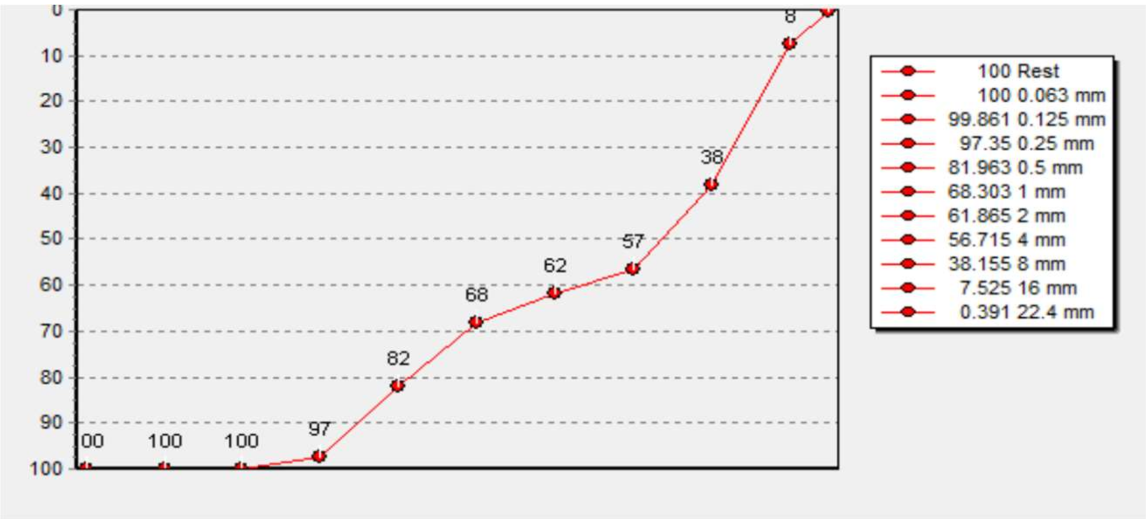


Recipe	10A

Brick content	0,5%
Water absorption of coarse aggregate	4,4%
stregth class	C30/37
Consistency	F4
Max Grain size	16
Water/cement ratio	0,49

Raw material	Description	Dosing mass
Cement	CEM III/B 42.5 N	342 kg
Fine fractions	Sand 0-4 mm	821 kg
Recycled aggregate	Gravel 4-22 mm	901 kg
Natural aggregate	Gravel 4-22 mm	0 kg
Flyash	Vliegas EFA Füller MR-3 Cat A	30 kg
Superplasticizer	VC 1550 con. 30%	0,91 kg
Water	Tap water	127 kg
Air	-	20 L
Total	-	2221 kg

Sieving according to NEN 2560

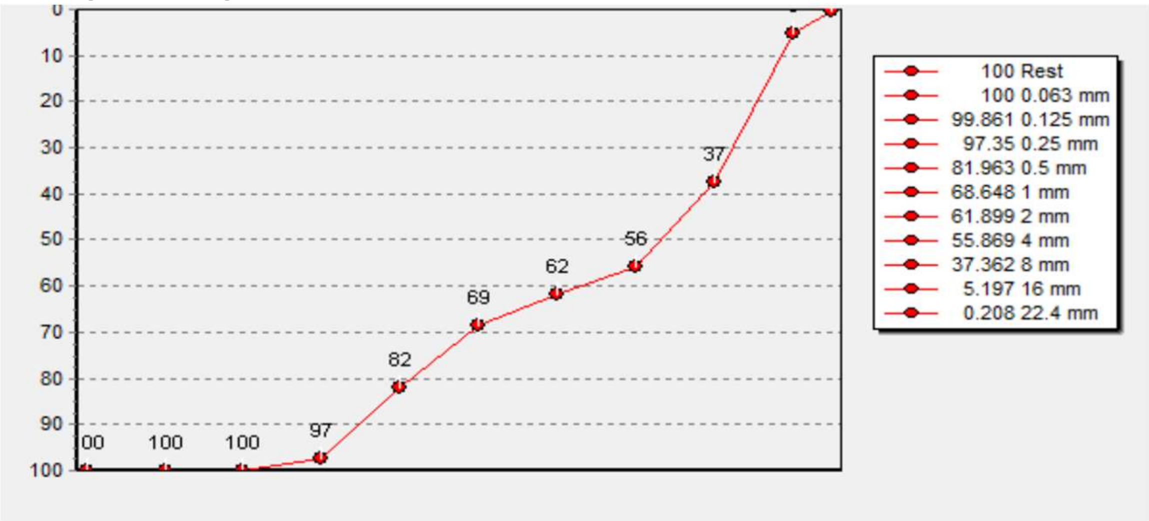


Recipe	8A

Brick content	0,5%
Water absorption of coarse aggregate	2,7%
stregth class	C30/37
Consistency	F4
Max Grain size	16
Water/cement ratio	0,49

Raw material	Description	Dosing mass
Cement	CEM III/B 42.5 N	344 kg
Fine fractions	Sand 0-4 mm	819 kg
Recycled aggregate	Gravel 4-22 mm	477 kg
Natural aggregate	Gravel 4-22 mm	461 kg
Flyash	Vliegas EFA Füller MR-3 Cat A	30 kg
Superplasticizer	VC 1550 con. 30%	0,91 kg
Water	Tap water	129 kg
Air	-	20 L
Total	-	2260 kg

Sieving according to NEN 2560

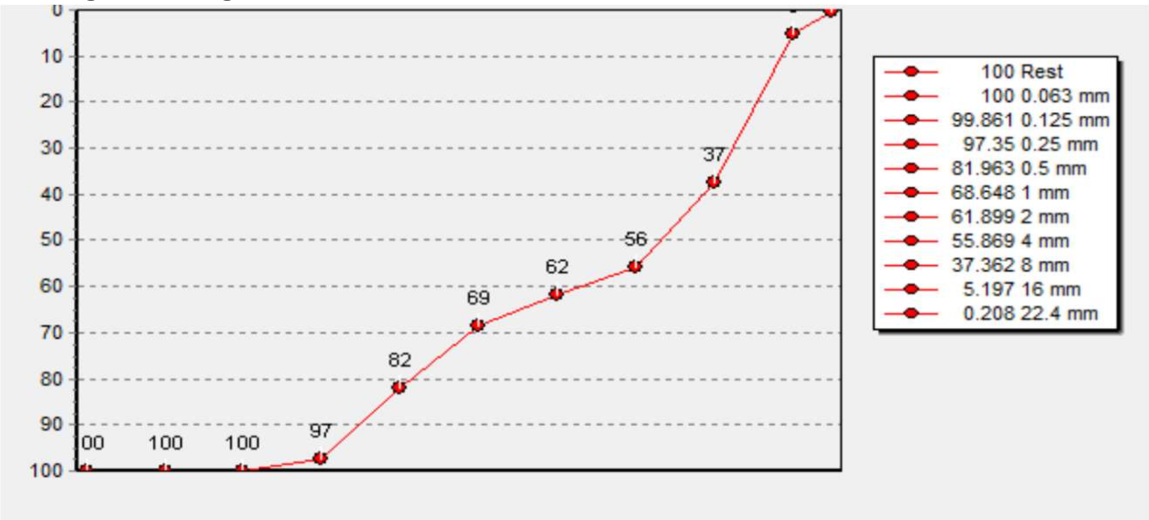


Recipe	8B

Water absorption of coarse aggregate	2,7%
stregth class	C30/37
Consistency	F4
Max Grain size	16
Water/cement ratio	0,49

Raw material	Description	Dosing mass
Cement	CEM III/B 42.5 N	344 kg
Fine fractions	Sand 0-4 mm	819 kg
Recycled aggregate	Gravel 4-22 mm	477 kg
Natural aggregate	Gravel 4-22 mm	461 kg
Flyash	Vliegas EFA Füller MR-3 Cat A	30 kg
Superplasticizer	VC 1550 con. 30%	0,91 kg
Water	Tap water	129 kg
Air	-	20 L
Total	-	2260 kg

Sieving according to NEN 2560

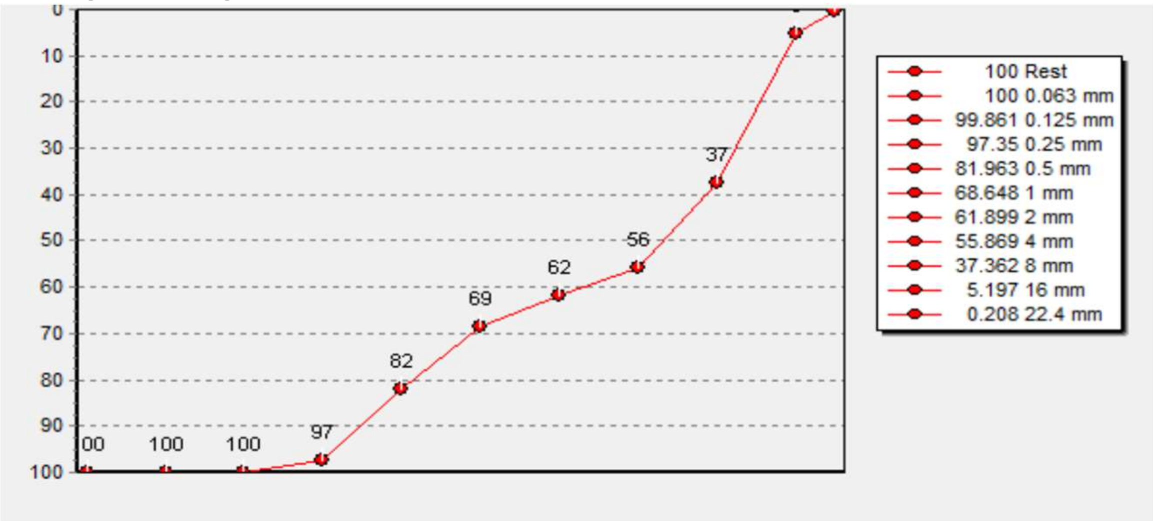


Recipe	8E

Brick content	1,0%
Water absorption of coarse aggregate	2,8%
stregth class	C30/37
Consistency	F4
Max Grain size	16
Water/cement ratio	0,49

Raw material	Description	Dosing mass
Cement	CEM III/B 42.5 N	344 kg
Fine fractions	Sand 0-4 mm	819 kg
Recycled aggregate	Gravel 4-22 mm	477 kg
Natural aggregate	Gravel 4-22 mm	461 kg
Flyash	Vliegas EFA Füller MR-3 Cat A	30 kg
Superplasticizer	VC 1550 con. 30%	0,91 kg
Water	Tap water	129 kg
Air	-	20 L
Total	-	2260 kg

Sieving according to NEN 2560

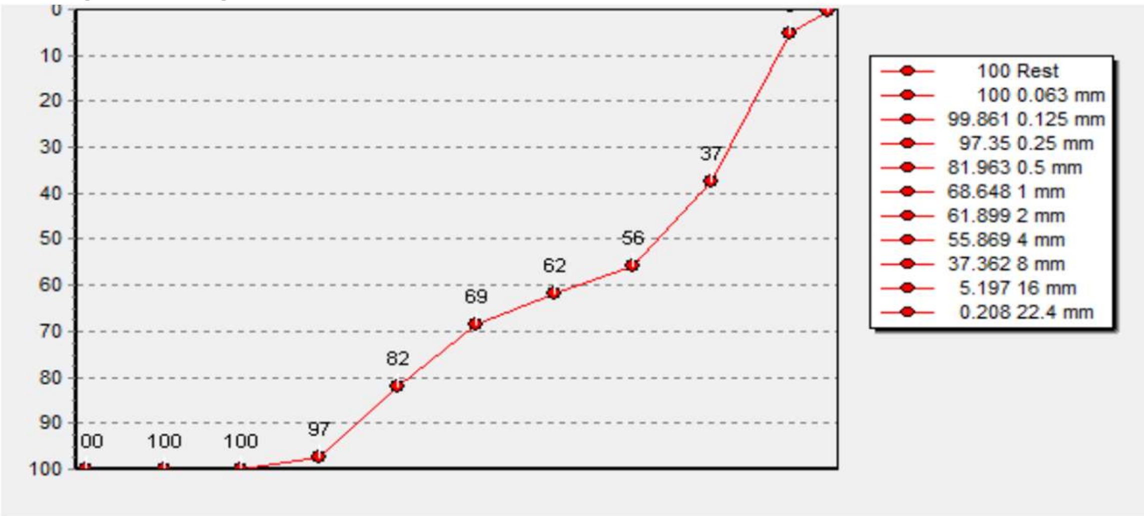


Recipe	7A

Brick content	0,5%
Water absorption of coarse aggregate	2,7%
stregth class	C30/37
Consistency	F4
Max Grain size	16
Water/cement ratio	0,49

Raw material	Description	Dosing mass
Cement	CEM III/B 42.5 N	350 kg
Fine fractions	Sand 0-4 mm	833 kg
Recycled aggregate	Gravel 4-22 mm	485 kg
Natural aggregate	Gravel 4-22 mm	469 kg
Flyash	Vliegas EFA Füller MR-3 Cat A	0 kg
Superplasticizer	VC 1550 con. 30%	0,91 kg
Water	Tap water	128 kg
Air	-	20 L
Total	-	2265 kg

Sieving according to NEN 2560

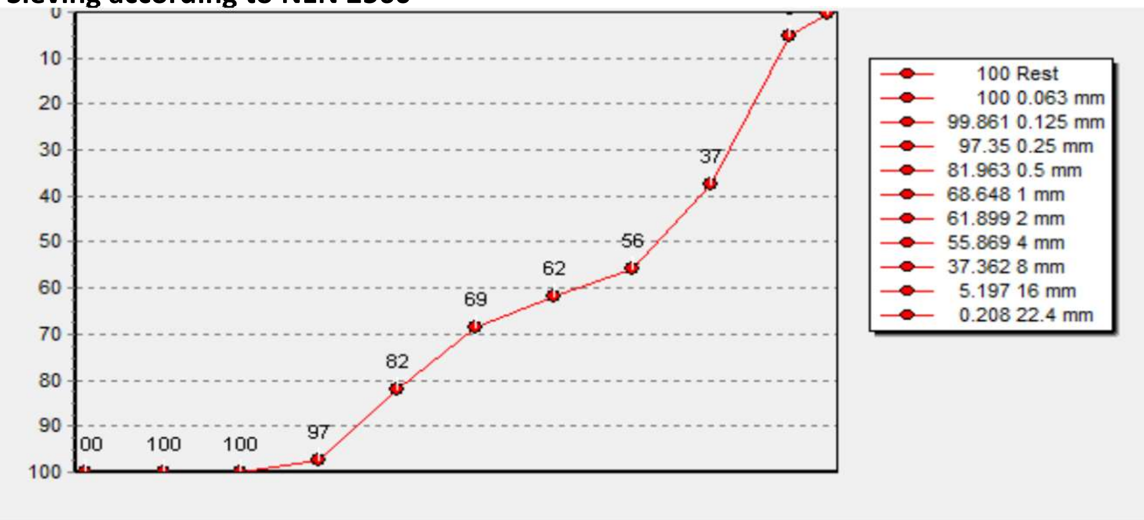


Recipe	9A

Brick content	0,5%
Water absorption of coarse aggregate	2,7%
stregth class	C30/37
Consistency	F4
Max Grain size	16
Water/cement ratio	0,49

Raw material	Description	Dosing mass
Cement	CEM III/B 42.5 N	338 kg
Fine fractions	Sand 0-4 mm	805 kg
Recycled aggregate	Gravel 4-22 mm	469 kg
Natural aggregate	Gravel 4-22 mm	453 kg
Flyash	Vliegas EFA Füller MR-3 Cat A	60 kg
Superplasticizer	VC 1550 con. 30%	0,91 kg
Water	Tap water	130 kg
Air	-	20 L
Total	-	2265 kg

Sieving according to NEN 2560

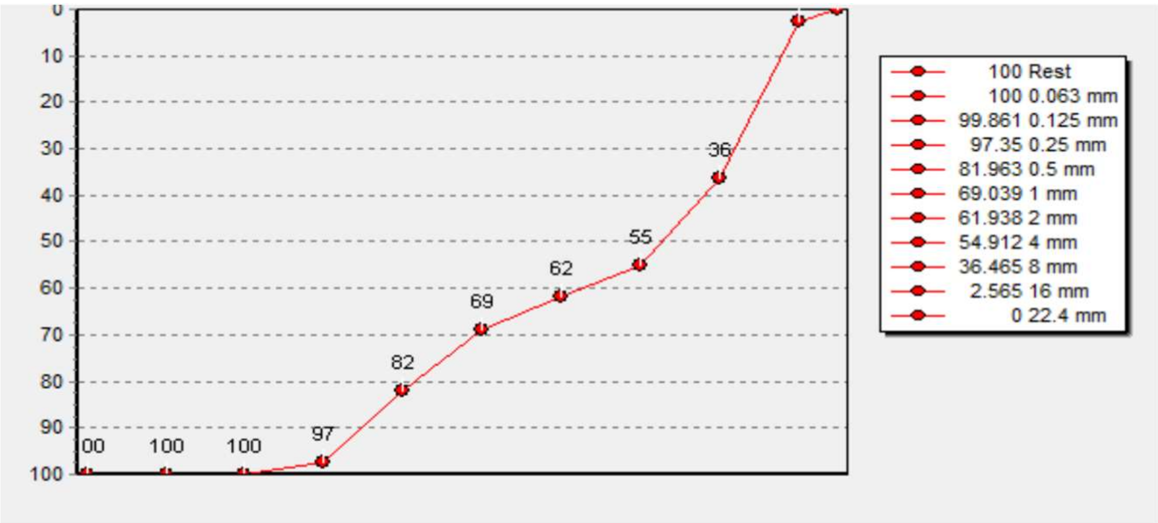


Recipe	3A

Brick content	0,5%
Water absorption of coarse aggregate	2,7%
stregth class	C30/37
Consistency	F4
Max Grain size	16
Water/cement ratio	0,45

Raw material	Description	Dosing mass
Cement	CEM III/B 42.5 N	365 kg
Fine fractions	Sand 0-4 mm	817 kg
Recycled aggregate	Gravel 4-22 mm	475 kg
Natural aggregate	Gravel 4-22 mm	460 kg
Flyash	Vliegas EFA Füller MR-3 Cat A	30 kg
Superplasticizer	VC 1550 con. 30%	1,34 kg
Water	Tap water	123 kg
Air	-	20 L
Total	-	2272 kg

Sieving according to NEN 2560

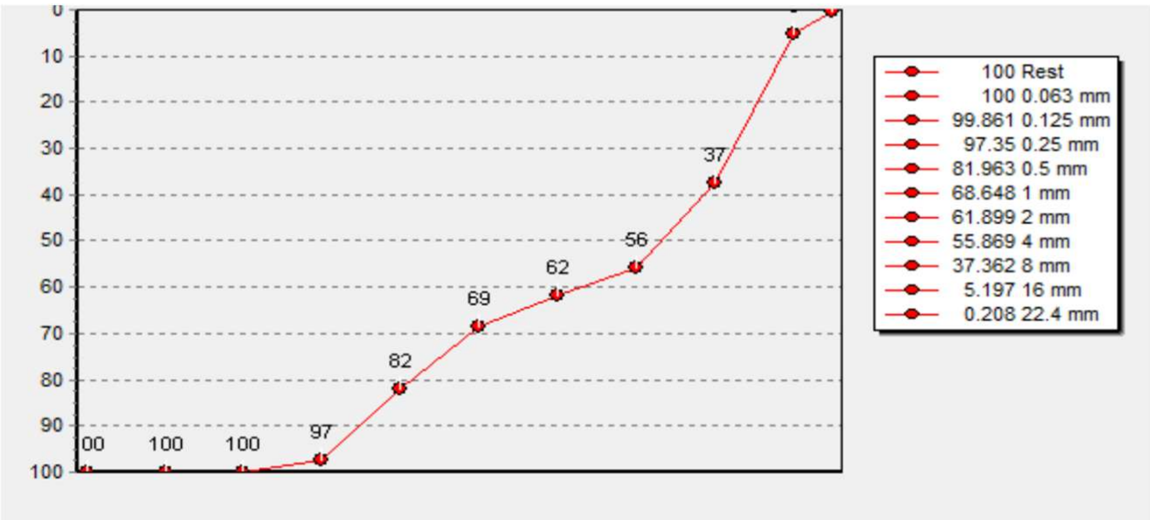


Recipe	13A

Brick content	0,5%
Water absorption of coarse aggregate	2,7%
stregth class	C30/37
Consistency	F4
Max Grain size	16
Water/cement ratio	0,54

Raw material	Description	Dosing mass
Cement	CEM III/B 42.5 N	317 kg
Fine fractions	Sand 0-4 mm	829 kg
Recycled aggregate	Gravel 4-22 mm	482 kg
Natural aggregate	Gravel 4-22 mm	467 kg
Flyash	Vliegas EFA Füller MR-3 Cat A	30 kg
Superplasticizer	VC 1550 con. 30%	0,74 kg
Water	Tap water	130 kg
Air	-	20 L
Total	-	2255 kg

Sieving according to NEN 2560

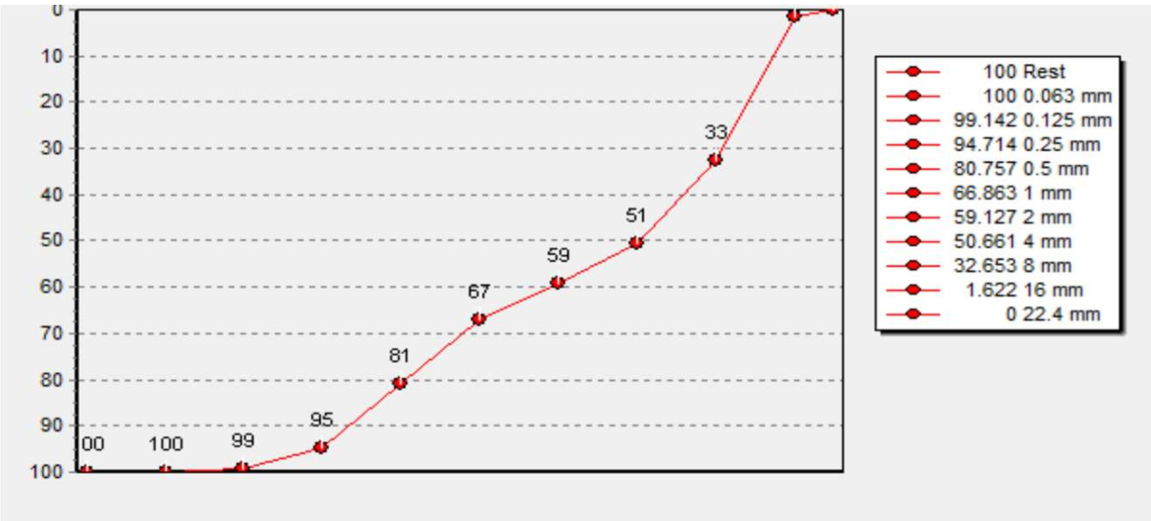


Recipe	12A

Brick content	1,0%
Water absorption of coarse recycled aggregate	1,2%
stregth class	C30/37
Consistency	F4
Max Grain size	16
Water/cement ratio	0,54

Raw material	Description	Dosing mass
Cement	CEM III/B 42.5 N	313 kg
Fine fractions	Sand 0-4 mm	811 kg
Recycled aggregate	Gravel 4-22 mm	0 kg
Natural aggregate	Gravel 4-22 mm	972 kg
Flyash	Vliegas EFA Füller MR-3 Cat A	60 kg
Superplasticizer	VC 1550 con. 30%	0,75 kg
Water	Tap water	137 kg
Air	-	20 L
Total	-	2294 kg

Sieving according to NEN 2560

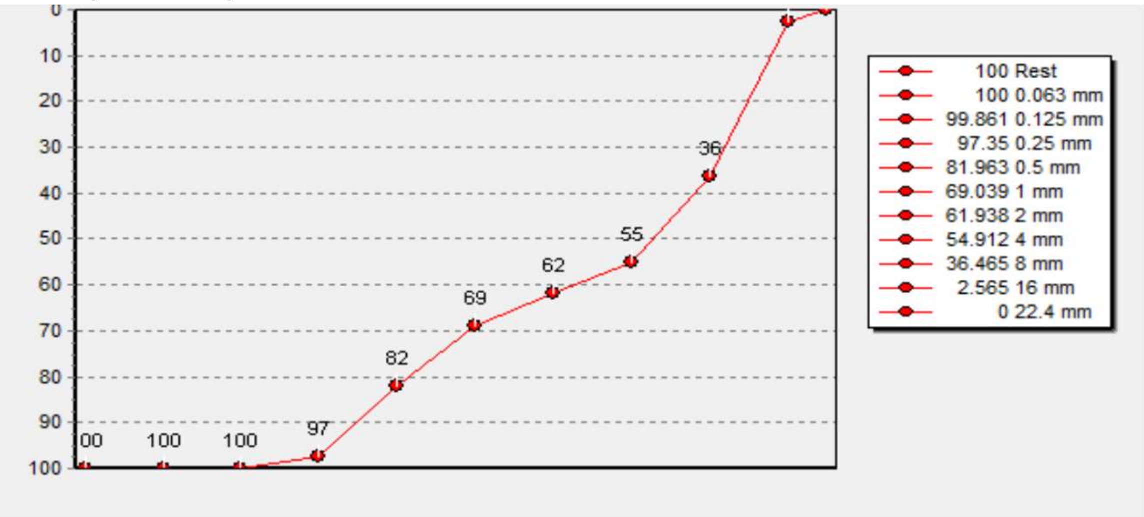


Recipe	11A

Water absorption of coarse aggregate	1,0%
stregth class	C30/37
Consistency	F4
Max Grain size	16
Water/cement ratio	0,54

Raw material	Description	Dosing mass
Cement	CEM III/B 42.5 N	321 kg
Fine fractions	Sand 0-4 mm	845 kg
Recycled aggregate	Gravel 4-22 mm	0 kg
Natural aggregate	Gravel 4-22 mm	1013 kg
Flyash	Vliegas EFA Füller MR-3 Cat A	0 kg
Superplasticizer	VC 1550 con. 30%	0,83 kg
Water	Tap water	129 kg
Air	-	20 L
Total	-	2308 kg

Sieving according to NEN 2560

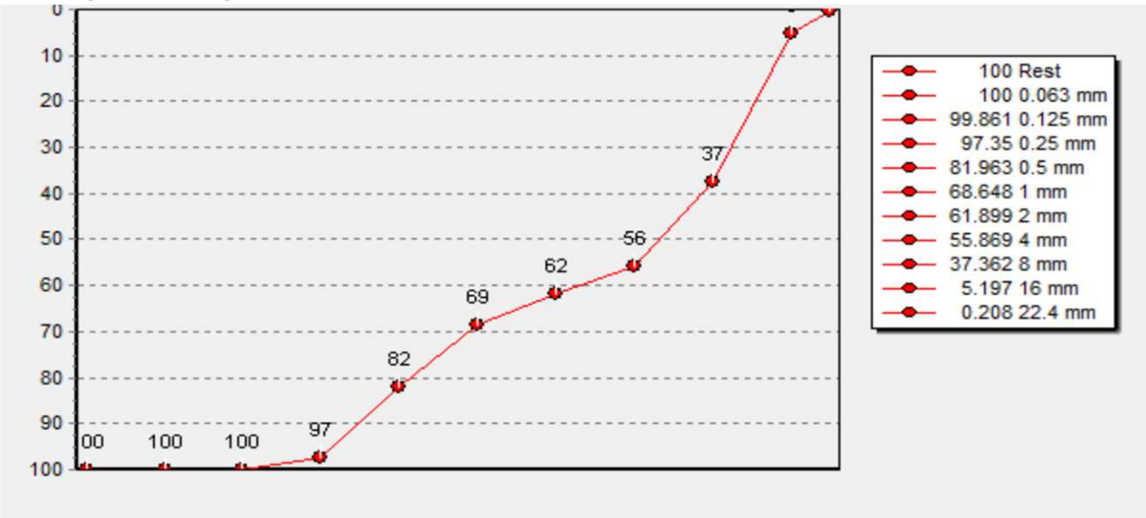


Recipe	8D

Water absorption of coarse aggregate	0,5%
Water absorption of coarse recycled aggregate	2,4%
stregth class	C30/37
Consistency	F4
Max Grain size	16
Water/cement ratio	0,49

Raw material	Description	Dosing mass
Cement	CEM III/B 42.5 N	344 kg
Fine fractions	Sand 0-4 mm	819 kg
Recycled aggregate	Gravel 4-22 mm	477 kg
Natural aggregate	Gravel 4-22 mm	461 kg
Flyash	Vliegas EFA Füller MR-3 Cat A	30 kg
Superplasticizer	VC 1550 con. 30%	0,91 kg
Water	Tap water	129 kg
Air	-	20 L
Total	-	2260 kg

Sieving according to NEN 2560

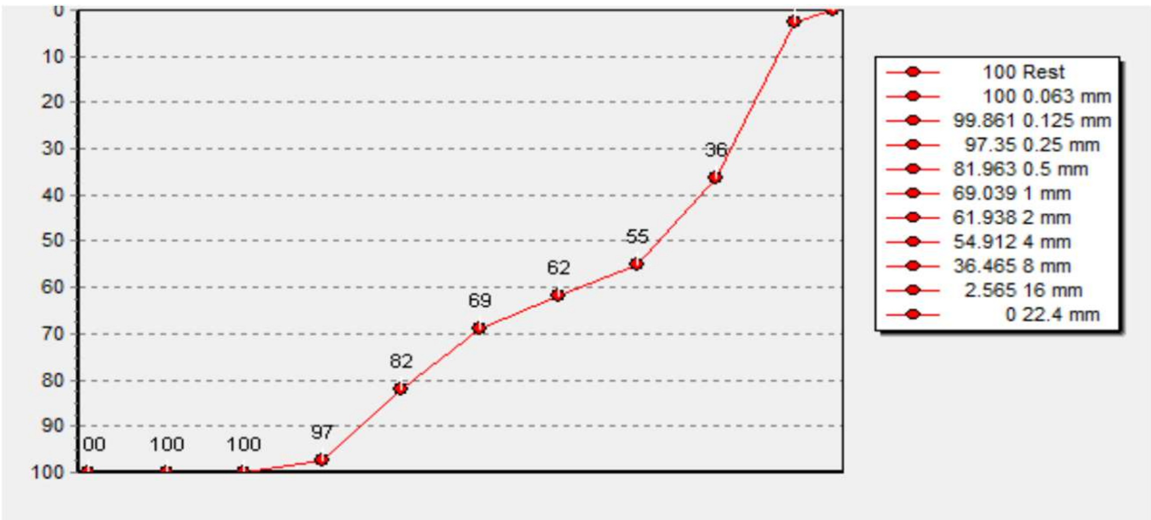


Recipe	1A

Brick content	1,0%
Water absorption of coarse aggregate	1,2%
stregth class	C30/37
Consistency	F4
Max Grain size	16
Water/cement ratio	0,45

Raw material	Description	Dosing mass
Cement	CEM III/B 42.5 N	368 kg
Fine fractions	Sand 0-4 mm	833 kg
Recycled aggregate	Gravel 4-22 mm	0 kg
Natural aggregate	Gravel 4-22 mm	1000 kg
Flyash	Vliegas EFA Füller MR-3 Cat A	0 kg
Superplasticizer	VC 1550 con. 30%	1,4 kg
Water	Tap water	122kg
Air	-	20 L
Total	-	2325 kg

Sieving according to NEN 2560

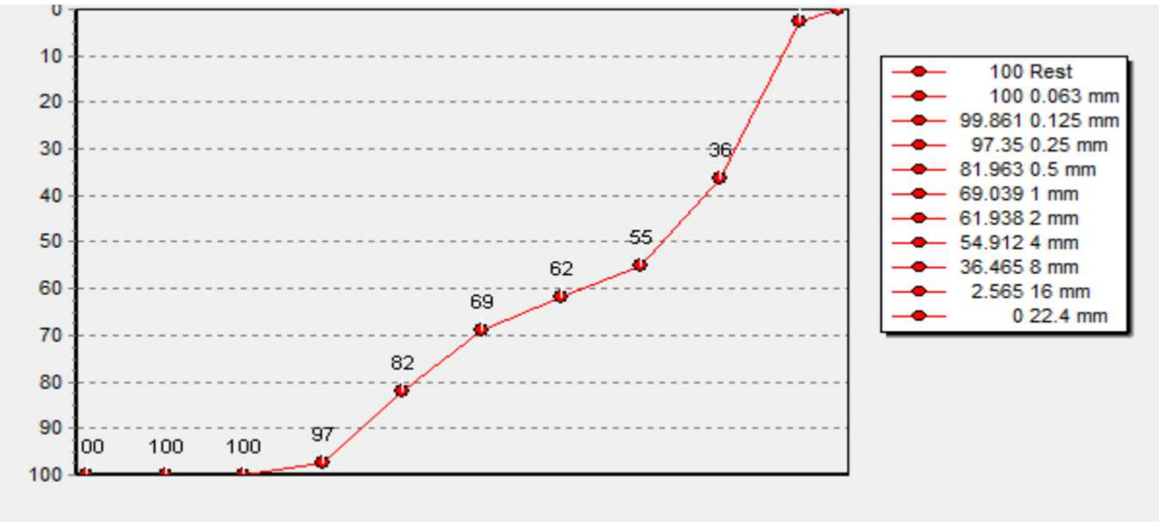


Recipe	2A

Water absorption of coarse aggregate	1,0%
stregth class	C30/37
Consistency	F4
Max Grain size	16
Water/cement ratio	0,45

Raw material	Description	Dosing mass
Cement	CEM III/B 42.5 N	362 kg
Fine fractions	Sand 0-4 mm	801 kg
Recycled aggregate	Gravel 4-22 mm	0 kg
Natural aggregate	Gravel 4-22 mm	960 kg
Flyash	Vliegas EFA Füller MR-3 Cat A	60 kg
Superplasticizer	VC 1550 con. 30%	1,35 kg
Water	Tap water	126 kg
Air	-	20 L
Total	-	2310 kg

Sieving according to NEN 2560

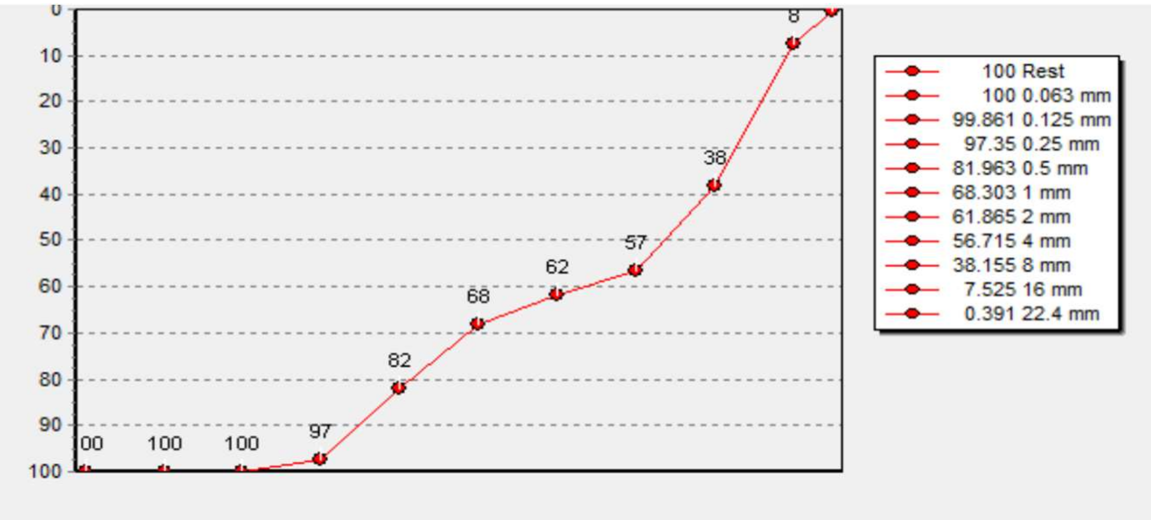


Recipe	4A

Water absorption of coarse recycled aggregate	4%
stregth class	C30/37
Consistency	F4
Max Grain size	16
Water/cement ratio	0,45

Raw material	Description	Dosing mass
Cement	CEM III/B 42.5 N	363 kg
Fine fractions	Sand 0-4 mm	838 kg
Recycled aggregate	Gravel 4-22 mm	919 kg
Natural aggregate	Gravel 4-22 mm	0 kg
Flyash	Vliegas EFA Füller MR-3 Cat A	0 kg
Superplasticizer	VC 1550 con. 30%	1,45 kg
Water	Tap water	118 kg
Air	-	20 L
Total	-	2240 kg

Sieving according to NEN 2560

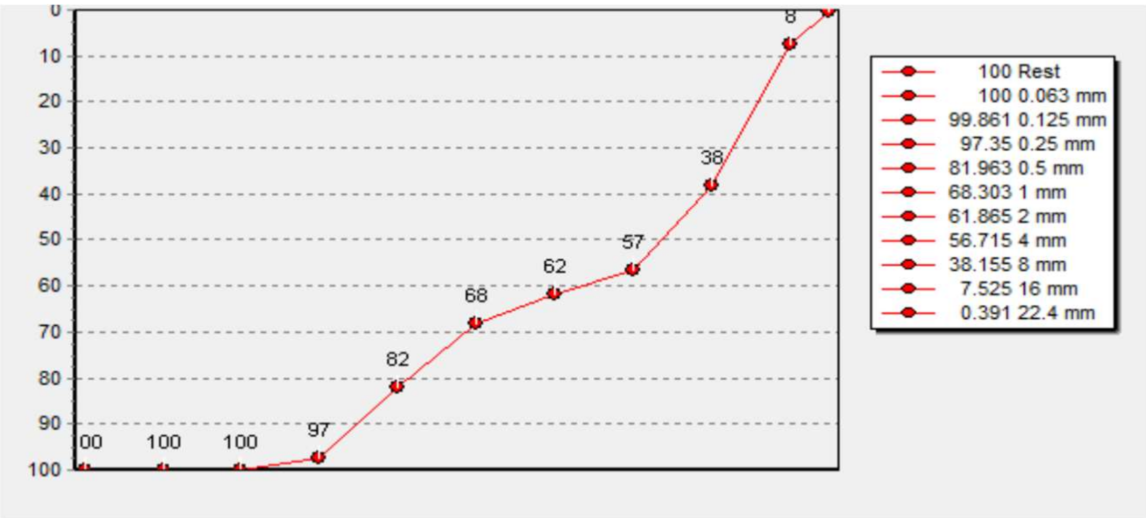


Recipe	4B

Brick content	1,0%
Water absorption of coarse aggregate	4,9%
stregth class	C30/37
Consistency	F4
Max Grain size	16
Water/cement ratio	0,45

Raw material	Description	Dosing mass
Cement	CEM III/B 42.5 N	363 kg
Fine fractions	Sand 0-4 mm	838 kg
Recycled aggregate	Gravel 4-22 mm	919 kg
Natural aggregate	Gravel 4-22 mm	0 kg
Flyash	Vliegas EFA Füller MR-3 Cat A	0 kg
Superplasticizer	VC 1550 con. 30%	1,45 kg
Water	Tap water	118 kg
Air	-	20 L
Total	-	2240 kg

Sieving according to NEN 2560

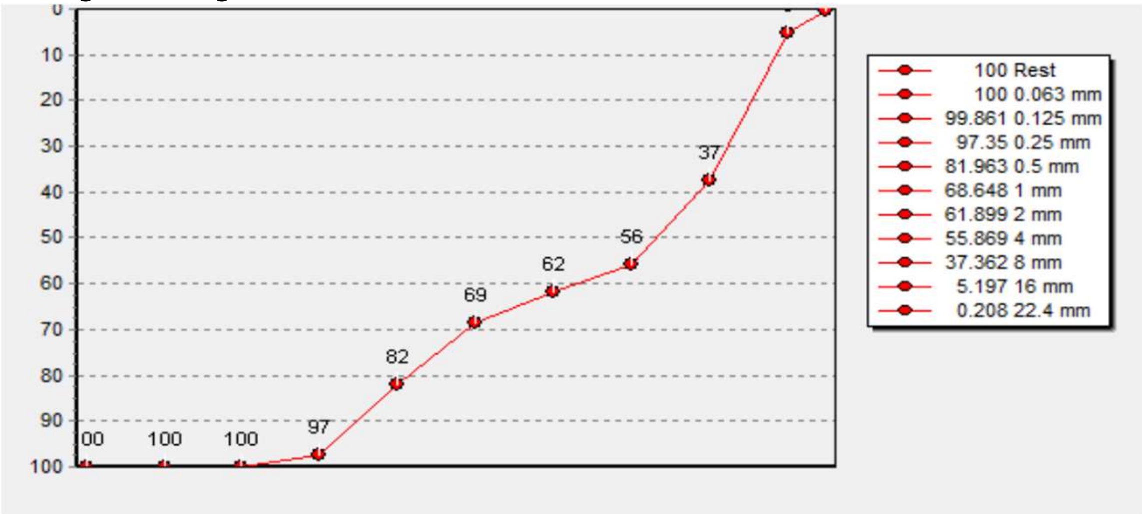


Recipe	8C

Brick content	0,5%
Water absorption of coarse recycled aggregate	3,2%
stregth class	C30/37
Consistency	F4
Max Grain size	16
Water/cement ratio	0,49

Raw material	Description	Dosing mass
Cement	CEM III/B 42.5 N	350 kg
Fine fractions	Sand 0-4 mm	833 kg
Recycled aggregate	Gravel 4-22 mm	485 kg
Natural aggregate	Gravel 4-22 mm	469 kg
Flyash	Vliegas EFA Füller MR-3 Cat A	0 kg
Superplasticizer	VC 1550 con. 30%	0,91 kg
Water	Tap water	128 kg
Air	-	20 L
Total	-	2265 kg

Sieving according to NEN 2560



Appendix H: Set of data from the UCI Machine Learning repository

Cement (kg/m^3)	Blast Furnace Slag (kg/m^3)	Fly Ash (kg/m^3)	Water(kg/m^3)	Superplasticizer (kg/m^3)	Coarse Aggregate(kg/m^3)	Concrete compressive strength(MPa)
153.0	145.0	113.0	178.0	8.0	1002.0	25.56
153.1	145.0	113.0	178.5	8.0	1001.9	25.56
144.0	136.0	106.0	178.0	7.0	941.0	26.14
143.8	136.3	106.2	178.1	7.5	941.5	26.15
153.0	145.0	113.0	178.0	8.0	867.0	26.23
153.1	145.0	113.0	178.5	8.0	867.2	26.23
153.0	239.0	0.0	200.0	6.0	1002.0	26.86
152.6	238.7	0.0	200.0	6.3	1001.8	26.86
238.2	158.8	0.0	185.7	0.0	1040.6	26.91
148.0	175.0	0.0	171.0	2.0	1000.0	26.92
147.8	175.1	0.0	171.2	2.2	1000.0	26.92
136.0	196.0	98.0	199.0	6.0	847.0	26.97
164.0	163.0	128.0	197.0	8.0	961.0	27.23
159.0	149.0	116.0	175.0	15.0	953.0	27.68
158.6	148.9	116.0	175.1	15.0	953.3	27.68
133.0	200.0	0.0	192.0	0.0	927.4	27.87
181.9	272.8	0.0	185.7	0.0	1012.4	27.94
139.6	209.4	0.0	192.0	0.0	1047.0	28.24
237.0	92.0	71.0	247.0	6.0	853.0	28.63
236.9	91.7	71.5	246.9	6.0	852.9	28.63
133.1	210.2	0.0	195.7	3.1	949.4	28.94
155.0	184.0	143.0	194.0	9.0	880.0	28.99
155.2	183.9	143.2	193.8	9.2	879.6	28.99
136.0	162.0	126.0	172.0	10.0	923.0	29.07
136.4	161.6	125.8	171.6	10.4	922.6	29.07
145.0	116.0	119.0	184.0	5.7	833.0	29.16
156.0	178.0	187.0	221.0	7.0	854.0	29.41
143.0	169.0	143.0	191.0	8.0	967.0	29.72
143.0	169.4	142.7	190.7	8.4	967.4	29.73
144.0	170.0	133.0	192.0	8.0	814.0	29.87
143.7	170.2	132.6	191.6	8.5	814.1	29.87
141.3	212.0	0.0	203.5	0.0	971.8	29.89
237.5	237.5	0.0	228.0	0.0	932.0	30.08
162.0	214.0	164.0	202.0	10.0	820.0	30.65
159.0	209.0	161.0	201.0	7.0	848.0	30.88
133.0	210.0	0.0	196.0	3.0	949.0	31.03
272.8	181.9	0.0	185.7	0.0	1012.4	31.38
255.5	170.3	0.0	185.7	0.0	1026.6	32.05
261.0	100.0	78.0	201.0	9.0	864.0	32.40
260.9	100.5	78.3	200.6	8.6	864.5	32.40
193.5	290.2	0.0	185.7	0.0	998.2	32.63
145.9	230.5	0.0	202.5	3.4	827.0	32.72
159.0	187.0	0.0	176.0	11.0	990.0	32.76

159.1	186.7	0.0	175.6	11.3	989.6	32.77
160.0	188.0	146.0	203.0	11.0	829.0	32.84
236.0	157.0	0.0	192.0	0.0	972.6	32.88
149.0	236.0	0.0	176.0	13.0	847.0	32.96
149.5	236.0	0.0	175.8	12.6	846.8	32.96
290.2	193.5	0.0	185.7	0.0	998.2	33.04
157.0	214.0	152.0	200.0	9.0	819.0	33.05
146.0	230.0	0.0	202.0	3.0	827.0	33.06
132.0	207.0	161.0	179.0	5.0	867.0	33.30
132.0	206.5	160.9	178.9	5.5	866.9	33.31
252.0	97.0	76.0	194.0	8.0	835.0	33.40
252.1	97.1	75.6	193.8	8.3	835.5	33.40
157.0	236.0	0.0	192.0	0.0	935.4	33.66
262.0	111.0	86.0	195.0	5.0	895.0	33.72
261.9	110.5	86.1	195.4	5.0	895.2	33.72
162.0	190.0	148.0	179.0	19.0	838.0	33.76
162.0	190.1	148.1	178.8	18.8	838.1	33.76
255.0	99.0	77.0	189.0	6.0	919.0	33.80
255.3	98.8	77.0	188.6	6.5	919.0	33.80
166.8	250.2	0.0	203.5	0.0	975.6	33.95
140.0	164.0	128.0	237.0	6.0	869.0	35.23
139.7	163.9	127.7	236.7	5.8	868.6	35.23
160.2	188.0	146.4	203.2	11.3	828.7	35.31
152.0	178.0	139.0	168.0	18.0	944.0	36.35
151.8	178.1	138.7	167.5	18.3	944.0	36.35
140.0	133.0	103.0	200.0	7.0	916.0	36.44
139.9	132.6	103.3	200.3	7.4	916.0	36.44
250.2	166.8	0.0	203.5	0.0	977.6	36.96
273.0	105.0	82.0	210.0	9.0	904.0	37.17
272.8	105.1	81.8	209.7	9.0	904.0	37.17
156.0	243.0	0.0	180.0	11.0	1022.0	37.36
155.6	243.5	0.0	180.3	10.7	1022.0	37.36
150.0	236.8	0.0	173.8	11.9	1069.3	37.43
150.0	237.0	0.0	174.0	12.0	1069.0	37.43
173.8	93.4	159.9	172.3	9.7	1007.2	37.81
210.7	316.1	0.0	185.7	0.0	977.0	37.81
166.0	260.0	0.0	183.0	13.0	859.0	37.91
166.0	259.7	0.0	183.2	12.7	858.8	37.92
288.0	192.0	0.0	192.0	0.0	932.0	38.80
178.0	129.8	118.6	179.9	3.6	1007.3	39.16
234.0	156.0	0.0	189.0	5.9	981.0	39.30
192.0	288.0	0.0	192.0	0.0	929.8	39.32
160.0	128.0	122.0	182.0	6.4	824.0	39.40
266.0	112.0	87.0	178.0	10.0	910.0	39.42
266.2	112.3	87.5	177.9	10.4	909.7	39.42
239.6	359.4	0.0	185.7	0.0	941.6	39.44
160.0	250.0	0.0	168.0	12.0	1049.0	39.45
159.8	250.0	0.0	168.4	12.2	1049.3	39.46

228.0	342.1	0.0	185.7	0.0	955.8	39.70
162.0	207.0	172.0	216.0	10.0	822.0	39.84
213.8	98.1	24.5	181.7	6.7	1066.0	40.23
190.0	190.0	0.0	228.0	0.0	932.0	40.86
167.4	129.9	128.6	175.5	7.8	1006.3	41.20
265.0	111.0	86.0	195.0	6.0	833.0	41.54
264.5	111.0	86.5	195.5	5.9	832.6	41.54
203.5	305.3	0.0	203.5	0.0	963.4	41.68
287.0	121.0	94.0	188.0	9.0	904.0	41.94
277.0	117.0	91.0	191.0	7.0	946.0	43.57
277.0	116.8	91.0	190.6	7.0	946.5	43.58
287.3	120.5	93.9	187.6	9.2	904.4	43.80
276.0	116.0	90.0	180.0	9.0	870.0	44.28
276.4	116.0	90.3	179.6	8.9	870.1	44.28
142.0	167.0	130.0	174.0	11.0	883.0	44.61
141.9	166.6	129.7	173.5	10.9	882.6	44.61
213.7	98.1	24.5	181.7	6.9	1065.8	45.71
165.0	128.5	132.1	175.1	8.1	1005.8	46.39
200.0	200.0	0.0	190.0	0.0	1145.0	49.25
260.0	101.0	78.0	171.0	10.0	936.0	49.77
259.9	100.6	78.4	170.6	10.4	935.7	49.77
280.0	129.0	100.0	172.0	9.0	825.0	52.82
279.8	128.9	100.4	172.4	9.5	825.1	52.83
298.0	137.0	107.0	201.0	6.0	878.0	53.52
297.8	137.2	106.9	201.3	6.0	878.4	53.52
285.0	190.0	0.0	163.0	7.6	1031.0	53.58