Design of ecological concrete by particle packing optimization

Pieter Ballieu

Supervisor: Prof. dr. ir. Geert De Schutter
Counsellor: Dr. ir. Jeroen Dils

Master's dissertation submitted in order to obtain the academic degree of
Master of Science in Civil Engineering

Department of Structural Engineering
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Pieter Ballieu

Foreword

Without the help of a lot of people, writing a thesis wouldn't be possible. Before starting I would like to thank those people!

First I would like to thank Prof. dr. ir. Geert De Schutter and Dr. ir. Jeroen Dils for sharing their knowhow which helped me in the right direction. Accepting me doing this subject was a first step in writing a successful thesis. Concrete is my passion! Writing a thesis takes a period of approximately one year. It is very important to have an interesting subject and this was the case. Thanks!

Also other persons from the University of Ghent were important for writing this thesis. The total staff of 'Magnel Laboratory for Concrete Research' helped me a lot with the tests, especially Nathan Lampens and Tom Stulemeijer. An example: they crushed 180 cubes of concrete. This means they measured 1080 times the width and the depth of a cube and 720 times the height… Thanks! Besides the staff of ''Magnel Laboratory for Concrete Research' also Dr. ir. Steffen Grünewald and ir Philip Van den Heede shared their knowledge.

Thanks ir. Johan Baeten and Steven Daniels from Interbeton! Without sand and superplasticizer it would be difficult to make concrete I think... Together with ing. Peter Minne from Odisee you launched me for this thesis. Thanks!

Thanks to Jacques Pareyn for searching for typos and syntax errors! After his corrections, the length of his pencil was halved. Without having a direct contribution to this thesis also other persons were important in this process. My parents for the financial support for 6 years university studies: it results in two Master's Degrees. My friends for the moments of relaxation: you changed my personality during the six years in Ghent.

Last but not least: Liselore for giving us beautiful perspectives. You came late but on an ideal moment. I was very busy and you make it busier but it was with pleasure. You were the motivation to finish this all.

Pieter Ballieu

May 2015

Abstract

Details

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Summary

This thesis tried to optimize a traditional concrete mixture according to the Compressible Packing Model. It was inspired by a work of Sonja Fennis in the Netherlands. Applying the packing model on the aggregate mixture leads to an optimized aggregate composition. That change should lead to a concrete mixture with a higher workability. To obtain the same workability as in the reference mixture the amount of water will be lowered. This normally results in a concrete mixture that is stronger than the reference concrete. Because a gain of strength is not the goal of this thesis the amount of cement was reduced. Cement replacement products as limestone powder, quartz powder, portaclay, fly ash and silica fume were used. Also adding aggregates instead of a cement replacement product was tested. Reducing the amount of cement is the ecological benefit. These were tested with the tool 'Groen Beton'. Besides the ecological evaluation also an economic evaluation was done.

Keywords

Ecological concrete, Compressible Packing Model (CPM), cement replacement products, binder, filler, cement reduction.

Design of ecological concrete by particle packing optimization

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Supervisor(s): Prof. dr. ir. Geert De Schutter & Dr.ir. Jeroen Dils

***Abstract* – This master thesis tried to design an ecological concrete, based on an optimization of the packing of the aggregates, using the Compressible Packing Model (CPM). In the first part all theoretical aspects were discussed. Also tests and materials were described. The second part gives a survey of all the produced mixtures, the calculations for those mixtures and the test results of those mixtures. Mixtures were evaluated on workability, durability, strength, economic cost and ecological cost.**

I INTRODUCTION

It is generally accepted: we should do something to save our environment. The concentration of CO_2 increases exponentially. This could be problematic for future generations. In the world of construction, cement is the most polluting material. Nowadays, cement production and consumption is responsible for approximately 6% of the total global CO_2 emission [1]. On top of that, due to the strong development of China, the prediction of the cement consumption shows a strong increase. This is shown in figure 1.

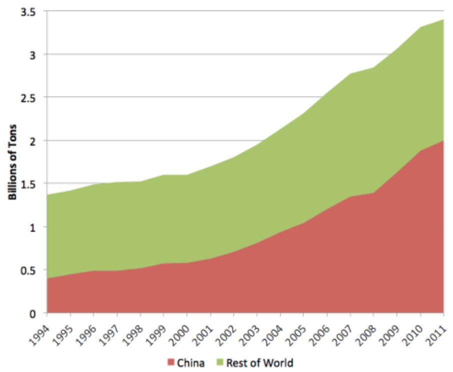

Figure 1: Evolution cement consumption

In this thesis, the goal was to design an ecological concrete. There are several possibilities to reduce the environmental impact of a concrete mixture: extending the life time of concrete structures, reducing the use of water, using recycled aggregates instead of new mined aggregates, lowering the cement content, … Tis last option was investigated in this thesis.

All the produced concrete mixtures were evaluated on an economic and ecological base. For the ecological evaluation, a Dutch tool 'Groen Beton' was used. In that tool, an Environmental Cost Indicator (ECI) was calculated [2]. This indicates the environmental cost of 1 m³ concrete. The database from that tool shows the importance of the amount of cement in concrete on the ecology.

For the design of such an ecological concrete (a concrete with a reduced cement content), existing theories were consulted. In the Netherlands, Sonja Fennis did her PhD about the design of an ecological concrete by particle packing optimization [3]. In her PhD, the CPM from F. De Larrard was discussed [4]. In a master thesis previous year at the University of Ghent, by Tom Bosmans and Jolien Van Der Putten, this CPM model was validated [5]. Based on those three works this thesis tried to check the experiences that were found by Sonja Fennis.

II THEORY

During the history, different packing models were developed such as the Furnas model (1929), the Toufar model (1976), the Linear-Mixture Packing Model (1991) the Dewar model (1999), the Schwanda model (2000) and the Linear Packing Density Model (1999) from F. De Larrard. Another model from F. De Larrard is the best applicable packing model for taking into account all different particle sizes: the CPM (1999). The CPM calculates the optimal ratio between different aggregates. This results in a maximum value for the packing density. It takes also into account the influence of the compaction energy (K). This is shown in figure 2. More compaction energy results in a higher packing density

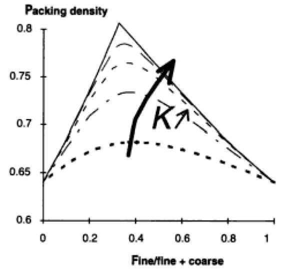

Figure 2: Influence of compaction energy

Using a packing model like the CPM makes it possible to optimize the packing of the total concrete mixture. This should result in a concrete with an improved/increased packing. An improved packing results in a higher workability. This makes it possible to decrease the water content which results in a gain of strength. In a last design step, a replacement of an amount cement by other materials is possible. This is the ecological benefit. The optimization process could also improve durability due to a better packing.

To take into account the packing of fine materials (<125 µm) the CIPM was developed [3]. In this thesis this was not used. Only the mix of aggregates (limestone aggregates & sands) was optimized. If necessary, it is also possible to optimize the packing of fine materials with the CPM.

Both packing models, the CPM and the CIPM, take geometrical interactions such as the wall effect and the loosening effect into account (figure 3), but the CIPM has coefficients to integrate effects due to surface forces in its model. Fine materials are due to surface forces as the van der Waals force, the electrostatic double layer forces and steric forces sensitive to phenomena such as agglomeration. This influences the packing density.

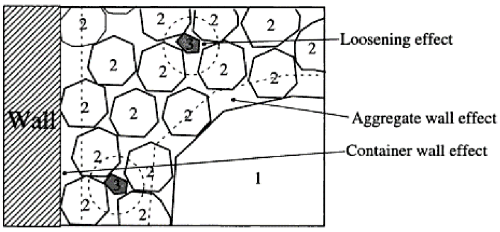

Figure 3: Wall & loosening effect

The packing density is the ratio of the solid volume of the particles (V_p) to the bulk volume of the particles (V_b). It is a value that shows something about the amount of voids in a mixture. The higher the value for the packing density, the lower the amount of voids in a mixture. A higher packing density should result in a higher workability or a lower water demand, to obtain the same workability as the reference concrete. This will also have effects on the concrete strength.

For coarse materials, the packing density can be determined experimentally on a dry manner, with a compaction test. Based on a previous thesis, a value of 9 was validated for the compaction index K [5]. This gave the best fit with the CPM. For fine materials a wet manner should be used such as the Marquardt test to determine the packing [5]. This reduces the surface forces because the particles are saturated with superplasticizer. In this thesis it was not necessary to use that because only the aggregate mix was considered.

III EXPERIMENTAL PART

A first part of the experimental part was the characterization of the aggregates. The sands and limestone aggregates were sieved, their density was determined with pycnometers and with the compaction test their packing density was measured. For the materials used to replace cement, a particle size distribution was defined based on the Laser Light Scattering (LLS) technique.

In a next step, with an MS Excel tool based on the CPM, it was possible to determine the packing density for each combination of aggregates. The combination with the highest packing density is considered as the most ideal combination of aggregates. In this thesis the aggregate composition of an existing concrete was optimized based on the CPM. This is the first step in the design of an ecological concrete. In total, there are three design steps, shown in figure 4.

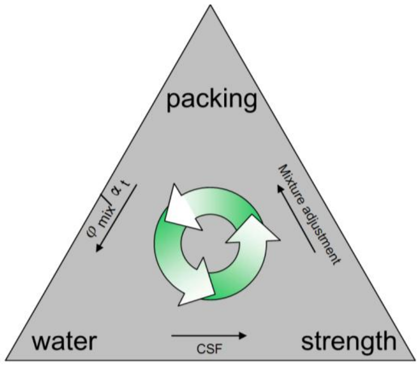

Figure 4: Design steps of an ecological concrete

Due to the optimized packing less water is necessary for the workability of the mixture. Lowering the water content is the second step in the design of an ecological concrete. Sonja Fennis has a theory claiming it is possible to calculate how much the water content could be reduced due to the optimized packing (α_t), to have a concrete mixture with a similar workability as the reference concrete. The parameter φ_{mix}/ α_t determines this, where φ_{mix} is the amount of the optimized material in a unit volume. Due to the decrease of water usage in the mixture, a gain of strength will occur.

The goal of this thesis was not designing a stronger concrete, it was designing an ecological concrete with the same properties as the reference concrete. So the last design step tried to achieve a concrete mixture with the same strength as the reference concrete. This was done with a rule of thumb: Sonja Fennis calculates the proportional gain of strength compared with the reference concrete and reduced the amount of cement in the optimized mixture with the same percentage. This is the ecological benefit.

A reduced amount of cement should be compensated by an increased amount of another material. Different fillers and binders were tested: fly ash, limestone powder, quartz powder, silica fume and portaclay. Also a mixture without a cement replacement product but with an increased amount of aggregates was tested.

To evaluate and compare the mixtures, a lot of data was collected. On fresh concrete the workability was tested with a slump and a flow table test. Also the air content and the density were tested. After 7 days all mixtures were tested on their strength. After 28 days the strength was tested again. To say something about the durability also a resistivity measurement was done and the water absorption under vacuum was tested. Further on, the cost of each mixture was calculated. Also the ECI was calculated based on the tool 'Groen Beton' [2]. With all that data, it was possible to make conclusions.

IV RESULTS AND CONCLUSIONS

In general, the idea behind the work of Sonja Fennis was confirmed by applying her theory only on the aggregate mixture. The first design step, the optimization of the packing, results in an increased packing by a changed aggregate composition. The mixture with the increased packing has an increased workability, as expected.

In order to design a mixture with the same workability as the reference mixture, the theory of the ratio φ_{mix}/α_t was applied. It does not result in a mixture with the same workability as Sonja Fennis claimed [3]. Well-chosen guesses were necessary to obtain the wanted workability. On the other hand her relation between the ratio φ_{mix}/α_t and the measured flow was confirmed. The correlation with the flow value was higher than the correlation with the slump value. This is shown in figure 5.

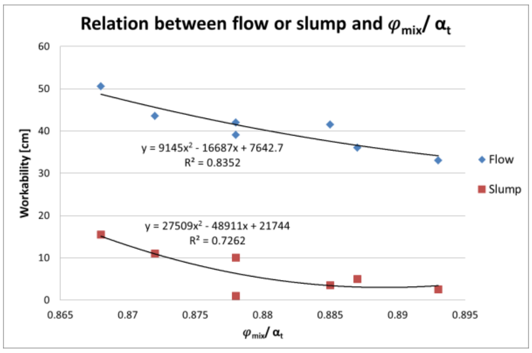

Figure 5: Confirmed relation claimed by Sonja Fennis

By decreasing the water content, in previous design step, a strength increase was noticed. Also durability indicators improved. This was as expected. Because a gain of strength was not wanted in the last design step the rule of thumb to decrease the amount of cement (and the strength) was applied. Several cement replacement products were tested.

Table 1 shows the test results of the reference mixture (mix 1) and those of an optimized mixture (mix 10) that was evaluated as one of the best optimizations. Limestone powder was used as cement replacing material. The optimizations were evaluated on how good they approximated the reference mixture and their cost. The benefit to the environment was about the same for all the optimized mixtures, 7%, while the cost increases with percentages from 2% up to 54%. Limestone powder is cheap, constant in terms of quality and available on earth in sufficient amounts. Based on the slump value, there was still some margin for further optimization.

Table 1: properties reference mixture and optimized mixture

	Mix 1	Mix 10
Slump [cm]	0.5	4.0
Strength 7d [N/mm²]	58.0	57.9
Strength 28d [N/mm²]	68.0	65.1
Water absorption [%]	4.26	4.42
Resistivity [Ωm]	0.42	0.51

Not only should the cost be defining, also the environmental benefit and possibly improved durability properties should be taken into account. In general, the optimized mixtures show better values for the both durability indicators: the resistivity test and the water absorption test under vacuum. The influence of an improved durability on the overall cost is not possible to estimate. It is certain that this is beneficial.

Further research should make it possible to obtain more improvement. There are different possibilities: optimizing other mixtures, including fine materials in the optimization process, more tests on the same, and on other, cement replacement materials, …

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Abbreviations and symbols

Abbreviations

0/2	Sea sand class 0/2
0/4	Sea sand class 0/4
2/6.3	Limestone aggregates class 2/6.3
6.3/20	Limestone aggregates class 6.3/20
AGG	Aggregates
CEM	CEM I 52.5 N
CIPM	Compressible Interaction Packing Model
CSF	Cement Spacing Factor
CPM	Compressible Packing Model
DLS	Dynamic Light Scattering
DLVO	Derjaguin, Landau, Verwey en Overbeek
ECI	Environmental Cost Indicator
FA	Fly ash
LLS	Laser light scattering
LP	Limestone powder
M400	Quartz powder M400
M800	Quartz powder M800
PC	Portaclay
PCE	Polycarboxylate ether-based superplasticizers
PD	Packing density
S90	Quartz sand S90
SF	Silica fume
W/C	Water cement ratio
W/P	Water powder ratio

Symbols - Greek

α	Packing density of a mixture	[-]
$\alpha_{aggregate}$	Defined packing density of an aggregate with compaction test	[-]
α_i	Packing density of size class i	[-]
α_j	Packing density of size class j	[-]

α_t	Calculated packing density of a mixture	[-]
β	Virtual packing density of a mixture	[-]
β_i	Virtual packing density of size class i	[-]
β_j	Virtual packing density of size class j	[-]
β_{ti}	Calculated virtual packing density when size class i is dominant	[-]
ε	Porosity	[-]
φ^*_{cem}	Maximum partial volume cement may occupy	[-]
φ_{cem}	Partial volume occupied by cement in a stable particle structure	[-]
φ_i^*	Maximum partial volume size class i may occupy	[-]
φ_{mix}	Partial volume of all the participles of a mixture in a unit volume	[-]
ρ	Resistivity	[Ωm]
ρ_b	Bulk density	[kg/m³]
ρ_p	Density particles	[kg/m³]
ρ_w	Density water, temperature related	[kg/m³]

Symbols - Roman

$2\pi a$	Correction factor for resistivity measurement	[-]
A	Surface electrode for resistivity measurement	[m²]
a_{ij}	Factor describing loosening effect by class j on class i	[-]
$a_{ij,c}$	Factor describing loosening effect by class j on class i for φ_i^*	[-]
b_{ij}	Factor describing wall effect by class j on class i	[-]
$b_{ij,c}$	Factor describing wall effect by class j on class i for φ_i^*	[-]
d_{10}	Diameter passed by 10% of the particles	[mm] or [µm]
d_{50}	Diameter passed by 50% of the particles	[mm] or [µm]
d_{90}	Diameter passed by 90% of the particles	[mm] or [µm]
d_i	Diameter of particle class j	[m]
d_j	Diameter of particle class j	[m]
d_{max}	Maximal particle diameter in concrete (Fuller)	[mm]
d_{min}	Minimal particle diameter in concrete (Andreasen & Andersen)	[mm]
e	Amount of pores	[-]
i	Integer denoting the dominant size class in a mixture	[-]
ik	Imaginary part of the refraction index	[-]
j	Integer denoting a size class in a mixture	[-]
K	Compaction index	[-]
K_i	Partial compaction index of size class i	[-]

L	Height of the cube for resistivity measurement	[m]
$m_{added\ water}$	Mass added water to define the density	[kg]
$m_{aggregate}$	Mass aggregate to define the density	[kg]
m_{dry}	Dry mass of concrete cube for water absorption test	[kg]
$m_{monster}$	Mass monster for compaction test	[kg]
m_p	Mass particles	[kg]
m_{sat}	Saturated mass of concrete cube for water absorption test	[kg]
m_w	Mass water	[kg]
N	Refraction index	[-]
n	Number of size classes in a mixture	[-]
n	Real part of refraction index	[-]
R	Measured electrical resistance for resistivity test	[Ω]
r_j	Volume fraction of size class j	[-]
V_{air}	Volume air in a unit volume of a mixture	[m³]
V_b	Bulk volume	[m³]
$V_{monster}$	Volume of the monster for compaction test	[m³]
V_p	Volume particles	[m³]
$V_{superplasticizer}$	Volume superplasticizer in a unit volume of a mixture	[m³]
V_{tot}	Unit volume	[m³]
V_{w+a+s}	Volume water, air and superplast in a unit volume of a mixture	[m³]
V_{water}	Volume water in a unit volume of a mixture	[m³]
W	Water absorption under vacuum	[%]

Part 0: Introduction

Besides the introduction this work consists of three parts: ‘part I: Literature’, ‘part II: Experimental part’ and ‘part III: Conclusions’

The first part consists of eight different chapters. The first four chapters give a survey of all the theory and inspiration, upon which this work is based: ecological concrete, packing, packing models and designing an ecological concrete. The following four chapters consist the necessary information for the second part: tests on aggregates and concrete in fresh and hardened state, a survey of the used materials and the reference mixture to begin the second part.

Part two contains all the information about the executed tests. First all the test results on aggregates and the reference concrete are listed up. Following chapters show the design steps to make an ecological concrete: optimization of the packing, optimization of the workability and optimization of the strength. In a last chapter some other executed experiments are discussed.

In the last part, conclusions are summarized and some possibilities for further research are given.

At the end of this document, different attachments are given. The attachments are split up in two groups. A first group consists of all the data about the mixtures: the mixture compositions, the test results, graphical representations of all the test results with standard deviations on tests on cubes and relative comparisons between some of the results. A second part shows all the available technical datasheets of the used materials for this thesis.

Using this structure should make it as easy as possible for the reader to understand what was done in this master thesis and to find out the reasoning underneath. I think everything should be clear. While this text explains the structure of this thesis, following chapter in part I is an introduction to the importance of ecological concrete.

Part I: Literature

The part ‘Literature’ consists of 8 chapters giving all the necessary information to understand what was done in the second part ‘Experimental part’. The first 4 chapters consist the theory. Chapter 1 about concrete and the environment attempts to show the importance of the subject of this thesis. In Chapter 2 the idea of packing is explained and in Chapter 3 the CPM is discussed more in detail. Chapter 4 consists of a summary of the design steps for an ecological concrete [Fennis, S.A.A.M., 2010]. In the following chapters, background information about the experimental part is given. Chapter 5 explains the tests on the aggregates while Chapter 6 explains the tests on concrete. Chapter 7 gives a survey of the used materials and Chapter 8 is the start of the experimental part with the idea behind the reference concrete.

Chapter 1 Ecological concrete

1.1 Concrete and the environment

Contradictory to some decades ago, nowadays the environment is becoming more and more important in political discussions. People realize that something has to change in our way of life. There are three main reasons for our environmental problems: the growth of the population on the earth, the industrial growth and the urbanization and the degree how a culture promotes wasteful consumption of natural resources. Based on assumptions, the evolution of the CO_2-level could be predicted. Figure 1-1 gives a prediction [Mehta, P.K., 2001].

As for the three most important reasons, it should be most effective to change the degree of how a culture thinks about the environment. Above all, the effect of a different way of thinking about our economic models and technological choices should have a larger effect than the one when something should change of the first two main reasons. Less waste of materials is the goal.

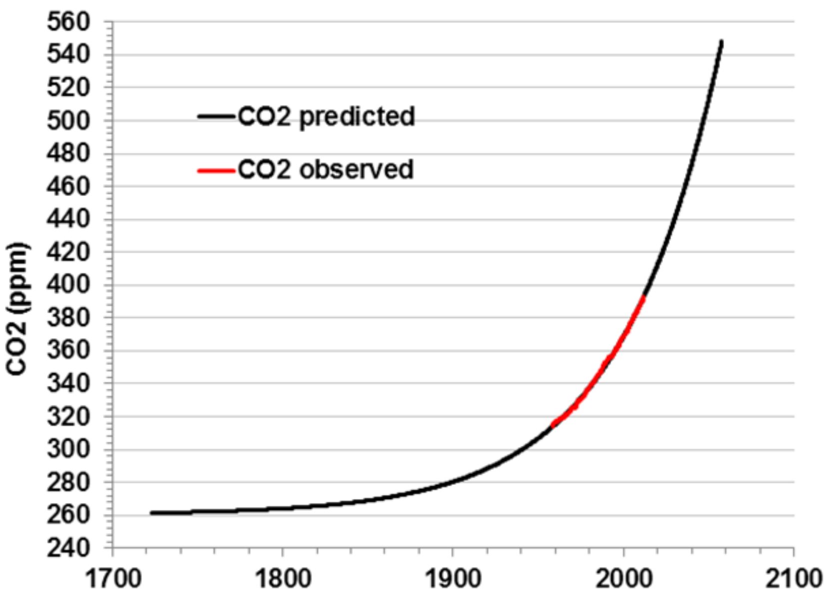


Figure 1-1: Prediction evolution CO_2

Nowadays, only 6% of the global flow of materials (500 billion tons a year) actually ends up in the desired products. The other 94% returns as harmful, solid, liquid and gaseous wastes.

Research about the way how we produce materials, and choices not only based on economic reasons, should make it possible to change that ratio in a positive direction. Certainly there is some margin. The natural capitalism has to be developed. A more efficient use of materials results in three significant benefits: slower resource depletion, less pollution and a worldwide employment increase [Mehta, P.K., 2001].

To have an influence on the global level the parts with the biggest proportion in that global level should be tackled first. Cement is a material with a big influence. The production/consumption of cement increases strongly these last decades: from 1.4 billion tons in 1994 to 3.4 tons in 2011. The economic development of China is partly responsible for that increase. This is shown in Figure 1-2.

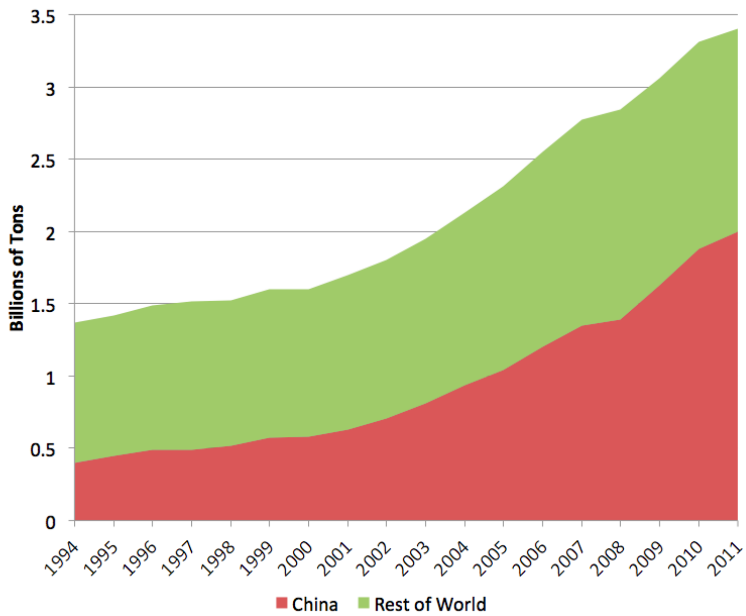


Figure 1-2: Evolution of cement consumption

Proportionally to the global flow of materials of 500 billion tons the amount of cement is not so big. Nevertheless the cement industry is responsible for about 6 % of the global loading of CO_2. This is shown in Figure 1-3. In most cases Portland cement is used and that's one of the most energy-intensive materials of construction. The production process is joined with a lot of heat and a large amount of greenhouse gases. Producing one ton of Portland cement requires approximately 4 GJ energy and 1 ton of CO_2 [Mehta, P.K., 2001].

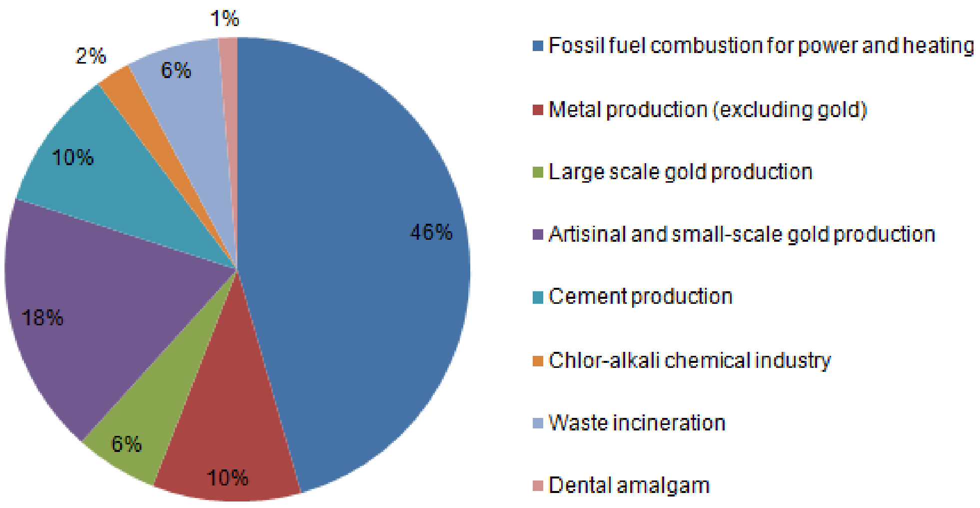


Figure 1-3: Global CO_2 loading [Mehta, P.K., 2002]

A typical concrete contains 12% cement and 80% aggregates by mass. This means that the concrete industry consumes dozens of billion tons of sand, gravel and crushed rock every year. Besides the aggregates a few trillion liter mixing water and an unknown amount of wash-water is used every year. Those materials (cement, aggregates & water) are not sufficient for a good concrete: you also need chemical and mineral admixtures. And what about the batching, mixing, transport, placement, consolidation and finishing of the concrete? It is clear that concrete is very energy-intensive [Mehta, P.K., 2001].

Instead of trying to lower the environmental impact of the production of concrete it is also possible to improve the durability of concrete. This results in a longer service life of the concrete and on the long run the concrete production could be lowered. Nowadays concrete is designed for a service life of 50 years. In practice it is often after 20 to 30 years that concrete structures start to deteriorate. Designing for a minimum service life of 100 to 120 years would have an enormous impact on the environment [The Cement Sustainability Initiative, 2014]

1.2 Environmental impact factors

Based upon previous part it should be clear how to reduce the environmental impact of the concrete production. There are two large different possibilities: reducing the amount of materials and energy in the production process and improving the durability of the produced mixtures. Following text gives a better view of those 2 possibilities.

1.2.1 Concrete durability: extending the service life

Improving the concrete durability presents a long-range solution for the improvement of the resource productivity of the concrete industry. If structural elements have a service life of 500 years instead of 50 years, the resource productivity jumps by a factor 10. What is the reason that our reinforced concrete structures start to deteriorate after 20 years while some of the unreinforced Roman concrete is still in a good condition after 2000 years?

Nowadays everything has to go fast in our lives, also the production of concrete elements. The most important industry goal is labor productivity, not resource maximization. This should be changed. A lot of Portland cement helps to fasten the hardening process but due to that there are more thermal contractions and also drying shrinkage and creep relaxation occur. Modern concrete mixtures are highly crack-prone and therefore they become permeable, which has a bad influence on the corrosion of the steel reinforcement and also on the durability. Romans used hydrated lime and volcanic ash in their concrete which led to a homogeneous hydration product that set and hardened slowly. They also used less water. Both differences result in a less crack-prone and hence, a highly durable concrete [Mehta, P.K., 2001].

In conclusion, leaving the way of thinking that high speed of construction and reducing the water content with the help of a superplasticizer for example, will result in more durable constructions. This is good for the environment. A practical example of such a project is already described [Langley, W.S., Mehta, P.K., 2000].

1.2.2 Reduction of the amount of water

At this moment there is not really a shortage of water but in the future this could become a problem. Only 3% of the water is fresh and a lot is locked up in fast-melting glaciers and ice caps, and so it is not possible to use all of that 3%. As with water we have the same problems with energy: we are exhausting non-renewable resources too fast. As with energy, also for water there should be searched for a more efficient use of the resources.

The concrete industry is one of the largest industrial consumers of fresh water so the impact of every change in water consumption by the concrete industry will be remarkable. In addition to approximately 100 l/m³ wash-water the concrete industry use about 1 trillion mixing water every year. It should be possible to lower this amount by better aggregate grading and by expanding the use of mineral admixtures and superplasticizers. A first step in the good direction would be to stop using drinking water for our concrete. Recycled industrial water is normally suitable for mixing water, wash-water and curing water. The necessary amounts of wash water and curing water could be minimized by different several measures [Mehta, P.K., 2001].

In this thesis the amount of water in a mixture should be lower than in the original mixture due to an optimized packing of the aggregates.

1.2.3 Reduction of the amount of aggregates due to recycling

About 66% of construction and demolition waste consists of concrete and masonry. Trying to use coarse aggregates derived from those wastes is a great opportunity to improve the resource productivity of the concrete industry. It is beneficial for the life cycle of the concrete/aggregates. Recycled concrete used as road fill is an example of down-cycling: virgin aggregates continue to be used for making new concrete. The more materials are used again, the lower the mining of new materials.

The problem of the recycled concrete aggregates is the fact that they have a higher porosity than natural aggregates, especially the masonry aggregates. More water is needed to give the concrete a same workability and that has a bad influence on mechanical properties of the hardened concrete. Using blends of natural and recycled aggregates of water-reducing admixtures with fly ash could cross this effect.

In this thesis the amount of aggregates will increase because the amount of water and cement will decrease due to an optimized packing and something has to compensate this. As the environment is concerned, this does not sound too good but there are still opportunities to use recycled aggregates, so that the environmental impact of the aggregates decreases in comparison with the actual situation. In this thesis this was not the goal. The goal was to research the impact of a decrease of the amount of cement on the environment, especially the emission of CO_2. The use of recycled aggregates could be a next step in this process of creating an ecological concrete. This was the subject of another thesis [Beirnaert, A., Ringoot, N., 2015].

Recycling concrete by the production of rubble granulates with the help of crushing plants creates a concrete life cycle as shown in Figure 1-4. As a consequence there is an economization on the use of virgin materials. Materials are used again. If there is no recycling, there is no life cycle. The life time stops with the dismantling process [De Schepper, M., 2014] [De Belie, N., Van den Heede, P., 2011].

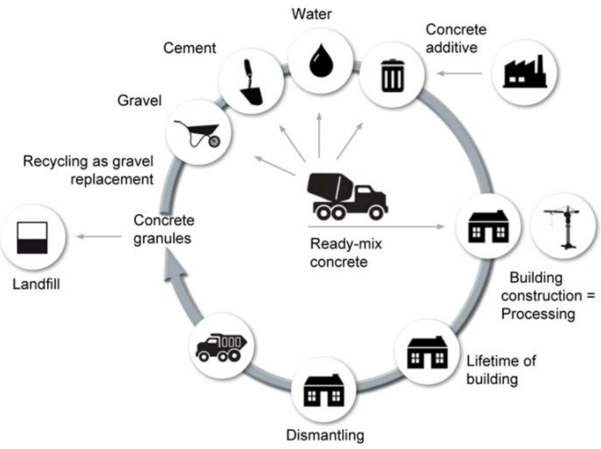


Figure 1-4: Lifecycle concrete

1.2.4 Reduction of cement and the use of replacement products

The energy consumption and greenhouse-gas emissions of concrete are mostly due to the use of cement. No other cements have the same qualities as the Portland cements for the setting, hardening and durability of the concrete. A first improvement would be an increased use of blends of Portland cement containing cementitious or pozzolanic by-products, such as ground granulated blast-furnace slag and fly ash.

Those materials replace partly the cement and that's good for the environment. A concrete with such a cement is sometimes more durable than a neat Portland cement is being used. The slower setting and hardening rate can be compensated by a reduced amount of water with the help of superplasticizers.

Due to the gain in strength of the optimized packing the amount of cement in the mixtures could be lowered in this thesis. This is very interesting for the environment. In this thesis different fillers will be used to replace the cement. The fillers have a different environmental impact and they behave different in the mixture: some have pozzolanic properties, other don't. A detailed survey and explanation about the fillers used in this thesis follows in 'Chapter 7: Used materials', where all the materials used in the mixtures are discussed.

In the replacement products for cement there is a difference between binders and fillers. Binders are a large group of materials that have a contribution to the strength of the concrete because their reactions form a product that could create a binding structure between inert particles. Fillers have no binding effects and act only as inert material: no reactions occur. In this thesis both types of replacement products will be used.

There are three types of binders: hydraulic binders, latent hydraulic binders and pozzolanic binders. Hydraulic binders react to water forming a cement gel. Portland cement is an example of this. Latent hydraulic binders have to be activated by for example alkalis or sulfates. The third category of binders is the one that could be used as cement replacement product: the pozzolanic binders/materials. Examples are fly ash and silica fume. They do not react with water. It is the reaction product of a hydraulic binder (Portland cement) and water that activates their reaction. An example of such a reaction is shown below. CSH (Calcium silicate hydrate) causing the binding of concrete is formed by $Ca(OH)_2$ (Calcium Hydroxide) which is the reaction product from Portland cement and water, SiO_2 (silicon dioxide) which is the main component of fly ash and silica fume and H_2O (water).

$$Ca(OH)_2 + SiO_2 + H_2O \rightarrow CSH$$

Contrary to binders, fillers do not react to other materials in the mixture. They are inert. Examples are quartz powder and limestone powder. In theory this is not completely the case but because the reactive part is negligible (5 %), it is assumed as inert in this thesis. Fillers do not have any direct contribution to the strength of the concrete, because they are inert. Indirectly, they may have a contribution because they may change the packing of the fine part of the materials and the packing influences the workability and also possibly the strength.

1.2.5 Influences of fillers

1.2.5.1 Workability

There is no general rule to predict what will be the effect of fillers on the workability. It depends on what filler is used. Differences can be caused by the size, the shape, the amount, the original concrete mixture and the use of superplasticizer. The use of a superplasticizer will always be beneficial, because it prevents flocculation of the filler. Due to flocculation, fillers would lose their influence of improving the packing partly. There are two different theories to predict something about the workability. First the water layer theory: the higher the specific surface (adding fillers), the lower the workability. Secondly the packing theory: the higher the packing (adding an ideal amount of fillers), the higher the workability. In practice a good balance between both theories is needed.

1.2.5.2 Strength

Because fillers are inert, it will be especially the size and the amount of the filler that will influence the strength of the mixture. Of course the effect of the filler on the water demand will also be important. Is it necessary to increase the amount of water because of the filler (higher specific surface), the concrete will be weaker. Can the amount of water be decreased because of the filler (higher packing), the concrete will be stronger. Most researchers agree that adding fillers will increase the strength [Fennis, S.A.A.M., 2010] [Dils, J., 2015].

1.2.5.3 Mechanical properties and durability

A higher packing and a lower water/cement ratio will restrain creep and shrinkage. The lower the amount of cement the lower the heat of hydration and drying shrinkage. If this is the case, the porosity should decrease and the microstructure should be more homogeneous and dense. This results in a more durable concrete. If adding a filler results in a higher water demand and consequently a weaker concrete, the effect of the filler would be adversely. So also in this case the properties of a concrete with fillers will depend on the characteristics of the filler and the effect on the concrete of adding the filler.

1.2.6 Influence of binders

Binders have two effects: the packing optimization effect of a filler and the effect of an additional chemical reaction due to its pozzolanic properties. It is difficult to separate both. Due to its second effect adding binders should result in stronger concrete. In this thesis, fly ash and silica fume will be used. The size of them has a big influence on the strength evolution of concrete.

1.3 Particle size optimization methods

The goal of this thesis is to create an ecological concrete by the optimization of the packing density of the materials in the concrete. That should result in a higher workability. In a next step it would be possible to reduce the water content, which leads to a stronger concrete. The last design step can be to decrease the amount of cement, in order to achieve the same strength as the original concrete. Doing these design steps should lead to an ecological concrete mix design.

Traditional design of mixtures starts with specifications about the mixture and based on that minimum contents cement and W/C recommendations can be found in documents such as the TRA 550 in Belgium. After taking into account air and admixtures, the remaining part of the design amount (1m³) is filled with aggregates. The question is always: what kind of aggregates and in which ratio? From the beginning, optimization curves were used to determine that. Nowadays they are still popular because they possess a lot of practical experience. With packing models a new and better way of proportioning the aggregates has emerged. Besides optimization curves and particle packing models also discrete element models are a third manner to determine the granular skeleton. Such a figure is shown in Figure 1-5. At this moment, calculations about those models on computers take too long. This is not interesting to optimize mixtures. A lot of research still has to be done and they are neither used or discussed in this thesis.

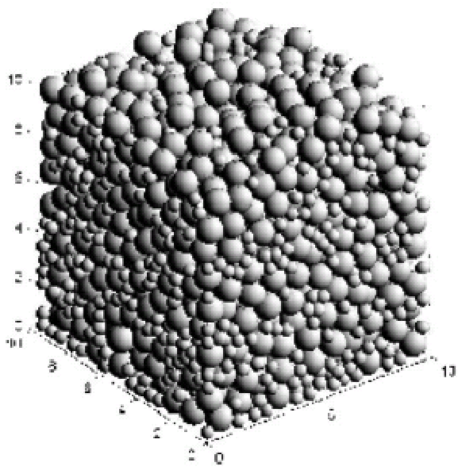


Figure 1-5: Discrete element model [Fennis, S.A.A.M., 2010]

1.3.1 Optimization curves

The idea was to design an ideal size distribution. Examples are the curve of Fuller and of Andreasen and Andersen [Fuller, W.B., Thompson, S.E., 1907] [Andreasen, A.H.M., Andersen, J., 1930]. An optimization curve or a given grading area makes sure that there is sufficient material from each size. Based on experiences, producers know what are good aggregate compositions for concrete.

The Fuller curve, equation (1.1) is one of the most used optimization curves worldwide. Since Fuller proposed his curve some adjustments were done but the principle remains the same. The Fuller curve depends on the maximum particle size in the concrete skeleton (d_{max}). For each particle size, equation (1.1) calculates the passing rate (P).

$$P(d) = (\frac{d}{d_{max}})^q \tag{1.1}$$

While Fuller proposed 0.5 for q, Andreasen and Andersen proposed to use an exponent q in the range between 0.33 and 0.5 depending on the application and the angularity of the aggregates. Funk and Dinger did in 1980 an adaptation to take into account the minimum particle size (d_{min}). This is shown in equation (1.2). A smaller exponent results in more fine aggregates in the aggregate composition. This results in curves as in Figure 1-6 if the maximum particle size is 32 mm.

$$P(d) = \frac{d^q - {d_{min}}^q}{{d_{max}}^q - {d_{min}}^q} \tag{1.2}$$

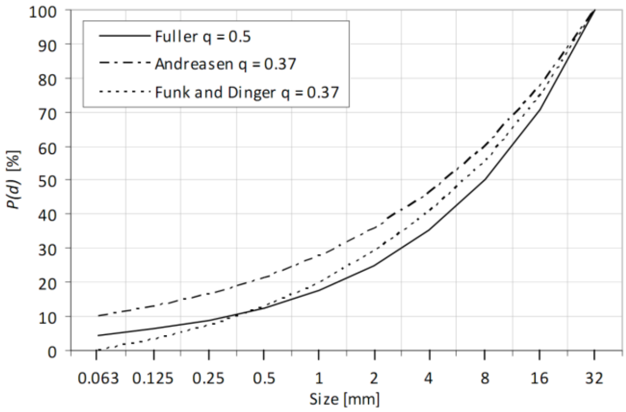


Figure 1-6: Optimization curves [Fennis, S.A.A.M., 2010]

Starting from the sieve curves of the individual aggregates it is possible to approximate the optimization curve with the help of the least squares method. Result of that method is the proportion of each individual aggregate to compose the concrete skeleton.

1.3.2 Particle packing models

With particle packing models it is possible to prescribe how particles with different size interact geometrically with each other, based on mathematical equations. Particle packing models use the particle size distribution and the packing density.

Furnas was the first to propose equations. His model was valid for two monosized groups of particles without interaction between the particles. Meanwhile packing models evolved and they were extended to multiple particle groups. Dewar and De Larrard were responsible for the last evolutions. Their models are the most recent and the best applicable ones [De Larrard, F., 1999] [Dewar, J.D., 1999].

So the function of a packing model is to calculate the theoretical maximal packing density of a mixture based on the particle size distribution of the aggregates and their individual packing density. To find that maximum, it is necessary to calculate the packing density of each possible combination of volumes between the aggregates. That combination with the highest packing density is the one that should be applied in the composition of the concrete skeleton of the concrete mix according to the packing theory. In 'Chapter 2: Packing', the concept packing is defined and explained further. Also some packing models will be discussed.

1.4 Evaluation of the environmental impact

To investigate the environmental influence of the mixtures the Dutch tool 'Groen Beton' was used. It is a tool developed by SGS Intron for the CUR-organization. That's an independent neutral Dutch organization of research in the construction [SGS Intron B.V., 2013].

This tool calculates, based on a database of materials, an environmental profile of concrete elements in constructions. It makes use of the contribution of eleven environmental effects of materials necessary for the production of concrete. The result is expressed as an Environmental Cost Indicator. The higher the value, the higher the environmental impact of the mixture. The eleven environmental effects and their weight factors are listed up in Table 1-1.

Table 1-1: The eleven environmental effects [SGS Intron B.V., 2013]

Environmental effect	Equivalent unity	Weight factor [€/kg equivalent]
Abiotic depletion, non-fuel (ADP)	kg Sb eq	0.16
Abiotic depletion, fuel (ADP)	kg Sb eq	0.16
Global warming (GWP)	kg CO_2 eq	0.05
Ozon layer depletion (ODP)	kg CFC-11 eq	30
Photochemical oxidation (POCP)	kg C_2H_4 eq	2
Acidification (AP)	kg SO_2 eq	4
Euthrophication (EP)	kg PO_4 eq	9
Human toxicity (HT)	kg 1.4 DB eq	0.09
Ecotoxicity, fresh water (FAETP)	kg 1.4 DB eq	0.03
Ecotoxicity, marine water (MAETP)	kg 1.4 DB eq	0.0001
Ecotoxicity, terrestric (TETP)	kg 1.4 DB eq	0.06

Impact category	MatProcType	depletion, non fuel (AD)	depletion, fuel (AD)	warming (GWP)	depletion (ODP)	cal oxidation (POCP)	acidification (AP)	eutrophication (EP)	human toxicity (H	fresh water (FAETP)	marine water (MAETP)	terrestric (TETP)	primary (MJ)	primary, renewab	primary, non-renewabl	Water, fresh water use	
Unit		kg Sb eq	kg Sb eq	kg CO2 eq	kg CFC-11 eq	kg C2H4	kg SO2 eq	kg PO4--- eq	kg 1,4-DB eq	kg 1,4-DB eq	kg 1,4-DB eq	kg 1,4-DB eq	MJ	MJ	MJ	m3	Bron
SBK CEM-I NL c2	bindmiddel	6.7E-07	5.7E-04	8.2E-01	5.2E-09	2.1E-04	2.7E-03	3.6E-04	5.0E-02	6.9E-04	5.1E+00	6.8E-04	7.0E+00	6.5E-01	6.3E+00	1.2E-01	MRPI
SBK CEM-III NL c2	bindmiddel	6.7E-07	8.5E-04	3.0E-01	5.4E-09	9.0E-05	1.0E-03	1.0E-04	2.7E-02	3.4E-04	8.2E+00	3.6E-04	3.3E+00	2.1E-01	3.0E+00	3.3E-02	MRPI
CEM III-A NL gemiddeld c3	bindmiddel	6.7E-07	7.7E-04	4.4E-01	5.4E-09	1.2E-04	1.5E-03	1.7E-04	3.3E-02	4.4E-04	7.3E+00	4.5E-04	4.3E+00	3.3E-01	4.0E+00	5.7E-02	Groen
CEM III-B NL gemiddeld c3	bindmiddel	6.5E-07	8.0E-04	3.0E-01	5.2E-09	9.0E-05	1.0E-03	1.0E-04	2.7E-02	3.4E-04	7.8E+00	3.6E-04	3.2E+00	2.2E-01	3.0E+00	3.4E-02	Groen
SBK Hoogovenslakken	vulstof	7.6E-10	1.7E-04	1.9E-02	1.1E-09	1.0E-06	5.8E-06	1.4E-06	3.6E-03	4.6E-06	2.0E+00	2.7E-06	3.8E-01	2.1E-04	3.8E-01	4.0E-04	NMD
SBK Betonzand (Nederland)	primair toeslagmateriaal fijn	1.3E-09	2.0E-05	2.9E-03	3.1E-10	2.3E-06	1.8E-05	4.2E-06	1.9E-03	3.1E-05	2.0E-01	1.1E-05	4.3E-02	5.9E-04	4.3E-02	1.2E-03	NMD
Zand (D)	primair toeslagmateriaal fijn	7.1E-09	2.7E-05	3.8E-03	3.1E-10	2.0E-06	1.6E-05	3.9E-06	2.2E-03	3.3E-05	1.7E-01	1.3E-05	6.1E-02	2.1E-03	5.9E-02	1.0E-02	NMD
SBK Zeezand - betonzand	primair toeslagmateriaal fijn	3.4E-09	7.4E-05	1.1E-02	1.3E-09	1.0E-05	7.9E-05	1.8E-05	8.0E-03	1.3E-04	7.4E-01	2.3E-05	1.6E-01	1.1E-03	1.6E-01	4.0E-03	NMD
Brekerzand (primair)	primair toeslagmateriaal fijn	1.9E-08	6.9E-05	9.0E-03	5.7E-10	3.1E-06	2.9E-05	6.1E-06	4.3E-03	5.4E-05	5.5E-01	3.2E-05	1.5E-01	5.8E-03	1.4E-01	1.4E-02	NMD
SBK Grind, rivier	primair toeslagmateriaal grof	1.2E-10	7.1E-06	1.1E-03	1.7E-10	3.6E-07	1.4E-06	2.3E-07	1.6E-04	8.4E-06	5.2E-02	7.0E-07	1.5E-02	3.8E-05	1.5E-02	2.1E-04	NMD
SBK Noordzeegrind	primair toeslagmateriaal grof	3.1E-09	7.2E-05	1.1E-02	1.3E-09	1.0E-05	7.9E-05	1.8E-05	7.9E-03	1.3E-04	7.3E-01	2.0E-05	1.5E-01	9.9E-04	1.5E-01	3.8E-03	NMD
Steenslag (D)	primair toeslagmateriaal grof	3.2E-09	5.9E-05	8.3E-03	7.1E-10	7.1E-06	5.6E-05	1.4E-05	1.7E-02	9.3E-05	3.9E-01	1.9E-05	1.3E-01	3.7E-03	1.3E-01	1.4E-02	Groen
Steenslag (BE)	primair toeslagmateriaal grof	3.1E-09	4.3E-05	6.2E-03	6.8E-10	7.1E-06	5.7E-05	1.3E-05	1.7E-02	8.9E-05	4.4E-01	1.7E-05	1.3E-01	1.6E-03	1.3E-01	5.7E-03	Groen

Figure 1-7: Screenshot database 'Groen Beton'

Each material in the database has values for those eleven environmental effects. Figure 1-7 shows, as illustration, a part of the database. Multiplying those values with the mentioned weight factors leads to an environmental cost for 1 kg of that material as this environmental effect is concerned. Multiplying that cost with the mass of that material in a mixture of 1m³ gives the environmental cost of that material for 1m³ concrete concerning this environmental effect. The sum of all those contributions of the different materials in 1m³ concrete results in the Environmental Cost Indicator.

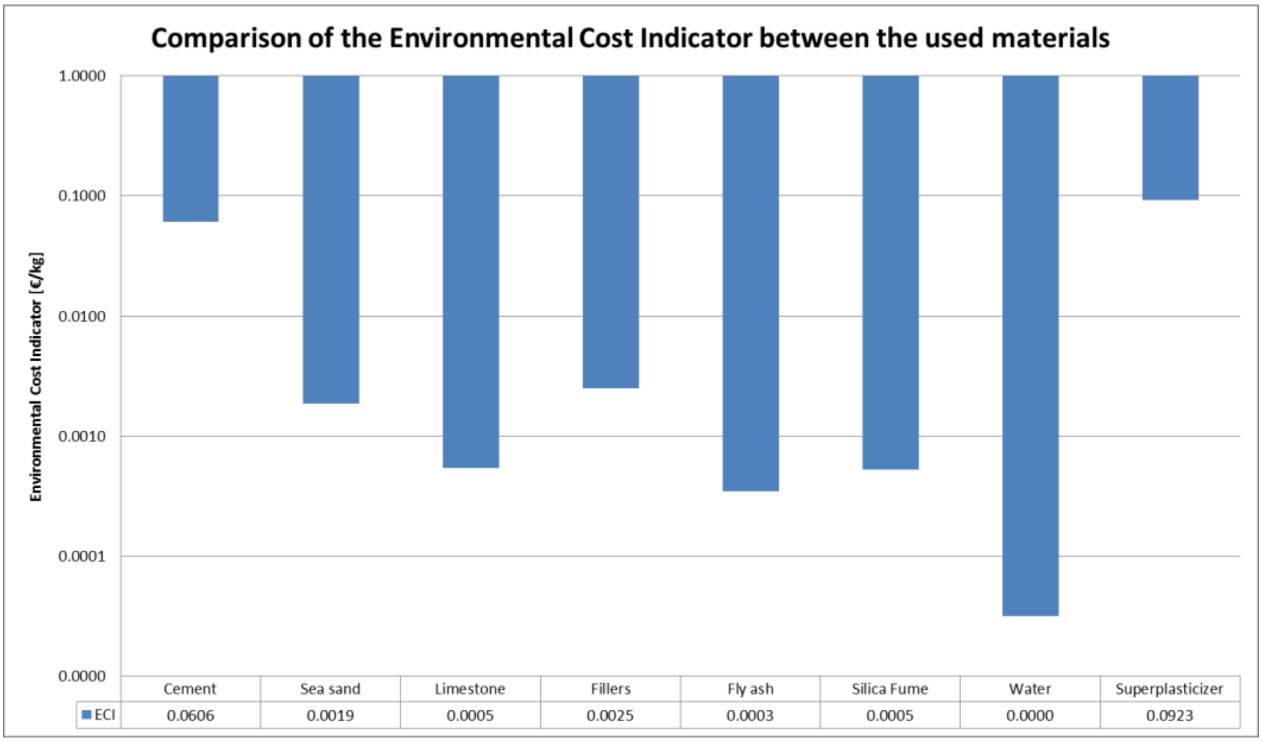
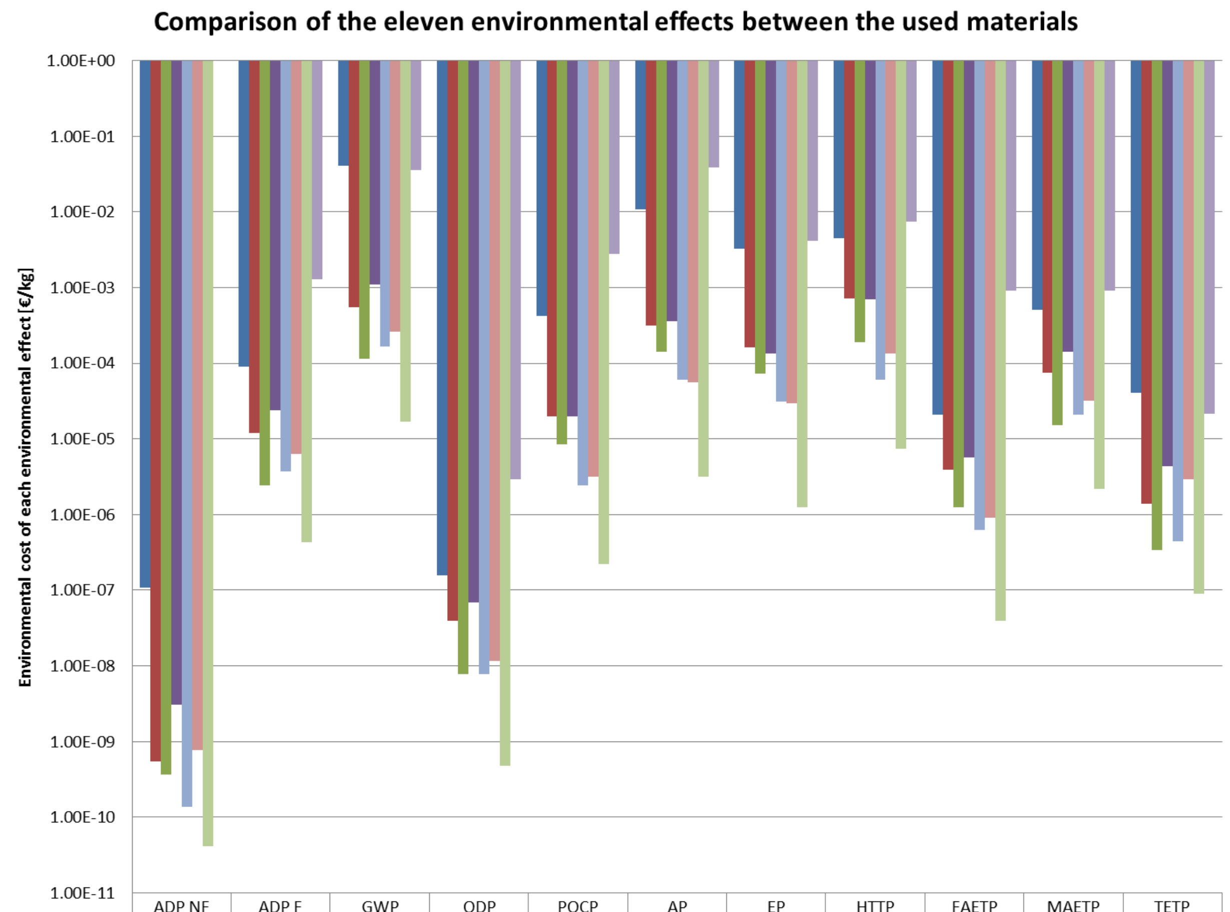


Figure 1-8: ECI of the used materials

Because the clumsy manner of entering a mixture in the tool and the detailed way of comparing environmental impacts of different mixtures an own Excel sheet was developed based on the data in the database of the tool 'Groen Beton'. That makes it easier to adjust mixtures and to control results. It makes it also possible to look at intermediate results. In Figure 1-8 these effects are summed up, which leads to the Environmental Cost Indicator of each material used in this thesis.

On Figure 1-9 the eleven environmental effects are compared on a logarithmic scale for all the materials used in this thesis. It is already clear that Global Warming is one of the most important factors. Values on Figure 1-8 and Figure 1-9 are compared on a logarithmic basis because the difference between values is too large. The lower the bar, the smaller the value. Table 1-1 explains the abbreviations for the different environmental effects.



	ADP NF	ADP F	GWP	ODP	POCP	AP	EP	HTTP	FAETP	MAETP	TETP
Cement	1.07E-07	9.12E-05	4.10E-02	1.56E-07	4.20E-04	1.08E-02	3.24E-03	4.50E-03	2.07E-05	5.10E-04	4.08E-05
Sea sand	5.44E-10	1.18E-05	5.50E-04	3.90E-08	2.00E-05	3.16E-04	1.62E-04	7.20E-04	3.90E-06	7.40E-05	1.38E-06
Limestone	3.68E-10	2.40E-06	1.15E-04	7.80E-09	8.40E-06	1.40E-04	7.29E-05	1.89E-04	1.26E-06	1.50E-05	3.42E-07
Fillers	3.04E-09	2.40E-05	1.10E-03	6.90E-08	1.96E-05	3.56E-04	1.35E-04	7.02E-04	5.70E-06	1.40E-04	4.32E-06
Flya ash	1.36E-10	3.68E-06	1.65E-04	7.80E-09	2.40E-06	6.00E-05	3.15E-05	6.03E-05	6.30E-07	2.10E-05	4.44E-07
Silica fume	7.68E-10	6.24E-06	2.60E-04	1.17E-08	3.20E-06	5.60E-05	2.97E-05	1.35E-04	9.00E-07	3.20E-05	2.88E-06
Water	4.16E-11	4.32E-07	1.70E-05	4.80E-10	2.20E-07	3.20E-06	1.26E-06	7.47E-06	3.90E-08	2.20E-06	9.00E-08
Superplast	0.00E+00	1.30E-03	3.60E-02	2.88E-06	2.80E-03	3.88E-02	4.14E-03	7.38E-03	9.00E-04	9.10E-04	2.16E-05

Figure 1-9: Comparison of the eleven environmental effects

In the tool it is possible to add the environmental impact of the transport of materials and for the production of specific concrete elements. In this thesis the Environmental Cost Indicator is calculated for 1m³ ready-mixed concrete. Production effects of specific materials or of the transport of materials were neglected because that is not the issue in this thesis. Only the impact of the mixtures is important.

From Figure 1-8 it is clear that the environmental impact of 1 kg superplasticizer is the largest one, but superplasticizer is only a small part in a mixture. According to this tool, it will always be the cement that has the biggest influence on the environment.

The database of the materials is rather large but in this thesis some special fillers were used that were not present in the database such as clay and limestone powder. Adding materials is nearly impossible because it is very difficult to determine the values of a material for these eleven environmental effects. According to Dr. ir. Steffen Grünewald, it is a good approximation to take the same values for clay and limestone powder as for quartz powder. In Figure 1-8 and Figure 1-9 these three cement replacing materials were called 'Fillers'. This is not completely correct but an abbreviation was necessary to make the graphs visual acceptable. In 'Chapter 7: Used materials' the difference between those materials are explained.

The end result of the tool 'Groen Beton', the Environmental Cost Indicator, is the summation of the masses of the used materials for 1m³ concrete times the values for the weight factors mentioned in Figure 1-8. This is the background information for the calculation and the results of the Environmental Cost Indicator in the experimental part of this thesis.

1.5 Evaluation of the economic impact

Besides the ecological effect of mixtures, also the economic part of it will be important. This is also calculated in this thesis, based on the costs for the used materials when they are ordered in big amounts by big companies. It was asked to keep these costs secret so only relative values will be mentioned, no absolute values. Table 1-2: Economic comparison contains the costs of the used materials and the cement was used as a standard.

In the experimental part of this thesis the economic cost of each produced mixture was calculated. Also for the total cost of 1m³ of a mixture, no absolute values will be used. The cost of each mixture will be mentioned and compared in the experimental part of this thesis in the same way as in Table 1-2 with the reference concrete as reference.

Table 1-2: Economic comparison – based on volumes

Material	Relative cost [-]
CEM I 52.5 N	1
Water	0.05
6.3/20	0.20
2/6.3	0.22
0/4	0.19
0/2	0.09
S90	0.22
Tixo	7.35
Air	0.00
Limestone powder	0.44
Quartz powder M400	2.03
Quartz powder M800	13.95
Silica fume	6.34
Fly ash	0.37
Portaclay	20.28

.

Chapter 2 Packing

2.1 Definitions

The packing density (α) of a mixture of different aggregates, shown in equation (2.1) is defined as the ratio of the solid volume of the particles (V_p) to the bulk volume of the particles (V_b). The bulk volume is the total volume of the container, in which the particles are stored

$$\alpha = \frac{V_p}{V_b} = \frac{\rho_b}{\rho_p} = \frac{m_p}{\rho_p V_b} \tag{2.1}$$

For coarse and dry materials this could be determined with a compaction test. The bulk density (ρ_b) is the ration between the mass of the particles (m_p) and the volume of the container. If the density of the particles (ρ_p) is known, it is possible to calculate the packing as in equation (2.1). The density of the particles could be determined by a pycnometer test. It is also possible to express the packing as a porosity of the mixture (ε) or as the amount of pores (e). This is shown in equations (2.2) and (2.3).

$$\varepsilon = 1 - \alpha \tag{2.2}$$

$$e = \frac{\varepsilon}{\alpha} = \frac{1}{\alpha} - 1 \tag{2.3}$$

Concrete is a composite material, consisting of aggregates that are glued by a binder. A good mix of particles with different sizes, will result in less pores. The higher the packing, the lower the voids content or the amount of pores. A lower voids content means less cement paste and is necessary to fill the voids or pores. Also the water demand should be lower. From an ecological point of view these are beneficial effects.

In concrete packing varies from 0.55 to 0.80. Porosity varies between 0.45 and 0.20. This has to be filled by the cement paste. Porosity determines the minimum amount of the volume of cement paste. To give the mix a sufficient workability, it is necessary to give the mixture an excess amount of the paste [Fennis, S.A.A.M., 2010].

According to the environment, it is already clear that a higher packing is beneficial. Also for the producers of concrete this would be good, because cement is one of the most expensive components. Lowering that amount means more margin. Also for the engineer it is interesting to lower the amount of cement because the hydration heat and drying shrinkage are directly proportional to the amount of cement. Less cement means less cracks.

2.2 Influencing factors

The packing density of a mixture aggregates with different size classes depending on the particle size and the size distribution, the angularity of the aggregates and the way in which they are packed individually [De Larrard, F., 1999].

2.2.1 The particle size and size distribution

The particle size is important for the packing density of fine materials, not for the packing density of coarse materials. There is a fundamental difference between packing of small materials and packing for coarse materials. The border is situated at a size of approximately 100 µm [Fennis, S.A.A.M., 2010].

Coarse particles are only influenced by granular interaction forces. Gravitation and shear forces are the most influencing forces. For smaller particles, the packing is normally lower. This is because they have a higher specific surface and a lower mass: the surface area to the volume ratio is higher. Also weak short-distance forces have an influence. The most important surface forces are the van der Waals forces, the electrostatic double layer forces and the steric forces. The surface forces could be influenced by the water and the superplasticizer [Fennis, S.A.A.M., 2010].

2.2.2 Shape of the particles

Shape can be characterized by the overall shape, the roundness and the surface texture. In theory these characteristics are independent of each other. However, it is possible that there is a relation between them, because physical processes could have influence on more than one characteristic.

The overall shape expresses the relation between the three dimensions of a particle. So it indicates when a particle is elongated, flat or rather spherical. The more particles are spherical, the better for the packing density. The roundness expresses the sharpness of possible corners. It could be subdivided in rounded, sub-rounded, sub-angular or angular. The roundness of angles is important to describe the abrasive and crushing resistance. The roundness of the perimeter is important for interlocking properties and packing density. The surface texture could be subdivided in very rough, rough, smooth or polished. This is a function of the size and sharpness of protrusions and indentations on the surface. Normally this is less important for the packing density. It is more determining for the adhesion ability between the particles and the cement paste [Kwan, A.K.H., Moa, C.F., 2001].

Angular particles have advantages and disadvantages. They help to maintain a homogenous mixture because they complicate segregation due to interlock. On the other hand, spherical particles minimize interparticle friction so packing density could be higher. With rounded particles less compaction energy is needed to achieve the maximum packing because they improve the workability. Angular aggregates needs more compaction energy to achieve the same packing density. It is not certain that it will be possible to achieve a same packing density. Otherwise their structure is stronger and more stable. An ideal situation is a mix. If the ratio of angular particles is small (+- 10%), the packing density is not significantly decreased. Due to the higher interparticle friction, the compact strength will be increased.

2.2.3 Packing method

The packing density is in function of the amount of energy that is added to a mixture. There is a remarkable difference in packing if particles are trilled and mixed or not. If particles are loosely deposited, the loose packing density is measured. This is the situation where the amount of pores is the highest.

Adding energy can be done by vibration or by mixing. With the vibrations, the pores will open themselves and other particles will fill the gaps. The mass of the particles is responsible for the addition packing. With mixing, an external force is added and gravity will have a higher influence in comparison with a mixture that is not mixed. The K-value is a constant indicating how much energy is added to the mixture. More energy results in a higher K-value.

A mixture of two aggregates can illustrate this very well. As you can see in Figure 2-1 the ratio between the two components is important. This illustrates what was said in paragraph ‘2.2.1: The particle size and size distribution’: there is an ideal amount of fine material to fill the gaps between coarse materials. More or less fine materials will result in a lower packing density. Also the influence of the compaction, the K-value, is shown in Figure 2-1. A higher K-value means more compaction energy is added and results in a increased packing density. There is also a shift of the optimum to the left. That indicates that less fine materials are necessary. This is related to the fact that the added energy is responsible for a better packing of the coarse materials, and so less fine materials are needed to fill those gaps.

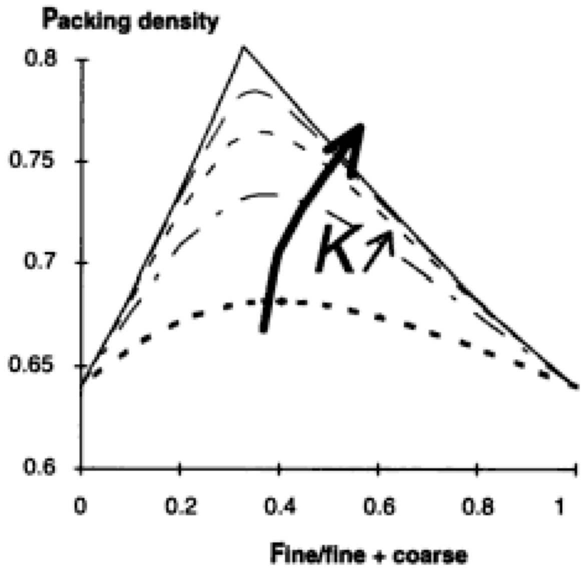


Figure 2-1: Comapaction energy - parameter K [De Larrard, F., 1999]

2.3 Structures

Based on the forces acting on the particles they could move away from each other or come closer to each other. That is the way how an independent particle structure is formed. In this particle structure, different effects could occur, which influences the packing density of the total mixture.

2.3.1 Geometrical interaction

Depending on the ratio of the particle size, the particle shape and the presence of different particle classes, two geometrical interactions could occur: the loosening effect and the wall effect.

When fine particles fill gaps between large particles, the packing will increase. This is the reason why the packing of an aggregate with a uniform size distribution increases if the size distribution becomes wider. Not only the number of different size classes is important, also the amount of material in each size class is important. If there are too much fine materials, they could push larger particles away from each other. When the fine materials are not fine enough, it is also possible that they push larger particles away. This is called the loosening effect and this is one of the reasons why the particle size and the size distribution are important parameters for the packing. Figure 2-2 illustrates this.

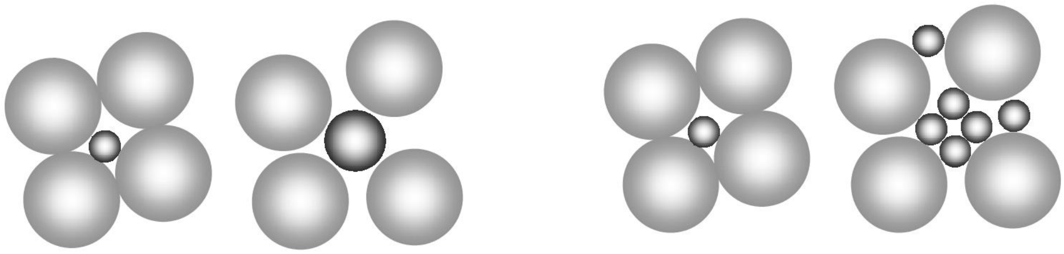


Figure 2-2: Illustration of the loosening effect [Fennis, S.A.A.M., 2010]

The wall effect is caused by the wall of the formwork in which the concrete is deposited. The smaller the volume of the formwork, the more the concrete will feel the wall and the higher its influence. Due to the wall the packing is not random but forced to some kind of ordered packing. Ten particle diameters from the wall could be needed to establish truly random packing. The distance depends on the packing structure and the shape of the formwork. The wall of the formwork behaves as a large particle. The wall effect will have a higher influence on mixtures with a high packing density, consisting of smoother, flatter or monosized spherical particles.

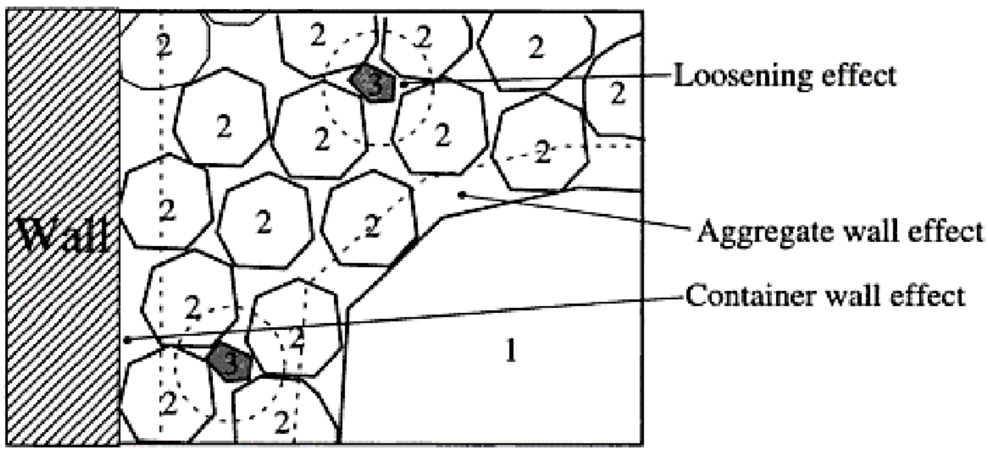


Figure 2-3: Illustration of wall effect and the loosening effect [De Larrard, F., 1999]

Figure 2-3 shows how the wall effect and the loosening effect could occur. As can be seen also one big particle could be responsible for the wall effect. Figure 2-4 shows the influence of the wall effect on the packing density in function of the distance to the wall.

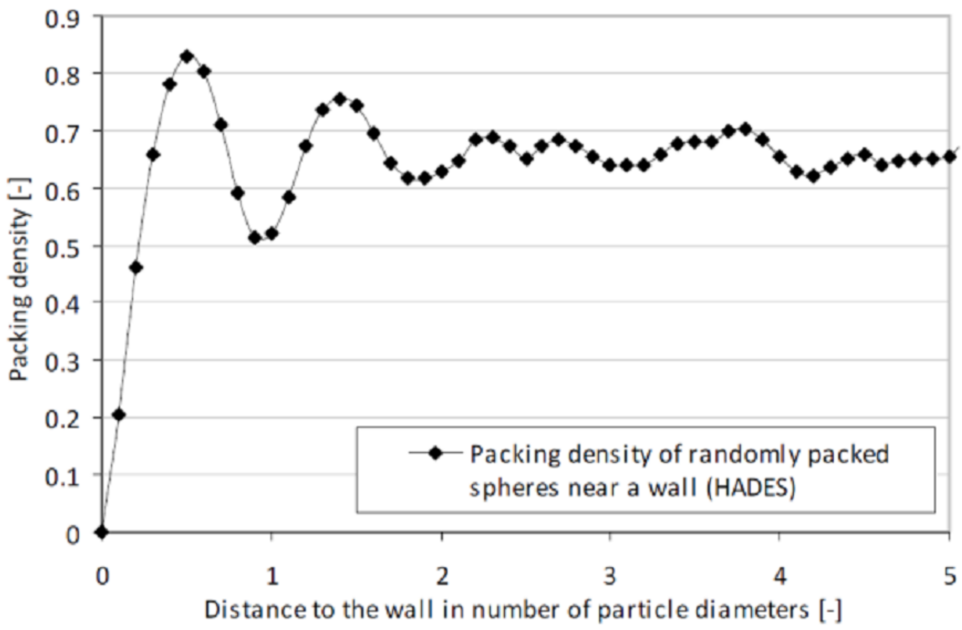


Figure 2-4: Influence of the wall effect on the packing density [Fennis, S.A.A.M., 2010]

2.3.2 Agglomeration

Surface forces between small particles as the van der Waals force, could attract those particles to each other. Due to this, relative movements of those particles between each of them are limited and agglomerates could be formed. This is the case when the combination of the van der Waals attraction, the electrostatic charges and the chemical bonding is larger than the gravitation and the shear force. Gravitation force, shear force and electrostatic forces try to break up the agglomerates while the van de Waals forces and chemical bonding causes attraction between particles. The size of the agglomerates depends on the size and size distribution of the particles, the shape and the surface roughness, the wettability of the particles and the viscosity and distribution of the liquid.

Due to agglomeration, the procedure of mixing and compacting becomes more difficult. The packing density will be lowered because agglomerates themselves are separated by high porosity regions. This is shown in Figure 2-5. The use of superplasticizer and a sufficient amount of mixing energy could break the agglomerates.

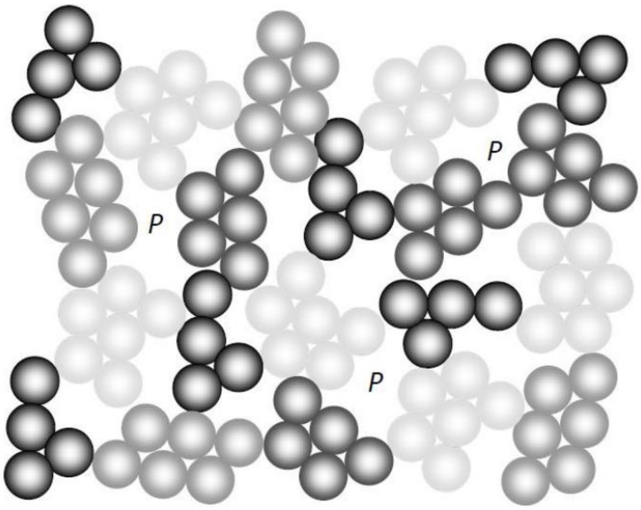


Figure 2-5: Agglomeration [Fennis, S.A.A.M., 2010]

2.3.3 Segregation

When variations in particle size, densities and shape are too high, segregation can occur. The gravitational forces are higher on the large particles and this causes a non harmonious packing structure. Also vibrations can be the reason for segregation. Segregation leads to point to point variations in the packing density, and so the overall packing density decreases. Also mechanical properties of the concrete will be adversely influenced.

An irregular particle shape diminish the possibility that segregation occurs. Segregation will also occur faster in mixture with coarse particles. The smaller the particles, the higher interparticle friction and the lower the chance that segregation can occur. The presence of smaller particles in a mixture also increases the viscosity, so that there is a higher resistance for coarse particles to segregate.

2.3.4 Arch building

Arch building is the creation of an arch by a number of particles. Due to arches, large pores beyond the arch arise. Pores lower the packing density. The more angular shapes the particles have, the higher the possibility that arches occur. Also the presence of smaller particles with sticky or cohesive surfaces increases the chances that arch building occurs. Mostly arch building will occur in the neighborhood of the wall of the formwork. Good vibration of the mixture could solve the problem of arch building.

2.4 Determining the packing

There are different methods to determine the packing. Which method has to be used depends on the size of the particles and personal preferences. General rule is that the packing has to be determined in the way how the particles are used. Globally seen, there are two methods to determine the packing: a dry one and a wet one. Because concrete is always in wet state it is logical to think that packing always must be determined with the wet method. The advantage of the wet methods is that they reduce the surface forces if the mixture is saturated. Because coarse particles only are affected by gravitation and shear forces and not really by surface forces it is also allowed to test them on a dry manner.

So for coarse aggregates (> 1 mm) a dry method is used because little surface forces occur and it is not necessary to use the wet method. There is a norm available to determine the loose packing density of a material: NBN EN 1097-3:1998. This describes how to fill a container and to measure the volume and the mass of them. With those results the packing could be calculated with expression 2.1. To know the maximal particle packing this method has to be adapted. In this thesis the adapted dry method was used. Because all executed tests are described in ‘Chapter 5: Executed tests on aggregates’, I refer to that chapter for more details.

For particles smaller than 125 µm a wet method has to be used because surface forces are gaining in importance. Those forces could be responsible for the agglomeration which leads to a lower packing density. Using a wet method means the mixture is saturated with polycarboxylate ether-based superplasticizers (PCE’s) to reduce surface forces. Two tests are proposed by Sonja Fennis: the water demand by determining mixing energy test of Marquardt and the centrifugal consolidation test of Kjeldsen and Miller [Fennis, S.A.A.M., 2010]. Because it was not necessary in this thesis to test packing in a wet manner, these tests are not explained [Bosmans, T., Van Der Putten, J., 2014].

2.5 Packing models

Packing models are used to determine the maximal packing density for different combinations of coarse aggregates (> 125 µm). There are also packing models to determine the packing of small particles (< 125 µm) but a lot of research is still necessary to make those models more accurate.

During the history, a lot of packing models were developed, every time with a higher performance. This thesis makes use of the Compressible Packing Model (CPM) [De Larrard, F., 1999]. In ‘Chapter 3: CPM‘ this packing model will be discussed in detail. In this paragraph other packing models will be shortly mentioned [Fennis, S.A.A.M., 2010].

The Furnas model was one of the first packing models in 1929. It was developed by Furnas. It is only valid for 2 groups of monosized particles without interaction between the particles. This means that the diameters of both groups monosized particles have to be clearly different. If they are too similar effect as the wall effect and the loosening effect occur. Current models make still use of the equations of Furnas.

In 1976 Toufar presented his Toufar model. He tried to implement interaction between particles if the diameters were rather equal. In his first model something was not correct: adding fine material in a sample of coarse particles does not lead to an increase of the packing. Therefore an adaptation was done and the modified Toufar model was developed. The goal of it was to estimate the packing of a multicomponent system. However, with his formula, the packing density was always underestimated. The more size classes were used, the higher the deviation. A stepwise calculation procedure could partly solve that problem. The modified Toufar model is limited to the prediction of the packing density of a mixture consisting of two monosized particle classes.

The Dewar model presented in 1999 by Dewar was something not really based on previous models. It calculates a voids ratio and this is linked to the porosity and the packing density. Starting with the smallest two size classes, the voids ratio and a new characteristic diameter is calculated. Step by step, this process goes on with the following size class. Based on the mean size and the amount of each monosized particle class, a total voids ratio of a concrete mixture can be calculated. However, due to the stepwise calculation the model becomes progressively slower with increasing amount of size classes, and the use of an average diameter leads to an underestimation of the packing density.

The Linear Packing Density Model by Stovall in 1986 and F. De Larrard in 1999 was an improvement of the Furnas model in two major respects. It was a multi-component model, instead of a two-component model, and it was able to take into account geometrical interaction between particles: the wall effect and the loosening effect. The Linear Packing Density Model has two disadvantages: the way how the mixture is packed does not have any influence and due to the linearity, the value of the optimal packing density was always overestimated. Further adaptations and research were necessary.

The Schwanda Model looks likes the Dewar Model. It also calculates a maximum voids ratio which corresponds to the minimum voids content and the maximum packing density. It considers three cases. Case 1 and 2 can be derived from the Furnas Model. Case 3 is the transition zone between case 1 and 2. In case 1 small particles fill up the voids between large particles. In case 2 there are much more fine particles than there are voids. In case 3 this is rather in balance. In 2000 Reschke described that the Schwanda model could be used for aggregates, fillers or a combination of both. The model can be extended to any desired amount of size classes. The set-up of the model creates possibilities to implement additional interaction effects.

The Linear-Mixture Packing Model from Yu and Standisch developed in 1991, makes a distinction between filling or additive components and occupying or mixing components. If particles are so small that they only fill gaps and they do not disturb the packing, than they are regarded as a filling or additive component. If they do not fit into the voids, they disturb the packing and a new packing structure is formed. The model is developed for predicting the packing density of mixtures, consisting of spherical particles. Initially, the model was not able to handle varying monosized packing densities and this is often the case for angular particles or very fine agglomerated particles. The Modified Linear Packing Model solved that problem.

Besides the CPM, discussed in next chapter, also the CIPM exists. This was developed by Sonja Fennis in her PhD [Fennis, S.A.A.M., 2010]. It is an extension of the CPM with additional factors to directly take into account effects by small particles, such as the creation of agglomerates or other phenomena during mixing and compaction.

Chapter 3 CPM

Paragraph '2.5: Packing models' gives a survey of the history of packing models. All of them have some limitations: the Toufar model and the Schwanda model are mathematically inconsistent regarding the calculated packing density, because of the way the size classes get grouped. The Dewar model becomes less accurate and increasingly time consuming with an increased number of size classes, due to the stepwise approach and The Linear-Mixture Packing Model can not handle varying monosized packing densities of the components. The CPM is the most accurate model, because it includes compaction and can therefore directly be used for wet and dry packing densities.

The Compressible Packing Model (CPM) was an extension of the Linear Packing Density Model [De Larrard, F., 1999]. It can include the compaction energy (K) during the mixing. It also calculates a virtual compactness β. This is the maximum potential packing density of a mixture, if the particles would have been placed one by one in such a way that they use the minimum amount of space. In other words, this means that the added compaction energy would be infinite. Regular monosized spheres would give a β-value of 0.74. If they would be randomly packed the β-value would be in the range of 0.60 – 0.64.

The virtual packing density of a mixture containing n size classes with category i being dominant is expressed in the general model equation as β_{ti}, shown in equation (3.1) [De Larrard, F., 1999].

$$\beta_{ti} = \frac{\beta_i}{1 - \sum_{j=1}^{i-1}\left[1 - \beta_i + b_{ij}\beta_i\left(1 - \frac{1}{\beta_j}\right)\right] r_j - \sum_{j=i+1}^{n}\left[1 - a_{ij}\frac{\beta_i}{\beta_j}\right] r_j} \tag{3.1}$$

With equation (3.2) it is possible to determine the value β_j for a monosized particle class with the help of the packing density α_j, that is experimentally determined. This is explained in paragraph '5.3: Packing density'. Equation (3.2) is in fact the link between the packing method (K), the virtual packing (β_j) and the actual packing (α_j). In equation (3.3) it is written in function of the packing method or the compaction energy.

$$\alpha_j = \frac{\beta_j}{(1 + \frac{1}{K})} \tag{3.2}$$

$$K = \frac{1}{\frac{\beta_j}{\alpha_j} - 1} \quad (3.3)$$

In the general model equation, also factors a_{ij} and b_{ij} are present. They represent the loosening effect, equation (3.4), and the wall effect, equation (3.5). They depend on the ratio between the particle diameters of class i and class j. They are determined by an evaluation with the CPM for binary mixtures [De Larrard, F., 1999].

$$a_{ij} = \sqrt{1 - (1 - \frac{d_j}{d_i})^{1.02}} \quad (3.4)$$

$$b_{ij} = 1 - (1 - \frac{d_i}{d_j})^{1.50} \quad (3.5)$$

The coefficients a_{ij} and b_{ij} from equations (3.4) and (3.5) are constant for a given size-ratio. The size ratio is a value between 0 and 1 and is defined as the diameter of a small size class, divided by the diameter of a large size class. The number of size classes is 'n' and the diameters of the size classes are ordered from d_1 (largest size class) to d_n (smallest size class). For the loosening effect the size-ratio is d_j/d_i. For the wall effect the size-ratio becomes d_i/d_j. This is because index j (of the larger size class) is always smaller than index i (of the dominating size class). Figure 3-1 is a graphical representation of the value for the wall effect and the loosening effect depending on their size-ratio. The loosening effect is larger for small size-ratios. For a size-ratio higher than 0.72 the wall effect becomes the most important geometrical interaction.

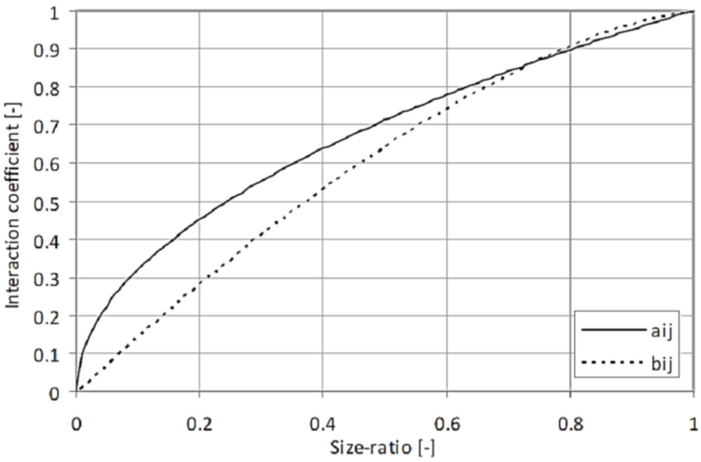


Figure 3-1: Wall effect and loosening effect related to size ratio [Fennis, S.A.A.M., 2010]

The virtual packing density β_t will always be higher than the real packing density α_t. This is because the added compaction energy can not be infinitely large. The compaction index K depends on the applied compaction and is a constant that is introduced to determine the real packing density based on the virtual packing density. The more a mixture is compacted, the higher the value is for the compaction index K and the more the real packing density should approximate the virtual packing density. With equation (3.6) the real packing density could be calculated indirectly based on the virtual packing density and the compaction index.

$$K = \sum_{i=1}^{n} K_i = \sum_{i=1}^{n} \frac{\frac{r_i}{\beta_i}}{\frac{1}{\alpha_t} - \frac{1}{\beta_{ti}}} \qquad (3.6)$$

Because K depends on the compaction energy applied to a mixture, it should be determined for each compacting process. For each size class the packing density and the accompanying compaction index K should be determined experimentally. Whit equation (3.6) it is possible to determine the K. If this is done, it is possible to predict the packing density of any mixture composition with the CPM. In Table 3-1 experimentally determined K-values are given for different compaction processes. Make sure the K-value is validated, before starting to predict packing densities with the CPM. For this thesis the CPM and the compaction processes were already investigated by a previous thesis so indirectly the K-values were validated [Bosmans, T., Van Der Putten, J., 2014]. Their conclusion was that the best correlation was found with a value of 9 for K. This is the case for a dry packing process when the mixture is vibrated and compacted with a pressure of 10 kPa. This was also used in this thesis to determine the packing density in paragraph ‘5.3: Packing density’.

Table 3-1: Experimentally obtained K-values [Fennis, S.A.A.M., 2010]

Packing process		K-value
Dry	Pouring	4.1
	Sticking with a rod	4.5
	Vibration	4.75
	Vibration + compaction (10kPa)	9
Wet	Smooth thick paste	6.7
	Proctor test	12
Virtual	-	∞

In conclusion, the CPM predicts the packing density of a mixture based on the size distribution and the packing densities of each monosized particle class. By way of α the particle shape and surface texture is indirectly taken into account. The interaction formulas a_{ij} and b_{ij} and the value for K determines the accuracy of the model.

Chapter 4 Design of an ecological concrete

Designing an ecological concrete can start from a reference concrete mixture. In 'Chapter 8: Reference concrete' the reference concrete for this thesis is shown. To start with the design process, it is important to determine all the necessary characteristics of the components of the mixture: densities, size distributions, packing densities measured with a suitable test.

If those parameters are known in a first step, the ratio between the used aggregates will be checked and, if necessary, adapted based on results of packing models. The new mixture of aggregates should be the one with the highest possible packing. That composition of the skeleton will lead to a concrete mixture with less pores. If the amount of water in the mixture stays the same as in the reference concrete, the workability will be higher due to an increased amount of excess water. Lowering the amount of water is the logical second step in designing an ecological mixture. It is possible to calculate theoretically how much water is needed. A lower amount of water will lead to a strength increase in comparison to the reference concrete. If this is not the goal of the optimization, the amount of cement could be lowered and this gives an ecological benefit.

The design of an ecological concrete is a cyclic procedure. Figure 4-1 shows how this cyclic procedure always keeps going on. For most of the designed/produced concrete mixtures, strength is the most important parameter of the mechanical properties. This parameter is a controlling parameter in the design procedure. The cyclic design can start on two positions in the triangle. If the ecological mixture starts from a total new mixture, the procedure starts in the top. If an ecological concrete is designed based on an existing concrete, the procedure starts in the top of the triangle. This was the case in this thesis.

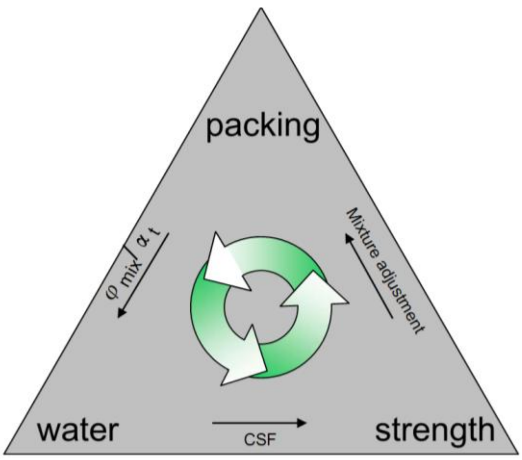


Figure 4-1: Cyclic process of designing an ecologic concrete [Fennis, S.A.A.M., 2010]

The procedure is a cyclic one, because every time the packing changes, this has consequences for the water demand and for the strength of the mixture. If also the fine materials as the cement and powders are taken into account for the packing the optimization process will take longer. This is because the design process of an ecological concrete is iterative. Lowering the amount of cement and adding a cement replacing material for example, would change the calculated packing density, so the design should start again.

In this thesis only the parts >125 µm were regarded for the packing because of 2 reasons: in the packing of smaller particles there are still too much uncertainties and the added amounts of cement replacing materials were not that large (< 10 %) that they would have a big influence on the packing. A previous thesis shows for example an optimal packing is achieved when 20% of the cement volume was replaced by silica fume [Bosmans, T., Van Der Putten, J., 2014]. Next paragraphs specify more each step in the cyclic design more in detail. In the experimental part of this thesis this explanation will be coupled to a calculation example.

4.1 Optimization of the packing

The skeleton of the concrete has to be composed in such a way, that the packing density is the highest possible one. Packing models are able to calculate the packing density for each possible combination. This thesis is based on the CPM-model. Based on an Excel sheet, it is possible to calculate packing densities of aggregate mixtures. In the beginning of this thesis, an Excel sheet was already available based on 15 size classes and 3 different aggregates. During the thesis this was extended. Now it is possible to calculate packing densities of combinations between 6 different aggregates and 40 size classes.

For each possible material influencing the packing density, some characteristics has to be known: the dry density, the particle size distribution and the packing density α of that material in combination with the compaction index K, depending on the applied compaction process to determine that packing density. Besides, it is also necessary to give the CPM the combination(s) for which the packing density has to be calculated. Because the goal is to look which combination results in the highest packing, all possible combinations must be calculated. Making all possible combinations was done manually, using some tips and tricks from Dr. ir. Van Coile. The number of combinations depends on the number of aggregates and the accuracy of the steps in between for the ratio of each aggregate.

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P
1		Name	%	Pdensity (for each size class)	Kvalue				#comb 2 componenten		11		Virtual packing density		0.669815	
2	1	GG	0	0.52149	9	0.587411		OK	#comb 3 componenten		66					
3	2	FG	0	0.52845	9	0.604198			#comb 4 componenten		286		K value mixture		9	0.0
4	3	GZ	0	0.60333	9	0.724198			#comb 5 componenten		1001					
5	4	FZ	0	0.59852	9	0.670821			#comb 6 componenten		3003					
6	5	S90	1	0.55902	9	0.615450							Packing density		0.615451	
7	6															
8																
9		(Leave blank if the value is N/A)													Solve	
10		sizes class	GG	FG	GZ	FZ	S90	0								
11	1	40	0	0	0	0	0			11	21	31	41	51		11 21 31 41 51
12	2	31.5	0	0	0	0	0			12	22	32	42	52		12 22 32 42 52
13	3	22.4	0.695807	0	0	0	0			13	23	33	43	53		13 23 33 43 53
14	4	20	5.127616	0	0	0	0			14	24	34	44	54		14 24 34 44 54
15	5	16	19.40226	0	0	0	0			15	25	35	45	55		15 25 35 45 55
16	6	12.5	23.29099	0	0	0	0			16	26	36	46	56		16 26 36 46 56
17	7	8	38.15755	0	1	0	0			17	27	37	47	57		17 27 37 47 57
18	8	6.3	9.082896	3.457251315	1.399286	0.036413	0			18	28	38	48	58		18 28 38 48 58
19	9	4	2.497754	30.15542806	5.504874	0.27107	0			19	29	39	49	59		19 29 39 49 59
20	10	2	0.311007	51.6171873	9.084008	1.030302	0			110	210	310	410	510		110 210 310 410 510
21	11	1.096478196	0.109982	9.376547756	10.025220	2.788125	0			111	211	311	411	511		111 211 311 411 511
22	12	1	0.011744	1.001229199	1.070494	0.297716	0			112	212	312	412	512		112 212 312 412 512
23	13	0.954992586	0.008713	0.123432618	2.035088	0.785878	0			113	213	313	413	513		113 213 313 413 513
24	14	0.831763771	0.023855	0.337954436	5.572003	2.151707	0			114	214	314	414	514		114 214 314 414 514
25	15	0.72443596	0.020777	0.294346009	4.853012	1.874058	0			115	215	315	415	515		115 215 315 415 515
26	16	0.630957344	0.018096	0.256364658	4.226796	1.632237	0			116	216	316	416	516		116 216 316 416 516
27	17	0.549540874	0.015761	0.22328428	3.681386	1.421619	0			117	217	317	417	517		117 217 317 417 517
28	18	0.5	0.00959	0.13586561	2.240076	0.865037	0			118	218	318	418	518		118 218 318 418 518
29	19	0.478630092	0.01999	0.053276794	3.423886	5.963362	0			119	219	319	419	519		119 219 319 419 519
30	20	0.416869383	0.057774	0.15397411	9.895299	17.23458	0.4			120	220	320	420	520		120 220 320 420 520
31	21	0.363078055	0.050319	0.134105842	8.618445	15.0107	1.7			121	221	321	421	521		121 221 321 421 521
32	22	0.316227766	0.043826	0.116801307	7.506352	13.07377	3.9			122	222	322	422	522		122 222 322 422 522
33	23	0.27542287	0.038171	0.101729686	6.537759	11.38678	6.9			123	223	323	423	523		123 223 323 423 523
34	24	0.25	0.023782	0.063381134	4.073251	7.094358	7.367999			124	224	324	424	524		124 224 324 424 524
35	25	0.239883292	0.015802	0.023705345	0.669469	1.363345	2.932001			125	225	325	425	525		125 225 325 425 525
36	26	0.208929613	0.048348	0.072530276	2.048348	4.17137	13.3			126	226	326	426	526		126 226 326 426 526
37	27	0.181970086	0.042109	0.063171229	1.784037	3.633112	14.9			127	227	327	427	527		127 227 327 427 527
38	28	0.158489319	0.036676	0.055019842	1.553831	3.164308	14.8			128	228	328	428	528		128 228 328 428 528
39	29	0.138038426	0.031943	0.047920279	1.353330	2.755997	12.9			129	229	329	429	529		129 229 329 429 529
40	30	0.125	0.020365	0.030551478	0.862813	1.75708	7.17363			130	230	330	430	530		130 230 330 430 530
41	31	0.120226443	0.060554	0.162065451	0.096814	0.018253	2.62637			131	231	331	431	531		131 231 331 431 531
42	32	0.104712855	0.196796	0.526696681	0.314636	0.059322	6.3			132	232	332	432	532		132 232 332 432 532
43	33	0.091201084	0.171402	0.458733656	0.274036	0.051667	3.3			133	233	333	433	533		133 233 333 433 533
44	34	0.079432823	0.149285	0.399540327	0.238676	0.045	1.3			134	234	334	434	534		134 234 334 434 534
45	35	0.069183097	0.130022	0.347985048	0.207878	0.039193	0.2			135	235	335	435	535		135 235 335 435 535
46	36	0.063	0.078435	0.209920276	0.125401	0.023643	0			136	236	336	436	536		136 236 336 436 536
47																
48																
49																
50																
51																
52																
53			OK	OK	OK	OK	OK	OK				100				
54																

Figure 4-2: Screenshot from the Exceltool [Fennis, S.A.A.M., 2010]

Figure 4-2 shows the input field. Each aggregate has a name, mentioned in cells B2:B7. The ratio of the aggregates in the mixture is entered in cells C2:C7. In cells F2:F7 the experimentally found packing value is entered. Based on the K-value in cells E2:E7 the packing density for each size class can be found by trial and error and is expressed in cells D2:D7. For example for the sand S90 the following was done: 100% of S90 (cell C6) with a packing density of 0.55902 for each size class, results in a packing density of 0.615451 (cell O6) and that is approximately the same value as the experimental found packing density for S90 in cell F6. If cells O6 and F6 have not the same value when 100% of S90 is taken, cell D6 should be adapted until the moment, when cells O6 and F6 are the same.

In fact, this is a reversed way of applying the CPM. Normally the CPM calculates the packing density of different size classes based on packing densities of individual size classes. Now the packing densities of individual size classes are determined by the experimental determined packing density of the aggregate.

In cell O1 and O6 packing densities are expressed. Cell O1 express the packing density when the compaction energy is infinite. Cell O6 express the real packing density with a K-value of 9. In cells B11:H50 it is possible to enter the particle size distributions. Because the size distribution of S90 was determined with a laserdiffractometer and other aggregates were manually sieved some interpolation calculations were done. With these interpolations calculations it is possible to have values for each size class, even if they were not measured. In cell H2 it was checked if the sum of C2:C7 is 1, which should always be the case. Cells B53:H53 check if the sum of all the size classes is 1. Also this should always be the case.

Also attention has to be paid to the K-value of 9 in cell O3. This is related to the manner how the compaction test, described in paragraph '5.3: Packing density', is executed to obtain a value for the packing.

Calculating the packing density for each combination was done with a VBA script, that takes the values of each combination, copies them in cells C2:C7, calculates the packing density and copies the result from cell O6 to a cell next to the relevant combination.

4.2 Optimization of the workability

The concrete mixture composed according to the aggregate composition with the highest packing determined in previous step should have a higher workability because the amount of pores is minimal. If the design of an ecological concrete starts from an existing mixture this would be especially the case. This is because the optimized mixture has less pores compared to the original aggregate mixture, which results in an increased amount excess water. Because the strength of concrete is related to the W/C factor, the overdose of water created by the packing optimization could decrease the strength of the concrete mixture.

According to the theory of Sonja Fennis [2010], there is a link between the workability of a mixture and the amount of water in combination with the packing density of the mixture. The packing density of the mixture is expressed with the parameter α_t and is by way of the compaction index K related to the virtual packing density β_t. This explanation was already given in paragraph '2.2.3: Packing method'. The amount of water is expressed by a new parameter φ_{mix}, which represents the amount of solids in the mixture. Equations (4.1) and (4.2) show the relation.

$$\varphi_{mix} = \frac{V_p}{V_{tot}} = \frac{V_p}{1} \tag{4.1}$$

$$V_{tot} = 1 = V_p + V_{water+air+superplasticizer} \tag{4.2}$$

The ratio φ_{mix}/α_t is directly related to the workability, which could for example be expressed by a flow value [Fennis, S.A.A.M., 2010]. This is shown in Figure 4-3. Due to the optimization of the packing of the mixture in previous step, the value for α_t will increase. The ratio φ_{mix}/α_t

should decrease. Figure 4-3 shows that the flow value or the workability would increase. This corresponds to the theoretical idea: higher packing results in less pores and this means an additional surplus of water in the mixture, to improve the workability. Based on the relation it should be possible to calculate/predict the flow values based on the ratio φ_{mix}/α_t but this is not the case in this thesis because that relation is not generally valid. It is a relation which is specific for a mixture, for the type of superplasticizer and the dose of it. If sufficient data would be available, a similar relation could be proposed. This was done in the experimental part.

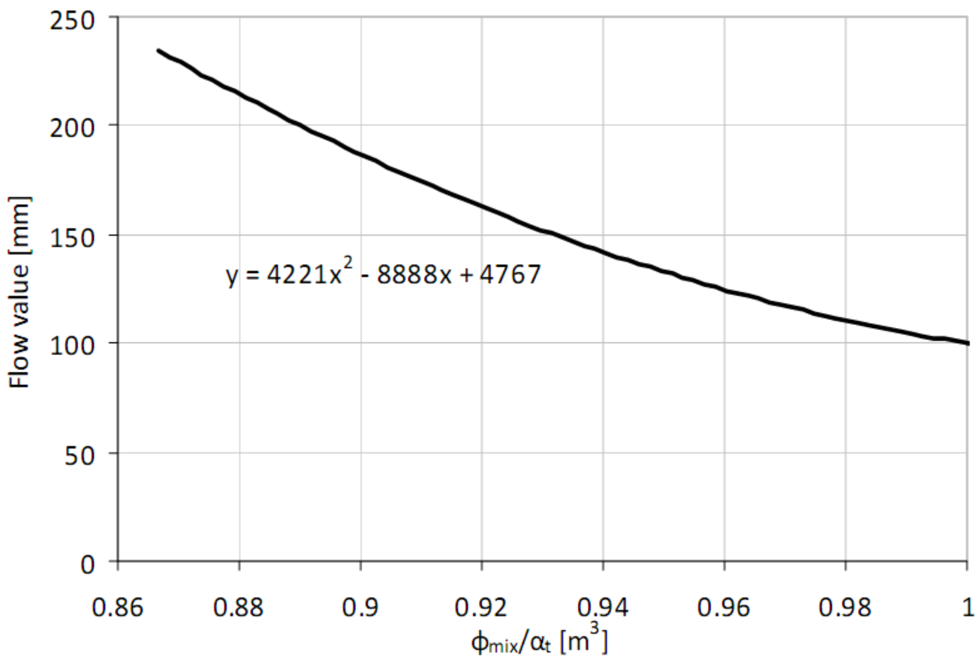


Figure 4-3: Link between ratio φ_{mix}/α_t and the flow value [Fennis, S.A.A.M., 2010]

In case the ecological concrete was not based on an existing mixture, a ratio φ_{mix}/α_t equivalent with a desired flow value could be chosen. Because α_t is known from the CPM, the value for φ_{mix} could be calculated and then it is possible to calculate the amount of water. In this thesis a reference concrete was used as a starting point. To reduce the increased workability of the optimized mixture, the ratio φ_{mix}/α_t of the optimized mixture should be equalized to the ratio φ_{mix}/α_t of the reference mixture, while adjusting the amount of water (φ_{mix}) in the optimized mixture. This is expressed in equation (4.3). Equation (4.4) calculates the φ_{mix} of the optimized mixture. Based on equations (4.1) and (4.2) equation (4.5) could be written, with ‘water, air, superplasticizer’ abbreviated to ‘w,a,s’. In equation (4.6), equation (4.5) is rewritten in function of the unknown. Equation (4.7) calculates what was searched for.

$$\frac{\varphi_{mix,optimized}}{\alpha_{t,optimized}} = \frac{\varphi_{mix,reference}}{\alpha_{t,reference}} \tag{4.3}$$

$$\varphi_{mix,optimized} = \frac{\varphi_{mix,reference}}{\alpha_{t,reference}} \alpha_{t,optimized} \tag{4.4}$$

$$\varphi_{mix,optimized} = \frac{V_{tot} - V_{w,a,s}}{V_{tot}} \tag{4.5}$$

$$V_{w,a,s} = V_{tot} - \varphi_{mix,optimized} V_{tot} \tag{4.6}$$

$$V_{water} = V_{w,a,s} - V_{air} - V_{superplasticizer} \tag{4.7}$$

With previous equations, a lower amount of water in comparison to the reference mixture should be found, and so the composition of the optimized mixture has to be adapted to that. The excess amount of water, taken out of the mixture, is compensated by an increased amount of the aggregates in the same ratio as calculated in the first design step. Because the packing density is only calculated based on the coarse particles, this proportional increase in amount of aggregates has no influence on the packing density α_t.

4.3 Optimization of the strength

Normally, previous design steps should result in a stronger concrete. This is not the goal of the new mixture. The goal was to design an ecological mixture, by lowering the amount of cement. In this last design step this was done.

There should be a relation between the strength and an introduced Cement Spacing Factor (CSF) [Fennis, S.A.A.M., 2010]. This is shown in Figure 4-4 and with equation (4.8) in which φ_{cem} is the amount of cement in the mixture and φ_{cem}^* is the maximum volume that cement could occupy in presence of the other particles. That relation makes it possible to predict the strength of mixtures that were determined according to previous design steps. Because this relation was specific for her data, it could not be used in this thesis. This relation was not checked in this thesis because φ_{cem}^* was unknown.

$$CSF = \frac{\varphi_{cem}\varphi_{mix}}{\varphi_{cem}^*\alpha_t} \tag{4.8}$$

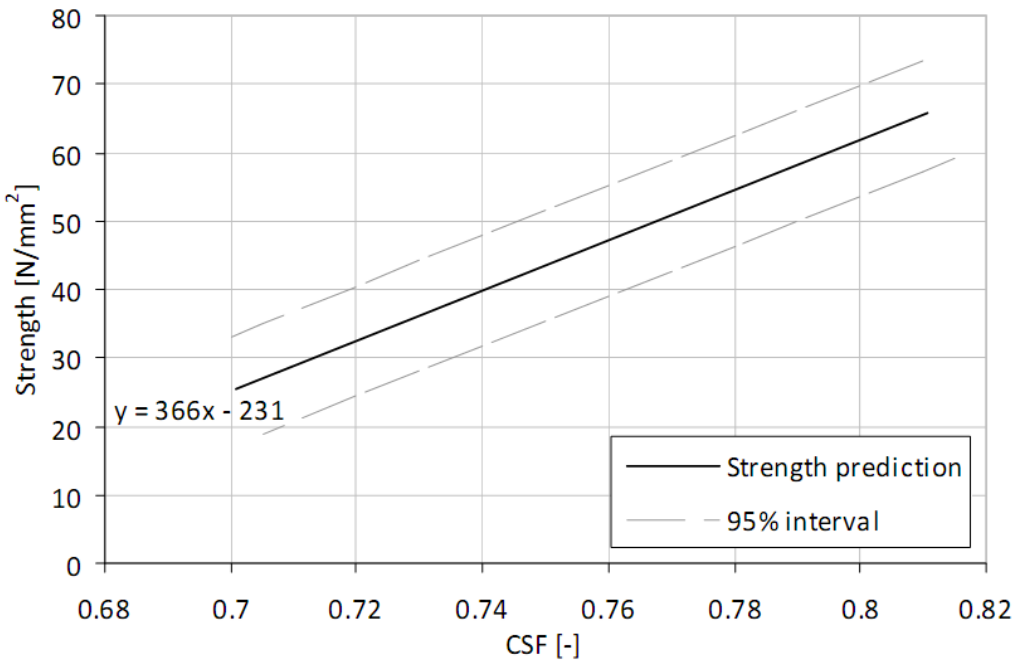


Figure 4-4: Relation between CSF and strength [Fennis, S.A.A.M., 2010]

Based on the measured strength increase of the produced mixtures a rule of was applied to reduce the amount of Cement. A mass percentage of the cement was replaced by a cement replacing material. That mass percentage was equivalent with the strength increase, after seven days, of the optimized mixture to the reference concrete [Fennis, S.A.A.M., 2010].

The first part of this chapter mentioned that the design of an ecological mixture was a cyclic process. However, in this thesis the optimization stopped here. This is because only the packing of the aggregates was taken into account. If the packing of fine materials would be taken into account, a new optimization cycle could start. Replacing an amount of cement by a cement replacement product changes the packing density.

Chapter 5 Executed tests on aggregates

As mentioned in previous chapter, tests have to be done on the aggregates to know their characteristics. These tests are necessary for the CPM. The CPM needs the particle size distribution and the packing density of each aggregate. To determine the packing density, also the density of particles has to be determined. Following paragraphs describe which tests were done on the aggregates and how they were executed. A survey of the used aggregates in this thesis is given in 'Chapter 7: Used materials'. The results of the tests are given in the experimental part of this thesis.

5.1 Particle size distribution

The particle size distribution is necessary because packing models are based on size classes. The size distribution is an indication of how many particles are present in a size class. Coarse materials could be sieved. For finer materials a laserdiffractometer should be used. In theory, for this thesis, it was not necessary to have a particle size distribution of the fine materials but it was done to make it possible to compare the fine materials with each other, and to have an idea of the mean size.

5.1.1 Sieve curves

The sieve test of materials was executed in agreement with the NBN EN 933-1:2012 and with sieves of the ISO-3310 series. The used sieves were the same as in the work of Sonja Fennis and are listed up in Table 5-1 [Fennis, S.A.A.M., 2010]. For the limestone aggregates all the sieves were used, for the sand the 6 largest ones were not used. The aggregates were not washed before they were sieved because the amount of fine materials in them was assumed limited. From every aggregate, three independent sieve tests were done. An average of them was further on used for the calculations. Attention was paid to the starting mass, which is related to the maximum particle size and has to satisfy a minimum value. No mechanical vibration was used. The total pile of sieves was shaken manually and then every sieve was shaken separately and manually during one minute until the amount of aggregates, falling through the sieve, was lower than the directive in the norm. Figure 5-1 shows the pile of sieves.

Table 5-1: Used sieves

Used sieves
40
31.5
22.4
20
16
12.5
8
6.3
4
2
1
0.5
0.25
0.125
0

Figure 5-1: Pile of sieves for limestone aggregates (left) and sands (right)

5.1.2 Laserdiffractometer measurements

Cement and cement replacing materials are too small to be sieved. More accurate results on the particle size distribution could be determined with a laserdiffractometer. In the laboratory the Malvern Mastersizer 2000 was used. It is possible to use it with a wet unit and a dry unit. Because with the wet unit risk the on agglomeration is lower this was preferred. Table 5-2 and Table 5-3 show the characteristics of the laserdiffractometer and the Hydro SM, the wet unit. In Figure 5-2 both can be seen.

Figure 5-2: Laserdiffractometer and Hydro SM (wet unit)

Table 5-2: Characteristics laserdiffractometer

Type	Mastersizer 2000
Measuring range	0.02 – 2000 µm
Measuring principle	Mie-method

Table 5-3: Characteristics Hydro SM (wet unit)

Pump speed	350 – 3500 rpm
Maximum discharge	2.3 l/min
Maximum volume	50 – 120 ml
Maximum particle size	600 µm
Time between two measurements	< 60 s

The measurements were based on the laser light scattering technique (LLS). This is based on the fact that diffraction angels are inversely proportional to the particle size. An analysis of the projection of the diffracted light wave, makes it possible to calculate the size of the particles based on the Lorenz-Mie model. Besides the diffracted light wave, this model also takes into account the broken and reflected light wave. A good knowledge of the optical properties of the materials is very important. These are expressed as a real and an imaginary part of the refraction index with equation (5.1) [Bosmans, T., Van Der Putten, J., 2014].

$$N = n - ik \tag{5.1}$$

- N [-] = the refraction-index
- n [-] = the real part of the refraction index depending on the used material
- ik [-] = the imaginary part of the refraction index. It characterizes the total absorption of the particles and is also depending on the used material.

In the database of the software, values for the real and the imaginary part of the refraction index are stored. It is important to select the correct material. Also the color of the material has an influence because this is related to the absorption index. Besides the optical properties, also geometrical properties are important: for each material the correct particle shape has to be chosen: irregular or spherical.

For each powder the same test procedure was used. Also here for each powder at least three measurements were done. An average of three qualitative measurements was taken as a final result. For each measurement 1 g of the powder was weighed. Than 50 ml isopropanol was added as dispersion medium. It is necessary to use isopropanol because some powders are reactive. To support the dispersion the mixture of the powder and isopropanol was, during 5 minutes, placed in an ultrasonic bath which was also filled with isopropanol at a frequency of 35 kHz. After the dispersion the mixture was injected with a pipette in the wet unit until the obscuration limit was reached. This is an indication for the concentration of the mixture in the wet unit. This was between 12% and 15%. The wet unit was for each test filled with 90 ml isopropanol and the pump speed was always 800 rpm.

5.2 Density

The density of particles of a material (ρ_p) should be determined according to NBN EN 1097-6:2013. This test set up makes use of pycnometers. Based on the norm, a minimal amount of material is needed for the test. This test was done four times for each aggregate and the average result was used further in this thesis. Figure 5-3 shows the pycnometers filled with both types of limestone aggregates and both types of the sea sands. Only the glass funnel on top of the pycnometers is missing for the test. The tests were always done in a time period of 24 hours.

Figure 5-3: Limestone aggregates and sea sands in the pycnometers

Equation (5.2) shows how the density ρ_p can be calculated. All other values in that equation are known. On the left side in the equation the volume of the pycnometer is expressed as the ratio between the mass of the water in the pycnometer when it is filled up to the indicated level and the density of the water, which depend on the temperature. On the right side of the equation, this same volume is expressed as the summation of the volume of the aggregates, expressed as a ratio between the mass of the aggregates and the unknown density and the volume of the water added, to fill the pycnometer up to the indicated level. That last volume is also expressed as a ratio between the mass of the added water and the density of the water, depending on the temperature. The mass of the added water could be calculated as the difference between the mass of the pycnometer, filled with aggregates and water, minus the mass of the aggregates and the mass of the dry and empty pycnometer.

$$\frac{m_w}{\rho_w} = \frac{m_{aggregate}}{\rho_p} + \frac{m_{added\ water}}{\rho_w} \tag{5.2}$$

5.3 Packing density

The packing densities were only determined for the coarse aggregates, and so a dry method could be used. An example of a dry method is the compaction test, which makes use of a light weight vibration table from the German manufacturer Testing. This method was used and validated in a previous thesis [Bosmans, T., Van Der Putten, J., 2014]. In Table 5-4 some properties are listed up.

Table 5-4: Properties vibrating table

Type	Light weight vibration table met on/off switch
Effective surface	350 x 350 x 225 mm
Speed engine	3000 rpm
Frequency	50 Hz

The test set-up consists of a steel base plate. A steel cylinder is placed UPON. The connection is taped, in a way that there are no openings and no small particles can escape from the monster. The aggregate is placed in the cylinder. The cylinder has a height of 128.52 mm and a diameter of 153.28 mm. The mass of the monster was always taken at 1.5 kg constantly. Above the monster, a mass of 8.253 kg was placed which resulted in an average pressure of 4.39 kPa. Also a device, guiding the mass and preventing the mass from irregular sinking, was necessary. That device makes sure that the mass can only move vertical. It has a mass of 1.723 kg, and so the total pressure in the monster increased to 5.30 kPa. To make sure there was a good transmission of energy the plate with the cylinder was fixed to the vibrating table with clamps. Figure 5-4 gives a survey of the test set-up. This test set-up correlate with a K value of 9 for the compaction [Bosmans, T., Van Der Putten, J., 2014].

Figure 5-4: Compaction test

The test procedure starts with taking a monster of 1.5 kg and placing it in the cylinder, which is taped to the base plate. When the masses are placed on it and the clamps are installed, the vibrating table is switched on, and during two minutes the mixture is vibrated at a frequency of 50 Hz, so that a good compaction of the mixture is realized. This is not the procedure proposed by De Larrard. He proposed to use three different frequencies: first 2 minutes vibrating with an amplitude of 0.4mm, than during 40 seconds an amplitude of 0.2 mm and in finally 1 minute of vibrating with an amplitude of 0.08 mm. However, tests of ing. P. Minne shows that it has no influence on the measurements to vibrate a mixture longer than 2 minutes, and that is the reason why this was also the compaction time in this thesis. The fact only 1 frequency was used is related to limitations of the vibrating table. Figure 5-5 shows how a compacted mixture looks.

Figure 5-5: A compacted limestone aggregate

After vibrating the monster, the volume taken by the monster of this aggregate has to be determined. The diameter is known. To determine the height, the distance between the top of the cylinder and the top of the monster was measured at 4 different locations with a caliper. This is necessary, because the top level of the compacted monster was not always perfectly flat. The total height of the cylinder minus the average of the 4 measurements is the height of the monster. Based on the height and the diameter a bulk density could be calculated. The packing density is the ratio between the bulk density from the compaction test, and the density of the particles, tested with the pycnometers as described in paragraph '5.2: Density'. This is shown in equation (5.3).

$$\alpha_{aggregate} = \frac{\frac{m_{monster}}{V_{monster}}}{\rho_p} \tag{5.3}$$

For each aggregate, one monster was taken but it was tested five times. So after the necessary measurements, the monster was taken out the cylinder and mixed. Then the procedure started again. The absolute deviation of the average was checked. Measurements of which the packing deviates more than two hundreds were neglected. The final result is an input parameter for the CPM

Chapter 6 Executed tests on concrete

To characterize calculated and produced mixtures some tests were done on the strength, workability and durability of the concrete. Tests were done immediately after making the concrete, after 7 days and after 28 days.

6.1 On fresh concrete

To say something about the workability of the concrete, the flow and the slump tests were done. With the test for the air content and the density, it was possible to say something about the amount of pores in the mixture. These tests were always done in the same sequence immediately after the mixing of the concrete was stopped.

6.1.1 Slump test

The slump was tested with the cone of Abrams, based on the NBN EN 12350-2:2009. The cone of Abrams is a truncated cone with a height of 300 mm. The internal diameter at the top is 100 mm and is 200 mm at the bottom. The cone is placed on a horizontal moistened surface. Also the test material itself is moistened. This is to minimize the influence of friction. The cone is filled in three layers.

Every layer is tamped by a normalized steel rod, with a length of 600 mm, a diameter of 25 mm and with rounded ends. Every layer is pricked 25 times. After pricking the third layer at the top of the cone, the surface of the monster is made flat by a saw movement of this same rod. Immediately after the cone is filled, it is slowly and perfectly lifted in a vertical manner. The height difference due to the collapse of the monster is measured according to the axis of the cone, is called the slump. Measurements are always rounded of to the nearest 10 mm. Figure 6-1 shows how the test is executed.

Based on the slump value, the concrete is given a slump class. This is shown in Table 6-1. The slump test is sensitive to changes in the consistency of concrete, which correspond to slumps between 10 mm and 210 mm. Mixtures of which almost no slump was measured can still be very different on the level of workability.

Figure 6-1: Slump test before and after lifting the cone of Abrams

Table 6-1: Slump classes

Slump class	Slump in mm
S1	10 – 40
S2	50 – 90
S3	100 – 150
S4	160 – 210
S5	≥ 220

In this thesis, most mixtures were from class S1. Such mixtures are typically used for roads. To show the difference between the mixtures, the measurements were not rounded of in this thesis.

6.1.2 Flow table test

The flow was tested with a shock table, consisting of a movable flat steel plate with a surface of 700 by 700 mm². This test is explained in the NBN EN 12350-5:2009. The movable steel plate is hinged connected to a stiff bottom plate and is allowed to fall down on that bottom plate from a fixed height. Also for this test a truncated cone is used, but the dimensions are different. The height is only 200 mm, the diameter at the bottom level is 200 mm and at the top level it has still a diameter of 130 mm. After every surface is made moistened, the cone is filled in two layers.

Each layer is lightly compacted ten times by the compacting bar. This same compacting bar is used to strike off the surface after the second layer was compacted. After resting for 30 seconds the cone can be slowly lifted vertically. A next step is to lift the upper part of the table and let it fall from that fixed height, with each time a period of one to three seconds in between. This has to be done manually for 15 times. After that procedure, the concrete is normally spread out. The flow value is the average of two perpendicular measurements of the diameter of the concrete, spread out on the table. Segregation has to be checked. It is important that the test is always done at the same time after mixing because hydration processes are started and they influence the value. Figure 6-2 shows the cone and the table with a mixture on it.

Figure 6-2: Flow test after execution and the used cone

The flow test is sensitive to changes in the consistency of concrete, which correspond to flow values between 340 mm and 600 mm. For mixtures with a limited slump value, the flow test is not reliable. A dry mixture does not flow. It falls apart in different pieces. The diameter of those different pieces could be higher than a mixture that really flows. In this thesis, this was often the case. Figure 6-3 shows a very dry mixture. However, the flow value is rather the same as the flow value in Figure 6-2.

Figure 6-3: Flow result of a dry mixture

6.1.3 Air content and density

The air content and density of fresh concrete is measured with the pressure gauge method in accordance with the NBN EN 12350-6:2009 and the NBN EN 12350-7:2009. Determining the density is easy. The concrete air meter has a volume of 8 liter. To measure the air density, it is important that the concrete air meter is totally filled with concrete. Otherwise not only air in the concrete is measured but also the enclosed air in the unfilled space of the meter is measured. When the mass is known, the density can be calculated based on the known volume.

To measure the air content the air concrete meter is totally filled with concrete. With a vibrating poker, the concrete is vibrated until full compaction is achieved. Overvibration should be avoided because loss of entrained air could occur. After striking of the concrete and cleaning the flanges, the cover assembly can be clamped in place. The container of the air pressure meter is filled with water through a valve and air escapes through another valve. When the water has reached the indicated level all valves are closed. Based on applied pressures the air density could be read. A typical value for the air content varies between 1 and 4%. This is already taken into account by an estimate when a concrete mixture is designed. Figure 6-4 shows the air concrete meter.

Figure 6-4: Apparatus for air content and density measurement

6.2 On hardened concrete

To say something about the strength and the strength evolution of the concrete, compression tests were done after 7 days and after 28 days. To say something about the durability of the mixtures, two tests were done as durability indicator after 28 days: the water absorption under vacuum and the resistivity of cubes. These are only indicators of durability because they don't say something about a specific durability topic. They only say something about the internal structure of the concrete and this is important for the durability of concrete.

Until the moment the cubes were tested they were stored in a room with a constant temperature of 20°C and a relative humidity of 90%, as prescribed in the norm. With the test for the air content and the density, it was possible to say something about the amount of pores in the mixture. These tests were always done in the same sequence, immediately after the mixing of the concrete was stopped.

6.2.1 Compression test

After 7 and after 28 days, each time 3 cubes of 150*150*150mm³ were compressed in the lab with the compression testing machine, according to the NBN EN 12390-3:2009. Before testing the depth and the width were measured 6 times. Based on the average depth and width of the cubes, the area of the compression surface could be calculated. Together with the measured force at the moment the cube crushed it makes it possible to calculate the compression stress at which the concrete fails. Also the height was measured 4 times. Based on the mass of the cube it was also possible to calculate the density.

6.2.2 Water absorption under vacuum

The water absorption was tested at an age of 28 days on two cubes. The average of both measured values was taken as final result. The used test is a destructive test method.

The ability of absorbing water is interesting because it says something about the amount of pores and how fast and how much water can be absorbed when the concrete is in a wet and possible aggressive environment. If the concrete can take a lot of water, the risk that harmful substances are absorbed is higher. Previous research shows two possibilities to test the water absorption under vacuum [Craenen, E., 2013].

A first possibility is following the procedure of the NBN B24-213:1976. In this test the cubes are first dried at a temperature of 105+-5°C. If the mass is constant (change in mass over 24 hours lower than 0.1%) they were placed in a vacuum tank. After 2h30', water comes slowly in the tank at a speed of 5 cm/h and is absorbed by the cubes. The cubes are immersend in water for 24h. Based on masses when the cubes were oven dry, in suspension and surface dry, the water porosity is calculated. Tests show that due to the high temperature the structure of the concrete changes. For UHPC this heat treatment has a beneficial effect. For normal concrete this was adverse: due to the applied heat, cracks were caused and that influences the result of the measurement [Craenen, E., 2013].

Because tests according to previous procedure give unreliable results, another procedure was used. The sequence of the steps was reversed. This is comparable with the desription in the NBN B15-215:1989, except for some details: in the norm the test is not done under vacuum pressure. So in a first step, the cubes are placed in a compression tank where vacuum pressure is applied. After 2h30' water comes in the tank with a speed of 5 cm/h, still under vacuum pressure. If the tank is filled, normal pressure is allowed. The cubes stay for 24 hours in the tank. When they are taken out of the tank their mass is determined surface dried. In a last step they are oven dried until constant mass over a period of 24 hours at a temperature of 105°C. This could take 10 days. The water absorption W is expressed as a percentage, according to equation (6.1).

$$W = \frac{M_{sat} - M_{dry}}{M_{dry}} 100 \qquad (6.1)$$

The water absorption under vacuum says something about the amount of pores in the concrete. A general assumption is that the higher the value for the water absorption, the easier it is for fluids to enter the concrete structure. This will result to a less durable concrete [Zhan, S.P., Zong L., 2014]. However there is a doubt about that. Research concluded that there was no direct link between the water absorption under immersion and concrete durability issues like carbonatation and chloride migration. The water absorption test tells only something about the volume of the pores, nothing about the concrete durability, which is more important [Audenaert, K., De Schutter, G., 2004].

6.2.3 Resistivity

To measure resistivity of concrete normally the surface resistivity is measured but because that is done on a cylinder and only cubes were produced, the bulk resistivity was measured. Literature proves that they are linked to each other [Pratanu, G., Quang, T., 2014]. It is a non-destructive test method. For this test a Resipod resistivity meter from PCTE was used. It is a fully integrated 4-point Wenner probe, that could be transformed to measuring bulk resistivity by using 2 metal contacts and sponges. Figure 6-5 shows how it looks in both ways [Repisod Family, 2013].

To measure surface resistivity on cylinders, the outer probes sends a current through the concrete and the inner probes measure the potential difference. The current is carried by ions in the pore liquid. Bulk resistivity measurements, on cubes, are taken in such a way that the whole volume of the cube informs the result, not only the surface. Before testing the sponges were moistened and their resistance was measured. Also the surface of the cubes was moistened to improve the contact with the concrete. To measure bulk resistivity the metal contacts are placed on both sides of a cube, with the sponges in between.

Figure 6-5: Apparatus for measuring bulk resistivity with electrodes (surface A)

The resistivity is an indication of the packing. A dense structure makes it difficult for the electric signal to pass the structure. There are relations between the resistivity and the corrosion rate and the chloride diffusion rate. Those damage phenomena are just like resistivity based on the flow of ions. The higher the resistivity the higher the resistance of concrete to those phenomena. A higher water content of the concrete, more pores, a higher temperature, a higher chloride content and a decreasing carbonatation depth influences the resistivity in a negative way.

Results are the average of measurements of three cubes. Each cube was also testes according to its three directions: the vertical one and his two horizontal directions. In most cases the vertical resistivity was higher than the horizontal resistivity. This could be caused by the influence of gravity on the formation of the hardened structure during the hardening process. The test measures an electric resistance between both surfaces of the cube and two sponges. Because the lower sponge is compressed under the mass of the cube its resistance was neglected. For the sponge on the upper side this was not the case and its resistance was measured separately and distracted from the measured resistance over the cube and sponges which gives the resistance of the concrete cube R. This is multiplied with the surface of the electrodes (A) and divided by 2πa which is a correction factor for the distance between the probes and by the length over which the electronic signal was send out and. The resistivity ρ is expressed in Ωm and is shown in equation (6.2).

$$\rho = \frac{RA}{L2\pi a} \tag{6.2}$$

Chapter 7 Used materials

In this chapter, all the materials used in the concrete mixtures are described. For each material a technical datasheet is attached at the end of this thesis. As described in 'Chapter 1: Ecological concrete' all costs, economic and environmental, of these materials were collected, which makes it possible to compare materials with each other. Densities, size distributions, packing values and other characteristics, which have to be determined with tests in the laboratory, are mentioned in the experimental part.

7.1 Cement

Although in theory there are five types of cement only 2 of them are frequently used: the CEM I and CEM III. CEM I is nearly completely based on Portland cement while CEM III contains, besides Portland cement, also an important part on blast furnace slags. CEM III is split in three categories (A, B and C), which are respectively equivalent with approximately 40%, 70% and 90% of blast furnace slags.

In this thesis, the choice had to be made between both cements. From ecological point of view, a choice for CEM III would be the most logical because less Portland cement is used. Testing CEM III on his Environmental Cost Indicator shows as expected a remarkable lower impact on the environment. The Global Warming is the most important environmental effect of cement. Especially this is the difference between CEM I and CEM III. This is showed in Figure 7-1 and Figure 7-2 where the influences of the eleven environmental effects are compared and the total impact on the environment.

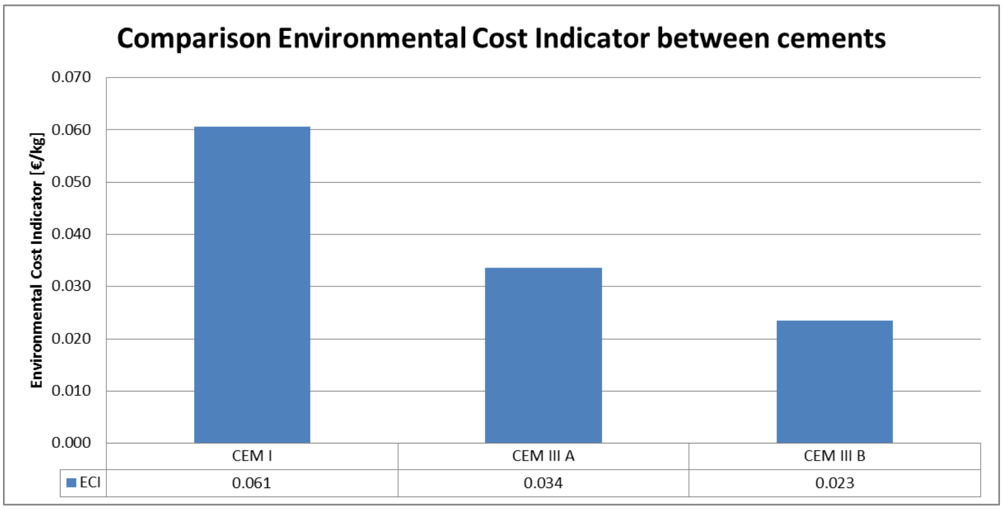
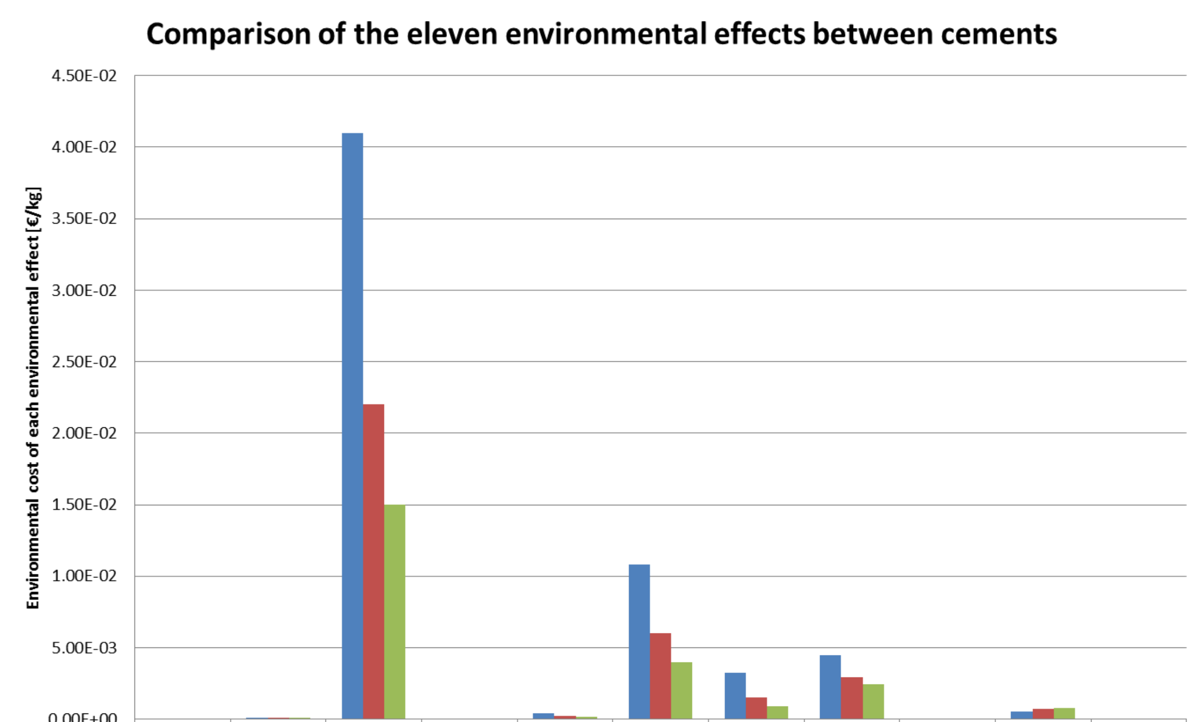


Figure 7-1: ECI for different types cement



	ADP NF	ADP F	GWP	ODP	POCP	AP	EP	HTTP	FAETP	MAETP	TETP
CEM I	1.07E-07	9.12E-05	4.10E-02	1.56E-07	4.20E-04	1.08E-02	3.24E-03	4.50E-03	2.07E-05	5.10E-04	4.08E-05
CEM III A	1.07E-07	1.23E-04	2.20E-02	1.62E-07	2.40E-04	6.00E-03	1.53E-03	2.97E-03	1.32E-05	7.30E-04	2.70E-05
CEM III B	1.04E-07	1.28E-04	1.50E-02	1.56E-07	1.80E-04	4.00E-03	9.00E-04	2.43E-03	1.02E-05	7.80E-04	2.16E-05

Figure 7-2: The eleven environmental effects contributing to the ECI of different cements

Although CEM I is the worst from environmental point of view, the decision was made to use this one. This is still corresponding with the goal of this thesis. The goal was not to design the most possible ecological concrete. The goal was to look how much improvement on environmental aspect was possible, by using the CPM. Because CEM I contains more Portland cement compared to CEM III, pozzolanic reactions will have a larger effect on the strength.

In a more detailed way, the used cement was a CEM I 52.5 N. This was the same for all the experiments. No specific durability requirements were asked, so a 'N' type was sufficient. With the choice for a CEM I 52.5 N, high strengths should be obtained. The higher the strength, the more clear differences between mixtures should be.

7.2 Superplasticizer

A superplasticizer makes it possible to reduce the water demand, without losing workability (a). Another possibility is to increase the workability without adding water (b). These working principles are shown in Figure 7-3. Mostly, the effect of a superplasticizer is something in between (c).

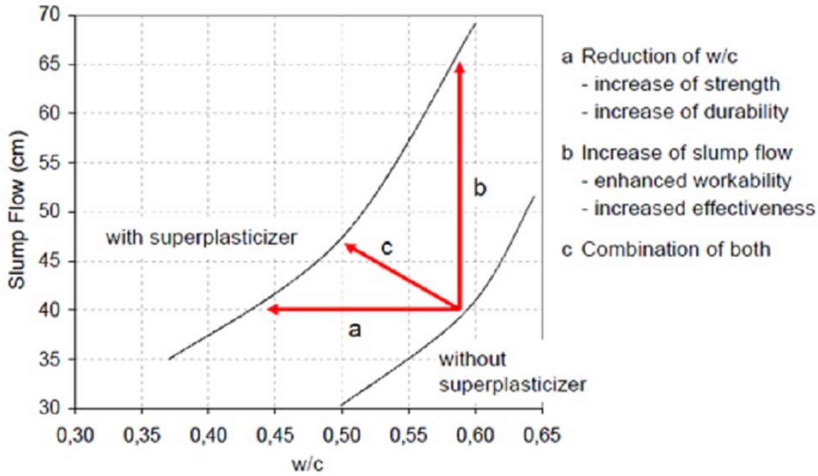


Figure 7-3: Working principle superlasticizer

In the composition of the reference concrete, the superplasticizer 'Tixo' from Sika was proposed. There was no reason to change that. According to the technical datasheet in Figure B-2 and Figure B-3 the recommended dose is between 0.5% and 2% of the cement mass. The density is 1090 kg/m³. Some experiments on the dose were done to produce the reference concrete. It is a superplasticizer from the last generation, namely the polycarboxylate ether-based superplasticizers. This is abbreviated as PCE.

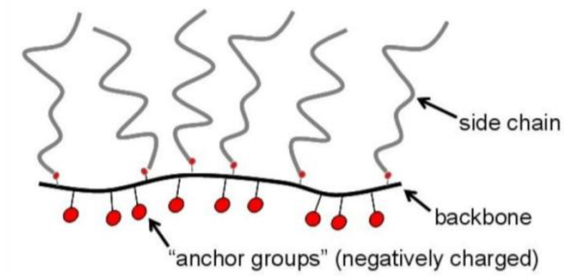


Figure 7-4: PCE molecule

PCE's are synthetic polymers. They consist of a main chain and different side chains. This is shown in Figure 7-4. The dimensions of those chains could change, depending on the application. The mechanism is based on adsorption due to a physical attractive force between the negative sides of the PCE molecules and the positive loaded cement particles. While previous generations, superplasticizers disperses cement particles by electrostatic repulsion. Nowadays new generations superplasticizers cause, besides by electrostatic repulsion, also by steric hindrance due to their side chains a good dispersion of cement particles. This is shown in Figure 7-5 [Gruber, M., Lesti, M., et al., 2008]

Figure 7-5: Steric hindrance by PCE superplasticizers

7.3 Coarse aggregates (2)

As coarse aggregates limestone aggregates were used. There were two different sizes: a limestone of class 2/6.3 and a limestone of class 6.3/20. Both are coming from the mine of Gaurain-Ramecroix from Holcim. They were delivered in the past, by Kestelyn, and they were still available at the laboratory.

7.4 Sands (3)

In a first part of the design process of an ecological concrete, only 2 types of sands were used. Both were sea sands, delivered by Interbeton. There was a sand in size class 0/2 through 'Bouwgrondstoffen De Hoop' from the North sea and another sand in size class 0/4 through SBV from Vlissingen. In a second phase an effort was made to optimize the packing with an additional fine sand. This attempt was done with sands from Sibelco. Sands M31, M32 and S60 do not improve the packing, only sands S80 and S90 do. These were all quartz sands. Because, in theory, the best improvement was achieved with S90 and this was also used for the mixtures. Figure 7-6 shows the used sea sands and limestone aggregates.

Figure 7-6: Limestone aggregates and sea sands

7.5 Fillers

To reduce the amount of cement, fillers or binders can be used. Fillers are chemically inert. They do not have reactions which contribute to the strength. Their effect is replacing cement and optimizing packing, due to their different particle size.

7.5.1 Limestone powder

Limestone powder is a natural product. It is extracted from limestone quarries and ground to the desired fineness. It mainly consists of calcium carbonate ($CaCo_3$). The amount of $CaCO_3$ is an indication on the purity of the limestone powder and is mostly higher than 97%. Normally the quality is very constant. Sufficient amounts of limestone powder are still available. In this thesis Calcitec from Carmeuze was used.

Limestone powder is assumed to be inert in this thesis but this is not totally the case. Research shows it is for approximately 5 % reactive. Because this is quite small this was neglected [De Larrard, F., 1999].

7.5.2 Quartz powder (M400 and M800)

Quartz powder comes from crushed quartz raw materials. It is a white powder. Different sizes are available. The finer it is ground, the more expensive. In this thesis, products from Sibelco were used. The Silverbond quartz powder contains a range of different sizes quartz powders. More than 99% consists of SiO_2. M400 is the one with the biggest size. M800 is the one with the smallest size. Both types were used.

7.6 Binders

Another option to reduce cement is using pozzolanic binders. They react with the reaction product from Portland cement and water. Next to their effect of packing optimization they should cause an additional strength increase due to their pozzolanic effect. The filler effect should result in a decreased porosity and an increased durability. In this thesis silica fume and fly ash were used. Blast-furnace slags were not used. When these are wanted to use, a choice for a CEM III could be made, CEM III contain them already [Pawan Kumar, P., Vipul Naidu, P; 2014]

7.6.1 Silica fume

Silica fume or microsilica is an ultrafine powder, collected as by-product of the silicon and ferrosilicon alloy production. It consists of very small spherical particles. Different sizes are available. In 1952 it was used for the first time in concrete based on Portland cement. Since 1970-1980 it became more common to use it, especially in Scandinavia [Chandra Sekhara Reddy, T., Elumalai, J.K., 2014].

Because of its fineness and the high silica content (> 80 % SiO_2), it is a very effective pozzolanic material. Different types of silica fume are available. Their size, densification and chemical composition can vary. A different chemical composition results in a different color. A more white kind of Silica fume contains less carbon in comparison to a grey one.

According to De Larrard, carbon absorb superplasticizer. And so, concrete based on white silica fume should have a higher workability than using grey silica fume. In general the workability decreases, if silica fume is added. Due to the very small particle size surface forces come more important and the risk of agglomeration increases.

For this thesis, the Silica fume Elkem Grade 920 was used. It has a grey look. Silica fume is normally dosed as a percentage of the cement mass. Mostly it varies between 5 to 10 %.

7.6.2 Fly ash

Fly ash is one of the naturally-occurring products from the coal combustion process. It is very similar to volcanic ash. Thousands years ago, Romans already used volcanic ash in their concrete structures such as the Colosseum. Nowadays, during burning of coal in electric generating plants, temperatures of combustion can reach 1500 °C. Non-combustible minerals forms bottom ash and fly ash. Bottom ash does not rise, while fly ash rises with the flue gases.

Fly ash can replace 20 to 30% of cement mass. It has a spherical shape, which has a favorable influence on the workability. Using fly ash results in a cheaper concrete: fly ash is far less expensive than Portland cement.

The fly ash used in this thesis comes from Govaerts Recycling NV in Alken. A Chemical analysis was done by Geos. It shows that the most important components were SiO_2 and Al_2O_3. Normally there is also an important part Fe_2O_3 and CaO but in this fly ash, this was not the case. It has a grey color.

7.7 Portaclay

Comparing the materials mentioned here on top of their availability on our planet, silica fume and fly ash scores bad. Most of those available materials are already used in the production of concrete. Limestone powder, quartz powder and clay are far more interesting in this prospective. Their stock is practical inexhaustible.

Portaclay is a raw form of the clay mineral kaolinite and has a strange property: it is not really a filler and not really a binder. On its own, it acts as a filler. When it is combined with limestone powder it acts as a binder. The combination of both causes chemical activity. Its particle size is between the one from cement and from silica fume.

A disadvantage of portaclay is the enormous water demand. Values for water absorption are extremely high. In this thesis only a small amount of portaclay was used. Tests were done in advance on mortars to estimate the effects on workability. At the University of Ghent, ir Florent Fornest is doing research on how raw clays could be useful in concrete mixtures.

The $CaCO_3$ from the limestone powder reacts with the alumina from the portaclay and forms supplementary AFm phase and stabilizing ettringite. Literature said that it would be possible to replace 45% of Portland cement by 30% portaclay and 15% limestone powder [Scrivener, K, Rossen, J., et al., 2014] [Justice, J.M., 2005]. In this thesis that was not possible: the mixture became too dry.

In this thesis Portaclay A90 was used. It is produced from a natural Sodium-bentonite, which is a very plastic clay. Portaclay A90 is produced by grinding that clay to a constant grain size and moisture content. The mean constituent is the clay-mineral montmorillonite. A chemical analyses shows SiO_2 and Al_2O_3 as the most important parts.

Chapter 8 Reference concrete

8.1 Mixture

With industrial help, a mixture was searched of class EE3 with CEM I 52.5 N, sands and lime stone aggregates. No fillers were allowed in the mixture because adding such materials was part of the experiment. It has a W/C factor lower than 0.5 and a minimum cement content of 320 kg. A theoretical calculation by Interbeton according the formula of Buyst predicts a strength of 54.2 N/mm² at 28 days [Belgische Betongroepering, 2009]. This results in a strength class C35/45. The mixture composition is shown in Table 8-1.

Table 8-1: Reference mixture for 1m³ concrete

	Volumes [m³]	Masses [kg]
CEM I 52.5 N	0.112	336
Water	0.166	166
Limestone aggregate 6.3/20	0.283	761.0
Limestone aggregate 2/6.3	0.094	251.5
Sand 0/4	0.194	499.3
Sand 0/2	0.129	339.3
Tixo	0.0024	2.568
Air	0.0196	-
Sum	1	2355.7

8.2 Mixing procedure – characteristics mixer

For this thesis, a non-continuous compulsory counterflow mixer was used. In the laboratory such a mixer of Eirrich is present since 1971 with a capacity of 50 l, type SKG-1. For each test mixture a quantity of 50 l concrete was produced. This was sufficient for 11 cubes of concrete to test strength and durability. In the mixing container vanes displace them with a circular movement. A fixed vane is also used to scrape concrete from the border of the mixing container. Further characteristics from the mixer in Figure 8-1 were not known.

The mixing procedure takes four minutes. First all the dry materials were put in the mixing container. The first minute of the mixing procedure consists of dry mixing. After that minute, the volume of water was added. One minute later, when the mixture was already two minutes mixed, the superplasticizer was added. After adding the superplasticizer the mixture was mixed for another two minutes. After four minutes, the mixing procedure was stopped and tests on fresh concrete were immediately executed. It was assumed that this mixing process was equivalent to a value of 9 for the compaction index K. This was not checked. If this was not the case, this could cause the optimal packing is not reached.

Figure 8-1: Concrete mixer in 'Magnel Laboratory for Concrete Research'

8.3 Vacuum mixer

Table 8-2: Characteristics 75 l vacuum mixer

Maximum mass [kg]	120
Speed mixing pan [rpm]	8 – 41
Speed rotor [rpm]	175 – 520
Maximum pressure [mbar]	40
Diameter mixing pan [mm]	750
Height mixing pan [mm]	380
Diameter rotor [cm]	30.9
Filling volume (l)	50

Besides the normal mixer for concrete tests there is also an intensive vacuum mixer in the laboratory. The vacuum mixer has a capacity of 75l. ‘Magnel Laboratory for Concrete Research’ is the only laboratory in the world which has such a vacuum mixer. Figure 8-2 on the next page shows it. Table 8-2 shows the characteristics of the mixer. This mixer was purchased for the PhD of Jeroen Dils about the influence of vacuum mixing, air entrainment or heat curing on the properties of hardened and fresh (ultra) high performance mortar [2014]. With the vacuum mixer, it is possible to control the pressure in which a mortar or concrete is produced. This makes it possible to relate it to the air content of concrete.

Vacuum mixing should lead to an increase of the compressive strength, the splitting and bending strength and the Young’s modulus. The air content also influences the workability. For traditionally vibrated concrete, increasing air content results in an increased workability. This is not the case for all types of concrete [Dils, J., 2015].

The reference concrete was also produced with the vacuum mixer to check influences of different mixing procedures and characteristics. The time schedule for the mixing procedure differs a little bit. Because of difficulties during adding dry material in the mixture, the dry mixing period takes much longer. The vacuum mixer was only used for the reference concrete.

Figure 8-2: Vacuum mixer in ‘Magnel Laboratory for Concrete Research’

Part II: Experimental part

In this second big, and important, part of this thesis all the tests and the intermediate conclusions and interpretations are given. In Chapter 9 all the characteristics of the used materials and the reference concrete is determined. Chapter 10, Chapter 11 and Chapter 12 explain the three different design steps in the design of an ecological concrete: optimization of the packing, optimization of the workability and optimization of the strength [Fennis, S.A.A.M., 2010]. In Chapter 13 two experiments not immediately linked to previous chapters are described. Finally in Chapter 14 all mixtures are evaluated on economic and ecologic aspects. Standard deviations for tests on concrete are given on the figures in the attachments.

Chapter 9 Characterizations

9.1 Coarse aggregates

As mentioned in paragraphs ‘7.3: Coarse aggregates (2)’ and ‘7.4: Sands (3)’ two limestone aggregates (6.3/20 – 2/6.3) and three sands were used (0/4 – 0/2 – S90). To limit the length of the labels the abbreviations 6.3/20, 2/6.3, 0/4, 0/2 and S90 will be used. Sand S90 was only used for tests at the end of the experimental part, ‘Chapter 13: Experiments’. The test results are already given in this chapter makes it possible to compare S90 to the other used materials.

9.1.1 Particle size distribution

Both limestone aggregates and the sea sands were sieved according to the procedure in paragraph ‘5.1.1: Sieve curves’. For fine quartz sand S90 data of a previous thesis was taken [Breyne, S., De Vos, B., 2013]. The sieve curves are shown in Figure 9-1. Also the standard deviations for the manual sieving (3) are represented. These are quite small.

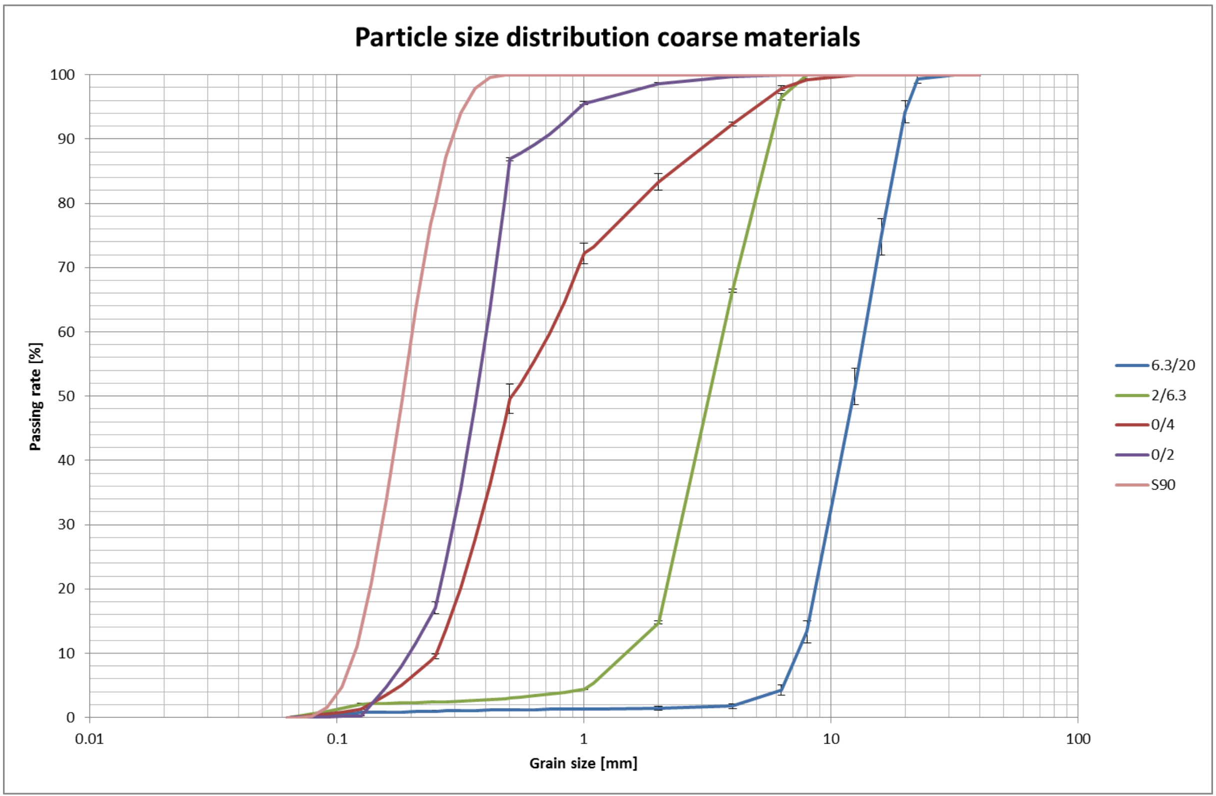


Figure 9-1: Particle size distribution coarse materials

Except the curve for the sea sand 0/4 all curves are steep. This means they contain a lot of material in a specific size class. For reasons of completeness, the values of the passing rates are also given in Table 9-1. This confirms the conclusion from the graph.

Table 9-1: Passing rates sieve curves

	6.3/20	2/6.3	0/4	0/2	S90
40	100.0	100.0	100.0	100.0	100.0
31.5	100.0	100.0	100.0	100.0	100.0
22.4	99.3	100.0	100.0	100.0	100.0
20	94.2	100.0	100.0	100.0	100.0
16	74.8	100.0	100.0	100.0	100.0
12.5	51.5	100.0	100.0	100.0	100.0
8	13.3	100.0	99.3	100.0	100.0
6.3	4.2	96.5	97.9	100.0	100.0
4	1.7	66.4	92.4	99.7	100.0
2	1.4	14.8	83.3	98.7	100.0
1	1.3	4.4	72.2	95.6	100.0
0.5	1.2	3.0	49.6	86.8	100.0
0.25	1.0	2.4	9.5	17.1	79.7
0.125	0.8	2.1	1.3	0.2	13.7
0.0	0.0	0.0	0.0	0.0	0.0

Table 9-1 shows that almost 70% of the particles of the sea sand 0/2 have a diameter between 0.25 mm and 0.5 mm. For sand S90, a comparable amount is located between 0.125 mm and 0 mm.

9.1.2 Density

The densities were tested with pycnometers, as described in paragraph ‘5.2: Density’. This test was only done for the limestone aggregates and the sea sands. The decision to use a fine quartz sand was made at a later time after the tests on aggregates were executed. A value found in a previous thesis was used [Breyne, S., De Vos, B., 2013]. These values are represented in Figure 9-2. For the self-conducted tests also the standard deviations are shown.

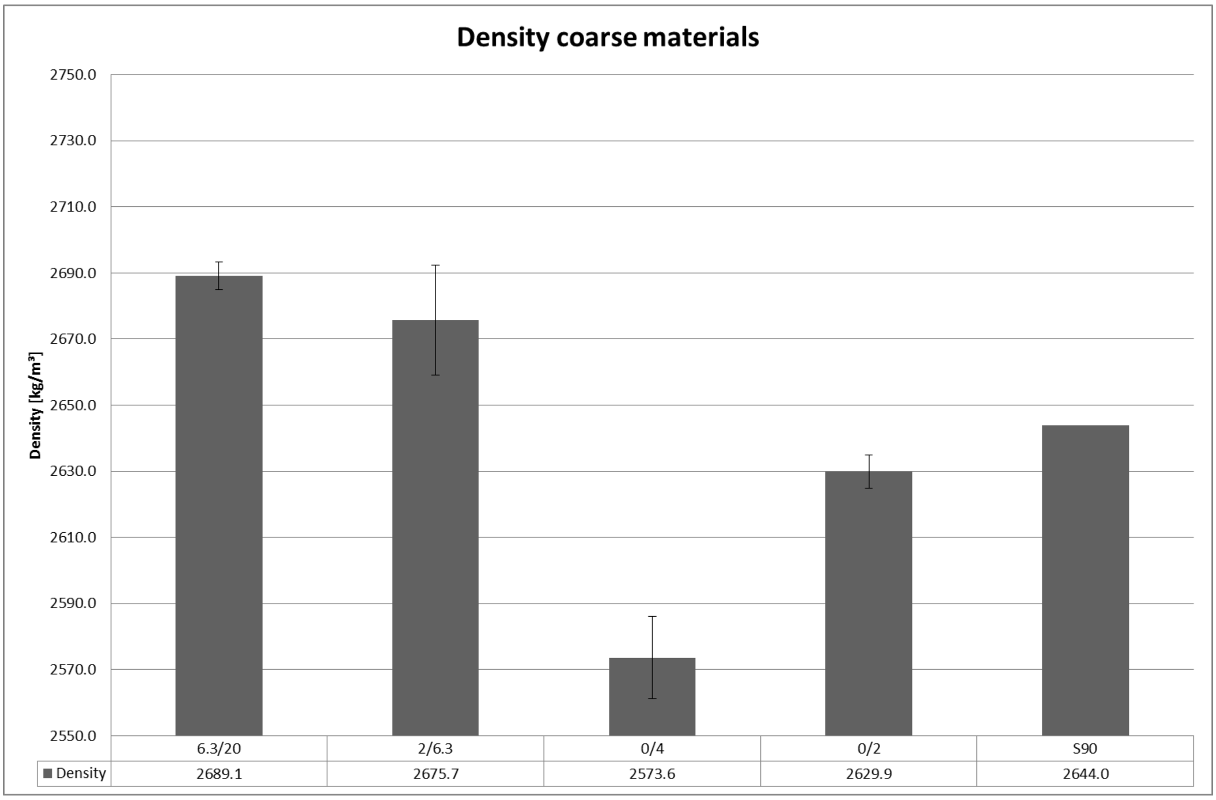


Figure 9-2: Densities coarse materials

The standard deviations are acceptable. Only for the limestone 2/6.3 and sea sand 0/4, these are higher. All measured values come to the literature value of 2650 kg/m³. The density for the sea sand 0/4 is remarkable lower, compared to densities of the other materials. There was no specific reason found causing this difference. The technical datasheet, shown in Figure B-6, prescribes a value of 2620 kg/m³ with a tolerance of 100 kg/m³. The own measurement is still in that range.

9.1.3 Packing density

For all the 5 coarse aggregates, the packing was determined according to paragraph '5.3: Packing density'. This implies that for all the presented values standard deviations were available. They were quite small. All the values are shown in Figure 9-3.

The higher packing for the sands is related to two phenomena. On the one hand, their size distribution is wider and contains more fine particles in comparison with the limestone aggregates. This results in a compacter material. On the other hand, they have a lower density. The density is in the denominator in the equation for the packing so this results in a higher value for the packing density. This is shown in equation (5.3). Especially for sand 0/4 these two phenomena are applicable.

Figure 9-3: Packing densities coarse materials

9.2 Fine aggregates

The used fine aggregates are described in paragraphs '7.5: Fillers', '7.6: Binders' and '7.7: Portaclay'. To limit the length of the labels the abbreviations LP, M400, M800, SF, FA and PC will be used. All these materials were used one time, in the third design step of the design of an ecological concrete to replace cement. This is mentioned in 'Chapter 12: Optimization of the strength'. With the particle size distribution and the density, maybe some effects on the concrete mixtures can be explained.

9.2.1 Particle size distribution

The particle size distributions were determined by the LLS technique. This is described in paragraph ''5.1.2: Laserdiffractometer measurements'. A laserdiffractometer measures data about many different size classes. This is the reason why this data is not given in a table. Only a figure is shown, without standard deviations. These would make the figure too dense. This should be sufficient because these values were only used to have an idea of the particle size distributions. No calculations were done with these results. Figure 9-4 shows the obtained results. Also the 'CEM I 52.5 N' was measured and is abbreviated with 'CEM'. For silica fume available measurements based on the DLS technique were used [Dils, J., 2015].

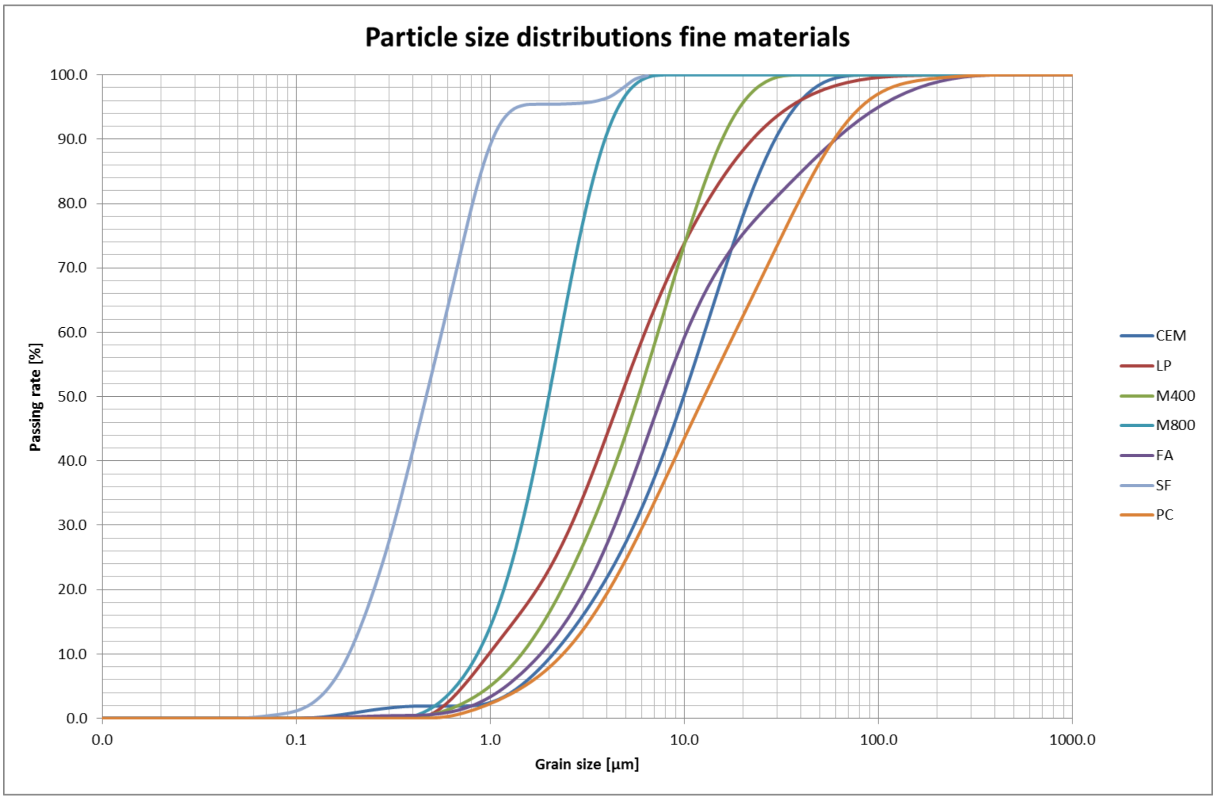


Figure 9-4: Particle size distribution fine materials

Based on Figure 9-4, it is noticed that the limestone powder, the quartz powder M400, the fly ash and the portaclay have particle sizes in the same range as the cement with a d_{10} of 1 µm up to 2 µm, a d_{50} between 6 and 10 µm and a d_{90} between 11 and 16 µm. Adding these particles should have a smaller impact on the packing optimization compared to adding smaller materials, such as the silica fume and the quartz powder M800. These consist of remarkable smaller particles, which could result in filling voids between cement particles and an improved packing.

9.2.2 Density

The density of the fine materials was only necessary in calculating the masses for the concrete mixtures. This could be determined according to the NBN-EN-1097-7. The choice was made to use already available data and values from the technical data sheets. The density of silica fume was determined during the PhD of Jeroen Dils [Dils, J., 2015]. The used values are shown in Table 9-2.

Table 9-2: Assumed densities fine materials

Material	Assumed density [kg/m³]
CEM	3000
LP	2650
M400	2650
M800	2650
FA	2650
SF	2187
PC	2600

9.3 Reference concrete

The first mixture, produced for this experimental part of this thesis, was the reference mixture. This was the starting point for the optimization process and all mixtures had to be compared with this mixture, in order to evaluate possible economic or ecological benefits. The mixture was already shown in Table 8-1 in paragraph '8.1: Mixture' but for reasons of completeness of this experimental part, Table 9-3 shows it again. The masses are calculated according to the mentioned densities in previous paragraphs.

Table 9-3: Mixture composition for 1 m³ – reference mixture

	Mix 1	
	[m³]	[kg]
CEM	0.112	336.0
Water	0.166	166.0
6.3/20	0.283	761.0
2/6.3	0.094	251.5
0/4	0.194	499.3
0/2	0.129	339.3
Tixo	0.002	2.568
Air	0.020	-
Sum	1	2355.7

In order to exclude variations for all the mixtures the content of air and superplasticizer (Tixo) stays the same. The mixing procedure is described in paragraph '8.2: Mixing procedure – characteristics mixer'. This is a constant factor for all mixtures. The used cement was a CEM I 52.5 N. This was the case for each mixture in this thesis, hence it is abbreviated to 'CEM'. The test results of the reference mixture are shown in Table 9-3.

For the reference concrete, the amount of superplasticizer was determined experimentally. In the original mixture the dose of superplasticizer was lower but this results in a concrete mixture with a very low workability. By trial and error, the dose was fixed at 2.568 kg per m³ or 120 ml for each test mixture of 50 l. This results in a mixture with a minimal workability. An amount of 50 l was the standard concrete quantity for each mixture in this thesis.

Table 9-4: Test result – reference mixture

	Mix 1
Slump [cm]	1.0
Flow [cm]	42.0
Air [%]	3.0
Density [kg/m³]	2375.0
Strength 7d [N/mm²]	58.0
Strength 28d [N/mm²]	68.0
Water absorption [%]	4.26
Resistivity [Ωm]	0.42

These results of the reference concrete will be the base for each comparison. It clearly fulfills the requirements for a C35/45. With a strength of 68 N/mm² it is from class C50/60. This additional strength compared to the predicted strength of 54.2 N/mm² could maybe be related to the perfect storage conditions in the wet room at the laboratory. Mixtures with strengths as this are often used in the prefab industry.

Chapter 10 Optimization of the packing

The optimization of the packing is a first step in the design of an ecological concrete [Fennis, S.A.A.M., 2010]. This is described in paragraph '4.1: Optimization of the packing'.

10.1 Calculations

After entering the size classes, the amount of particles in each size class and the packing measured, according to paragraph '5.3: Packing density' and represented in paragraph '9.1.2: Density', the Excel sheet calculates the packing of a number of given possible combinations of aggregates. From all of these combinations, the combination leading to the highest packing value is restricted as the one for the most optimal design of the concrete skeleton, according to the packing.

As a kind of experiment besides the total optimization of the 4 aggregates (mix 4'), it was also investigated what the effect should be by only optimizing the 2 coarse aggregates (mix 2'), or the 2 sands (mix 3'). The results of these optimizations between the considered aggregates are shown in Table 10-1. These results consist of a ratio between the considered aggregate and the corresponding value for the packing, when the considered aggregates are mixed together according to the optimized ratio.

Table 10-1: Optimal ratios between different aggregates

	6.3/20 [%]	2/6.3 [%]	0/4 [%]	0/2 [%]	Corresponding value for packing
Mix 2'	56.0	44.0	-	-	0.675
Mix 3'	-	-	100.0	0	0.724
Mix 4'	52.4	0.0	47.6	0.0	0.806

These results show already interesting things. Combining sands results in a higher packing density than combining coarse aggregates. This is logical because coarse aggregates miss fine materials to fill the voids. It is also remarkable that the optimal ratio between the sea sand 0/4 and the sea sand 0/2 is taking 100% of the sea sand 0/4. This could be explained by the relative high difference between the individual packing densities of both sands. The sand 0/4 has a packing density of 0.724 while this is for the other sand only 0.671. Logically the value for the packing of mix 3 is the same as the individual packing density for sea sand 0/4 from paragraph '9.1.3: Packing density'. It is also shown that for the most optimal packing only two of the four aggregates are used. Others were ignored. This could be interesting for the industry because only two aggregates must be ordered, stored and used.

In a next step, the optimal ratio between the coarse limestone aggregates (mix 2') or the fine sea sands (mix 3') from Table 10-1 are applied to the ratio between the coarse aggregates and the fine aggregates from the reference mixture (mix 1) shown in Table 10-2. By this step in Table 10-2 the new compositions for the aggregate mixtures for mix 2, mix 3 and mix 4 are shown. The values for mix 4' from Table 10-1 can be copied because they already considered all the aggregates.

Table 10-2: Ratios between all the aggregates for the concrete mixtures

	6.3/20 [%]	2/6.3 [%]	0/4 [%]	0/2 [%]	Packing aggregate composition in concrete skeleton (α_t)
Mix 1	53.9		46.1		-
	40.5	13.4	27.7	18.4	0.797
Mix 2	30.2	23.7	27.7	18.4	0.791
Mix 3	40.5	13.4	46.1	0	0.803
Mix 4	52.4	0.0	47.6	0.0	0.806

Based on these ratios, the concrete mixtures were calculated in Table 10-3. From Table 10-2 it can be noticed that adding the fraction sands in mix 2 to the optimal ratio between the coarse aggregates (mix 2') results in a decreased packing density. Adding the coarse aggregates in mix 3 to the optimal ratio sands (mix 3') results in an increased packing. The decreased packing from mix 2 shows the idea of only optimizing a part of the aggregates is nonsense. Mix 2 and mix 3 were only interesting experiments to get feeling with packing. Further on, the increase in packing between mix 1 and mix 4 is rather limited (0.009).

In this paragraph, the composition of the concrete skeleton is calculated based on packing. Besides this, there are also other possibilities to determine the skeleton of the concrete as mentioned in paragraph '1.3: Particle size optimization methods'. The most common manner of composing an aggregate mixture for concrete is the approximation of an optimization curve as the Fuller curve, with the method of the least squares. In Figure 10-1 curves presenting the aggregate mixture for mix 1 to mix 4 are compared with different optimization curves such as the Fuller curve and the curve from Andreasen and Anderson. These are equations (1.1) and (1.2). This last one was once represented with a d_{min} of 0.063 and once with a d_{min} of 0.

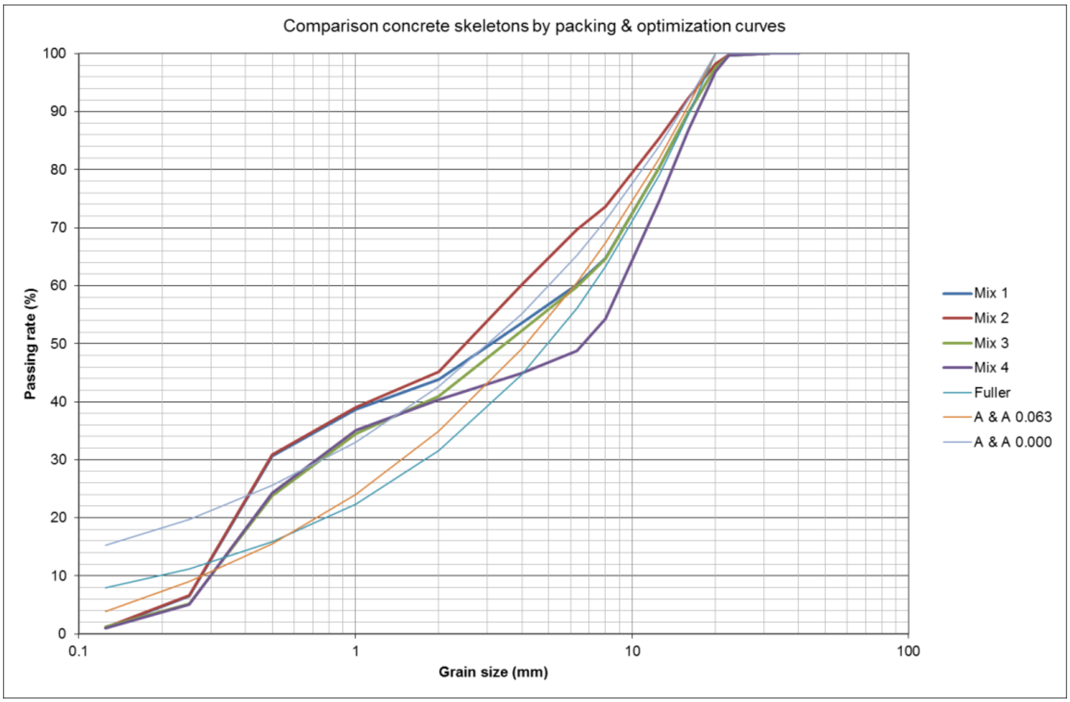


Figure 10-1: Optimization curves & concrete skeletons

Based on Figure 10-1, it is shown that the optimization curves have a strange behavior at the level of the smallest grains. In the part of the coarser grains, all curves come together. Between 0.5 and 10 mm there are non-negligible differences. Mostly all the optimization curves contain a lower amount of fine materials. Further on, the process of the packing optimization results, on average, in a shift downwards and to the right (mix 1 to mix 4). This results in a coarser mixture. The curve with the ideal packing (mix 4) contains a high amount of particles smaller than 1 mm and bigger than 7 mm. In between, only a small amount of particles is present in the optimized skeleton composition.

10.2 Mixture compositions

In Table 10-3, the mixture compositions are shown. These are based on the optimal ratios between aggregates from Table 10-2. Those percentages were applied to the total volume of aggregates. Also the reference mixture (mix 1) is shown. This makes it possible to compare the mixtures. The bold numbers show what the changes are. This is in according to what was mentioned in previous paragraph: first an optimization of the coarse aggregates (mix 2), than an optimization of the fine aggregates (mix 3) and finally an optimization of all the aggregates (mix 4).

Due to a higher packing, an increase of the density of the mixtures could be expected. This is not the case. This is related to the densities of the aggregates, shown in Figure 9-2 in paragraph ‘9.1.2: Density’. The density of the aggregates which volume increased due to packing optimization is smaller than the density of the aggregates which volume decreased. Packing is related to volumes of solids or aggregates, not to the density of a mixture.

Table 10-3: Mixture compositions for 1m³ - optimization of the packing

	Mix 1		Mix 2		Mix 3		Mix 4	
	[m³]	[kg]	[m³]	[kg]	[m³]	[kg]	[m³]	[kg]
CEM	0.112	336.0	0.112	336.0	0.112	336.0	0.112	336.0
Water	0.166	166.0	0.166	166.0	0.166	166.0	0.166	166.0
6.3/20	0.283	761.0	**0.211**	**567.7**	0.283	761.0	**0.367**	**986.4**
2/6.3	0.094	251.5	**0.166**	**443.8**	0.094	251.5	**0**	**0**
0/4	0.194	499.3	0.194	499.3	**0.323**	**831.3**	**0.333**	**857.5**
0/2	0.129	339.3	0.129	339.3	**0**	**0**	**0**	**0**
Tixo	0.002	2.568	0.002	2.568	0.002	2.568	0.002	2.568
Air	0.020	-	0.020	-	0.020	-	0.020	-
Sum	1	2355.7	1	2354.7	1	2348.4	1	2348.5

10.3 Results

Table 10-4 shows the test results. The general idea of a higher packing resulting in an increased workability is correct. The increased workability is caused by an increased amount of free water, due to the better packing. That increased amount excess water causes a decrease of strength and a worse score for the water absorption, which indicates a decreased durability.

Table 10-4: Test results - optimization of the packing

	Mix 1	Mix 2	Mix 3	Mix 4
Packing [-]	0.797	0.791	0.803	0.806
Slump [cm]	1.0	3.5	11	15.5
Flow [cm]	42.0	41.5	42.5	50.5
Air [%]	3.0	4.2	3.2	2.5
Density [kg/m³]	2375.0	2343.8	2375.0	2398.8
Strength 7d [N/mm²]	58.0	55.5	54.9	55.3
Strength 28d [N/mm²]	68.0	64.4	62.9	62.4
Water absorption [%]	4.26	4.87	5.05	4.92
Resistivity [Ωm]	0.42	0.38	0.44	0.44

Chapter 11 Optimization of the workability

The optimization of the workability is the second step in the design of an ecological concrete [Fennis, S.A.A.M., 2010]. This is described in paragraph ‘4.2: Optimization of the workability’. The principle is to equalize the ratio φ_{mix}/ α_t between the reference mixture and the mixture with an optimized packing, resulting in an increased workability (mix 4).

11.1 Calculations

To show how the principle works, some parameters of mixtures are shown in Table 11-1. Some mixtures are relevant (mix 1, mix 4 and mix 5), other are not really necessary (mix 2, mix 3, mix 6 and mix 7). The reason why they are given is because the additional data makes it possible to check the relation between the ratio φ_{mix}/ α_t and the value for the slump and the flow. This is done in paragraph ‘11.3: Results’.

First of all, the values in Table 11-1 should be determined. The value for φ_{mix} is calculated according to equations (4.1) or (4.5), based on values in Table 11-2. The only difference is that besides the volume water, air and superplasticizer also the volume of cement is subtracted from a unit volume. This is because only the aggregates were optimized in this thesis, while Sonja Fennis also considered fine materials, including cement [Fennis, S.A.A.M., 2010].

Table 11-1: Necessary parameters

	φ_{mix}	α_t	φ_{mix}/ α_t	Flow [cm]	Slump [cm]
Mix 1	0.700	0.797	0.878	42	1
Mix 2	0.700	0.791	0.885	41.5	3.5
Mix 3	0.700	0.803	0.872	43.5	11
Mix 4	0.700	0.806	0.868	50.5	15.5
Mix 5	0.708	0.806	0.878	39	10.0
Mix 6	0.715	0.806	0.887	36	5.0
Mix 7	0.720	0.806	0.893	33	2.5

For mix 1 until 4, this value is the same because the volume water, air and superplasticizer was constant. The values for α_t were already given in Table 10-2. Because the ratio between the aggregates is the same in mix 5, mix 6 and mix 7 as in mix 4 they have the same value for α_t.

For this second design steps three different mixtures were calculated. As shown in Table 11-1, mix 5 is the one which is theoretically calculated and should have the same workability as the reference concrete. Because this was not the case, mix 6 and mix 7 were produced. They were calculated in the same way as mix 5, starting from well-chosen guesses for the ratio φ_{mix}/ α_t, taking into account the state of workability.

Based on the values in Table 11-1, it was possible to calculate the mixture compositions in Table 11-2. In Table 11-1, the value for φ_{mix} is calculated for mix 5, based on the known value for α_t and the wanted ratio φ_{mix}/ α_t. With the value for φ_{mix}, it is possible to calculate the new water content, based on equation (4.7), because the volume air and superplasticizer are constant. Also the volume of cement should be added to the term taking into account the volume water, air and superplasticizer in equation (4.7). This is because the cement was not included in the optimization process. The decrease of the water content is compensated by an increase in the volume of aggregates, keeping the ratio between the aggregates constant according to the determined ratio for optimal packing.

11.2 Mixture compositions

Table 11-2: Mixture compositions for 1m³ - optimization of the workability

	Mix 4		Mix 5		Mix 6		Mix 7	
	[m³]	[kg]	[m³]	[kg]	[m³]	[kg]	[m³]	[kg]
CEM	0.112	336.0	0.112	336.0	0.112	336.0	0.112	336.0
Water	**0.166**	**166.0**	**0.158**	**158.4**	**0.151**	**150.8**	**0.146**	**146.0**
6.3/20	0.367	986.4	0.371	997.1	0.375	1007.8	0.377	1014.5
2/6.3	0	0	0	0	0	0	0	0
0/4	0.333	857.5	0.337	866.8	0.340	876.2	0.343	882.0
0/2	0	0	0	0	0	0	0	0
Tixo	0.002	2.568	0.002	2.568	0.002	2.568	0.002	2.568
Air	0.020	-	0.020	-	0.020	-	0.020	-
Sum	1	2348.5	1	2360.9	1	2373.3	1	2381.2

Table 11-2 shows the mixture compositions. Also the result of previous design step, mix 4, is shown, to make it possible to compare the mixtures. It shows that the amount of cement, air and superplasticizer stays the same. The water content decreases in every step and the amount of aggregates increases with a volume equivalent to the decrease of water.

11.3 Results

The results of these mixtures are given in Table 11-3, together with the results of the previous design step (mix 4) and the reference mixture. Everything was as could be expected. The workability decreases. This is shown by decreased values for the slump and flow measurements. The air content is approximately constant. The values for the density show an increase from mix 5 until mix 7. This is logical because a volume aggregates has a larger mass compared to a volume of water.

The decreased workability and water content results in a decreased value for the W/C factor and a lower amount of excess water. This results in an increased strength on 7 days as on 28 days. The lower the amount of water, the smaller the amount of hydrates per m³ concrete. This leads to a less porous structure, with a decreased amount of percolating surface. This has a beneficial influence on durability indicators. This is shown by an increase of the value for the resistivity and a decrease for the water absorption value.

Table 11-3: Test results - optimization of the workability

	Mix 1	Mix 4	Mix 5	Mix 6	Mix 7
Slump [cm]	1.0	15.5	10.0	5.0	2.5
Flow [cm]	42.0	50.5	39.0	36.0	33.0
Air [%]	3.0	2.5	2.8	2.6	2.5
Density [kg/m³]	2375.0	2398.8	2369.8	2395.6	2404.6
Strength 7d [N/mm²]	58.0	55.3	58.4	60.9	62.6
Strength 28d [N/mm²]	68.0	62.4	63.8	67.6	71.6
Water absorption [%]	4.26	4.92	4.39	4.13	3.85
Resistivity [Ωm]	0.42	0.44	0.45	0.50	0.56

Mix 5 was the theoretical calculated mixture, which should have the same workability as the reference mixture. This was not the case. The slump value shows a higher workability. This is the reason why mix 6 and mix 7 were produced. The workability of mix 7 was assumed to be equal to the workability of the reference mixture (mix 1) and was used for the next design step.

Finally the relation between the ratio $\varphi_{mix}/\ \alpha_t$ and workability parameters as well as the slump and the flow are checked. This was done by a graphical representation of the data in Table 11-1.

As already said, mix 2 and mix 3 were rather experimental but they gave additional data in searching for relations. According to the literature, the ratio $\varphi_{mix}/\ \alpha_t$ and the value for the flow should be correlated to each other [Fennis, S.A.A.M., 2010]. This was shown in Figure 4-3. In total, 7 data sets were available for a graphical representation to check this relation. This was done in Figure 11-1.

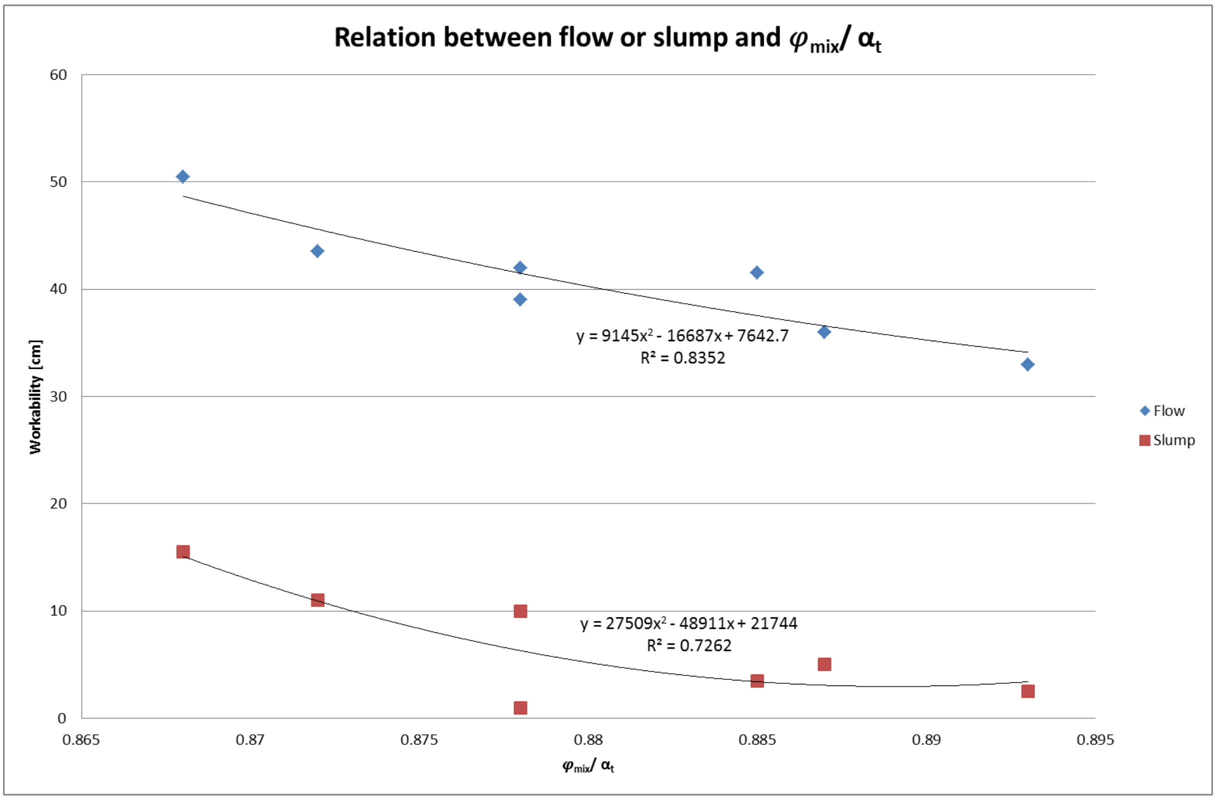


Figure 11-1: Relation between flow/slump and $\varphi_{mix}/\ \alpha_t$

Figure 11-1 confirms what was found by Sonja Fennis. There is a clear relation between workability parameters as the slump and the flow, and the ratio $\varphi_{mix}/\ \alpha_t$. The relation for the flow shows the best accuracy.

Chapter 12 Optimization of the strength

The optimization of the strength is the third and last step in the design of an ecological concrete [Fennis, S.A.A.M., 2010]. This is described in paragraph '4.3: Optimization of the strength'. Shortly, this means calculating the percentage of the gain in strength between the reference concrete and the optimized mixture from previous design step. Thereafter the cement content can be decreased with that same percentage. This is a rule of thumb found in the literature.

12.1 Calculations

In order to replace cement, different materials were used. These are described in paragraphs '7.5: Fillers', '7.6: Binders' and '7.7: Portaclay'. As fillers quartz powders (M400 for mix 8, M800 for mix 9) and limestone powder (mix 10) were used while as binders fly ash (mix 11) and silica fume (mix 12) were used. Also a combination between limestone powder and portaclay was tested (mix 13). The idea behind that combination can be found in paragraph '7.7: Portaclay'. As last option the idea of replacing an amount of cement by an increased amount of aggregates was investigated (mix 14).

Table 12-1: Mortar compositions and slump results

	100 % LP	90 % LP	80 % LP
CEM [kg]	1.734	1.734	1.734
Water [kg]	0.818	0.818	0.818
0/4 [kg]	4.940	4.940	4.940
Tixo [kg]	0.014	0.014	0.014
LS [kg]	0.148	0.133	0.118
PC [kg]	0.000	0.015	0.030
Slump [cm]	8.0	5.0	2.8

In order to determine the optimal ratio between limestone powder and portaclay, three tests on mortar level were done. Table 12-1 shows the mixture compositions and the results for the slump value. The mortar composition was obtained by neglecting the coarse aggregates in the concrete mixture (mix 10 in

Table 12-2), with limestone powder as cement replacing material. This mortar composition was rescaled to a volume of 3.5 l, the maximum capacity of the mortar mixer. From those mixtures a slump value on a mortar cone was tested [Dils, J., 2015]. In steps of 10 %, it was tested what the influence was of portaclay on the slump.

Based on Table 12-1 it was decided to replace only 10% of the limestone powder by portaclay. Replacing 20 % results in a mortar with a very low workability, while the original mortar has a good workability. On concrete level, this could be problematic because the concrete mixtures were already quite dry.

Based on the '% - rule' [Fennis, S.A.A.M., 2010], the calculation of the mixtures was easy. The strength increase by previous design step, is shown in Table 11-3. To gain time, the strength increase was measured after 7 days. The reference mixture (mix 1) has a strength of 58 N/mm² after 7 days, while the mixture based on an optimized packing with a comparable workability as the reference mixture has a strength of 62.6 N/mm² after 7 days. This is equivalent with a gain of strength of approximately 7.87 %. Further on the amount of cement, 336 kg, is lowered with that same percentage. This is equivalent with a mass of 26.4 kg per m³.

This mass of cement is replaced by the same mass of one of the mentioned cement replacement products. This has some consequences. Because of different values for the densities of the cement replacement products, shown in Table 9-2, the total volume of the mixture changes.

This means that the concrete compositions were not designed to a volume of 1 m³. The difference is small but it causes some variations in the amount of some components, when the mixtures are rescaled to an amount of 1 m³. This explains some strange values in the tables on following paragraph. This is for example the case for the mixture with silica fume (mix 12).

12.2 Mixture compositions

In Table 12-2 and Table 12-3, the mixture compositions are shown. As mentioned in previous paragraph, always the same mass of cement replacement products was added to compensate the decrease of the amount of cement. Only the type of cement replacement product differs. The amount of water stays the same. This means the W/C factor increases, while the W/P factor stays constant. This means that it was assument the cement replacements products needs the same amount of water as the cement. Maybe this is not correct. Based on the results for workability in Table 12-4, it could be a suggestion to keep the W/C factor constant, instead of the W/P factor. This should result in a decrease of the workability and an increase of the strength. On the other hand this assumes the cement replacement products need no water: also this is not correct.

Table 12-2: Mixture compositions for 1m³ - optimization of the strength (Mix 8 – Mix 10)

	Mix 7		Mix 8		Mix 9		Mix 10	
	[m³]	[kg]	[m³]	[kg]	[m³]	[kg]	[m³]	[kg]
CEM	**0.112**	**336.0**	**0.103**	**309.2**	**0.103**	**309.2**	**0.103**	**309.2**
Water	0.146	146.0	0.146	145.8	0.146	145.8	0.146	145.8
6.3/20	0.377	1014.5	0.377	1013.4	0.377	1013.4	0.377	1013.4
2/6.3	0	0	0	0	0	0	0	0
0/4	0.343	882.0	0.342	881.0	0.342	881.0	0.342	881.0
0/2	0	0	0	0	0	0	0	0
Tixo	0.002	2.568	0.002	2.565	0.002	2.565	0.002	2.565
Air	0.020	-	0.020	-	0.020	-	0.020	-
Additional	**-**	**-**	**0.010**	**26.4**	**0.010**	**26.4**	**0.010**	**26.4**
Sum	1	2381.2	1	2378.4	1	2378.4	1	2378.4
Remark	**-**		**M400**		**M800**		**LP**	

Table 12-3: Mixture compositions for 1m³ - optimization of the strength (Mix 11 – Mix 14)

	Mix 11		Mix 12		Mix 13		Mix 14	
	[m³]	[kg]	[m³]	[kg]	[m³]	[kg]	[m³]	[kg]
CEM	**0.103**	**309.2**	**0.103**	**308.5**	**0.103**	**309.2**	**0.103**	**309.1**
Water	0.146	145.8	0.146	145.5	0.146	145.8	0.146	145.8
6.3/20	0.377	1013.4	0.376	1011.2	0.377	1013.4	0.382	1027.4
2/6.3	0	0	0	0	0	0	0	0
0/4	0.342	881.0	0.342	879.2	0.342	881.0	0.347	893.3
0/2	0	0	0	0	0	0	0	0
Tixo	0.002	2.565	0.002	2.560	0.002	2.565	0.002	2.565
Air	0.020	-	0.020	-	0.020	-	0.020	-
Additional	**0.010**	**26.4**	**0.012**	**26.4**	**0.010**	**26.4**	**-**	**-**
Sum	1	2378.4	1	2373.4	1	2378.4	1	2378.3
Remark	**FA**		**SF**		**90% LP + 10% PC**		**-**	

12.3 Results

Table 12-4 shows the test results of all the mixtures with a reduced cement content (8 until 14). Also the test results for mix 1 and mix 7 are shown, to make it possible to compare with those results. A first remark is the increased slump value. Only for the mixture with portaclay, this was not the case. This is because portaclay has a very large water absorption. The increased workability could be related to the fact that cement absorbs more water than the replacement products. Also the shape of the added particles could influence the workability. Fly ash is for example very spheric and this improves the workability.

When the strength is considered, most mixtures score strengths in the same range as the reference mixture after 7 days. The strength for mix 9 with quartz powder M800 could be related to an improved effect on the packing, due to the very fine particles of that material [Bosmans, T., Van Der Putten, J., 2014] [Breyne, S., De Vos, B., 2013].

Mix 13 with portaclay has the worst result, on 7 days as on 28 days. The high water absorption of the clay could be a reason for this. Maybe there was not sufficient water available for the hydration reactions. The absolute amount of portaclay was very limited (2.4 kg on 1m³ concrete), but it has a strong influence. Further research to apply portaclay or other clayey materials should focus on a reduction of the water absorption of such materials.

Table 12-4: Test results – optimization of the strength

	Mix 1	Mix 7	Mix 8	Mix 9	Mix 10	Mix 11	Mix 12	Mix 13	Mix 14
Slump [cm]	1.0	2.5	2.5	3.5	4.0	6.0	2.5	1.0	2.0
Flow [cm]	42.0	33.0	37.0	39.5	38.0	41.0	42.5	41.5	43.5
Air [%]	3.0	2.5	2.5	3.2	2.1	2.5	2.5	2.6	2.7
Density [kg/m³]	2375.0	2404.6	2391.3	2378.8	2402.3	2375.0	2390.1	2392.5	2375.9
Strength 7d [N/mm²]	58.0	62.6	58.9	60.1	57.9	56.4	57.0	54.7	56.1
Strength 28d [N/mm²]	68.0	71.6	65.9	67.6	65.1	63.3	67.8	59.7	61.8
Water absorption [%]	4.26	3.85	4.34	4.54	4.42	4.23	4.23	4.54	4.41
Resistivity [Ωm]	0.42	0.56	0.52	0.51	0.51	0.58	1.04	0.51	0.47
Additional material	-	-	M400	M800	LP	FA	SF	LP & PC	AGG

After 28 days, all the values for strength scores lower, compared to the reference mixture. Mix 12 with silica fume approximates the reference concrete the best. This could be related to the pozzolanic effect which binders have. Fly ash is also seen as a binder but the result does not reflect that.

The mixture with an additional amount of aggregates (mix 14) has also not sufficient strength. This could be related to a lack of fine materials: an amount of 26.4 kg per m^3 (7.87 %) was taken away from the mixture and was replaced by a material with total other grain sizes. All the values for strength are compared graphically on Figure A-1 and Figure A-2 in the attachments.

On durability level, the values for the water absorption show in general a small increase, which is normally not beneficial for the durability. However, the difference is negligible. The values for resistivity all show a clear increase. This is beneficial. It is assumed that a better packing is the reason: on the level of the aggregates by the optimization of the packing in design step 1, and on the level of the fine materials by the combination of cement particles and other fine particles with slightly different sizes.

The value for the resistivity for mix 12 with silica fume is extremely good. This is a nice example of two effects: an improved packing of the fine materials by the very fine silica fume particles, and the pozzolanic effect resulting in more reactions on a very small scale between the silica fume particles and the cement particles. This results in a denser and stronger structure.

Chapter 13 Experiments

13.1 Further optimization with another fine sand

Because in the first design step in paragraph '10.1: Calculations', besides the limestone aggregate 2/6.3 also the fine sea sand 0/2 was neglected, the idea raises that maybe with the help of another fine sand the packing could be further optimized, by filling some voids in the mixture. In order to investigate that, different fine quartz sands from Sibelco were considered.

The same material characteristics as determined in paragraph '9.1: Coarse aggregates' were needed to check which sand should be the best. The particle size distribution was already determined in a previous thesis [Breyne, S., De Vos, B., 2013]. This data was copied and is represented in Figure 13-1.

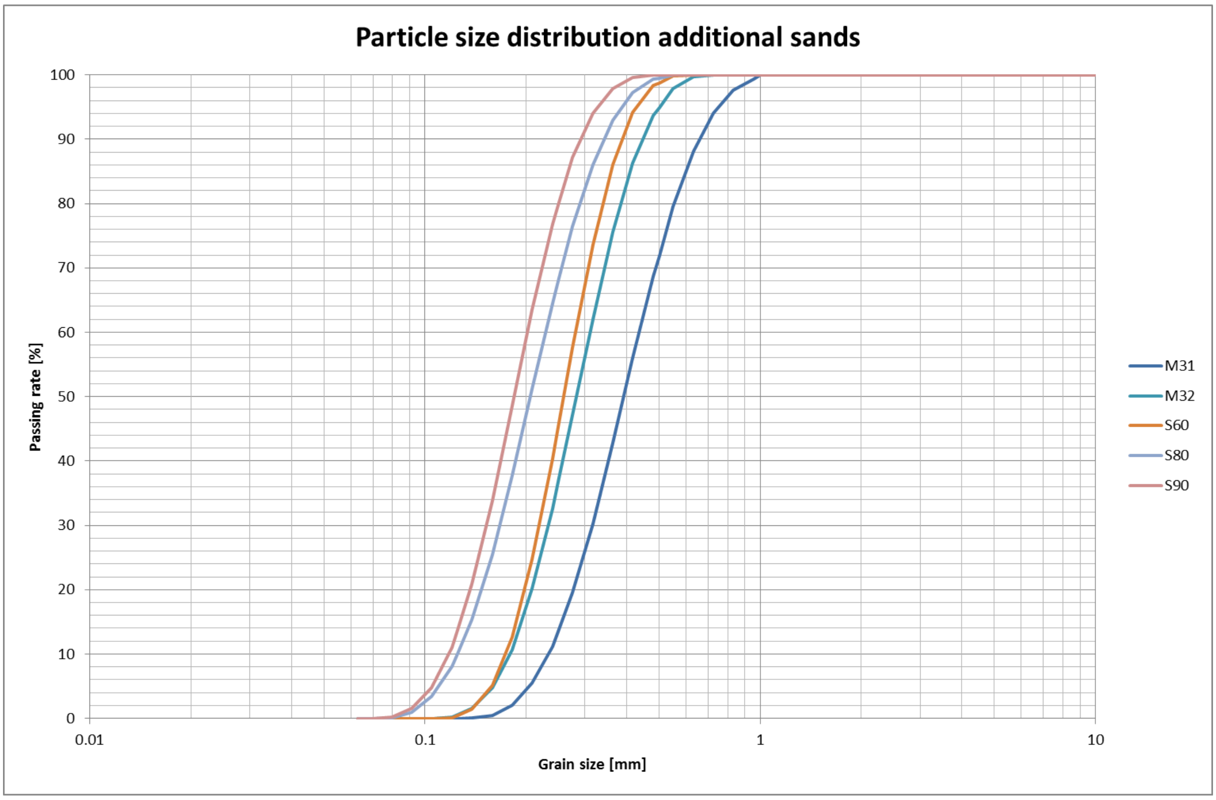


Figure 13-1: Particle size distribution additional sands

Besides the particle size distribution, also for the densities values determined by a previous thesis were used. These values are shown in Table 13-1. It was necessary to know these densities: for the determination of the packing densities, and for the calculations of the concrete mixtures.

Table 13-1: Densities for additional sands

Sand	Density [kg/m³]
M31	2640
M32	2634
S60	2667
S80	2661
S90	2644

With these densities it was possible to determine the packing density. For the materials present in the laboratory the compaction test, described in paragraph '5.3: Packing density', was done and the standard deviations were calculated. Only for sand M31 this was not possible. This value was calculated, based on measurements on different fractions of that sand in a previous thesis [Bosmans, T., Van Der Putten, J., 2014]. The results for the packing densities are shown in Figure 13-2.

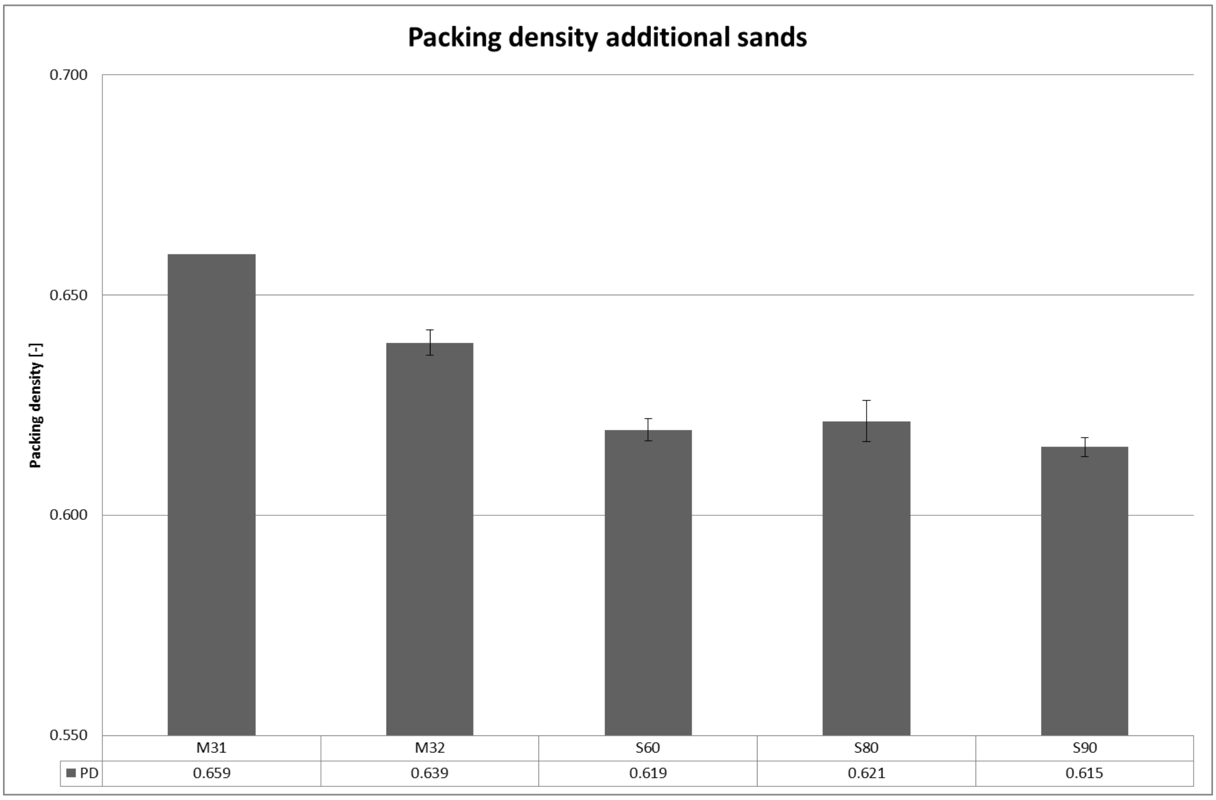


Figure 13-2: Packing densities additional sands

With the particle size distribution and the packing densities, it was possible to determine an optimized packing with the excel sheet described in paragraph ‘4.1: Optimization of the packing’.

By entering this data, it was possible to calculate which material in which combination results in the highest value for the packing. For this calculation, the excel sheet was extended to a version which can handle 6 different aggregates consisting of 40 size classes

After this was done for all the five fine quartz sands, only two sands result in a mixture with a higher packing: S80 and S90. All other optimizations with other sands results in an optimal mixture composition only consisting of limestone aggregate 6.3/20 and sea sand 0/4.

13.1.1 Optimization of the packing

Table 13-2 shows the outcome of previous analysis in the rows named ‘Mix S80’ and ‘Mix S90’. These results are compared with the aggregate composition in the reference concrete (mix 1) and the aggregate composition of the reference concrete optimization, without adding other materials (mix 4).

Table 13-2: Ratios between all the aggregates for the concrete mixtures

	6.3/20 [%]	2/6.3 [%]	0/4 [%]	0/2 [%]	S80 [%]	S90 [%]	Packing aggregate composition in concrete skeleton
Mix 1	40.5	13.4	27.7	18.4	-	-	**0.789** --- (0.797)
Mix 4	52.4	0.0	47.6	0.0	-	-	**0.798** --- (0.806)
Mix S80	50.0	0.0	40.0	0.0	10.0	-	**0.799**
Mix S90	50.0	0.0	40.0	0.0	-	10.0	**0.802**
Mix 15	52.2	0.0	38.6	0.0	-	9.2	**0.803**

The reader paying attention to details, noticed the values for the packing density changes for mix 1 and mix 4 in comparison with Table 10-2 (values between brackets). This is related to the interpolations that were necessary to obtain corresponding size classes between the results from manual sieving and laserdiffractometer measurements.

The additional (fine) size classes with interpolated values lead to a decreased value for the packing for mix 1 and mix 4. The values for the packing density according to the new size classes were calculated and given in bold. They show there is an improvement of the packing density when S80 and S90 are added

Because the mix S90 results in the highest packing, it was decided to use that sand for the further optimization. In the excel sheet, the optimum for mix S90 was further investigated by additional combinations in the same range. This results in a ratio between the aggregates, shown in the row of mix 15.

This ratio was applied to the total volume on aggregates (0.7 m³) in the mixture. Those volumes of aggregates were multiplied with their densities to obtain a new mixture composition. This is shown in Table 13-3 by bold numbers. All parameters stay the same, only the aggregate composition for the mixtures changes.

Table 13-3: Mixture compositions for 1m³ - optimization of the packing with S90

	Mix 1		Mix 4		Mix 15	
	[m³]	[kg]	[m³]	[kg]	[m³]	[kg]
CEM	0.112	336.0	0.112	336.0	0.112	336.0
Water	0.166	166.0	0.166	166.0	0.166	166.0
6.3/20	**0.283**	**761.0**	**0.367**	**986.4**	**0.365**	**982.6**
2/6.3	**0.094**	**251.5**	**0**	**0**	**0**	**0**
0/4	**0.194**	**499.3**	**0.333**	**857.5**	**0.270**	**695.4**
0/2	**0.129**	**339.3**	**0**	**0**	**0**	**0**
Tixo	0.002	2.568	0.002	2.568	0.002	2.568
Air	0.020	-	0.020	-	0.020	-
S90	**-**	**-**	**-**	**-**	**0.064**	**170.3**
Sum	1	2355.7	1	2348.5	1	2352.9

Table 13-4 shows the test results of mix 15. These are compared with those from mix 4, because that was a mixture in the same design step. However the packing density value for mix 15 was higher, mix 4 has a higher workability. This is contradictory.

Also on the level of strength, mix 4 scores better than mix 15. Because mix 4 had a higher workability and more excess water, the opposite was expected. The durability indicators act contrary. The value for the water absorption indicates a decreased durability, the value for the resistivity indicates an increased durability. Possible reasons for this strange behavior are given in paragraph ‘13.1.4: Possible reasons for the fail of the optimization‘.

Table 13-4: Test results - optimization of the packing with S90

	Mix 1	Mix 4	Mix 15
Slump [cm]	1.0	15.5	8.0
Flow [cm]	42.0	50.5	43.0
Air [%]	3.0	2.5	2.3
Density [kg/m³]	2375.0	2398.8	2370.0
Strength 7d [N/mm²]	58.0	55.3	51.8
Strength 28d [N/mm²]	68.0	62.4	60.5
Water absorption [%]	4.26	4.92	5.23
Resistivity [Ωm]	0.42	0.44	0.48

13.1.2 Optimization of the workability

However, as the results were not what could be expected the optimization process was continued. In a next step, the workability from the optimized mixture (mix 15) should be reduced to the workability of the reference mixture. This was done in the same way as mentioned in ‘Chapter 11: Optimization of the workability’.

The results of these calculations are shown in Table 13-5. Mix 16 is the theoretical calculated identical mixture on level of workability, according to the theory [Fennis, S.A.A.M., 2010]. This could be compared with mix 5, which was the theoretical calculated identical mixture on level of workability in previous optimization process. In mix 16 the amount of water is lower now.

In contradiction to previous design step, the theoretical identical calculated mixture was too dry now. Table 13-6 shows that the value for the slump was the same as for the reference concrete, but the structure of the concrete was totally different. This is indicated by the flow value. There was no cohesion in the mixture. It collapses in loose pieces of concrete.

While in mix 5 it was possible to further decrease the water content (mix 6 and mix 7), now the water content must be increased in mix 16. Mix 17 has the same slump value as mix 16 but there was more cohesion, resulting in a smaller flow value. It was not ideal but this mixture was accepted as the one with the same workability as the reference concrete. Based on a possible gain of strength this mixture was the starting point for the third design step.

Table 13-5: Mixture compositions for 1m³ - optimization of the workability with S90

	Mix 5		Mix 16		Mix 7		Mix 17	
	[m³]	[kg]	[m³]	[kg]	[m³]	[kg]	[m³]	[kg]
CEM	0.112	336.0	0.112	336.0	0.112	336.0	0.112	336.0
Water	0.158	158.4	**0.146**	**145.9**	0.146	146.0	**0.150**	**150.0**
6.3/20	0.371	997.1	0.376	1010.8	0.377	1014.5	0.374	1005.1
2/6.3	0	0	0	0	0	0	0	0
0/4	0.337	866.8	0.278	715.4	0.343	882.0	0.276	711.3
0/2	0	0	0	0	0	0	0	0
Tixo	0.002	2.568	0.002	2.568	0.002	2.568	0.002	2.568
Air	0.020	-	0.02	-	0.020	-	0.02	-
S90	-	-	0.066	175.2	-	-	0.066	174.2
Sum	1	2360.9	1	2385.9	1	2381.2	1	2379.1

The results of these mixtures are shown in Table 13-6. They were already discussed partly in previous paragraph. On the level of strength, the increase of the amount of water caused a decreased strength at 7 days. At 28 days, this difference was remarkable smaller. Adding water was also unfavorable for the values for the water absorption as for the resistivity. This is according to what should be expected. Mix 17 scores worse than mix 7, while mix 16 scores better than mix 5.

Table 13-6: Test results - optimization of the workability with S90

	Mix 1	Mix 5	Mix 16	Mix 7	Mix 17
Slump [cm]	1.0	10.0	0.5	2.5	0.5
Flow [cm]	42.0	39.0	53.0	33.0	46.5
Air [%]	3.0	2.8	2.0	2.5	2.6
Density [kg/m³]	2375.0	2369.8	2418.8	2404.6	2406.1
Strength 7d [N/mm²]	58.0	58.4	63.2	62.6	58.4
Strength 28d [N/mm²]	68.0	63.8	68.5	71.6	68.1
Water absorption [%]	4.26	4.39	3.95	3.85	4.58
Resistivity [Ωm]	0.42	0.45	0.54	0.56	0.42

13.1.3 Optimization of the strength

Unfortunately, it was not possible or useful to do this last step. Normally in this step, based on the gain of strength of mix 17, an amount of the cement should be placed. The strength of mix 17 after 7 days is 58.4 N/mm², while the strength of the reference concrete was 58 N/mm². The increase in strength is too small to continue this optimization.

13.1.4 Possible reasons for the fail of the optimization

Previous results are strange. With S90 the packing is higher, according to the CPM and the excel sheet, but it does not result in a further optimization of the design of an ecological concrete. The optimization failed due to small strength increase, maybe linked with the too low workability.

Quartz sands does not absorb important amounts water normally. If that is the case, this could not be the reason of the low workability. An explanation for the strongly decreased workability is the fineness of the sand. The finer a material, the larger the specific surface. The specific surface of S90 is much higher compared to the specific surface of the other aggregates. Adding S90 to the composition of the aggregate mix increases its specific surface. The function of water in a mixture is to form a water layer around the particles, to fill voids and to give the mixture a sufficient workability. An increase of the specific surface means more water is needed to form a water layer around the particles. Less water is available to give the mixture sufficient workability.

However the specific surface of fine materials, as cement, is much larger compared to the specific surface of sands or aggregates, it is not correct to take that into account. Superplasticizer works on the surface of those small materials. For sands, this is not the case. Only the specific surface of the aggregate mixture counts.

13.2 Reference concrete with vacuum mixer

To investigate the impact of the mixing procedure, the reference mixture was also made with the vacuum mixer close to the end of the thesis. All the information about the mixing procedure and the characteristics for both ways of mixing (standard mixer and vacuum mixer) are discussed in ‘Chapter 8: Reference concrete’. The mixture was not mixed vacuum. It was mixed with the vacuum mixer, which results in another, more intense mixing procedure. The mixture composition for the reference concrete was already given in Table 9-3.

Table 13-7: Test result – reference mixture with the vacuum mixer

	Mix 1	Mix 18
Slump [cm]	1.0	3.0
Flow [cm]	42.0	39.0
Air [%]	3.0	4.2
Density [kg/m³]	2375.0	2335.0
Strength 7d [N/mm²]	58.0	49.1
Strength 28d [N/mm²]	68.0	51.2
Water absorption [%]	4.26	5.21
Resistivity [Ωm]	0.42	0.37

Table 13-7 contains the results for the reference mixture, when it was mixed with the vacuum mixer (mix 18). These are compared to the results for the reference mixture mixed according to the standard procedure (mix 1). Important differences can be noticed.

In fresh state, the mixture has an increased workability. The values for the flow are not relevant for mixture with such a low slump value. The increased air content could partially explain the decreased density. An increased air content results in an increased workability for traditionally vibrated concrete [Dils, J., 2015].

In hardened state, the properties of the mix 18 are remarkable bad, in comparison with mix 1. It was the first time the vacuum mixer was used to mix lime stone aggregates. In the PhD of Jeroen Dils always gravel was used. Maybe the mixing procedure is too intensive for limestone aggregates, which could result in broken aggregate and in a negative influenced packing and weaker test specimens. Comparing the strength at 7 days to the strength at 28 days it is also noticed there is almost no gain of strength. Also on the level of durability mix 18 scores worse results compared with mix 1.

Based on these results, and the importance of the reference mixture in this thesis, it should be useful to make mix 1 and mix 18 again. In this thesis this was not done. Mix 18 was made during the last possible test day. When the first results of it were available the time to obtain test results for new mixtures was too short, according to the deadline of this thesis.

Chapter 14 Economic and ecological comparison

In previous chapters, test results directly related to the concrete mixtures and determined by tests on fresh or hardened concrete were given. Two things were saved for this last chapter: the economic and ecological comparison. The reason is that it seems to be more useful to compare this for all mixtures together. In previous chapters, only some groups of mixtures are listed up next to each other. In this chapter, all the values are given in tables. In the attachments these are also graphically represented and compared in Figure A-8 and Figure A-9.

14.1 Economic comparison

Table 14-1 shows the relative cost of each mixture. Giving absolute values for the cost was not allowed by the company who gave the costs for the individual components.

Table 14-1: Comparison between mixtures on level of economics

Mixture	Relative cost
Mix 1	1.00
Mix 2	1.01
Mix 3	1.05
Mix 4	1.04
Mix 5	1.04
Mix 6	1.05
Mix 7	1.05
Mix 8	1.09
Mix 9	1.54
Mix 10	1.03
Mix 11	1.02
Mix 12	1.25
Mix 13	1.10
Mix 14	1.02
Mix 15	1.05
Mix 16	1.06
Mix 17	1.06
Mix 18	1.00

Table 14-1 shows that no cheaper mixtures were produced during this optimization process. Due to the optimization of the packing, the amount of the more expensive materials increases (mix 1 until 4). In the next design step (mix 5 until 7), the amount of water is decreased and compensated by an increased amount of aggregates. This also results in a higher cost.

In the third and last design step (mix 8 until 14), a decrease of the cost is possible when the cement replacing material is cheaper than the cement. For limestone powder (mix 10), fly ash (mix 11) and replacement by an additional amount of aggregates (mix 14), this is the case. Other materials, as quartz powder M800 (mix 9) and silica fume (mix 12) are far too expensive in comparison to cement and results in a strong increase of the costs. Also portaclay (mix 13) is expensive, but it was only used for a small part. The relative cost for the individual components of the concrete, is shown in Table 1-2.

On the other hand it is also important to think about the durability. Reparations and replacements have influences on the transport side. Also diversions have a high economic impact [Denarié, E., Gabert, G. et al., 2013]. The impact of traffic and durability on the economic and ecologic impact of concrete, should be investigated. The fact that traffic has also an impact on the environment makes it complicated. An increased durability is of course beneficial. This seems to be the case with the optimized mixtures.

14.2 Ecological comparison

The ecological comparison between the mixtures is quite easy, when Table 14-2 is considered. All the mixtures part of design step 3, the reduction of the amount of cement, have a lower value for the ECI than the other mixtures. In general, it seems that adjustments on the level of the water content, or the level of the amount of aggregates (mix 1 unitl 7), have a negligible influence.

In return, the small decrease of the cement content with 7.87 %, due to a gain of strength with the same percentage at 7 days caused by the optimization process, result in a decrease of 7 % of the ECI for mix 8 until 14. This is quite interesting on the level of decreasing the ecological impact. A further research, resulting in a higher reduction of the cement content, could be useful. The differences for the ECI between mix 8 until 14 are caused by the different environmental impact of the cement replacement materials mentioned in Figure 1-8.

Also in the ecological comparison, the durability should be kept in mind. An improved durability results in a longer service life time. In this thesis values for resistivity measurements, and water absorption tests under vacuum, show that the durability should be increased, by the optimization process. An increased durability and a longer service life saves new raw materials. The lower the production of materials, the better for the environment.

Table 14-2: Comparison between mixtures on level of ecologics

Mixture	Absolute ECI [€/m³]	Relative ECI
Mix 1	22.72	1.00
Mix 2	22.72	1.00
Mix 3	22.71	1.00
Mix 4	22.74	1.00
Mix 5	22.77	1.00
Mix 6	22.79	1.00
Mix 7	22.80	1.00
Mix 8	21.24	0.93
Mix 9	21.24	0.93
Mix 10	21.24	0.93
Mix 11	21.18	0.93
Mix 12	21.14	0.93
Mix 13	21.24	0.93
Mix 14	21.20	0.93
Mix 15	22.76	1.00
Mix 16	22.82	1.00
Mix 17	22.80	1.00
Mix 18	22.72	1.00

14.3 Combined cost

Attention should be paid to the fact that a gain of 7% on the ecological cost and an increase of 2% on the economic cost could result in a total cost that is higher than the reference cost. This is the case if the weight of the economic cost is higher than the weight of the ecological cost. This is the case. The comparison of the values for the relative combined cost is given in Table 14-3. This is also shown by Figure A-9.

From Table 14-1, it was already clear that the design of an ecological concrete does not result in a cheaper concrete. On the other hand, maybe taking into account the cost to the environment could make it cheaper in total. However, in Table 14-3 it is shown that this is only the case for some mixtures. Three mixtures gave the best result: replacement by limestone powder (mix 10), by fly ash (mix 11) and by increased amount of aggregates (mix 14). The weight factor of the economic cost is several times the weight factor of the ecological cost.

Table 14-3: Comparison of the combined cost

Mixture	Relative combined cost
Mix 1	1.00
Mix 2	1.01
Mix 3	1.03
Mix 4	1.03
Mix 5	1.03
Mix 6	1.03
Mix 7	1.04
Mix 8	1.04
Mix 9	1.36
Mix 10	**1.00**
Mix 11	**1.00**
Mix 12	1.16
Mix 13	1.05
Mix 14	**0.99**
Mix 15	1.03
Mix 16	1.04
Mix 17	1.04
Mix 18	1.00

Besides the comparison on the level of the costs also the properties of the concrete for the three mixtures in fresh and hardened state should be compared. Table 12-4 shows mix 10 with limestone powder scores the best when strength is considered. For reasons of durability also mix 11 with fly ash is an option.

When durability is important for the economic and ecological cost, this is also the case for the combined cost. Because of the positive effect of the packing optimization process on durability indicators, durability should be better. This is beneficial for the total cost. Because durability is not taken into account in the total cost, the combined cost in this thesis is estimated to large.

Part III: Conclusions

In the last part the conclusions are collected in Chapter 15 and Chapter 16 gives some recommendations for possible further research.

Chapter 15 Conclusions

The general conclusion is that the applied design process to obtain an ecological concrete with a lower cement works, even when the packing optimization is only applied on the aggregates. The evaluation tool 'Groen Beton' shows that reducing the cement content is the most efficient way in the design of ecological concrete.

In the first design step, an optimization of the packing results in a different aggregate composition for the mixture. The influence of the increased packing was, as expected, an increased workability of the mixture by a higher amount of excess water. On the other hand, this results in a decrease of the strength and an increased value for the water absorption test under vacuum, and a decreased value for the resistivity measurement.

In the next design step the workability was reduced to the workability of reference concrete. According to the theory of Sonja Fennis, this should be possible, based on the ratio $\varphi_{mix}/\ \alpha_t$. This was tested, but the mixture calculated with such an equal ratio as the reference concrete gives a higher workability as was expected. However this theory does not result in a mixture with the expected workability, the relation between $\varphi_{mix}/\ \alpha_t$ and the value for the flow was proven, based on a limited amount of tests. Decreasing the water content results, as expected, in improved values for strength, water absorption and resistivity. This is because of the decreasing amount of excess water.

In the third and last design step, the gain of strength was reduced by lowering the cement content. This reduction was calculated based on a percentage, equivalent to the percentage related to the gain of strength after 7 days, between the optimized and the reference mixture. Different cement replacement materials were used. The way of calculating the reduction of the cement content, results in a reduction of the strength which was slightly too high. This was maybe related to the fact that the W/C ratio increases, due to the amount of water, which was kept constant.

The optimized mixtures were about 7% more ecologic than the reference concrete while the production cost only shows a small increase, depending on what cement replacement material was used. Using the quartz powder M800 or silica fume results in mixtures with good test results but also in a strong increase of the cost. The cost increased with both 54 % and 25 %.

On top of that, the mixture with silica fume has better properties, compared to the mixture with quartz powder M800. Because of the cost and results for strength and durability, it seems to be more interesting to use silica fume instead of quartz powder M800. Quartz powder M400 results in an increase of the cost by 9 %.

Based on the cost, the mixture with limestone powder and fly ash give the best results, with an increase of only 2 to 3 %. Their properties on level of strength and durability are comparable with the reference concrete, which was the goal. Also the mixture without cement replacement products and an increased amount of aggregates to replace the decreased amount of cement was only 2 % more expensive. Because the properties in hardened state were worse, the mixtures using limestone powder or fly ash seems to be the most interesting.

On the other hand, the production cost is not the most important factor. When the Environmental Cost Indicator was taken into account, the total costs of the three mixtures mentioned in the paragraph above were the same or slightly lower compared to the cost for the reference concrete. An increased durability is another beneficial effect on the total cost. Durability indicators, such as the water absorption and the resistivity, show favorable changes by designing an ecological concrete. The effect of a more durable mixture on the total cost is not known, but it is sure it is beneficial. The question is how big the contribution by the durability is, on the level of the cost.

The experiment with portaclay was interesting but it is not good for common application yet. Due to the fact portaclay is not a common used product, the cost was very high. Due to the water absorption it was only usable for a very low amount. The expected reaction between the limestone powder and the portaclay was not noticed.

Besides this positive story also some remarks are posed. A first remark is the results for the reference mixture when it was mixed with the vacuum mixer. However reasons were given to explain the difference, this cause some uncertainty about the properties for the reference mixture. A second remark is the failed optimization based on using a fine quartz sand (S90). This was strange because the packing was improved by adding S90. Because no strength increase was achieved, the optimization process was stopped. It is assumed this is related to the low workability of the mixture. This could be caused by a strong increase of the specific surface, due to the fineness of S90. This results in a higher water demand.

Chapter 16 Further research

The results of this thesis open perspectives for further optimization. The reduction of the amount of cement with 8%, results in a reduction of the ECI with 7%. The relation between the environment and the use of cement is clear. Certainly, it is worth trying to optimize the design of an ecological concrete further.

A continuation of this thesis should start with a confirmation of the test results for the reference mixture, when it is mixed according to the normal procedure, and when it is mixed by the vacuum mixer. Those results are too different to neglect this. In general, this could be extended in research about the influence of the mixing procedure on the optimization process.

Another interesting mixture to produce is a mixture where the aggregate composition is determined by an optimization according to an optimization curve, as the Fuller curve. With the method of the least squares, it is possible to approximate such a curve. The mixture with optimized according to the packing theory could be compared with the mixture optimized according the optimization curve. This could give interesting information about the difference between both ways of determining the aggregate composition. This idea came too late to execute it in this thesis.

Further on, this optimization procedure should be tested on big scale with different and especially other reference mixtures. This could check if results and conclusions from this thesis are always the case or not.

Doing tests in other regions of workability could also result in interesting information. Now the reference mixture does not have a high workability. This results in mixtures that were often to dry. By setting another standard of workability this problem is avoided.

Also about the cement replacement products, further research is necessary. Their influence was only tested on one mixture. This is not sufficient. More tests on the same cement replacement products seem to be more interesting than testing other cement replacement products. This is due to the fact that already many cement replacement products were used.

About the portaclay further research is necessary, in order to limit its water absorption. An increased use of clayey materials should result in a strongly decrease of the cost of the material, because of the high amounts of clayey materials present in our environment.

To investigate the environmental benefits and the overall cost, including life time cycle analysis, a study about the sustainability could be useful. This coud go very wide. Even traffic and diversions due to roadworks, caused by less durable concrete, should be taken into account. Traffic influences strongly our environment. Combining packing optimization, the use of recycled aggregates and recycled cement, an increased workability and other ideas to reduce the environmental impact of concrete is the future.

Besides the extension of the research in this thesis, other slightly different optimization methods should be taken into account. There are several possibilities.

First of all, based on the results of this thesis, it seems to be useful to take into account the packing of the total amount of solids as Sonja Fennis did. Because of the limited time in this thesis only the limestone aggregates and sands were optimized on the level of packing. By taking into account also cement and cement replacement materials for the packing, it will be more realistic. On the other hand, this will result in a more iterative process of optimization. The reduction of cement by a cement replacement material will not be the final step but an intermediate step in the design. That replacement will influence the packing and the optimization could start again.

Secondly, changes in the way in how the research was done in this thesis are possible. In the third design step, when the amount of cement reduces, the amount of water was kept constant. This results in an increased W/C ratio. All the optimized mixtures had a little less strength than the reference mixture, and a little increased workability. Also reducing the water content, together with the cement content, could be the solution.

Al these ideas should result in a general accepted way of thinking of optimizing concrete mixtures according to the principles of packing. This reduces the amount of cement and the environmental impact of concrete consumption and production. Further research should also make it possible to replace more cement by less polluting materials. This should result in a higher environmental improvement. The higher the possible improvement, the more chance that this way of thinking becomes the standard way of designing concrete!

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Norms

NBN B24-213:1976	Masonry units testing - Water absorption under vacuum
NBN B15-215:1989	Concrete testing - Absorption of water by immersion
NBN EN 933-1:2012	Tests for geometrical properties of aggregates - Part 1: Determination of particle size distribution - Sieving method
NBN EN 1097-3:1998	Tests for mechanical and physical properties of aggregates - Part 3: Determination of loose bulk density and voids
NBN EN 1097-6:2013	Tests for mechanical and physical properties of aggregates - Part 6: Determination of particle density and water absorption
NBN EN 12350-2:2009	Testing fresh concrete - Part 2: Slump-test
NBN EN 12350-5:2009	Testing fresh concrete - Part 5: Flow table test
NBN EN 12350-6:2009	Testing fresh concrete - Part 6: Density
NBN EN 12350-7:2009	Testing fresh concrete - Part 7: Air content - Pressure methods
NBN EN 12390-3:2009	Testing hardened concrete - Part 3: Compressive strength of test specimens (+ AC:2011)

Attachments

The attachments consist of 2 big parts. First all the data about the produced mixtures is summarized in tables: the mixture compositions and the test results. Further on some figures compares all test results graphically and contain also standard deviations for the tests on concrete cubes. The second part of the attachments contains all technical datasheets from the used materials.

A Data & graphs about all the mixtures

Table A-1: Description of mixtures and their codes

Mixture code	Description
Mix 1	Reference concrete with the standard mixer & the standard procedure
Mix 2	Optimization of the packing applied on the coarse aggregates (limestone 6.3/20 and 2/6.3))
Mix 3	Optimization of the packing applied on the sands (sea sand 0/4 and 0/2
Mix 4	Optimization of the packing applied on the total skeleton (both sands and limestone aggregates)
Mix 5	Optimization of the workability – theoretical calculated optimal water content
Mix 6	Optimization of the workability – decreased water content but not yet sufficient to obtain the same workability as the reference concrete
Mix 7	Optimization of the workability – workability in accordance with the workability of the reference concrete
Mix 8	Optimization of the strength – replacement of cement by M400
Mix 9	Optimization of the strength – replacement of cement by M800
Mix 10	Optimization of the strength – replacement of cement by limestone powder
Mix 11	Optimization of the strength – replacement of cement by fly ash
Mix 12	Optimization of the strength – replacement of cement by silica fume
Mix 13	Optimization of the strength – replacement of cement by portaclay and limestone powder
Mix 14	Optimization of the strength – replacement of cement by increased amount of aggregates (sea sand & limestone aggregates
Mix 15	New optimization process with S90 – optimized packing on the skeleton
Mix 16	New optimization process with S90 – workability, theoretical calculated
Mix 17	New optimization process with S90 – workability, in accordance with the workability of the reference concrete
Mix 18	Reference concrete with the vacuum mixer

Table A-2: Mixture compositions mix 1 - 9

	Mix 1		Mix 2		Mix 3		Mix 4		Mix 5		Mix 6		Mix 7		Mix 8		Mix 9	
	[m³]	[kg]	[m³]	[kg]	[m³]	[kg]	[m³]	[kg]	[m³]	[kg]	[m³]	[kg]	[m³]	[kg]	[m³]	[kg]	[m³]	[kg]
CEM	0.112	336.0	0.112	336.0	0.112	336.0	0.112	336.0	0.112	336.0	0.112	336.0	0.112	336.0	0.103	309.2	0.103	309.2
Water	0.166	166.0	0.166	166.0	0.166	166.0	0.166	166.0	0.158	158.4	0.151	150.8	0.146	146.0	0.146	145.8	0.146	145.8
6.3/20	0.283	761.0	0.211	567.7	0.283	761.0	0.367	986.4	0.371	997.1	0.375	1007.8	0.377	1014.5	0.377	1013.4	0.377	1013.4
2/6.3	0.094	251.5	0.166	443.8	0.094	251.5	0	0	0	0	0	0	0	0	0	0	0	0
0/4	0.194	499.3	0.194	499.3	0.323	831.3	0.333	857.5	0.337	866.8	0.340	876.2	0.343	882.0	0.342	881.0	0.342	881.0
0/2	0.129	339.3	0.129	339.3	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Tixo	0.002	2.568	0.002	2.568	0.002	2.568	0.002	2.568	0.002	2.568	0.002	2.568	0.002	2.568	0.002	2.565	0.002	2.565
Air	0.020	-	0.020	-	0.020	-	0.020	-	0.020	-	0.020	-	0.020	-	0.020	-	0.020	-
Additional	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.010	26.4	0.010	26.4
Sum	1	2355.7	1	2354.7	1	2348.4	1	2348.5	1	2360.9	1	2373.3	1	2381.2	1	2378.4	1	2378.4
Remark	-		-		-		-		-		-		-		M400		M800	

Table A-3: Mixture compositions mix 10 - 18

	Mix 10		Mix 11		Mix 12		Mix 13		Mix 14		Mix 15		Mix 16		Mix 17		Mix 18	
	[m³]	[kg]	[m³]	[kg]	[m³]	[kg]	[m³]	[kg]	[m³]	[kg]	[m³]	[kg]	[m³]	[kg]	[m³]	[kg]	[m³]	[kg]
CEM	0.103	309.2	0.103	309.2	0.103	308.5	0.103	309.2	0.103	309.1	0.112	336.0	0.112	336.0	0.112	336.0	0.112	336.0
Water	0.146	145.8	0.146	145.8	0.146	145.5	0.146	145.8	0.146	145.8	0.166	166.0	0.146	145.9	0.150	150.0	0.166	166.0
6.3/20	0.377	1013.4	0.377	1013.4	0.376	1011.2	0.377	1013.4	0.382	1027.4	0.365	982.6	0.376	1010.8	0.374	1005.1	0.283	761.0
2/6.3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.094	251.5
0/4	0.342	881.0	0.342	881.0	0.342	879.2	0.342	881.0	0.347	893.3	0.270	695.4	0.278	715.4	0.276	711.3	0.194	499.3
0/2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.129	339.3
Tixo	0.002	2.565	0.002	2.565	0.002	2.560	0.002	2.565	0.002	2.565	0.002	2.568	0.002	2.568	0.002	2.568	0.002	2.568
Air	0.020	-	0.020	-	0.020	-	0.020	-	0.020	-	0.020	-	0.02	-	0.02	-	0.020	-
Additional	0.010	26.4	0.010	26.4	0.012	26.4	0.010	26.4	-	-	0.064	170.3	0.066	175.2	0.066	174.2	-	-
Sum	1	2378.4	1	2378.4	1	2373.4	1	2378.4	1	2378.3	1	2352.9	1	2385.9	1	2379.1	1	2355.7
Remark	LP		FA		SF		90% LP + 10% PC		-		S90		S90		S90			

Table A-4: Test results mix 1 - 9

	Mix 1	Mix 2	Mix 3	Mix 4	Mix 5	Mix 6	Mix 7	Mix 8	Mix 9
Slump [cm]	1.0	3.5	11	15.5	10.0	5.0	2.5	2.5	3.5
Flow [cm]	42.0	41.5	42.5	50.5	39.0	36.0	33.0	37.0	39.5
Air [%]	3.0	4.2	3.2	2.5	2.8	2.6	2.5	2.5	3.2
Density [kg/m³]	2375.0	2343.8	2375.0	2398.8	2369.8	2395.6	2404.6	2391.3	2378.8
Strength 7d [N/mm²]	58.0	55.5	54.9	55.3	58.4	60.9	62.6	58.9	60.1
Strength 28d [N/mm²]	68.0	64.4	62.9	62.4	63.8	67.6	71.6	65.9	67.6
Water absorption [%]	4.26	4.87	5.05	4.92	4.39	4.13	3.85	4.34	4.54
Resistivity [Ωm]	0.42	0.38	0.44	0.44	0.45	0.50	0.56	0.52	0.51
Relative cost [-]	1.00	1.01	1.05	1.04	1.04	1.05	1.05	1.09	1.54
Relative ECI [-]	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.93	0.93

Table A-5: Test results mix 10 - 18

	Mix 10	Mix 11	Mix 12	Mix 13	Mix 14	Mix 15	Mix 16	Mix 17	Mix 18
Slump [cm]	4.0	6.0	2.5	1.0	2.0	8.0	0.5	0.5	3.0
Flow [cm]	38.0	41.0	42.5	41.5	43.5	43.0	53.0	46.5	39.0
Air [%]	2.1	2.5	2.5	2.6	2.7	2.3	2.0	2.6	4.2
Density [kg/m³]	2402.3	2375.0	2390.1	2392.5	2375.9	2370.0	2418.8	2406.1	2335.0
Strength 7d [N/mm²]	57.9	56.4	57.0	54.7	56.1	51.8	63.2	58.4	49.1
Strength 28d [N/mm²]	65.1	63.3	67.8	59.7	61.8	60.5	68.5	68.1	51.2
Water absorption [%]	4.42	4.23	4.23	4.54	4.41	5.23	3.95	4.58	5.21
Resistivity [Ωm]	0.51	0.58	1.04	0.51	0.47	0.48	0.54	0.42	0.37
Relative cost [-]	1.03	1.02	1.25	1.10	1.02	1.05	1.06	1.06	1.00
Relative ECI [-]	0.93	0.93	0.93	0.93	0.93	1.00	1.00	1.00	1.00

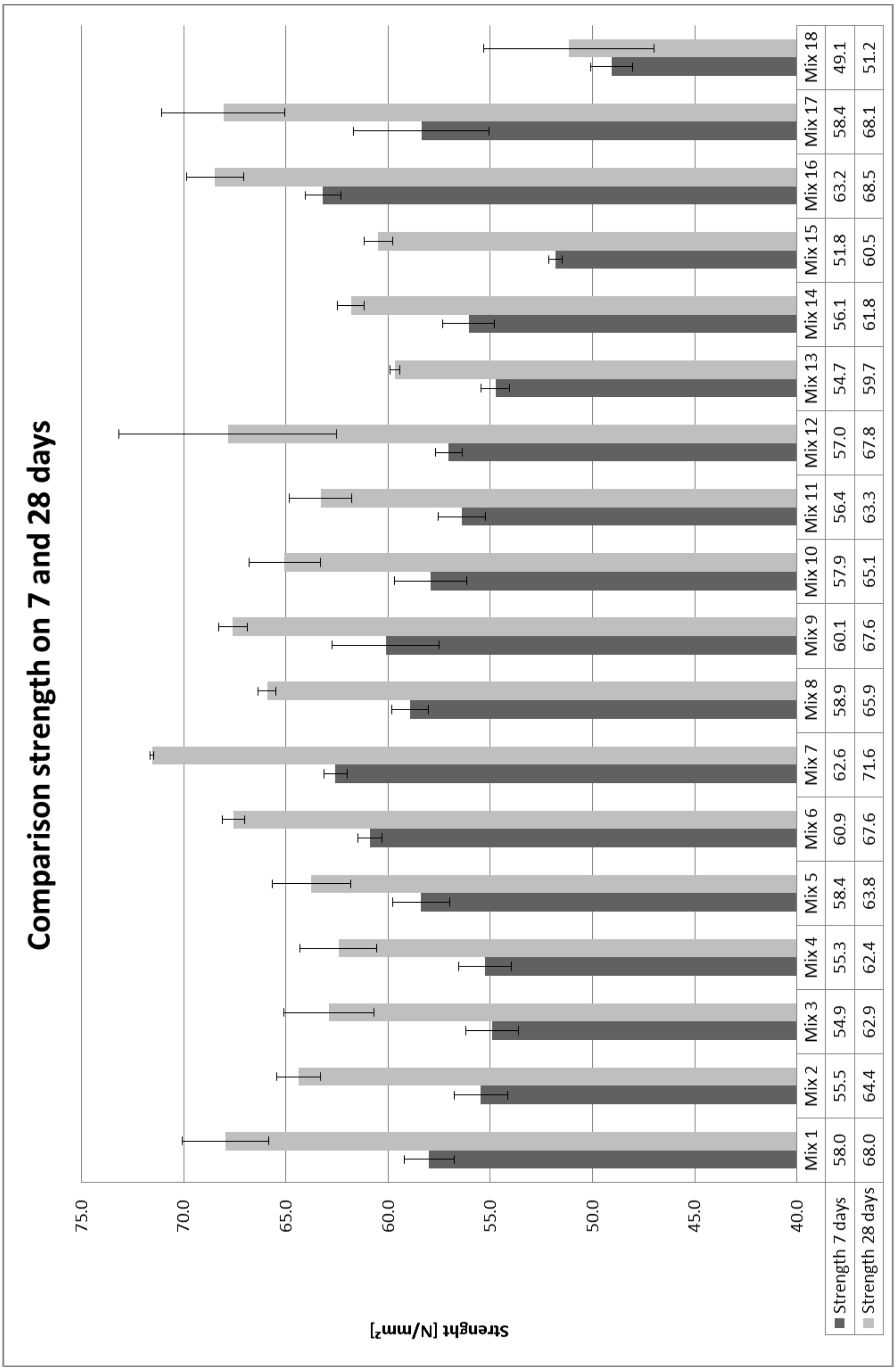


Figure A-1: Comparison strength on 7 and 28 days

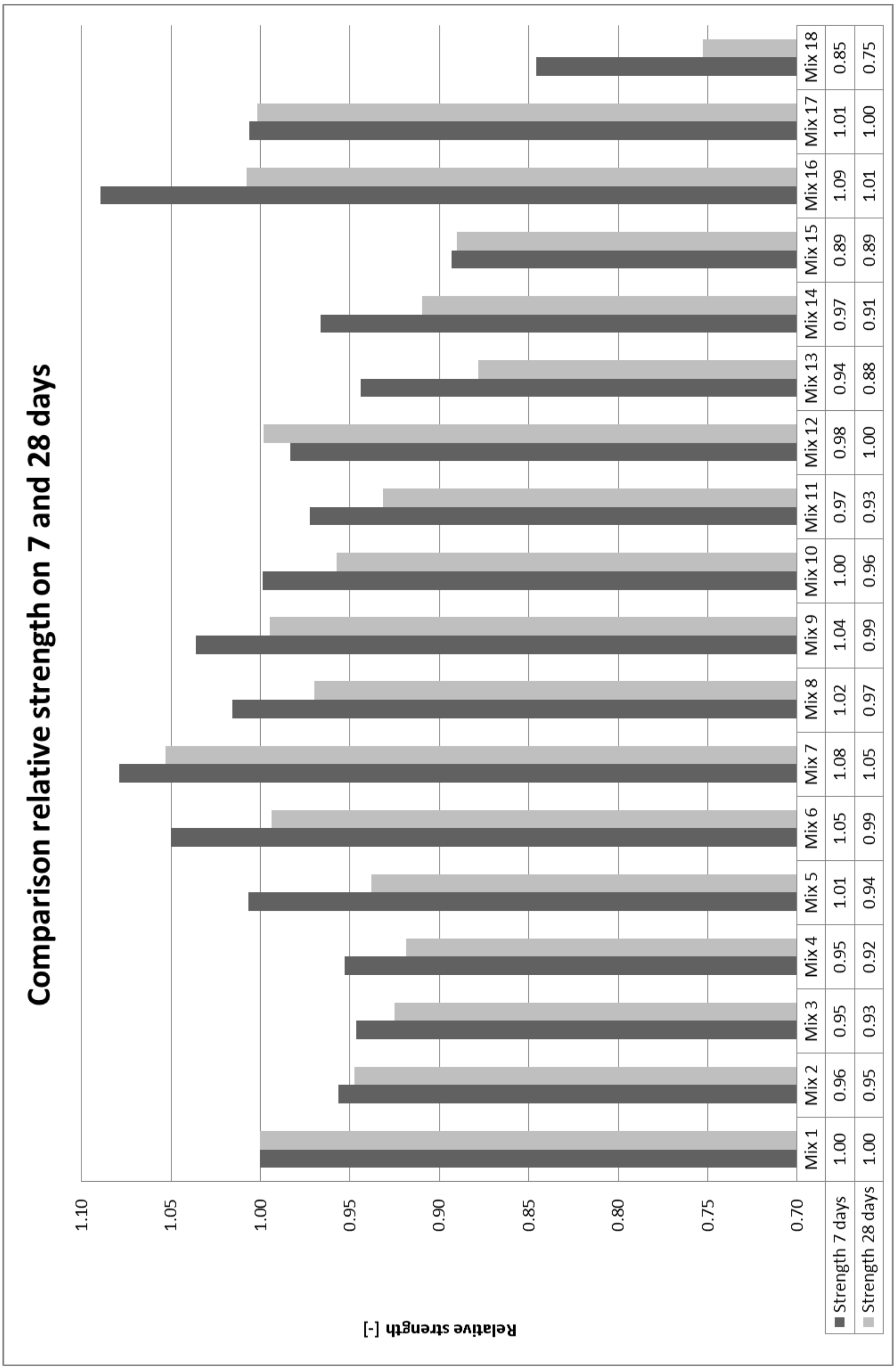


Figure A-2: Comparison relative strength on 7 and 28 days

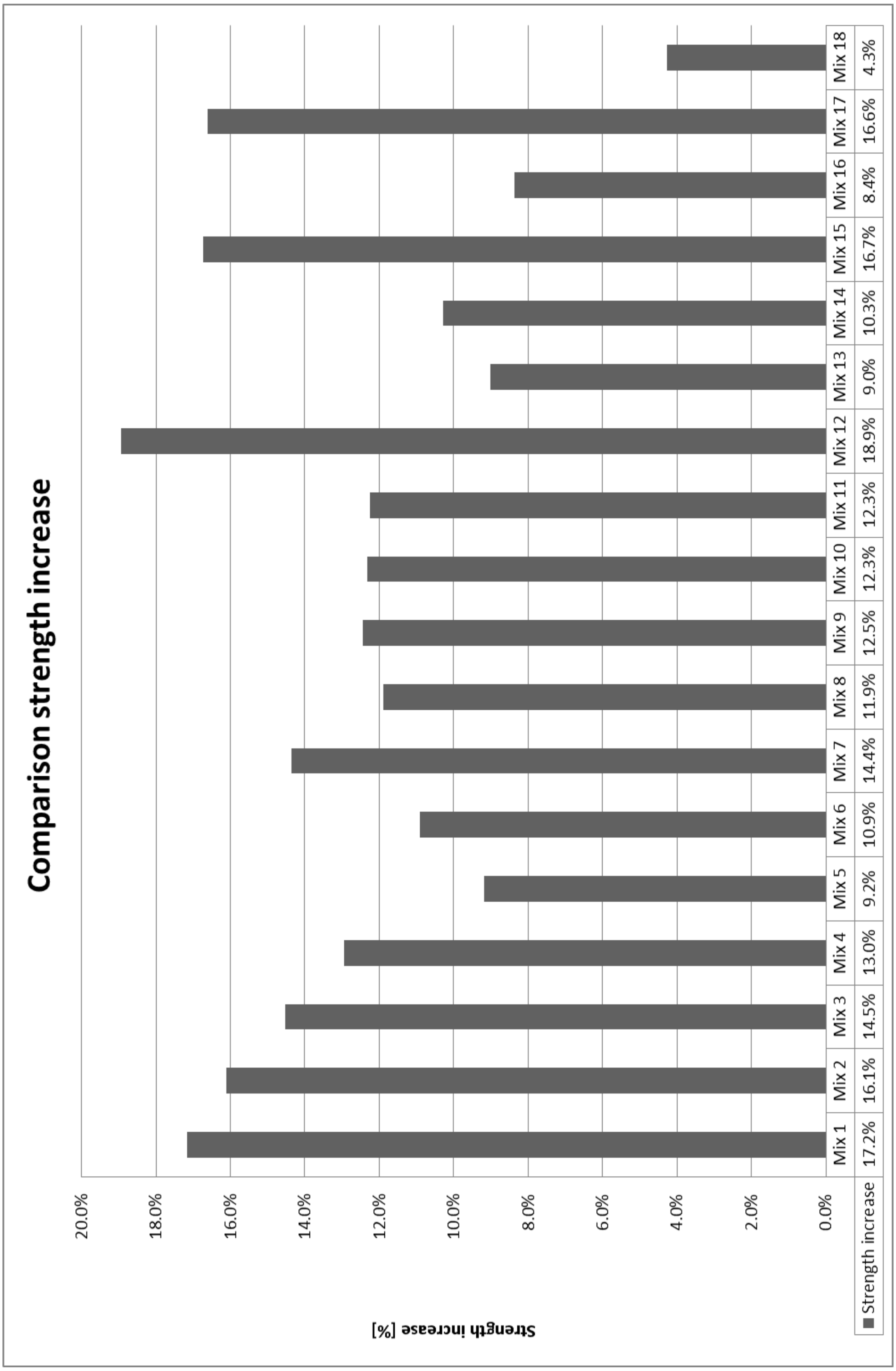


Figure A-3: Comparison strength increase

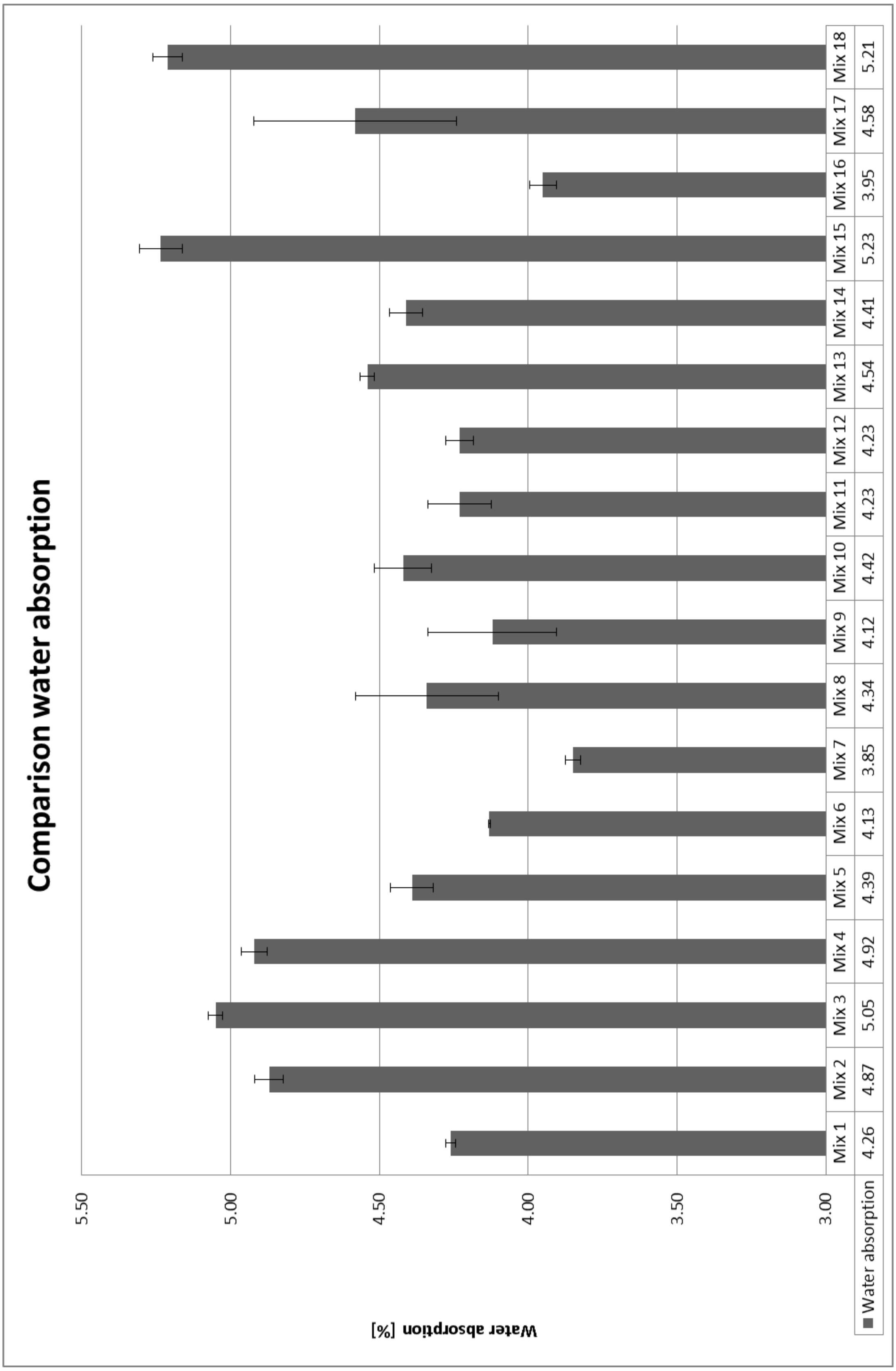


Figure A-4: Comparison water absorption

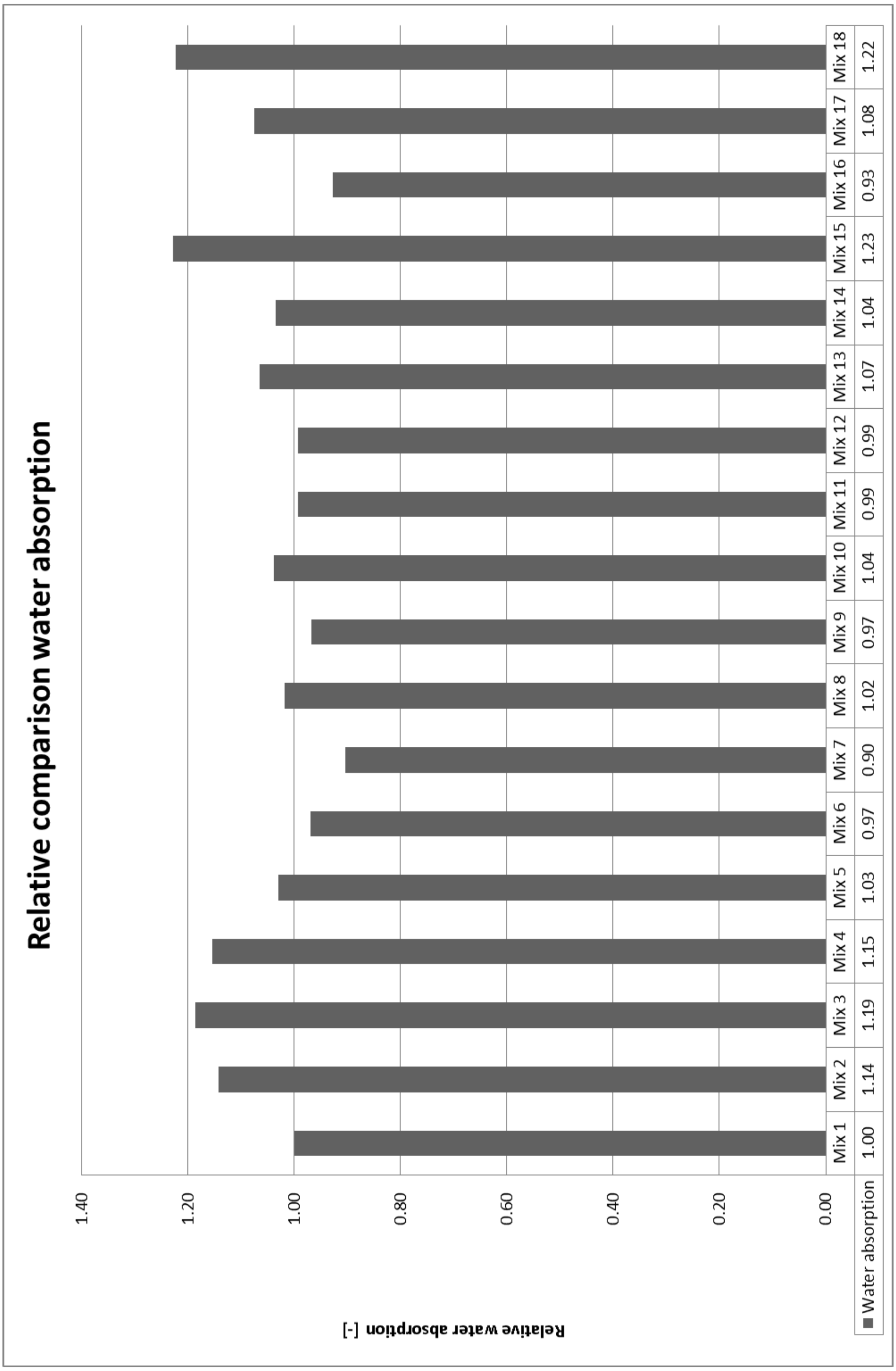


Figure A-5: Relative comparison water absorption

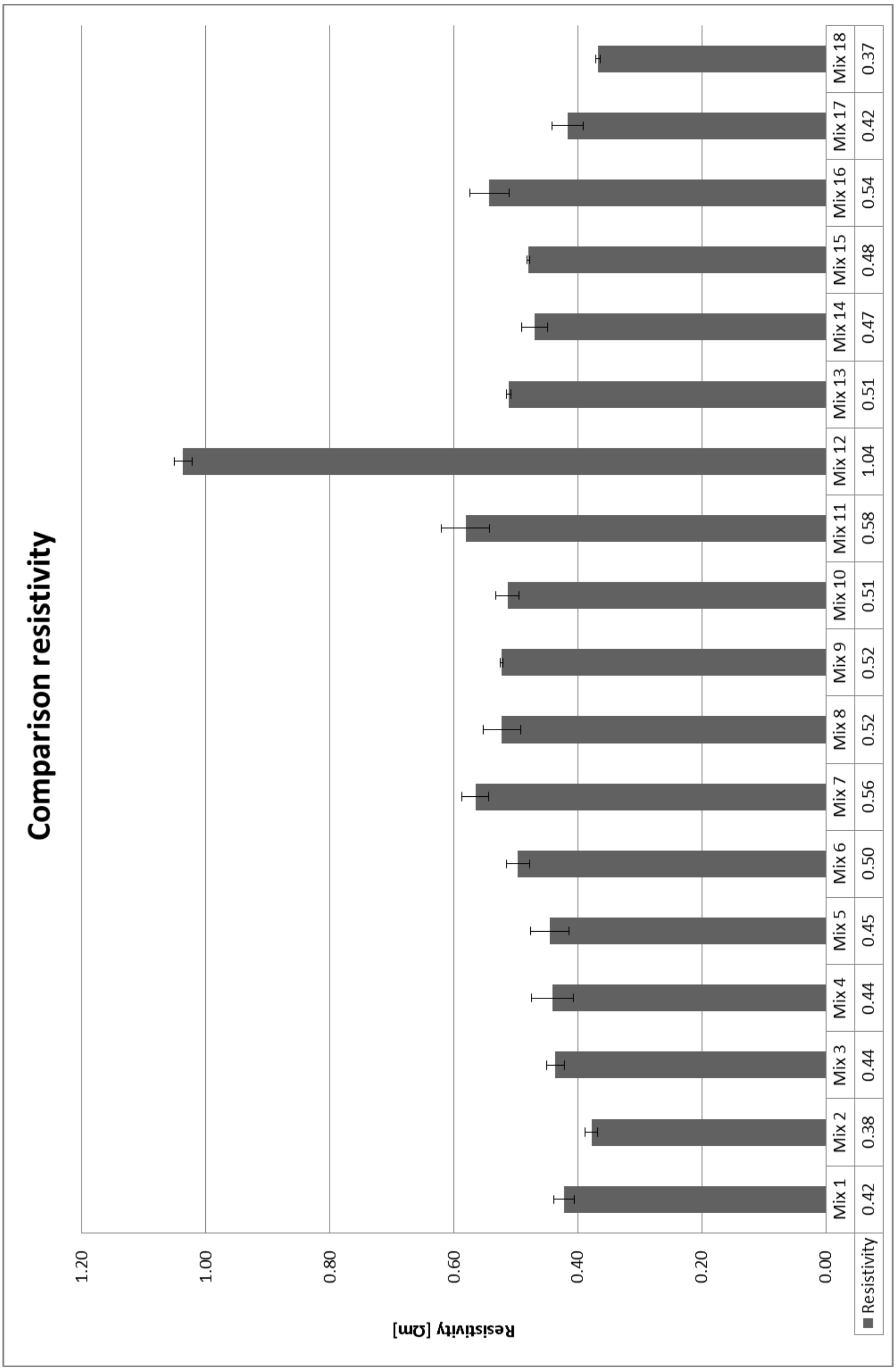


Figure A-6: Comparison resistivity

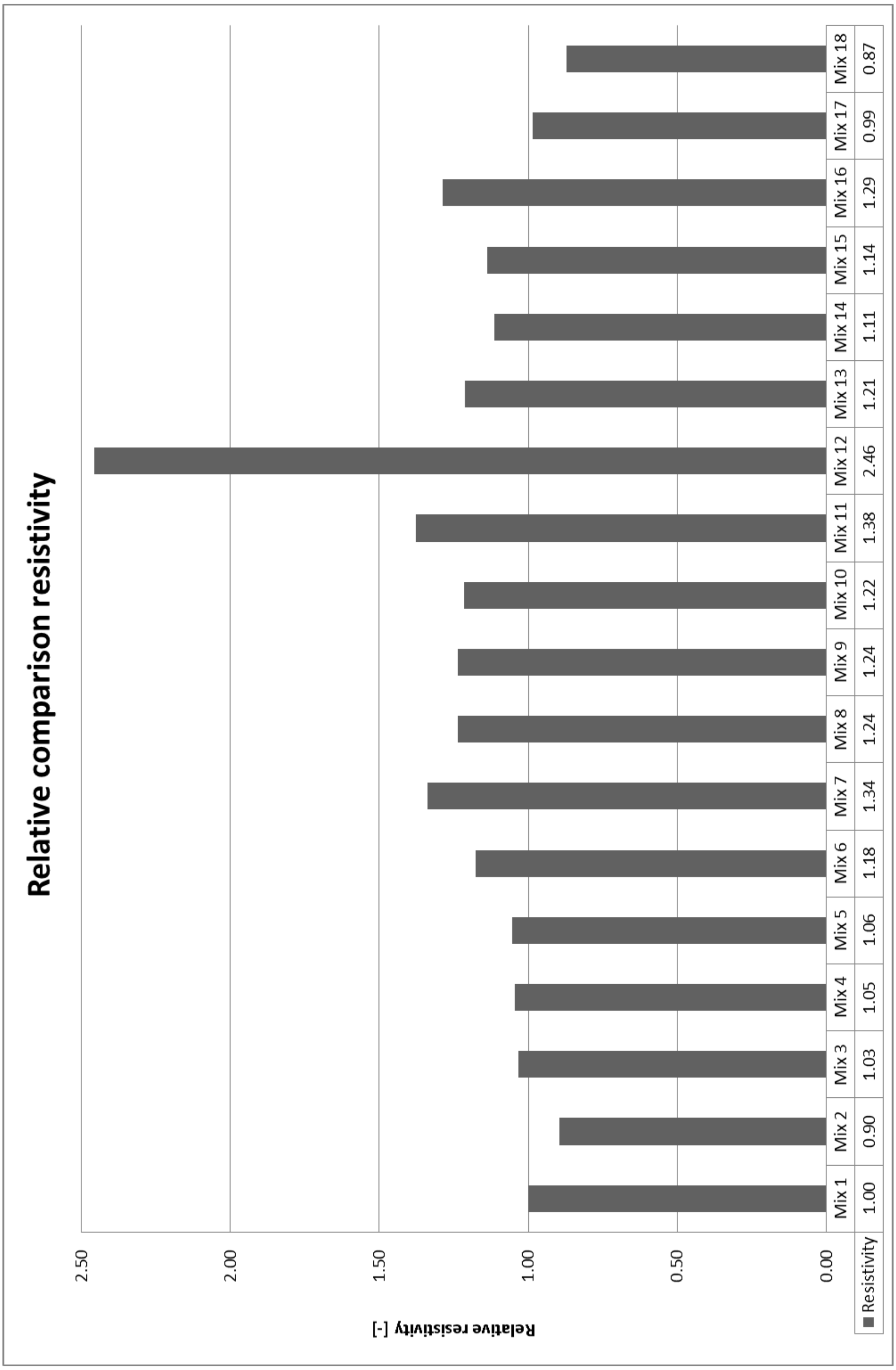


Figure A-7: Relative comparison resistivity

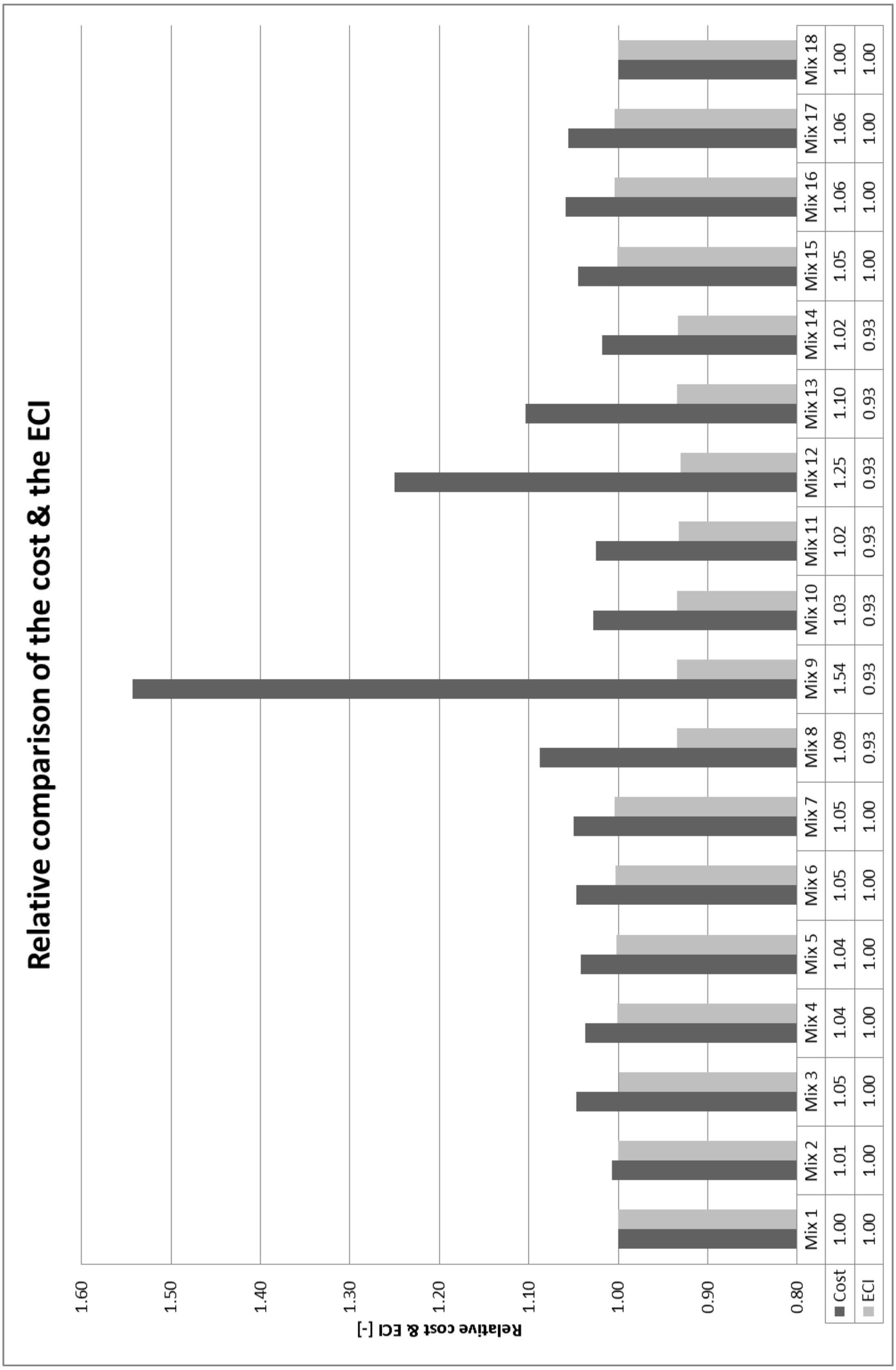


Figure A-8: Relative comparison of the cost & the ECI

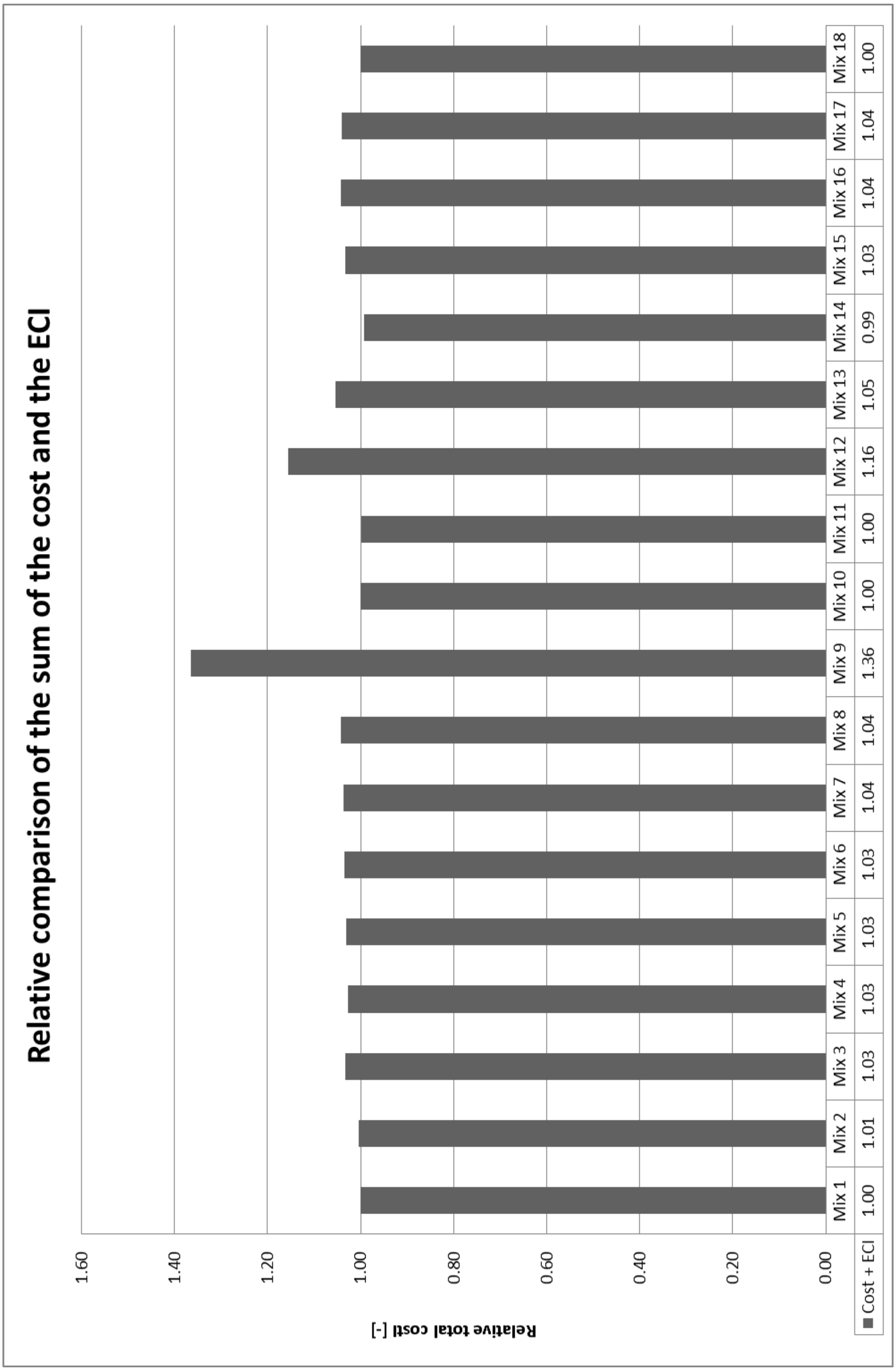


Figure A-9: Relative comparison of the sum of the cost and the ECI

B Technical information used products

CEM I 52,5 N

Hoogperformant cement

BULK

Het product en zijn toepassingen

Het cement CEM I 52,5 N is een portlandcement dat als enig hoofdbestanddeel portlandklinker (K) bevat.
Het klinkergehalte bedraagt minstens 95%.

Aanbevolen toepassingsgebieden

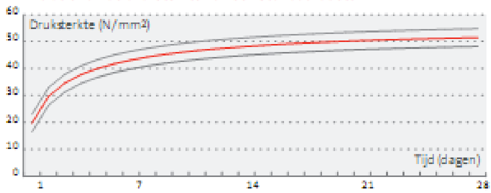
- Beton in niet agressief milieu (omgevingsklassen E0, EI en EE volgens de norm NBN B15-001), dat een normale of snelle ontkisting, behandeling of ingebruikname vraagt
- Beton voor middelmatige of hoge sterkteklassen
- Beton storten in de winterperiode
- Prefabricatie van betonproducten

Tegenindicaties

- Beton in agressief milieu (omgevingsklassen EA2 en EA3 volgens de norm NBN B15-001)
- Beton voor massieve constructies
- Bij gebruik van granulaten die gevoelig zijn voor de alkali-granulaatreactie, indien het beton aan vochtig milieu wordt blootgesteld

Druksterkte van beton

Evolutie van de druksterkte van een standaardbeton*



Deze figuur geeft de evolutie van de druksterkte weer, gemeten in ons laboratorium, op kubussen van 150 mm zijde, aangemaakt met het cement CEM I 52,5 N.
De voornaamste eigenschappen van het beton zijn:

- een continue korrelverdeling: kalksteen 4/20 + grof rivierzand
- cementgehalte: 300 kg/m³
- vloeibaarheid: zetmaat (slump) van 80 mm
- W/C-factor: ongeveer 0,58

LAND	NORM	BENAMING	MERK
België	NBN EN 197-1 PTV 603	CEM I 52,5 N	Benor
Frankrijk	NF EN 197-1 NF P15-318	CEM I 52,5 N CP2	NF

Fabriek Lumbres gecertificeerd

ISO 9001 CERTIFIED VINÇOTTE

ISO 14001 CERTIFIED VINÇOTTE

Het cement CEM I 52,5 N is CE-gemarkeerd (als cement CEM I 52,5 N), hetgeen zijn overeenkomstigheid garandeert met de norm EN 197-1. Bovendien beantwoordt het aan meerdere nationale normen en draagt het verschillende nationale kwaliteitsmerken, zoals hieronder aangegeven:

CE

BENOR

NF

De veiligheidsfiche en de prestatieverklaring van dit product zijn beschikbaar op www.holcim.be

Voordelen van CEM I 52,5 N

- Snelle verharding
- Hoge sterkte op korte en middellange termijn

Technische specificaties

Mechanische en fysische eigenschappen **

	EENHEDEN	RESULTATEN	EISEN NORM(EN)
Binding Waterbehoefte Begin Einde	 % hh:mm hh:mm	 31 2:30 3:35	 - ≥ 0:45 ≤ 12:00
Stabiliteit	mm	< 1	≤ 10
Druksterkte 1 dag 2 dagen 28 dagen	 N/mm² N/mm² N/mm²	 24 38 61	 ≥ 20 ≥ 52,5
Specifieke oppervlakte Blaine	m²/kg	433	-
Absolute volumemassa	kg/m³	3090	-
Schijnbare volumemassa	kg/m³	1080	-
Zeefrest 200 µm	%	< 0,5	≤ 3,0

Chemische samenstelling **

	RESULTATEN (%)	EISEN (%) NORM(EN)
CaO	63,9	-
SiO_2	20,0	-
Al_2O_3	5,1	-
Fe_2O_3	3,4	-
MgO	0,8	-
Na_2O	0,34	-
K_2O	0,75	-
SO_3	3,1	≤ 4,0
Cl^-	0,05	≤ 0,10
Gloeiverlies	1,9	≤ 5,0
Onoplosbare rest	0,5	≤ 5,0

* Opmerking: Omdat de sterkte van beton afhangt van verschillende factoren, is de curve op de figuur niet noodzakelijk representatief voor de evolutie van de sterkte van eender welk beton aangemaakt met CEM I 52,5 N.

** Opmerking: De resultaten weergegeven in de tabellen zijn gebaseerd op gemiddelde waarden en zijn louter indicatief. Zij hebben dus geen contractuele waarde. Holcim (België) n.v. kan er dus op geen enkele wijze verantwoordelijk voor worden gesteld.

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Figure B-1: Technical datasheet - Cement

BUILDING TRUST

TECHNISCHE FICHE
Tixo®

SUPERPLASTIFICEERDER, STERK WATERREDUCEERDER, WATERDICHTINGSMIDDEL IN DE MASSA
CONFORM DE NORM NBN EN 934-2 T3.1 – T3.2

PRODUCTBESCHRIJVING

Tixo® is een superplastificeerder, sterke water reduceerder, waterdichtingsmiddel in de massa van de laatste generatie.

TOEPASSINGEN

Tixo® wordt aanbevolen voor beton dat geproduceerd wordt in de betoncentrale en prefab fabrieken.

Dankzij de zeer sterke watervermindering, de uitstekende vloeibaarheid gecombineerd met een sterke cohesie en dankzij de zelfverdichtende kenmerken, wordt Tixo® 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 reologie behoud,
- waterdichtbeton.

Wij bevelen het niet aan voor de productie van gepolijst beton.

Tixo® kan gebruikt worden met andere hulpstoffen (ons raadplegen).

EIGENSCHAPPEN / VOORDELEN

Tixo® 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 reologie,
- verhoogt sterk de waterdichtheid,
- vermindert de snelheid van de carbonatatie van beton.

Tixo® bevat geen chloriden of andere producten die de corrosie van staal bevordert. Kan eveneens gebruikt worden zonder beperkingen wat betreft gewapend en voorgespannen beton.

Technische fiche
Tixo®
05/02/2014, VERSIE 1
02 08 0101 002 000003

NL/België

Figure B-2: Technical datasheet - Tixo (part 1)

PRODUCTINFORMATIE

VORM	**UITERLIJK / KLEUR** Vloeibaar, bruinachtig **VERPAKKING** Vat van 200 kg (verloren verpakking) Container van 1000 L (met statiegeld)
OPSLAG	**OPSLAGCONDITIES / HOUDBAARHEID** 12 maanden vanaf de productiedatum indien opgeslagen in de origine verpakking in een lokaal dat beschermd is tegen vorst en hoge temperaturen en bij een temperatuur tussen de +5°C en +35°C.
TECHNISCHE GEGEVENS	**CHEMISCHE BASIS** Water gebaseerde polymeeroplossing **DENSITEIT** 1,090 kg/l ± 0,020 **pH** 4,6 ± 1,5 **Cl^- IONENGEHALTE** Minder dan 0,10 % **DROGESTOF** (NBN EN 480-8) 25,0 % ± 1,50 **Na_2O EQ.** Maximum 1,0 %

SYSTEEMINFORMATIE

TOEPASSINGSDETAILS	**VERBRUIK** De aanbevolen dosering bedraagt ▪ als superplastificeerder: 0,5 tot 2 % van het cementgewicht. ▪ als waterdichtingsmiddel: 1 % van het cementgewicht. Overdoseringen zijn mogelijk. De juiste dosering wordt vastgesteld door proeven uit te voeren, aangezien ze afhangt van da aard van de componenten van het beton, de gewenste kwaliteit en de weersomstandigheden. In functie van de gebruikte cement kan een bindingsvertraging opgemerkt worden. **TE VERMIJDEN CONTACTEN** Tixo® is een wateroplossing en kan dus bevriezen. Teruggebracht op +20°C en correct gehomogeniseerd, na een intense menging, behaald het product zijn initiale kwaliteiten terug. In dit geval ons raadplegen.
TOEPASSINGSINSTRUCTIES	**TOEPASSINGSMETHODE / GEREEDSCHAP** Tixo® wordt na het aanmaakwater, of terzelfder tijd als het water toegevoegd in de menger. Voor een optimale watervermindering, raden wij aan om het mengsel vochtig te mengen gedurende minimum 60 seconden. Tenslotte om een zo goed mogelijke dichtheid te bekomen, mag het toevoegen van het resterend water alléén gebeuren na 40 seconden mengtijd teneinde alle overtollig water te vermijden. Gebruikmakend van Tixo® realiseert men een beton van zeer hoge kwaliteit. De regels der kunst voor de productie en het plaatsen van beton moeten eveneens gerespecteerd worden voor de Tixo® Vers beton moet altijd beschermd worden tegen uitdroging.
WAARDENBASIS	Alle technische gegevens vermeld in deze Technische Fiche zijn gebaseerd op laboratoria testen. Actueel gemeten gegevens kunnen verschillend zijn door omstandigheden buiten onze controle.
LOKALE BEPERKINGEN	Let op dat als gevolg van specifieke plaatselijke voorschriften, de prestaties van dit product van land tot land kunnen variëren. Raadpleeg het lokale productinformatieblad voor de precieze beschrijving en toepassingsmogelijkheden.
VEILIGHEIDS- EN GEZONDHEIDSVOORSCHRIFTEN	Voor informatie en advies over de veilige hantering, opslag en verwijdering van chemicaliën verwijzen wij naar het meest recente veiligheidsinformatieblad die fysische, ecologische, toxicologische en andere veiligheidsgegevens bevat.
HERINNERING	Tixo® wordt ook gebruikt voor het realiseren van zelfverdichtend beton. In dit geval, is een bijzondere samenstelling onontbeerlijk. Ons raadplegen. Onze hulpstof kan niet als verantwoordelijk worden gesteld voor een eventuele kleurverandering van het beton in de tijd. Onze producten dienen zorgvuldig te worden opgeslagen, aangebracht en gehanteerd.
WETTELIJKE INFORMATIE	De informatie, en met name de aanbevelingen met betrekking tot de toepassing en het eindgebruik van Sika-producten, wordt in goed vertrouwen verstrekt op basis van de huidige kennis en ervaring van Sika met producten die op de juiste wijze zijn opgeslagen, behandeld en toegepast onder normale omstandigheden in overeenstemming met de aanbevelingen van Sika. In de praktijk zijn de verschillen in materialen, onderlagen en werkelijke omstandigheden ter plaatse zodanig dat er geen garantie kan worden ontleend met betrekking tot verhandelbaarheid of geschiktheid voor een bepaald doel, noch enige aansprakelijkheid voortvloeiend uit enige juridische relatie, op basis van deze informatie, of uit enige schriftelijke aanbevelingen of enig ander advies dat wordt gegeven. De gebruiker van het product moet de verenigbaarheid van het product testen voor de beoogde toepassing en doel. Sika behoudt zich het recht om de producteigenschappen te wijzigen. Onze verantwoordelijkheid zou in geen enkel geval in het gedrang kunnen worden gebracht, in de veronderstelling van een uitvoering die niet conform is met onze inlichtingen. De eigendomsrechten van derden dienen te worden gerespecteerd. Alle bestellingen worden aanvaard onder de huidige verkoop- en leveringsvoorwaarden. Gebruikers dienen altijd de meest recente uitgave van het lokale technische informatieblad te raadplegen voor het betreffende product; exemplaren hiervan worden op verzoek verstrekt.

Figure B-3: Technical datasheet - Tixo (part 2)

Holcim Granulats (Belgique) S.A.

Laboratoire central

B-7530 Gaurain-Ramecroix

Tél(00) 32 69 25 14 07 Fax(00) 32 69 25 14 76 email: serge.willocq@holcim.com

Technische ProductFiche

vanaf 05/11/2014 op 04/05/2015

Referentie : 620a01.SEL

Pagina 1/1, gedrukt op 04/05/2015

Uitbatingssite :	Site de Gaurain-Ramecroix	***Gebruiker :***	Kesteleyn NV
Granulaten :	6/20 Cat4 1 f1.5 NG SBENOR de Gaurain		Zuiddokweg. 50
Petrografie :	Kalksteen		9000 Gent-Zeehaven
Uitwerking :	Droog		
norm(en) :	NF & BENOR & CE2+ (EN12620-13043-13242)		
Certificatie organisme :	Be-Cert (0965) & www.marque-nf.com		
Certificaat Nr :	CPR-GTO501 & 023-15		

Normatieve gedeelte

Gespecifieerde waarden waartoe de producent zich verbindt

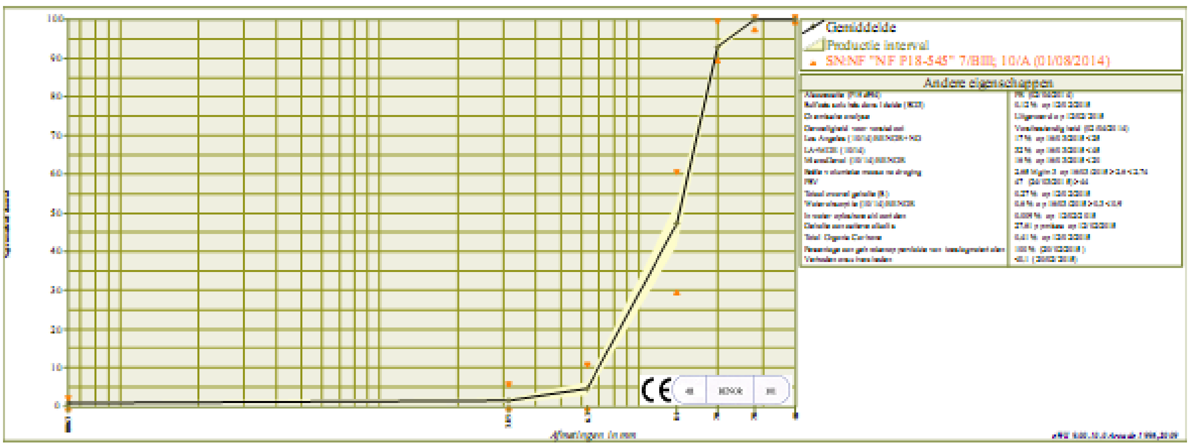
Korrelmaat		Norm	Code
6.3	*20*	*Intern*	*NF "NF P 18-545" 7/BIII; 10/A (01/08/2014)*

	0.063	3.15	6.3	14	20	28	40	FI
Spreiding e			10	30				
Onbepaaldheid U	0.3	1	5	6	5	1		4
V.S.S.+U	1.8	6	15	66	100	100		19
V.S.S.	1.5	5	10	60	99	100	100	15
V.S.I.	0.0	0	0	30	90	98	100	
V.S.I.-U	0.0	0	0	24	85	97		
Standaard afwijking max				9.09				

Informatieve gedeelte

Productie resultaten

	vanaf 05/11/14 op 23/04/15							
	0.063	3.15	6.3	14	20	28	40	FI
Maximum	1.4	3	8	56	96	100	100	15
[illegible]	1.2	2	6	53	95	100	100	13
Gemiddelde Xf	0.9	2	5	47	93	100	100	11
[illegible]	0.6	1	3	42	91	100	100	9
Minimum	0.4	1	3	38	90	100	100	9
Standaardafwijking	0.25	0.5	1.4	4.5	1.3	0.0	0.0	2.0
Aantal resultaten	39	39	39	39	39	39	39	9



EN 12620 (Gc90/15-GT15)
EN 13043 (Gc85/20-G20/15)
EN 13242 (Gc80/20-GTc20/15)

Onze producten evolueren, maak geen contracten en geef geen waarborgtermijnen zonder ons te raadplegen

Figure B-4: Technical datasheet - Limestone 6.3/20

Holcim Granulats (Belgique) S.A.

Laboratoire central
B-7530 Gaurain-Ramecroix
Tél: (00) 32 69 25 14 07 Fax: (00) 32 69 25 14 76 email: serge.willocq@holcim.com

Technische ProductFiche
vanaf 05/11/2014 op 04/05/2015
Referentie : 26a01.SEL
Pagina 1/1, gedrukt op 04/05/2015

Uitbatingssite :	**Site de Gaurain-Ramecroix**	***Gebruiker :***	**Kesteleyn NV**
Granulaten :	**2/6 Ca4a 1 B NG S BENOR de Gaurain**		**Zuiddokweg. 50**
Petrografie :	Kalksteen		**9000 Gent-Zeehaven**
Uitwerking :	Droog		
norm(en) :	CE 2+ (EN12620-13043-13242)		
Certificatie organisme :	Be-Cert (0965)		
Certificaat Nr :	CPR-GT0501		

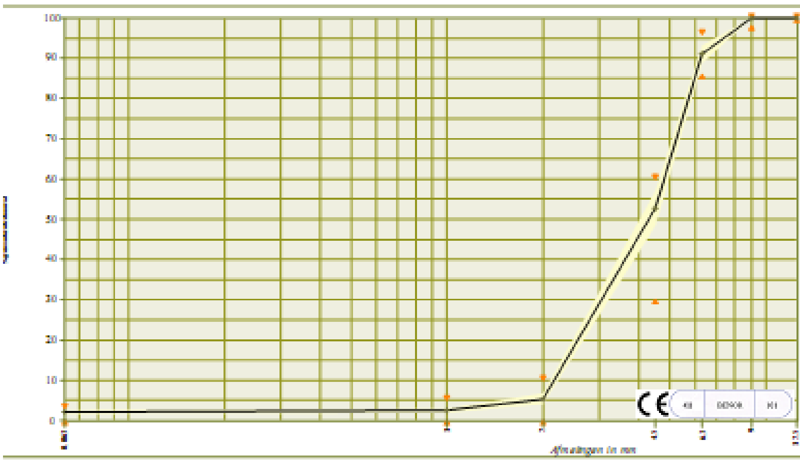
Normatieve gedeelte
Gespecifieerde waarden waartoe de producent zich verbindt

Korrelmaat		Norm	Code
2	*6.3*	*Intern*	*"NF P 18-545" 7/BIV; 10/A sauf FI=B (01/08/2014)*

	0.063	1	2	4.5	6.3	9	12.5	FI
Spreiding e			10	30	10			
Onbepaaldheid U	0.6	1	5	6	5	1		4
V.S.S.+U	3.6	6	15	66	100	100		29
V.S.S.	3.0	5	10	60	96	100	100	25
V.S.I.	0.0	0	0	30	86	98	100	
V.S.I.-U	0.0	0	0	24	81	97		
Standaard afwijking max				9.09				

Informatieve gedeelte
Productie resultaten

	vanaf 05/11/14 op 29/04/15							
	0.063	1	2	4.5	6.3	9	12.5	FI
Maximum	2.9	3	8	57	94	100	100	24
Xf+1.28s Standaardafwijking	2.5	3	7	57	93	100	100	23
Gemiddelde Xf	2.1	2	5	53	91	100	100	22
Xf-1.28s Standaardafwijking	1.6	2	4	48	89	100	100	20
Minimum	1.5	2	4	43	86	100	100	21
Standaard afwijking	0.37	0.4	1.1	3.5	1.7	0.0	0.0	1.0
Aantal resultaten	25	25	25	25	25	25	25	8



Gemiddelde
Productie interval
SN:"NF P 18-545" 7/BIV; 10/A sauf FI=B (01/08/2014)

Andere eigenschappen	
Alca-reactie (P18-594)	PR (02/04/2014)
Sulfaten oplosbaar in zuur (SO3)	0.12 % op 12/02/2015
Chemische analyse	Uitgevoerd op 12/02/2015
Gevoeligheid voor vorst-dooi	Vorstbestendigheid (02/04/2014)
Los Angeles (10/14) BENOR+NG	17 % op 16/03/2015 <25
LA+MDE (10/14)	32 % op 16/03/2015 <45
Micro-Deval (10/14) BENOR	16 % op 16/03/2015 <20
Reëlevolumieke massa na droging	2.65 Mg/m3 op 16/03/2015 >2.6 <2.74
PSV	47 (24/03/2015) >44
Totaal zwavelgehalte (S)	0.27 % op 12/02/2015
Water absorptie (10/14) BENOR	0.6 % op 16/03/2015 >0.3 <0.9
In water oplosbare chloriden	0.009 % op 12/02/2015
Gehalte aan actieve alkalie	27.61 ppm/eac op 12/02/2015
Total Organic Carbone	0.41 % op 12/02/2015

EN 12620 (Gc85/20-GT15)
EN 13242 (Gc80/20-GTc20/15)

Onze producten evolueren, maak geen contracten en geef geen waarborgtermijnen zonder ons te raadplegen

Figure B-5: Technical datasheet - Limestone 2/6.3

Productspecificatieblad	zand 0 4	d.d. 1 januari 2014

Kwartszand 0 4 conform NEN EN 12620

B.V. Sorteerbedrijf voor grint en zand "Vlissingen"
Westerhavenweg 14
4382 NM Vlissingen
Nederland

CE
0956 CPD 834

BENOR

4.3 korrelgradering

zeef volgens ISO 565:1990 R20 (mm)	grenswaarde voor doorval volgens NEN EN 12620			
	norm	BENOR	gemiddelde	grenst.o.v. gemiddelde
C8	100-100	95-100	100	
C5,6	95-100		98	
C4	85-99	89-99	94	88-98
2	55-94	72-92	82	71-91
1	30-85	60-80	70	49-89
0,5	15-67		45	
0,25	0-20	0-18	8	0-20
0,125	0-3		1	
0,063	0-3	0-3	0	0-3

* Kenm

			BENOR Volgens PTV
4.3	categorie	GF_{85}	GF_{85}
4.5	schelpgehalte	SC_{10}	SA
4.6	hoeveelheid fijne deeltjes < 0,063	< 0,5% f_3	f_3
5.5	dichtheid prd	2620 kg/m^3	tollerantie ± 100
5.5	waterabsorptie	0,4%	tollerantie ± 0,3
5.7.1	vorst/dooi bestandheid	<1,0 F1	NG
5.7.3	ASR gevoeligheid	PR CUR aanbeveling 89	
6.2	chloridegehalte	0,020%	CB
6.3.1	in zuur oplosbaar sulfaat	$AS_{0,2}$	
6.3.2	totaal zwavelgehalte	0,0%	
6.4.1	bindings- en verhardingsvertragers	Voldoet	
	aanwezigheid o.s.		*negatief

* Kenm

BENOR-aanduiding volgens PTV 411
Gewassen zeezand 0/4 CF A f3 a CB SA

Oorsprong
ECP

EG conformiteitsverklaring

Ondergetekende, verklaart op grond van artikel 9 van de Richtlijn Bouwproducten (89/106/EEG) namens B.V. Sorteerbedrijf voor grint en zand "Vlissingen", gevestigd: Westerhavenweg 14, 4382 NM te Vlissingen dat het in dit product specificatieblad genoemd product, voldoen aan de eisen in NEN-EN 12620 voor de eigenschappen genoemd in tabel ZA.1a van bijlage ZA van deze norm
Het FPC systeem is door de certificatie-instelling BMC beoordeeld en het FPC certificaat met nummer:
0956-CPD-0834
werd per 1 juni 2004 toegekend

Vlissingen, 1 juni 2004 getekend: H.J. Strijdonk, directeur

Figure B-6: Technical datasheet - Sea sand 0/4

DE HOOP
BOUWGRONDSTOFFEN

Technische specificatie nr.: TS 06-01 Datum : 08-01-2014 Vervangt: 01-07-2013	CE 14 0965-CPR-GT0532	411 BENOR 187	KOMO NL BSB

Aanduiding	Handelsnaam	Winning
Kwartszand Rondzand 0/2 (0/1) MF A f3 a CC SA S	Zeezand 0/2 S	Noordzee

Norm van toepassing	Prestatieverklaring
EN 12620 : Toeslagmaterialen voor beton EN 13139 : Toeslagmaterialen voor mortel EN 13242 : Toeslagmaterialen voor ongebonden- en gebonden toepassing	PV 06011412620-2 PV 06011413139-2 PV 06011413242-2

Korrelverdeling (periode 01-10-2013 tot 31-12-2013)

Zeef EN 933-1	(mm)	4	2.8	2	1	0.500	0.250	0.125	<0.063	
Gem doorval	%	100	100	99	98	93	22	0	0.1	
Min.	%	100	98	94	93	83	7	0	0	
Max.	%	100	100	100	99	99	37	10	3	
FM	1.88									

Kenmerken	Norm	Gemiddelde	CE			BENOR
			12620	13139	13242	-
Korrelgroep			0/2	0/2	0/2	
Catagorie			G_F85	0/2	G_F85	-
Dichtheid ρ_{rd}	EN 1097-6	2.63 Mg/m³	2.63 Mg/m³			±0.10Mg/m³
Absorptie	EN 1097-6	0.2%	0.2%			± 0.3%
Gehalte fijne deeltjes	EN 933-1	0.1%	Cat.f_3	Cat.1	Cat.f_3	Cat.f_3
Chloorionen	EN 1744-1	0.075%	0.100%			-
In zuur opl. Sulfaten	EN 1744-1		Cat. $AS_{0.2}$	Cat. $AS_{0.2}$	Cat. $AS_{0.2}$	-
Totaal zwavel	EN 1744-1		S1	<1%	S1	-
Bindtijd vertragend stoffen	EN 1744-1		Geen	Geen	Geen	-
Schelpgehalte	NEN 5922	8.4	Max. 20%			-
Zware metalen+pak's			Voldoet aan BSB KIWA K20450A+B			-
Alkali silica gevoeligheid			NPD			-
Na_2O-eq.	Cur 89-6.2	0.020%				

EG conformiteitsverklaring

Ondergetekende, verklaart op grond van artikel 9 van de Richtlijn Bouwproducten (89/106/EEG) namens De Hoop Bouwgrondstoffen BV, gevestigd Duitslandweg 2 te 4538BK Terneuzen, dat het in deze technische specificatie beschreven zand, afkomstig van de productie-eenheid Havenbedrijf te Terneuzen, voldoet aan de eisen in de EN 12620, EN 13139 en EN 13242 voor de eigenschappen genoemd in de tabellen ZA.1a van bijlage ZA van deze normen.
Het FPC systeem is door de certificatie-instelling CRIC beoordeeld en het FPC certificaat met nummer 0965-CPR-GT0 532 werd per 25 oktober 2004 toegekend.

Terneuzen, 8 januari 2014 getekend: B. Groeneweg, adjunct directeur

De Hoop Bouwgrondstoffen BV

Postbus 19, 4530 AA Terneuzen
Duitslandweg 2, 4538 BK Terneuzen
Havennummer 1421
telefoon (0115) 680911
Handelsregister Terneuzen no. 21018312
www.dehoop-bouwgrondstoffen.nl
info@dehoop-bouwgrondstoffen.nl

Faxnummers afdelingen:
Commercieel (0115) 610097
Logistiek (0115) 615095
Administratie (0115) 619556

kiwa gecertificeerd ISO 9001 KWALITEIT 2000

Figure B-7: Technical datasheet - Sea sand 0/2

SILICA SAND S50 - S60 - S80 - S90

Technical Data

After mining, the silica sands **S50**, **S60**, **S80** and **S90** are industrially processed: sieved, washed and classified. These qualities are available moist or dried; by truck, wagon or ship; in bulk or bagged (dried sands).
These silica sands are an excellent raw material for the glass-, crystal- and ceramic industry, for foundries, for tile glues, plasters, mortars, coatings etc…

GRANULOMETRIC DATA AND PHYSICAL CHARACTERISTICS
Method : ISO-sieving

		S50	S60	S80	S90	
D50 / AGS		285	230	170	150	µm
AFS		50	60	80	90	
> 500 µm		1				%
> 355 µm		15	1			%
> 250 µm		64	28	6		%
> 180 µm		96	86	33	10	%
> 125 µm		99.8	99.4	86	74	%
> 90 µm		100	99.9	99.8	97	%
< 63 µm		traces	traces	< 0.1	< 0.1	%
density		2.65	2.65	2.65	2.65	kg/dm³
bulk density		1.50	1.50	1.40	1.40	kg/dm³
hardness		7	7	7	7	Mohs
pH		7	7	7	7	
loss on ignition		0.15	0.15	0.15	0.15	%
colour	L*	70.5	73.7	74.8	74.9	Minolta CM-3610d
	a*	3.1	2.8	1.8	1.8	D65/10°
	b*	10.1	9.2	9.0	9.1	

CHEMICAL ANALYSIS (XRF) %

	S50	S60	S80	S90
SiO_2	99.5	99.5	99.5	99.5
Fe_2O_3	0.03	0.03	0.04	0.04
Al_2O_3	0.10	0.15	0.2	0.2
TiO_2	0.07	0.07	0.07	0.07

TDS.03.05.71 2009-05-25 1/2

Sibelco Benelux
De Zate 1 - BE-2480 Dessel
tel. +32 14 83 72 11 - fax +32 14 83 72 12
www.sibelco.be

Figure B-8: Technical datasheet - Sand S90

CARMEUSE
NATURAL CHEMICALS

TECHNISCHE FICHE

CALCITEC 2001M

KALKSTEENMEEL – $CaCO_3$

CHEMISCHE ANALYSE (gemiddelde waarden)

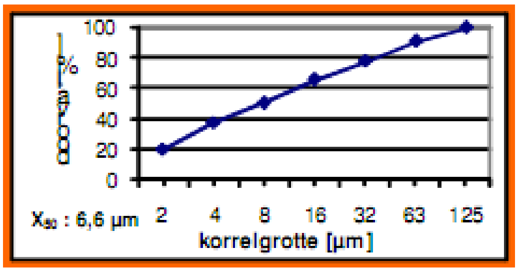
	Absolute Eis BRL 1804	Eis BRL 1804	90% gebied	Gemiddelde
Carbonaten	≥ 87	≥ 90	94-100	99,5 %
$CaCO_3$	≥ 72	≥ 75	94-100	98,8 %
MgO				0,32 %
SiO_2				0,11 %
Al_2O_3				0,04 %
Fe_2O_3				0,04 %

Reactiviteit tov alkaliën	niet reactif
$Na_2O_{eq} = Na_2O + 0{,}658 \times K_2O$	0,01 %
Vochtgehalte	0,03 %
Totaal zwavelgehalte (S)	0,01 %
In zuur oplosbare sulfaten (SO_3)	0,02 %
In water oplosbare chloorionen (Cl^-)	< 0,008 %
Organische stoffen	pas de M.O.
pH	9,4

FYSISCHE PARAMETERS & KORRELVERDEELING (gemiddelde waarden)

VISEAANSE KALKSTEEN	
Reële volumieke massa	2.690 kg/m³
Los stortgewicht	900 kg/m³
Aangestampt stortgewicht	1.350 kg/m³
Waterbehoefte β_p	0,76
Specifieke oppervlakte Blaine	440 m²/kg
Methyleen blauw waarde MB	1,3 g/kg
Witheid FY	57
Hardheid (Mohs)	3

KORREL VERDELING
Laser SYMPATEC



Luchtstraalzeven	Eis BRL 1804 % m/m	90% gebied % m/m	Gemiddelde % m/m
2 mm	100	100	100
500 µm	-	99 - 100	99,9
125 µm	85 - 100	90 - 100	98
63 µm	70 - 100	84 - 94	89

PRODUCTIELOCATIE
B - 4520 MOHA

REF/NORMEN
EINECS 215-279-6
CAS 471-34-1
Vrij van REACH
0785-CPD-31217-10
EN 12620
EN 13139

VEILIGHEID
Veiligheidsfiche verkrijgbaar op aanvraag

BEHANDELING & OPSLAG
Droog opslaan. Het product is inert en niet gevaarlijk

Certified ISO 9001 by BVQi

CE 0785

Daar het product van natuurlijk oorsprong is, zijn de vermelde waarde gemiddeldes die enigzins kunnen variëren en die niet bindend zijn voor het bedrijf.

UPDATE 26/05/2010 EDITIE 20.55.230 CARMEUSE SA www.carmeuse.be info@carmeuse.be

Figure B-9: Technical datasheet - Limestone powder

SilverBond®
KWARTSMEEL

Technical Data

KENMERKEN EN VOORDELEN — **DESSEL, BELGIË**

SILVERBOND® kwartsmeel wordt geproduceerd uit zuivere kwartsgrondstoffen.
Het wordt gebruikt in toepassingen die minerale vulstoffen behoeven die mechanisch performant zijn, chemisch van hoge zuiverheid en niet reactief.

SILVERBOND® is inert, heeft een neutrale pH, en zal geen chemisch reactie ondergaan of initiëren in gekatalyseerde of meer-component systemen. Evenmin zal SILVERBOND® degraderen in extreme temperaturen of omstandigheden. SILVERBOND® biedt formulatoren een laag specifiek oppervlak en olieabsorptie, zodat een hoge vulgraad kan behaald worden in verven en cementgebaseerde systemen, en een hoge stijfheid in elastomeren en epoxy-formuleringen. SILVERBOND® is chemisch zuiver en fungeert als excellente isolator in electrische en electronische componenten, en als stabiele vulstof in thermische isolatie.

Het SILVERBOND® gamma wordt geproduceerd volgens ISO-standaarden of interne kwaliteitsprogramma's.
Het resultaat is een chemische zuiverheid en een consistent uniforme korrelgrootteverdeling voor voorspelbare performantie, ondersteund door betrouwbare dienstverlening.

KORRELVERDELING EN FYSISCHE EIGENSCHAPPEN
Gemiddelde waarden. Deze geven geen specificatie weer.

		M400	M500	M600	M800		Methode
controlezeef	> 40 µm	0,1	0,012	0,004		%	Alpine
	< 5 µm				95	%	Malvern MS2000
D10		3	2	2	0,6	µm	Malvern MS2000
D50		12	4	4	1,8	µm	Malvern MS2000
D90		26	10	9	4,1	µm	Malvern MS2000
soortelijk gewicht		2,65	2,65	2,65	2,65	kg/dm^3	
stortgewicht		0,7	0,65	0,6	0,4	kg/dm^3	
specifieke oppervlakte		1,9	4.2	4.2	7.8	m^2/g	BET
		6500	12000	13000	21500	cm^2/g	Blaine
olieabsorptie		20	23	24	32	g/100 g	
hardheid		7	7	7	7	Mohs	
pH		7	7	7	7		
gloeiverlies		0,12	0,3	0,3	0,3	%	
kleur	L*	93	94	94	96		Minolta CM-3610d
	a*	0,55	0,46	0,46	0,4		D65/10°
	b*	3,00	2,78	2,78	0,8		
lichtbrekingsindex		1,55	1,55	1,55	1,55		

CHEMISCHE SAMENSTELLING (XRF) %
Gemiddelde waarden. Deze geven geen specificatie weer.

	M400	M500	M600	M800
SiO_2	99,5	99,2	99,2	99,0
Fe_2O_3	0,03	0,05	0,05	0,01
Al_2O_3	0,20	0,40	0,40	0,80
TiO_2	0,03	0,03	0,03	0,03
K_2O	0,05	0,05	0,05	0,05
CaO	0,02	0,02	0,02	0,02

SIBELCO BENELUX

Contacteer ons vrijblijvend voor verdere informatie.

www.sibelco.be

Figure B-10: Technical datasheet - Quartz powders M400 and M800

Elkem Microsilica®

CONCRETE

Grade 920 for construction

C2-01
Product

General

Elkem Microsilica® Grade 920 is dry silica fume available in two main forms:

- **Undensified - 920 U**, with a typical bulk density of 200 - 350 kg/m^3
- **Densified - 920 D**, with a typical bulk density of 500 - 700 kg/m^3

Packaging

The products are supplied in a range of packaging:

- 25 kg paper bags
- Big bags in a variety of designs and sizes depending on product and production plant.
- Bulk in road tanker

Special packaging can be supplied on request.

Quality Control

Elkem Materials is certified according to ISO 9001.

The chemical composition and physical properties are regularly tested in accordance with ASTM standards.

Conformance to Standards

Elkem Microsilica® Grade 920 conforms to the mandatory requirements of ASTM C1240 from **American Society for Testing and Materials**

Mandatory chemical and physical requirements	ASTM C1240	
	Spec.	Frequency
SiO_2 (%)	> 85,0	400 MT
Alkalies (as equivalent Na_2O, %)	Report	400 MT
Moisture (%)	< 3,0	400 MT
Loss on Ignition, LOI (%)	< 6,0	400 MT
Specific surface (BET - m^2/gram)	> 15	3200 MT/3 months
Bulk density (kg/m^3)	Report	400 MT
Pozz. Activity Index (%) - 7 days accelerated curing	> 105	3200 MT/3 months
Retained on 45 micron sieve (%)	< 10	400 MT
Variation from avg. retained on 45 micron (%-points)	< 5	avg. of last 10 tests
Density (kg/m^3)	Report	400 MT

The information given on this datasheet is accurate to the best knowledge of Elkem Materials. The information is offered without guarantee, and Elkem Materials accepts no liability for any direct or indirect damage from its use. The information is subject to change without notice. For latest update or further information or assistance, please contact your local representative, the Internet address or the e-mail address given on this datasheet.

CONCRETE PRODUCT SEPTEMBER 2008 C2-01

Contact/representative:

Elkem Materials
Internet: www.concrete.elkem.com
e-mail: microsilica.materials@elkem.no

Figure B-11: Technical datasheet - Silica fume

GEOS
constructive testing

Laboratorium Magnel voor
Betononderzoek
Technologiepark Zwijnaarde 9
9052 Gent (Zwijnaarde)

04-09-2012

Hertenstraat 30
B-3830 Wellen

Tel +32(0)12 67 09 09
Fax +32(0)12 74 54 05

www.geos.be

Beproevingsrapport : **638931**

Opdrachtgever : Laboratorium Magnel voor Betononderzoek, Technologiepark Zwijnaarde 9, 9052 Gent (Zwijnaarde)

Referentie : 07/400-PVdH

Materiaal : Een monster vliegas (12/331).

Afgeleverd door : De Post op 14-08-2012

Proefmethoden :
- ■ Gloeiverlies (NBN EN196-2)(2005)
- ■ Fijnheid door nat zeven (NBN EN451-2)(1995)
- ■ Sulfaatgehalte (NBN EN196-2)(2005)
- ■ Chloridegehalte (NBN EN196-2)(2005)
- ■ Gehalte aan reactief SiO2 (EN 197-1)(2000)
- ■ Chemische analyse (WD-XRF)(ISO/DIS 29581-2)(2007)
- ■ Vrije calciumoxide (NBN EN451-1)(2004)

■ : Proef uitgevoerd onder BELAC ISO 17025 accreditatie

Behandeld door : Marc Jeuris (techn.), Greet Vanstreels (adm.).

RESULTATEN

Gloeiverlies (%)	1,84
Fijnheid (%)	16,4
Sulfaatgehalte (SO_3) (%)	0,94
Chloride (Cl^-) (%)	0,003
Reactief SiO_2 (%)	41,86
SiO_2 (%)	54,19
Al_2O_3 (%)	23,50
Fe_2O_3 (%)	7,92
CaO (%)	3,02
MgO (%)	1,92
Na_2O (%)	1,08
K_2O (%)	3,38
P_2O_5 (%)	0,27
Na-equivalent (%)	3,31
$SiO_2+Al_2O_3+Fe_2O_3$ (%)	85,61

ir. J. Soers
Directeur

BELAC
010-TEST

Figure B-12: Technical datasheet - Fly ash

Portaclay® A 90

Sodium bentonite

Technical Data

FEATURES AND BENEFITS

Portaclay® A 90 is produced from a natural Sodium-bentonite. This is a very plastic clay which is very suitable as a binder and as a viscosifier. **Portaclay® A 90** is produced by grinding this clay to a constant grain size and moisture content. The mean constituent is the clay-mineral montmorillonite.

The standardised quality of **Portaclay® A 90** is guaranteed by means of an ISO 9001 certified quality management plan. The raw materials and production are closely monitored to ensure a constant quality with regard to its chemical composition and grain size.

Portaclay® A 90 is used in ceramics as a binder in foundry moulding sand. It is used as an anti settling agent in the production of casting fluxes during the process of spray-drying and in asphalt emulsions.

PARTICLE SIZE ANALYSIS AND PHYSICAL PROPERTIES

Mean values. These do not represent a specification.

			Method
– 90 µm	%	94	Alpine air jet
Moisture	%	9.5	Halogen moisture analyser (105 °)
Water absorption	%	1100	Enslin, 24 hours
Methylene blue absorption	mgMB/g	325	API
Bulk density	kg/m³	850	Böhme
pH		9.5	10% in water
Hardness		1.5	Mohs' scale
Density	g/cm³	2.6	He-pyknometer

CHEMICAL ANALYSIS

Mean values. These do not represent a specification.

	Weight %	Method
Na_2O	2.2	XRF
K_2O	0.55	XRF
Al_2O_3	19	XRF
SiO_2	63	XRF
MgO	2.4	XRF
CaO	1.45	XRF
BaO	0.03	XRF
MnO	0.03	XRF
Fe_2O_3	4	XRF
TiO_2	0.2	XRF
P_2O_5	0.05	XRF
SO_3	0.3	XRF
L.o.I.	5.7	1000 °C, 1 hour

Figure B-13: Technical datasheet - Portaclay A90