

# Effect of binder-to-sand ratio on the workability and mechanical properties of GGBS-CDW based geopolymer mortars

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# Preface

A master's thesis marks the final big chapter in a student's academic journey. I am happy to share this work with the reader. My passion for construction engineering started at a young age, and grew through the years. Although this thesis might seem as the end of this journey, it is truly the beginning to a life as an engineer.

This thesis wouldn't have been possible without the help and support of many people. First of all, I would like to sincerely thank my promoter, Prof. Dr.-Ing. Jiabin Li, for his continuous support, valuable feedback and guidance throughout the year. I would also like to thank him for the time he devoted to assist me during this master's thesis. Moreover, I am deeply grateful for the opportunity to work on this research.

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Katlyn Caerels  
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# Samenvatting

De opwarming van de aarde is een van de dringendste problemen van deze tijd. De bouwsector speelt hierin een belangrijke rol, zijnde door het ontginnen van grote hoeveelheden grondstoffen, het energieverbruik, de uitstoot van broeikasgassen en het genereren van grote hoeveelheden bouw- en slooppuin (CDW). Dit onderzoek focust op een milieuvriendelijk alternatief voor traditioneel cement, meer bepaald door het onderzoeken van de optimale zand-binderverhouding voor gegranuleerd hoogovenslak (GGBS) en CDW-gebaseerde geopolymeermortels. Zo worden alle huidige milieuproblematieken in de bouwsector aangekaart.

De geopolymeersamenstelling in dit onderzoek bestaat uit 60% GGBS, 15% gerecycleerde betonpoeder (RCP) en 25% gerecycleerde baksteenpoeder (RBP). Deze samenstelling is bepaald rekening houdend met verschillende belangrijke aspecten, zoals de druksterkte, de bindingstijden, en de vloeibaarheidsindex.

Om de verschillende binder-zandverhoudingen te onderzoeken worden geopolymeermortels gemaakt met variërende zandgehaltenes (0-60 m%). Dit wordt gedaan voor drie verschillende zandsoorten: zeezand 0/2 mm, zeezand 0/1 mm en CEN Standaard zand. De verwerkbaarheid van de mortels wordt beoordeeld door de vloeibaarheidsindex te berekenen. Een vloeibaarheidsindex rond 2.5 wordt als optimaal beschouwd. Daarnaast worden de mechanische eigenschappen van de mortels bepaald, zijnde de buigtreksterkte en druksterkte.

Een vermeerdering van het zandgehalte vermindert de vloeibaarheid van de geopolymeermortels. Een grotere daling in vloeibaarheid wordt opgemerkt wanneer er fijnere zandsoorten gebruikt worden. Voor zeezand 0/2 mm en zeezand 0/1 mm wordt er een optimale zandverhouding van 50 m% gevonden, wat overeenkomt met een binder-zandverhouding van 1:1. Het vermeerderen van het zandgehalte boven de 50 m% zorgt voor een verslechterde verwerkbaarheid en verhoogde porositeit. Grovere zandsoorten, zoals CEN Standaard zand, veroorzaken een mildere daling in vloeibaarheid, waardoor het optimale zandgehalte kan stijgen tot 60 m%.

Het zandgehalte en type zand hebben een directe invloed op de buigtreksterkte van de mortels. Een verhoging in zandgehalte en fijnheidsmodulus zorgt voor een verhoogde buigtreksterkte. Grotere zanddeeltjes hebben verbeterde bindeigenschappen en versterken de geopolymeermatrix, waardoor vervormingen tijdens buigbelasting gereduceerd worden. Buigtreksterktes tot  $9.5 \pm 0.1$  MPa worden bereikt na 28 dagen met 60 m% zand en grove zanddeeltjes.

Het gebruikte zandtype speelt een belangrijke rol voor de druksterkte. Fijne zanddeeltjes absorberen meer water dan grovere zanddeeltjes, waardoor de vloeibaarheid van het mengsel sneller daalt en de hoeveelheid poriën stijgt, wat tot een vermindering in druksterkte leidt. Mortels met grovere zandtypes behouden betere vloeibaarheid en vertonen minder porositeit. De druksterkte van de geopolymeermortels gemaakt met CEN Standaard zand hebben na 28 dagen een waarde van  $87.4 \pm 2.5$  MPa voor 50 m% zand, wat bijna 20 MPa hoger ligt dan mortels gemaakt met zeezand 0/1 mm, maar amper een verschil van 2 MPa met zeezand 0/2 mm. Het zandgehalte heeft geen significante invloed op de druksterkte.

Uit de bevindingen van dit onderzoek kan er algemeen gesteld worden dat een binder-zandverhouding van 1:1 optimaal is voor de verschillende zandtypes. Indien grovere zandsoorten gebruikt worden, kunnen lagere binder-zandverhoudingen overwogen worden.

# Abstract

Global warming is one of the most pressing challenges of our time. The construction sector plays a significant role in global environmental challenges. As one of the largest consumers of raw materials and energy, and a major producer of greenhouse gases and waste, its impact cannot be overstated. This research focuses on a sustainable alternative to conventional cement, specifically by investigating the optimal binder-to-sand ratio for geopolymer mortars based on ground granulated blast furnace slag (GGBS) and construction and demolition waste (CDW). This approach addresses all current environmental challenges the construction sector is facing.

The geopolymer composition used during this research consists of 60% GGBS, 15% recycled concrete powder (RCP), and 25% recycled brick powder (RBP). This mix design has been determined by taking some key considerations into account, such as the compressive strength, the setting times, and the flowability index.

To research the binder-to-sand ratios, different geopolymer mortars were made with varying sand contents (0-60 wt.%). This was done for three different types of sand: sea sand 0/2 mm, sea sand 0/1 mm and CEN Standard sand. The workability of the mortars was assessed by measuring the flowability index. A flowability index around the 2.5 is taken as optimal. Furthermore, the flexural and compressive strength of the geopolymer mortars have been tested.

Increasing the sand content leads to a decrease in flowability index for each sand type. A larger decrease is noted when smaller sand particles are used. For the sea sands, an optimum was found at 50 wt.%, corresponding with a binder-to-sand ratio of 1:1. When increasing the sand content further, the compactability of the mortars decreases, increasing the pore-formation. Coarser sand types, such as CEN Standard sand, exhibits a milder decrease in workability. The optimal sand content based on the workability can be increased up to 60 wt.% sand.

The sand content and type have a direct impact on the flexural strength of the mortars. Increasing the sand content and fineness modulus leads to an increase in flexural strength. Larger sand particles have an increased binding capacity and strengthen the overall geopolymer matrix, hindering deformation during flexural loading. The flexural strength of the mortar samples reaches up to  $9.5 \pm 0.1$  MPa at 28 days when incorporating 60 wt.% sand and using coarse sand particles.

The sand type plays an important role for the compressive strength. Fine sand particles absorb more water than coarse sand particles, decreasing the workability of the mixture and increasing the amount of pores. The compressive strength decreases with an increase in pore formation. Mortars made with coarser sand types can accommodate a higher sand content than mortars made with finer sands. The compressive strength of geopolymer mortars made with 50 wt.% CEN Standard sand reach a value of  $87.4 \pm 2.5$  MPa, which is nearly 20 MPa higher than sea sand 0/1 mm, but only 2 MPa higher than sea sand 0/2 mm. The sand content has no significant impact on the compressive strength of the mortars.

Based on the findings from this research, a binder-to-sand ratio of 1:1 has been found optimal across the three different sand types. If coarser sands are used, a lower binder-to-sand ratio might be considered, meaning the sand content can be increased.

**Keywords:** geopolymer mortars, binder-to-sand ratio, construction and demolition waste, workability, strength

# *Effect van de binder-zandverhouding op de verwerkbaarheid en mechanische eigenschappen van GGBS-CDW-gebaseerde geopolymeermortels*

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**Abstract** — De bouwsector heeft een negatieve impact op de omgeving, zijnde door het ontginnen van een grote hoeveelheid grondstoffen, het uitstoten van broeikasgassen en door het genereren van grote hoeveelheden bouw- en slooppuin (CDW). Het zoeken naar een cementalternatief zoals GGBS-CDW-gebaseerde geopolymeren kaart al deze problemen aan.

In dit onderzoek wordt het effect van de binder-zandverhouding op de verwerkbaarheid en mechanische eigenschappen van geopolymeermortels onderzocht. Dit wordt gedaan door geopolymeermortels te maken met gegranuleerd hoogovenslak (GGBS), gerecycleerde baksteenpoeder (RBP) en gerecycleerde betonpoeder (RCP). Als activatoren wordt er gewerkt met natriumhydroxide (NaOH) en natriumsilicaat ( $\text{Na}_2\text{SiO}_3$ ). In dit onderzoek worden er drie zandtypes onderzocht, zijnde zeezand 0/2 mm, zeezand 0/1 mm en CEN Standaard zand. De zandhoeveelheid wordt van 0 m% naar 60 m% gevarieerd.

Een stijging in zandhoeveelheid zorgt voor een vermindering van vloeibaarheid van de geopolymeermortel. Een optimaal vloeibaarheidsindex rond de 2.5 wordt bekomen bij een zandgehalte van 50 m% voor elk zandtype. Het verhogen van de hoeveelheid zand heeft eveneens een invloed op de mechanische eigenschappen van het materiaal. De buigtreksterkte van het materiaal stijgt met een toenemend zandgehalte tot 50 m%. Een stijging in zandgehalte heeft een minder significante invloed op de druksterkte van het materiaal. Rekening houdend met deze factoren kan een optimale binder-zandverhouding van 1:1 bekomen worden voor GGBS-CDW-gebaseerde geopolymeermortels.

**Kernwoorden**—geopolymeermortel; binder-zandverhouding; hoogovenslak; bouw- en slooppuin; vloeibaarheid; buigtreksterkte; druksterkte

## I. INTRODUCTIE

### A. Impact van de bouwsector op de omgeving

De opwarming van de aarde is één van de grootste problemen van onze tijd. De bouwsector speelt hierin een belangrijke rol, onder meer door de uitputting van grondstoffen, het uitstoten van broeikasgassen, en de productie van bouw- en slooppuin (CDW).

Op vlak van materiaalontginning is de bouwsector verantwoordelijk voor ruim 50% van de verbruikte grondstoffen [1], [2]. De meeste van deze grondstoffen zijn niet hernieuwbaar, wat leidt tot groeiende bezorgdheid. Eveneens is het zoeken naar nieuwe grondstoffen geen oplossing op lange termijn, aangezien dit zou leiden tot een toename aan transport. Dit heeft een directe invloed op de uitstoot van broeikasgassen, de kostprijs van de materialen, en een negatieve impact op de omgeving in het algemeen.

Hier bovenop is de bouwsector één van de grootste bijdragers tot de uitstoot van broeikasgassen wereldwijd. Op wereldschaal is de bouwsector verantwoordelijk voor 39% van de energie gerelateerde koolstofdioxide [3]. Hiervan zijn 28% het gevolg van operationele uitstoten, terwijl de resterende 11% van de bouwprocessen en materialen zelf komen. Om de impact van de broeikasgassen door de bouwsector tegen te gaan zijn er verschillende doelstellingen opgesteld, zowel op wereldschaal als op Europees niveau. Hierbij mikken de belangrijkste doelstellingen op  $\text{CO}_2$ -neutraliteit tegen 2050, met tussentijdse reducties tegen 2030 (World Green Building Council, Europese Green Deal) [3], [4].

De bouwsector heeft eveneens een significante impact op de omgeving in termen van afvalproductie. In Europa wordt circa een derde van alle afval door de bouwsector geproduceerd, wat bouw- en slooppuin de grootste afvalstroom in Europa maakt [5]. Deze afvalproductie kan jaarlijks oplopen tot 450 tot 500 miljoen ton [6]. Een groot deel van dit afval komt terecht in stortplaatsen, wat een negatief gevolg heeft voor de omgeving, zijnde door de vervuiling van de bodem, lucht, of grondwater. Ook op dit vlak zijn er verschillende doelstellingen opgesteld door de Europese Unie [7].

### B. Geopolymeren

Eén van de mogelijke oplossingen voor deze milieu-problematieken ligt in het gebruik van geopolymeren als alternatief voor traditioneel cement. Cement is één van de belangrijkste bouwmaterialen wereldwijd, maar het productieproces ervan is verantwoordelijk voor 7-8% van de wereldwijde  $\text{CO}_2$ -uitstoot [8]. Geopolymeer is een term dat in de huidige bouwsector vaak als synoniem wordt gebruikt voor alkalisch geactiveerde materialen (AAM), ook al werd deze term oorspronkelijk geïntroduceerd als subklasse van AAM,

om AAM met een laag calciumgehalte te kunnen onderverdelen. De CO<sub>2</sub>-uitstoot bij geopolymeren ligt beduidend lager dan bij cement, terwijl het mogelijk is om industriële bijproducten in geopolymeren te incorporeren, samen met CDW fijnen.

Er bestaan verschillende studies die de vloeibaarheid en mechanische eigenschappen van geopolymeren met verschillende precursoren onderzoeken, maar het onderzoek naar het incorporeren van CDW fijnen is nog relatief beperkt. Hier bovenop is data betreffende verschillende binder-zandverhoudingen quasi onbestaand voor geopolymeren gedeeltelijk gemaakt van CDW fijnen. Daarom onderzoekt deze studie het effect van de binder-zandverhouding op de verwerkbaarheid en mechanische eigenschappen van GGBS-CDW-gebaseerde geopolymeermortels.

## II. METHODOLOGIE

### A. Materialen

Geopolymeren zijn binders gemaakt uit de reactie tussen een precursor en een activator [9], [10]. Als precursor wordt een vast aluminosilicaat gebruikt. Dit kan zowel een calciumsilicaat zijn, of een materiaal met hoger aluminosilicaatgehalte, zoals metallurgische slak of vliegslak. Als activator wordt een stof gebruikt die alkalische hydroxiden, silicaten, carbonaten, sulfaten, aluminaten of oxiden bevat.

#### 1) Precursoren

In dit onderzoek wordt er met twee verschillende precursoren gewerkt. De eerste precursor is gegranuleerd hoogovenslak (GGBS). Dit is een industrieel bijproduct. Het materiaal dat in dit onderzoek gebruikt wordt is afkomstig van Ecocem Benelux, B.V., Moerdijk, Nederland. De tweede precursor die gebruikt wordt is bouw- en slooppuin fijnen. Hiervan worden er twee verschillende fijnen gebruikt, namelijk gerecycleerde baksteenpoeder (RBP) en gerecycleerde betonpoeder (RCP). RBP wordt geproduceerd door het versnijden van gebakken bakstenen, terwijl RCP afkomstig is van gebroken betonblokken. Tijdens het breken van betonblokken komt er stof vrij. Dit stof wordt opgevangen in een water bassin en zinkt naar de bodem. Na het drogen vormt dit een 'filter cake', beter gekend onder de naam RCP. De materialen die in dit onderzoek gebruikt worden zijn respectievelijk afkomstig van Prefaxis-Ploegsteers, Komen-Waasten, België, en AC Materials, Brugge, België. Op Figuur II.1 zijn de precursoren die tijdens dit onderzoek zijn gebruikt te zien in de volgorde waarin ze besproken zijn. De chemische compositie en de eigenschappen van de deeltjesgrootte van de precursoren worden respectievelijk in Tabel II-1 en Tabel II-2 weergegeven.



Figuur II.1: Precursoren

Tabel II-1: Chemische eigenschappen precursoren

| Precursor | SiO <sub>2</sub> | Al <sub>2</sub> O <sub>3</sub> | Fe <sub>2</sub> O <sub>3</sub> | CaO  | MgO  | K <sub>2</sub> O | Na <sub>2</sub> O |
|-----------|------------------|--------------------------------|--------------------------------|------|------|------------------|-------------------|
| GGBS      | 33.3             | 12.6                           | 0.41                           | 40.4 | 8.28 | 0.74             | 0.63              |
| RBP       | 63.2             | 13.0                           | 4.58                           | 10.8 | 1.83 | 2.72             | 1.89              |
| RCP       | 38.3             | 7.02                           | 5.41                           | 42.4 | 1.59 | 1.21             | 0.42              |

Tabel II-2: Eigenschappen deeltjesgrootte precursoren

| Precursors | Specific surface [m <sup>2</sup> /g] | D10 [μm] | D50 [μm] | D90 [μm] |
|------------|--------------------------------------|----------|----------|----------|
| GGBS       | 1.48                                 | 1.60     | 11.0     | 31.3     |
| RBP        | 0.96                                 | 2.93     | 23.4     | 70.9     |
| RCP        | 1.07                                 | 2.04     | 28.5     | 92.9     |

#### 2) Activatoren

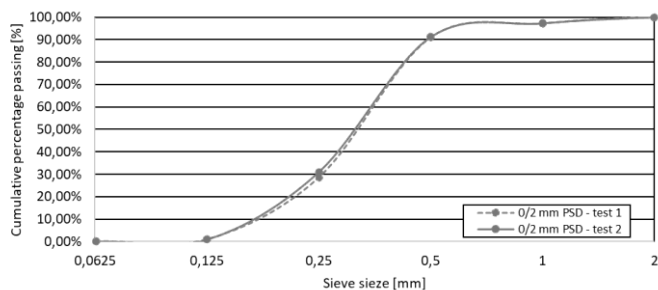
Voor dit onderzoek wordt er een combinatie van twee verschillende activatoren gebruikt, namelijk natriumhydroxide (NaOH) en natriumsilicaat (Na<sub>2</sub>SiO<sub>3</sub>). De silicaatgehalte in de natriumsilicaatoplossing bedraagt 25.9%, terwijl de natriumoxidegehalte 7.9% is. De natriumhydroxideoplossing heeft een molariteit van 12M.

#### 3) Zand

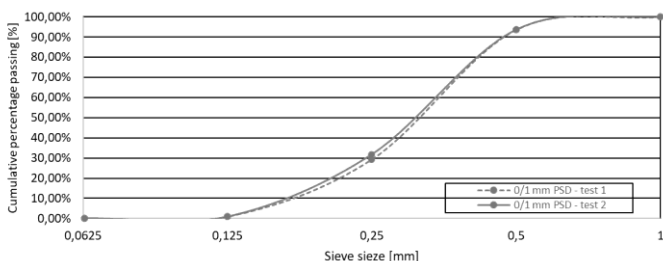
Om geopolymeermortels te maken moet er zand worden toegevoegd aan de geopolymerpasta. In dit onderzoek worden er drie verschillende zandsoorten onderzocht, zijnde zeezand 0/2 mm en zeezand 0/1 mm afkomstig uit de Noordzee, en CEN Standaard zand. Als CEN zand wordt er met CEN-normsand DIN EN 196-1 gewerkt afkomstig uit Beckum, Duitsland. De desbetreffende zanden worden weergegeven volgens volgorde van bespreking in Figuur II.2. De partikelgrootteverdeling van elk van de zandsoorten wordt weergegeven in Figuur II.3, Figuur II.4 en Figuur II.5. De verdelingen zijn opgesteld volgens NBN EN 933-1. De onder- en bovengrens van het CEN zand is in overeenstemming met NBN EN 196-1. De fijnheidsmodulussen van de zanden zijn als volgt: 1.81 voor 0/2 mm, 1.75 voor 0/1 mm, en 2.79 voor CEN zand.



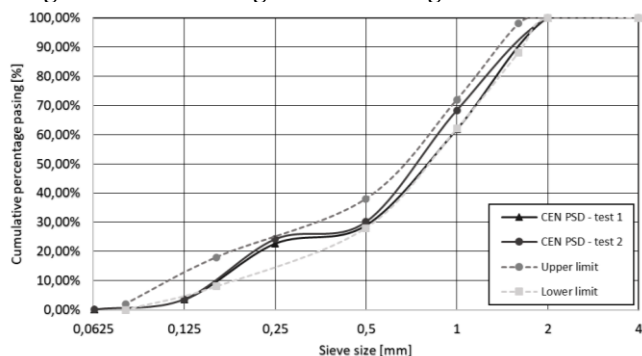
Figuur II.2: Zandsoorten



**Figuur II.3: Partikelgrootteverdeling zeezand 0/2 mm**



**Figuur II.4: Partikelgrootteverdeling zeezand 0/1 mm**



**Figuur II.5: Partikelgrootteverdeling CEN Standaard zand**

## B. Mengselontwerp

In dit onderzoek wordt de binder-zandverhouding van geopolymeermortels onderzocht. Voor de geopolymeerpasta wordt er met een precursor verhouding van 60 m% GGBS, 25 m% RBP en 15 m% RCP gewerkt. De water-binder ratio heeft een waarde van 0.40, de natriumoxide-binder ratio 8 en de siliciumdioxide-natriumoxide ratio 1.38. Het zandgehalte wordt gevarieerd van 0 m% tot 60 m% voor de drie zandsoorten. Het mengselontwerp is weergegeven in Tabel II-3.

**Tabel II-3: Mengselontwerp**

| sand [%] | sand [g] | geopolymer [%] | GGBS [g] | RCP [g] | RBP [g] | activator [g] |
|----------|----------|----------------|----------|---------|---------|---------------|
| 0        | 0        | 100            | 960      | 240     | 400     | 960,5         |
| 10       | 256,1    | 90             | 864      | 216     | 360     | 864,5         |
| 20       | 512,1    | 80             | 768      | 192     | 320     | 768,4         |
| 30       | 768,2    | 70             | 672      | 168     | 280     | 672,4         |
| 40       | 1024,2   | 60             | 576      | 144     | 240     | 576,3         |
| 50       | 1280,3   | 50             | 480      | 120     | 200     | 480,3         |
| 60       | 1536,3   | 40             | 384      | 96      | 160     | 384,2         |

## C. Voorbereiding van proefmonsters

### 1) Activatoren

De eerste stap in de voorbereiding van de proefmonsters is het maken van de alkalische activatoren. Ten eerste moeten de natriumhydroxidekorrels met water vermengd worden. Aangezien dit een exotherme reactie oplevert, moet er 24 uren gewacht worden voordat de natriumhydroxide oplossing met de natriumsilicaatoplossing gemengd mag worden. Deze tweede stap zal eveneens warmte vrijgeven, waardoor er 24 uren gewacht moet worden voordat de activatoren gebruikt morgen worden.

### 2) Geopolymeer mortel

Het maken van de geopolymeermortels wordt uitgevoerd zoals beschreven in de literatuur [11]. Eerst wordt de geopolymeerpasta gemaakt. Dit wordt gedaan door de precursoren gedurende twee minute droog te mixen op lage snelheid (140 rpm). Vervolgens worden de activatoren toegevoegd, dit wordt gedaan terwijl de mixer op lage snelheid draait gedurende 2 minuten, waarna de mixer omgeschakeld wordt naar hoge snelheid (285 rpm) gedurende 2 minuten. Vervolgens wordt het zand toegevoegd. Dit wordt gedaan terwijl de mixer op lage snelheid draait gedurende 30 seconden, waarna de mixer omgeschakeld wordt naar hoge snelheid gedurende 30 seconden. Vervolgens wordt de mixer gestopt gedurende 90 seconden, waarbij de zijkanten van de mix terug in het midden van de pot worden geschrapt gedurende de eerste 30 seconden. Vervolgens moet er nog 1 minuut op hoge snelheid gemixt worden.

De geopolymeermortel moet daaropvolgend in mallen gegoten worden en verdicht worden. De gebruikte mallen zijn balkvormige mallen met afmetingen 160x40x40 mm<sup>3</sup>. Het verdichten wordt gedaan met een triltafel die vibreert gedurende 60 seconden met een frequentie van 1 Hz. Daarna worden de proefmonsters naar een ruimte met gecontroleerde omgeving verplaatst (20°C, RV 60%) en afgedekt met een ondoordringbaar materiaal, zoals een plastic folie (Figuur II.6).



**Figuur II.6: Proefmonsters  
klimaatruimte**

Het ontkisten van de mallen gebeurt volgens NBN EN 196. De proefmonsters worden tussen 20 en 24 uur na het maken ontkist. Indien de proefmonsters na 24 uur getest worden, worden ze niet vroeger dan 20 minuten voor de test ontkist.

#### D. Testmethodes

##### 1) Vloeibaarheid

De vloeibaarheid van de vers gemaakte geopolymeermortels wordt getest met behulp van de mini slump test, zoals aangegeven in NBN EN 1015-3. De vloeibaarheidsindex wordt berekend gebruik makende van Vergelijking II-1 [12]. Een optimale vloeibaarheidsindex of 2.5 wordt aangenomen.

##### Vergelijking II-1: Vloeibaarheidsindex

$$D = \frac{(d_1 \times d_2) - d_0^2}{d_0^2}$$

Met:

D = vloeibaarheidsindex [-];  
 $d_1$  = grootste diameter [mm];  
 $d_2$  = diameter loodrecht op  $d_1$  [mm];  
 $d_0$  = diameter mini slump kegel [mm].

Op Figuur II.7 wordt de opstelling van de mini slump test weergegeven.



**Figuur II.7: Opstelling mini slump test**

##### 2) Volumieke dichtheid

De volumieke massa van de uitgeharde geopolymeermortels wordt berekend volgens NBN EN 12390-7. Hierin wordt vermeld dat de dichtheid van het monster bepaald mag worden door de droge massa van het monster te delen door het geometrisch berekende volume [13].

##### 3) Buigtreksterkte

De buigtreksterkte van de uitgeharde geopolymeermortels wordt op verschillende tijdstippen getest zoals aangegeven in NBN EN 196-1 [14], zijnde  $24 \pm 15$  min,  $72 \pm 30$  min,  $7 \pm 2$  u en  $28 \pm 8$  u. Deze test wordt met de MacBen Servo Plus Evolution uitgevoerd (Figuur II.8). Vergelijking II-2 wordt gebruikt voor het berekenen van de buigtreksterkte:

##### Vergelijking II-2: Buigtreksterkte

$$R_f = \frac{1.5 * F_f * l}{b^3}$$

Met:

$R_f$  = buigtreksterkte [MPa];  
 $b$  = vierkantszijde balk [mm];  
 $F_f$  = belasting midden balk bij breuk [N];  
 $l$  = afstand tussen ondersteuning [mm].



**Figuur II.8: MacBen Servo Plus Evolution**

##### 4) Druksterkte

De druksterkte van de proefstaven wordt bepaald volgens NBN EN 196-1. Voor deze test worden de in de helft gebroken proefstaven van de buigtreksterkte gebruikt. Deze test wordt eveneens met de MacBen Servo Plus Evolution uitgevoerd. De vergelijking gebruikt voor het berekenen van de druksterkte wordt hieronder weergegeven (Vergelijking II-3):

##### Vergelijking II-3: Druksterkte

$$R_c = \frac{F_c}{1600}$$

Met:

$R_c$  = druksterkte [MPa];  
 $F_c$  = maximale belasting bij breuk [N];  
 $1600$  = oppervlakte proefmonster [mm] (=  $40 \times 40$  mm).

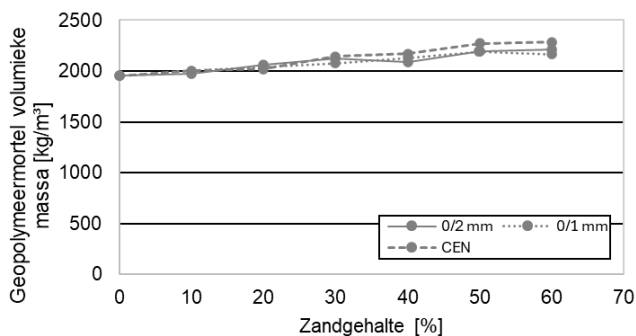
### III. RESULTATEN EN DISCUSSIE

#### A. Volumieke massa

De gemeten volumieke massa van geopolymeermortels met verschillende zandhoeveelheden en -types is weergegeven in Figuur III.1 De volumieke massa van de geopolymeermortels stijgt bij een stijging in zandhoeveelheid voor elk type zand. De maximale volumieke massa voor elk zandtype ligt rond de 50 m% zand. Bij een verdere stijging van zandhoeveelheid, kent de volumieke massa een daling in waarde. Dit komt doordat er een gebrek aan binder is bij hogere zandhoeveelheden, wat leidt tot een slechtere verwerkbaarheid en verdichting van het materiaal. De slechte verdichting zal in luchtbellens en grove poriën resulteren.

De maximale volumieke massa komt overeen met het laagst aantal poriën. Dit is het geval voor elk type zand rond 50 m% zand, wat overeenkomt met een binder-zandverhouding van 1:1.

Deze waarnemingen komen overeen met de bevindingen uit de literatuur. Uit de literatuur blijkt dat de volumieke massa een stijging kent in waarde met een stijgende zandhoeveelheid tot een bepaalde waarde [15]. Waar de maximale volumieke massa bereikt is, zullen de minste poriën aanwezig zijn. Bij een verdere stijging in zandhoeveelheid zal de porositeit snel toenemen. De zandhoeveelheid voor aan de maximale volumieke massa te komen is erg afhankelijk van de vloeibaarheid van de geopolymeerpasta waarmee er gewerkt wordt.



Figuur III.1: Volumieke massa

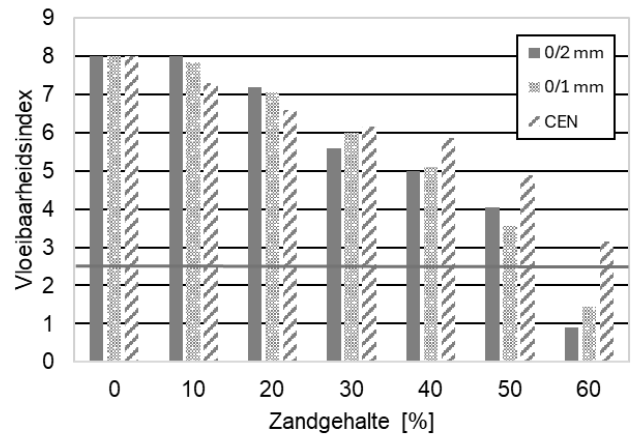
#### B. Vloeibaarheid

De vloeibaarheid van de verse geopolymeermortels wordt uitgedrukt volgens hun gemeten vloeibaarheidsindex. In Figuur III.2 is de vloeibaarheidsindex voor geopolymeermortels met verschillende zandhoeveelheden en -types te zien. De waarden weergegeven op de grafiek zijn de gemiddeldes van twee afzonderlijke metingen. Uit de metingen blijkt dat een stijging in zandhoeveelheid voor een daling in vloeibaarheidsindex zorgt voor elk zandtype. Dit komt overeen met bevindingen uit de literatuur, aangezien zanddeeltjes water opnemen waardoor de water-binderverhouding zal dalen [16].

Uit de metingen kan eveneens bevonden worden dat fijne zandtypes voor een snellere daling in vloeibaarheid zorgen. Kleine zanddeeltjes hebben een grotere specifieke oppervlakte,

waardoor deze meer water opnemen en de water-binderverhouding sneller later zakken.

Aangezien er naar een optimale vloeibaarheidsindex van 2.5 wordt gestreefd, ligt de optimale zandhoeveelheid rond de 50 m%, afhankelijk van het type zand. Bij een zandhoeveelheid hoger dan 50 m% valt de slechte verwerkbaarheid van het mengsel op.

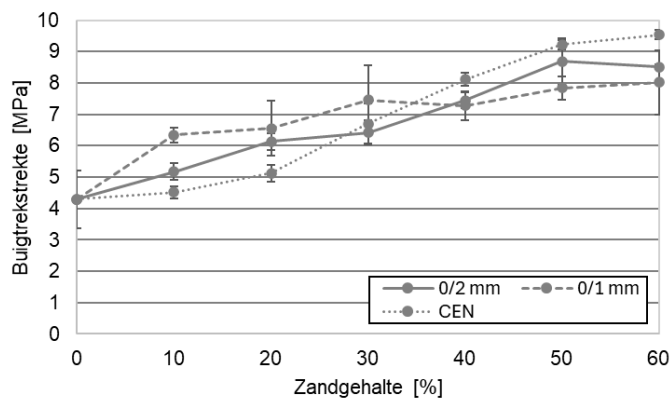


Figuur III.2: Vloeibaarheidsindex

#### C. Buigtreksterkte

De buigtreksterkte van de geopolymeermortels na 28 dagen is weergegeven in Figuur III.3 voor zeezand 0/2 mm, zeezand 0/1 mm en CEN zand. Uit deze metingen kan gezien worden dat de buigtreksterkte van geopolymeermortels stijgen met stijgende zandhoeveelheden tot de optimale zandhoeveelheid bereikt is. Nadat de optimale zandhoeveelheid bereikt is, zal de buigtreksterkte stagneren en dalen. Deze optimale waarde wordt bereikt bij een zandgehalte van 50 m%. De maximale buigtreksterkte van de geopolymeermortels ligt tussen de  $7.8 \pm 0.4$  MPa en  $9.5 \pm 0.1$  MPa na 28 dagen, afhankelijk van het zandtype.

Uit de literatuur kan een gelijkaardig verloop gevonden worden [15]. Een stijging in zandhoeveelheid leidt tot een stijging in buigtreksterkte tot een optimale waarde. Nadat de optimale waarde overschreden is, zal de hoeveelheid zand voor een gebrek aan binder zorgen, waardoor de vloeibaarheid en verdichting van het mengsel afneemt en resulteert in poriënvorming. De luchtbellens in het mengsel zorgen voor een daling van sterkte. De optimale zandgehalte is afhankelijk van de vloeibaarheid van de geopolymeerpasta. In dit onderzoek is het optimale zandgehalte rond de 50 m%, wat licht kan stijgen bij het analyseren van grovere zandsoorten zoals het gebruikte CEN zand. Deze optimale zandgehalte komt overeen met een binder-zandverhouding van 1:1.

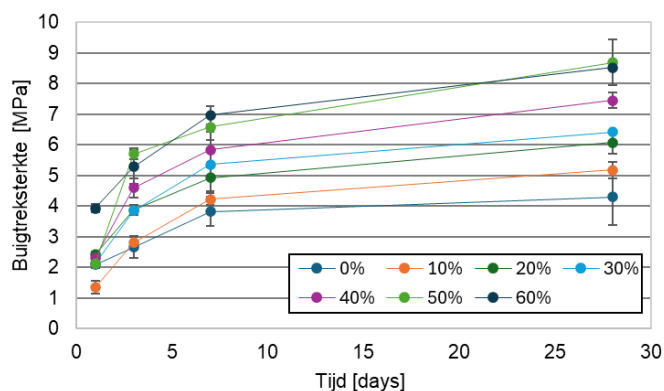


**Figuur III.3: Buigtreksterkte na 28 dagen**

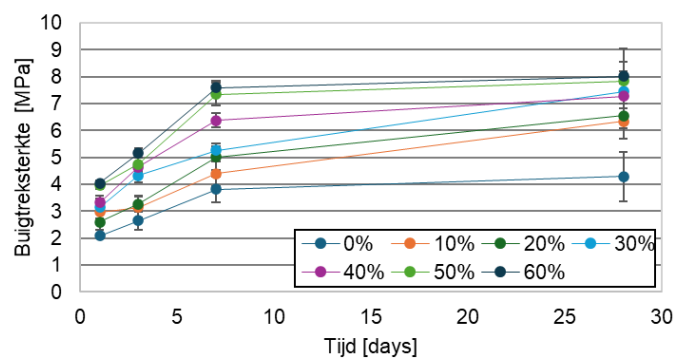
De buigtreksterkte in functie van de tijd is weergegeven voor de verschillende zandgehaltenes in Figuur III.4, Figuur III.5 en Figuur III.6 voor respectievelijk zeezand 0/2 mm, zeezand 0/1 mm en CEN zand. De buigtreksterkte stijgt in functie van de tijd voor elke zandhoeveelheid en -type. Voor zeezand 0/2 mm wordt er opgemerkt dat een stijging in zandhoeveelheid weinig invloed heeft op korte termijn. Dit komt doordat de hechting tussen het zand en de geopolymerpasta nog niet sterk genoeg is. Vanaf 3 dagen is de hechting sterker, waardoor een stijging in zandgehalte voor een stijging in buigtreksterkte zorgt.

Voor zeezand 0/1 mm wordt een ander verloop opgemerkt. Op korte termijn kent een stijging in zandhoeveelheid een stijging in buigtreksterkte, terwijl op lange termijn (28d) de buigtreksterkte stabiliseert. Dit komt door de fijnheid van de zandpartikels. De invloed van de zanddeeltjes op de sterkte is beperkt, wat vooral zichtbaar wordt eenmaal de binding tussen de zanddeeltjes en de geopolymerpasta sterker wordt.

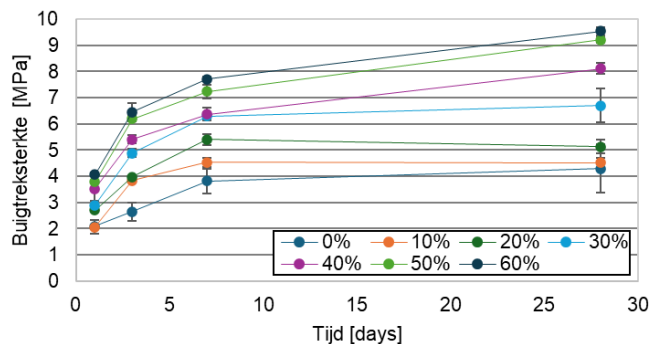
In tegenstelling tot zeezand 0/2 mm en zeezand 0/1 mm, vertoont CEN zand een stijging in buigtreksterkte over alle meetmomenten. De grotere zanddeeltjes kunnen sneller en beter binden met de geopolymerpasta, wat resulteert in een sterkere structuur van op korte termijn. Door de grotere fijnheidsmodulus van het zand blijft het mengsel langer vloeibaar, waardoor er meer zand in het mengsel geïncorporeerd kan worden.



**Figuur III.4: Buigtreksterkte tegenover tijd – 0/2 mm**



**Figuur III.5: Buigtreksterkte tegenover tijd - 0/1 mm**



**Figuur III.6: Buigtreksterkte over tijd - CEN zand**

Rekenmodellen kunnen opgesteld worden om de buigtreksterkte in functie van de tijd te berekenen voor elk type zand. De rekenmodellen worden weergegeven in Vergelijking III-1, Vergelijking III-2 en Vergelijking III-3 voor respectievelijk zeezand 0/2 mm, zeezand 0/1 mm en CEN zand, met bijhorende determinatiecoëfficiënt  $R^2$  is 0.9367, 0.8926, 0.8480.

#### Vergelijking III-1: Rekenmodel buigtreksterkte – 0/2 mm

$$F_f(t) = [0.1946 * \ln(t) + 0.3857] * F_f(28)$$

#### Vergelijking III-2: Rekenmodel buigtreksterkte – 0/1 mm

$$F_f(t) = [0.1691 * \ln(t) + 0.4499] * F_f(28)$$

#### Vergelijking III-3: Rekenmodel buigtreksterkte – CEN

$$F_f(t) = [0.167 * \ln(t) + 0.5012] * F_f(28)$$

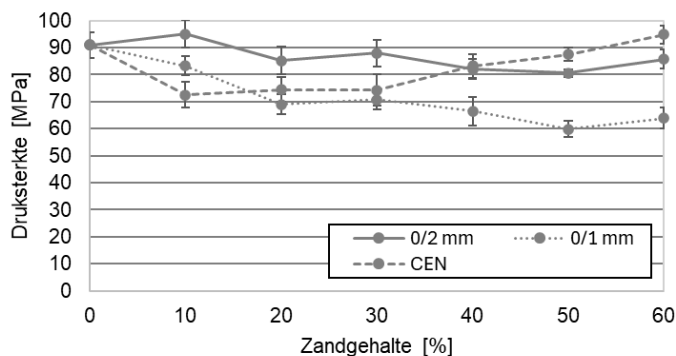
Met:

$$F_f(t) = \text{buigtreksterkte op tijdstip } t.$$

#### D. Druksterkte

De druksterkte van de geopolymermortels na 28 dagen is weergegeven in Figuur III.7 voor zeezand 0/2 mm, zeezand 0/1 mm en CEN zand. Het incorporeren van zeezand 0/2 mm en CEN zand heeft na 28 dagen geen significante invloed op de druksterkte van de geopolymermortels. Dit komt overeen met bevindingen uit de literatuur [17]. De druksterkte is afhankelijk van zowel de sterkte van de geopolymerpasta, als de binding tussen de zanddeeltjes en de geopolymerpasta. Na 28 dagen is er een sterkte van  $80.5 \pm 1.5$  MPa bereikt voor 50 m% zeezand 0/2 mm en  $87.4 \pm 2.5$  MPa voor 50 m% CEN zand.

Het gebruik van zeezand 0/1 mm kent een verschillend verloop. De druksterkte daalt met een stijging in zandhoeveelheid. Dit komt doordat fijne zanddeeltjes meer water absorberen. De verwerkbaarheid van het mengsel zal dalen, en de hoeveelheid aanwezige luchtballen zal stijgen. Dit zorgt voor een daling in sterkte. Na 28 dagen ligt de sterkte rond de  $59.9 \pm 3.1$  MPa voor 50 m% zand, wat meer dan 20 MPa lager ligt dan zeezand 0/2 mm en CEN zand. In de literatuur kan zo een verloop ook vastgesteld worden [16].



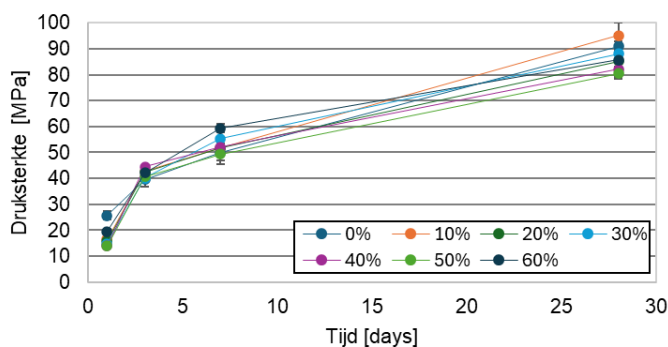
**Figuur III.7: Druksterkte na 28 dagen**

De druksterkte over tijd wordt weergegeven in Figuur III.8, Figuur III.9 en Figuur III.10 voor respectievelijk zeezand 0/2 mm, zeezand 0/1 mm en CEN zand. Voor zeezand 0/2 mm kan opgemerkt worden dat het toevoegen van zand op korte termijn (1 dag) een negatieve invloed heeft. Daarna wordt het effect van zand minder opvallend, en worden er geen beduidende verschillen opgemerkt.

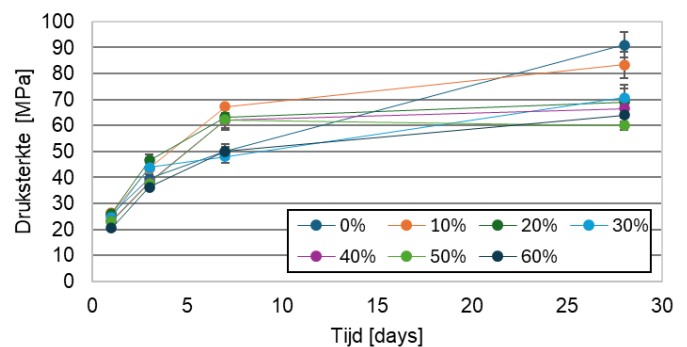
Bij zeezand 0/1 mm wordt het tegengestelde vastgesteld. Op korte termijn heeft het zand weinig invloed op de sterkte van het materiaal, terwijl op lange termijn de toevoeging van zand voor een daling in sterkte zorgt.

Bij grovere zandtypes zoals CEN zand heeft de toevoeging van zand geen significante invloed op de sterkte van het materiaal op alle leeftijden.

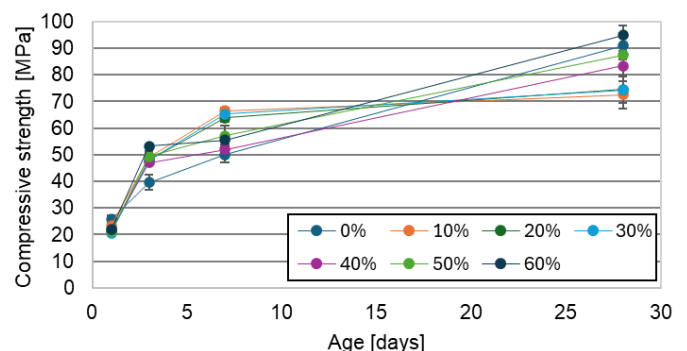
De sterkte van de geopolymeermortels over tijd is afhankelijk van de fijnheid van de zandkorrels. Fijnere korrels absorberen meer water, wat voor een daling in waterbinderverhouding zorgt. Het mengsel wordt minder vloeibaar en zal moeilijker verdichten, waardoor er meer luchtballen en poriën in de mortel aanwezig zijn. De binding tussen de geopolymeerpasta en de zanddeeltjes is slechter. Dit zorgt voor een daling van de sterkte.



**Figuur III.8: Druksterkte over tijd - 0/2 mm**



**Figuur III.9: Druksterkte over tijd - 0/1 mm**



**Figuur III.10: Druksterkte over tijd - CEN**

Voor de druksterkte op een bepaald tijdstip te bepalen kunnen er rekenmodellen opgesteld worden. De rekenmodellen voor zeezand 0/2 mm, zeezand 0/1 mm en CEN zand worden respectievelijk in Vergelijking III-4, Vergelijking III.5 en Vergelijking III.6 weergegeven. Deze drukmodellen hebben een bijhorende determinatiecoëfficiënt  $R^2$  van 0.9758, 0.8734, 0.8993

#### Vergelijking III-4: Rekenmodel druksterkte – 0/2 mm

$$F_c(t) = [0.2359 * \ln(t) + 0.1963]$$

#### Vergelijking III-5: Rekenmodel druksterkte – 0/1 mm

$$F_c(t) = [0.2019 * \ln(t) + 0.3603] * F_c(28)$$

#### Vergelijking III-6: Rekenmodel druksterkte – CEN

$$F_c(t) = [0.2142 * \ln(t) + 0.3034] * F_c(28)$$

Met:

$$F_c(t) = \text{druksterkte op tijdstip } t.$$

#### IV. CONCLUSIE

In dit onderzoek werd het effect van de binder-zandverhouding op geopolymeermortels gedeeltelijk gemaakt van CDW-fijnen geanalyseerd. De volumieke massa van geopolymeermortels stijgt met een stijgende zandhoeveelheid. Elk type zand kent een maximale volumieke massa rond de 50 m%, wat overeen komt met een binder-zandverhouding van 1:1. Voor het incorporeren van grovere zandsoorten licht de

maximale volumieke massa van de geopolymeermortels lichtjes hoger dan wanneer er fijnere zandsoorten gebruikt worden. De maximale volumieke massa komt overeen met de minimale porositeit. Indien er meer zand toegevoegd wordt dan de optimale hoeveelheid, zal er een gebrek aan geopolymeerpasta zijn voor de aanwezige zanddeeltjes, waardoor de verwerkbaarheid van het mengsel daalt en er luchtbellen en poriën ontstaan.

Een stijging van zandhoeveelheid resulteert eveneens in een daling van vloeibaarheid. De optimale vloeibaarheidsindex van 2.5 komt voor bij een zandgehalte van 50 m% voor fijnere zandsoorten (zeezand 0/2 mm en 0/1 mm), terwijl grovere zandsoorten een licht hogere zandgehalte mogen hebben om aan de optimale vloeibaarheidsindex te voldoen.

De buigsterkte van de geopolymeermortels kent een stijgend verloop met een verhoging van de zandhoeveelheid. De maximale buigsterkte komt voor bij een zandhoeveelheid van 50 m%, en heeft waardes variërend van  $7.8 \pm 0.4$  MPa tot  $9.5 \pm 0.1$  MPa afhankelijk van het gebruikte zandtype.

De druksterkte van de geopolymeermortels is minder afhankelijk van het zandgehalte. Bij fijnere zandtypes, zoals zeezand 0/1 mm, zal een stijging in zandhoeveelheid voor een daling in druksterkte zorgen. Voor de andere zandtypes is er geen significant invloed te zien bij een stijging van zandhoeveelheid. De druksterkte van de geopolymeermortels met zeezand 0/2 mm en CEN zand hebben een waardes van respectievelijk  $80.5 \pm 1.5$  MPa en  $87.4 \pm 2.5$  MPa voor 50 m% zand, terwijl geopolymeermortels met zeezand 0/1 mm een waarde van  $59.9 \pm 3.1$  MPa bereiken.

De optimale zandhoeveelheid voor GGBS-CDW-gebaseerde geopolymeermortels, rekening houdend met de vloeibaarheid en mechanische eigenschappen, bedraagt 50 m%. Dit komt overeen met een binder-zandverhouding van 1:1.

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Dit onderzoek zou niet mogelijk zijn geweest zonder de steun van mijn promotor, Prof. Dr.-Ing. Jiabin Li, en copromotoren, Ing. Jasper Vitse en MSc. Dongsheng Zhang. Ik wil hen van harte bedanken voor me de mogelijkheid te hebben gegeven om dit onderzoek uit te voeren, en voor de ondersteuning en waardevolle feedback die ik gedurende dit onderzoek heb mogen krijgen.

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|                           |                                                     |        |
|---------------------------|-----------------------------------------------------|--------|
| $b$                       | Side of square section prism                        | [mm]   |
| $d_0$                     | Diameter mini slump cone                            | [mm]   |
| $d_1$                     | Maximum spread diameter slump                       | [mm]   |
| $d_2$                     | Diameter perpendicular to $d_1$                     | [mm]   |
| $l$                       | Distance between supports                           | [mm]   |
| $n$                       | Amount of substance                                 | [mol]  |
| $s$                       | Sample standard deviation                           | [-]    |
| $s^2$                     | Sample variance                                     | [-]    |
| $t$                       | Age specimen/time                                   | [days] |
| $x_i$                     | Sample value                                        | [-]    |
| $\bar{x}$                 | Mean sample value                                   | [-]    |
| $D$                       | Flowability index                                   | [-]    |
| $D_{\text{mean}}$         | Mean flowability index                              | [-]    |
| $F_c$                     | Maximal load at fracture                            | [N]    |
| $F_f$                     | Load applied to the middle of the prism at fracture | [N]    |
| $FM$                      | Fineness modulus                                    | [-]    |
| $R^2$                     | Coefficient of determination                        | [-]    |
| $R_c$                     | Compressive strength                                | [MPa]  |
| $R_{c,\text{mean}}$       | Mean compressive strength                           | [MPa]  |
| $R_{c,\text{normalized}}$ | Normalized compressive strength                     | [-]    |
| $R_f$                     | Flexural strength                                   | [MPa]  |
| $R_{f,\text{mean}}$       | Mean flexural strength                              | [MPa]  |
| $R_{f,\text{normalized}}$ | Normalized flexural strength                        | [-]    |

# Abbreviations

|         |                                               |
|---------|-----------------------------------------------|
| AAM     | Alkali activated material                     |
| b       | Binder                                        |
| CDW     | Construction and demolition waste             |
| C-S-H   | Calcium silicate hydrate                      |
| EU      | European Union                                |
| GGBS    | Ground granulated blast furnace slag          |
| LCA     | Life cycle analysis                           |
| MRAP    | Mixed recycled aggregate powder               |
| N-A-S-H | Sodium aluminosilicate hydrate                |
| RBP     | Recycled brick powder                         |
| RCP     | Recycled concrete powder                      |
| rpm     | Rotations per minute                          |
| SDG     | Sustainable Development Goals                 |
| SH      | Sodium hydroxide (NaOH)                       |
| SS      | Sodium silicate ( $\text{Na}_2\text{SiO}_3$ ) |
| w       | Water                                         |



# 1 INTRODUCTION

---

## 1.1 Sustainability challenges within the construction industry

### 1.1.1 Environmental impact of the construction sector

Global warming is one of the most pressing challenges of our time. Climate change cannot be ignored, with scientists warning of its accelerating pace. The average global temperature has risen by 1.5°C since industrial era, and is predicted to increase even further if no significant actions are taken [1]. The Paris Agreement set a long term temperature goal to limit the impact of the climate change, keeping the global average temperature below 2°C above pre-industrial levels, while aiming to contain the rise below 1.5 °C [2].

The construction sector plays a significant role in global environmental challenges. As one of the largest consumers of raw materials and energy, and a major producer of greenhouse gases and waste, its impact cannot be overstated. Three key issues stand out in particular: the depletion and scarcity of natural resources and energy sources, high CO<sub>2</sub> emissions, and excessive waste generation. The environmental impact of the construction sector is illustrated in Figure 1.1.



**Figure 1.1: Environmental impact of the construction sector [3]**

The construction industry is known to be the largest consumer of raw materials and energy worldwide [4]. Around 35% of all the energy consumed is directly linked to the construction industry, while 50% of raw materials extracted from the earth are used as construction materials and products [5], [6]. Most of these materials are nonrenewable, like rocks and aggregates, and would, if recycled, be used for other purposes. Concerns arise regarding iron ore and other raw steel materials used in the industry, regarding the depletion of their high-

grade presence in many places. Other materials, like sands, are also the debate of rising concerns, as river sands is not allowed to be used since 1996 in Belgium, and sea sand stands to be depleted within the next 80 years. Looking for new resources increases the transportation and destroys habitat, increasing the distance between sources and centers of growth and construction.

Secondly, carbon emissions is a leading contributor to climate change, accounting for approximately 79% of the total greenhouse gas emissions [7]. From the global energy related carbon emissions, around 39% is directly linked to the construction industry, with 28% being from operational emissions, and the remaining 11% from the construction process and materials themselves [8]. World Green Building Council has issued new objectives: reducing the embodied carbon with 40% in all new buildings, infrastructures and renovations by 2030, while keeping a net zero operational carbon for all new buildings. By 2050, all new buildings, infrastructures and renovations must have net zero embodied carbon, while all existing buildings will have net zero operational carbon.

The European Green Deal aims to reduce all net greenhouse gas emissions by minimum 55% by 2030 compared to 1990 levels, and to be the first climate neutral continent by 2050 [9]. Additionally, 3 billion supplementary trees needs to be planted in the EU by 2030.



**Figure 1.2: Greenhouse gases [10]**

The construction sector does not only have a significant impact on the environment in terms of emissions (Figure 1.2) and depletion of raw resources, but also in terms of waste generation. About a third of the total waste generated in the EU exist exclusively of waste originated from the construction sector, making construction and demolition waste (CDW) the largest waste stream in the EU [11]. This reaches up to 450 to 500 million tons of waste per year, which is equivalent to the weight of 75 million adult elephants [12]. Most of the generated waste ends up in landfills, which leads to degradation of the environment by polluting the ground, groundwater and air. Furthermore, the space for landfills in Flanders is extremely limited. The European Union set targets to reduce the negative impact of the construction and demolition waste [13]. These new targets focus on waste management and recycling. By the end of 2025,

recycling and material recovery of non-hazardous CDW must reach a minimum of 70% by weight.

These environmental challenges present the construction sector with an ideal opportunity for transformation. The EU is committed to leading the construction industry towards more sustainable practices by incorporating circular economy principles. The circular economy model can be described as a model of production and consumption, where the life cycle of the products is elongated [14]. Existing materials and products will be recycled, reused and repurposed to last as long as possible. By keeping the materials in the economy through recycling, the waste generation will be reduced, decreasing the pressure on landfills while addressing the growing concerns around resource scarcity. Figure 1.3 illustrates the principle of circular economy perfectly.



**Figure 1.3: Circular economy model [14]**

This circular economy model is a departure from the linear economic model, which is characterized by resource extraction, use and disposal. The term “linear” indicates the progress of the materials, which follows a straight path with a visible beginning and end. This model goes hand in hand with a high volume of new resource extraction and product manufacturing. For this model, unlimited resources and landfill space would be needed.

The EU is looking to make the construction sector more sustainable. Sustainability can be described as the ability to sustain, while aiming for sustainable development. This means being able to meet the needs of our generation without standing in the way of future generations. The three pillars, social, environmental and economic, need to be balanced and maximized.

The three aspects need to be interconnected with one another to truly be able to speak about sustainability, as can be seen in Figure 1.4. Environmental sustainability, for example, can be achieved by reducing or minimizing the impact of human activities on the natural environment. The European Green Deal thrives to protect the global ecosystem by decarbonizing our world in the light of future generations, which makes it a perfect example for environmental sustainability. Economic sustainability, on the other hand, can be achieved by keeping the costs for a good living standard affordable, while thriving for long-term economic growth. The economic growth shouldn't come at the cost of social, environmental, or cultural aspects of the society. Lastly, social sustainability is attained by encouraging the well-being of the members of the community, without negatively affecting future generations.

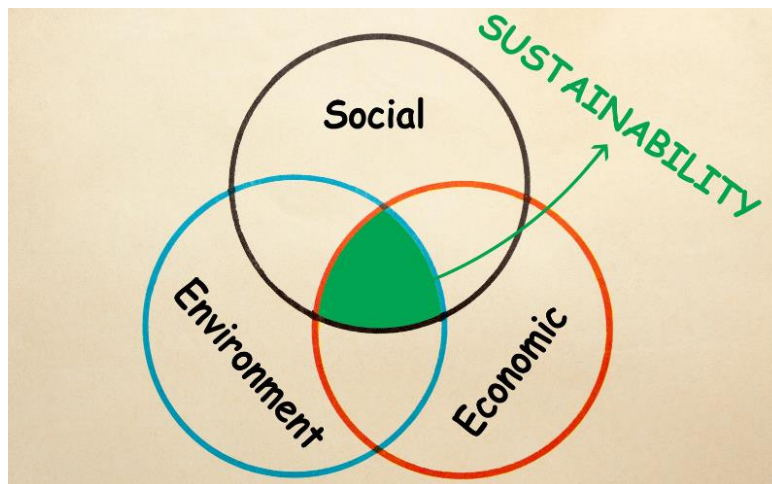


**Figure 1.4: Three pillars of sustainability [15]**

To be able to achieve sustainability worldwide, the United Nation set 17 Sustainable Development Goals (SDGs) in The 2030 Agenda for Sustainable Development. These goals have as objective to “provide a shared blueprint for peace and prosperity for people and the planet, now and in the future” [16]. The SDGs in question are visible in Figure 1.5. This research in question focuses on two of these SDGs in particular, namely SDG 12: Responsible consumption and production, and SDG 13: Climate action.



**Figure 1.5: Sustainable Development Goals [16]**

### **1.1.2 Building materials and their environmental impact**

The construction sector has a significant environmental impact. This impact is closely tied to the current building materials in use, not only due to the large amount consumed, but also because of their energy-intensive production processes and high embodied carbon. The term “building materials” covers a wide range of products, from structural elements like concrete and steel to insulation, wood, brick, and glass. Each of these materials comes with its own environmental profile, but one common factor remains: their production, processing and transport are responsible for a considerable share of CO<sub>2</sub> emissions.

Binders are one of the most important materials in the construction industry, with cement being one of the most used binders. Cement is responsible for about 8% of the global CO<sub>2</sub> emissions, mainly due to the decomposition of the limestone and the high temperature required during manufacturing of cement clinkers [17]. This makes cement one of the most carbon-intensive materials currently in use. As construction activities continue to grow globally, the demand for cement remains high, placing even more pressure on the environment.

At the same time, the transportation of raw materials from quarries to factories, and from factories to construction sites, further increase the environmental burden. Choosing more sustainable alternatives, like recycled materials, would reduce the impact of the construction industry on the environment.

Addressing the sustainability of construction materials, and especially binders, is essential. Exploring alternatives that reduce embodied carbon and promotes the use of secondary materials is a crucial step to achieve a circular, low-carbon construction sector.

### 1.1.3 Sustainability of alkali-activated materials

A promising way to assist in the transition from a linear to a circular economy model, and to achieve sustainability in the construction industry, is by looking into cement alternatives. Among these alternatives, alkali-activated materials have attracted significant interest due to their lower carbon footprint and potential to integrate industrial by-products such as ground granulated blast furnace slag (GGBS) and fly ash. Alkali-activated materials are a class of alternative binders that are produced through the reaction between an aluminosilicate-rich precursor and an alkaline activator. These materials are generally known for their high early strength, good chemical resistance, and low permeability, which makes them suitable for a wide range of construction applications. Their mechanical and durability properties can be tailored depending on the type of precursor and activator used.

The industrial by-products have been extensively researched and successfully been implemented in various cement applications. However, the availability of industrial by-products is expected to decline due to the ongoing electrification of the steel and coal-fired power industries, which traditionally produce these materials. By electrification, the current processes that use fossil fuels are being replaced by electrically powered technologies. As a result, the construction sector must explore new sources of suitable precursors. One promising approach is the partial use of fine fractions derived from construction and demolition waste, which encouraged the transition to a circular economy model by recycling and reusing construction materials, and reducing the need for raw material extraction and landfills.

Investigating alkali-activated materials at the mortar scale provides a more realistic approach than by researching alkali-activated binders, as mortars are more likely to be used on large scale than binders. Incorporating sand into the mixture not only decreases the overall cost of the material, but also reduces shrinkage.

There are a few questions that need to be addressed before being able to use alkali-activated mortars within the construction industry. Firstly, there are different types of sand currently on the market, each with their own gradings and properties. Analyzing the effect of the different types of sand can help in identifying the optimal sand. Furthermore, the sand content to be added in traditional cementitious mortar is well known, but the optimal sand content for alkali-activated mortars, and more specifically alkali-activated mortars with partial CDW use, remains unknown. The mortars need to have adequate flow and mechanical properties to be used within the industry.

## 1.2 Research question

The research question that this study aims to answer is as follows:

**“What is the effect of the binder-to-sand ratio on the workability and mechanical properties of GGBS-CDW based geopolymer mortars?”**

To find a solution to the above mentioned main question, the following sub-questions are formulated:

- “What is the optimal GGBS-CDW content for geopolymer pastes in terms of workability and mechanical properties?”

- “How does the binder-to-sand ratio influence the flowability and mechanical properties of geopolymer mortars?”
- “How do different types of sand affect the overall performance of the geopolymer mortars?”
- “What is the optimal binder-to-sand ratio for geopolymer mortars taking both workability and strength into account?”

Based on this research question, the study can be divided into two main parts. Firstly, a literature review is conducted, specifying the differences between cement and alkali-activated binders. The distinction between geopolymers and alkali-activated binders is analyzed, clarifying the use of the term “geopolymer”. Furthermore, the materials used in this study is examined at both production and chemical levels, and the chemical reactions involved in alkali-activated materials are looked into. Moreover, different types of sand, the requirements for sand in mortar applications, and the effect of varying sand contents from previous studies is reviewed.

The second part of this research focusses on laboratory work, where sand content is varied to investigate its effect on the workability and the strength properties of the mortars. This is done using three different types of sand, in order to examine the influence of sand types on the aforementioned properties.

### **1.3 Research objectives**

The aim of this research is to optimize the binder-to-sand ratio of GGBS-CDW based geopolymer mortars, taking the workability and mechanical properties into account. The research objectives are as follows:

- To assess the feasibility of using ground mineral CDW as precursors for new alkali-activated binders
- To evaluate the effect of sand addition on the fresh and hardened properties of alkali-activated pastes
- To investigate the influence of different sand types and grain size distribution on mortar performance
- To determine the optimal binder-to-sand ratio for balancing workability and mechanical strength in GGBS-CDW based geopolymer mortars
- To compare experimental results with existing literature to identify consistencies, deviations, or gaps in current knowledge

Additionally, this study can contribute to the achievement of several Sustainable Development Goals set by the United Nations, as described above, especially SDG 12: responsible consumption and production and SDG 13: climate action.

### **1.4 Research methodology**

This research is divided into six main phases. Firstly, a literature study is conducted on cement, alkali-activated materials, geopolymers, sand-types and mortars. Secondly, geopolymer pastes are designed based on optimal compositions found in literature. Third, geopolymer

mortars are designed by varying both sand content and sand type. In the fourth step, these mortars are tested for their workability and mechanical properties. Once all tests are completed, the results are analyzed and compared with findings from the literature. Finally, an answer to the research question is formulated.

The first semester consisted mainly of theoretical research and familiarization the testing methods by experimenting with several geopolymer pastes. As such, the first three steps of this methodology were carried out during this period. During the second semester, all mortars were produced and tested, followed by the analysis of the results and comparison with existing literature. At the end of the second semester, an answer to the research question was formulated.

The research methodology is illustrated in the flowchart shown in Figure 1.6.

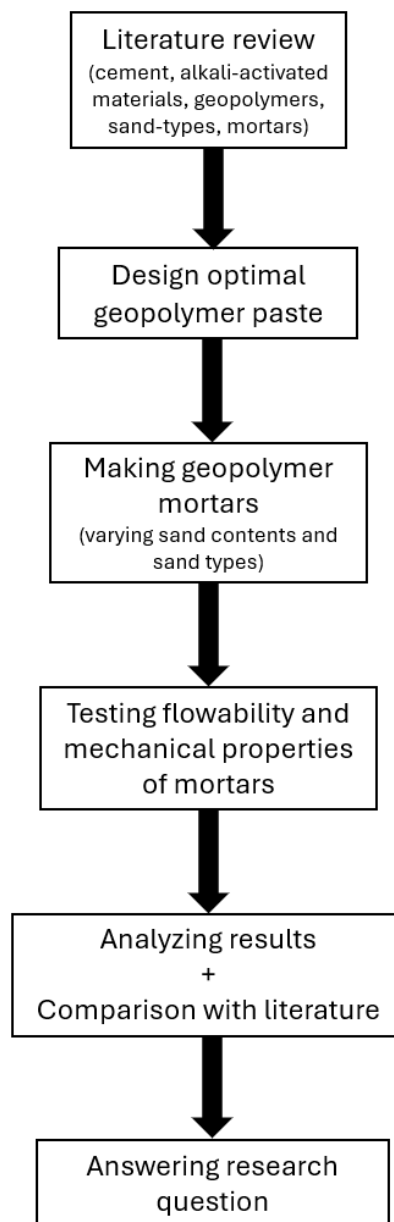


**Figure 1.6: Research methodology**

## 2 LITERATURE REVIEW

---

### 2.1 Cement

Cement is a key material in the construction industry. In 2023, approximately 4.1 billion metric ton of cement was produced worldwide [18]. Cement is mainly used as hydraulic binder in the production of mortar and concrete [19]. This is a material that, when mixed with water, forms a paste which sets and hardens due to chemical reactions. After hardening, the material retains its strength and stability.

To illustrate the scale of its use, global cement production significantly surpasses that of other major construction materials, such as steel, of which around 1.9 billion metric tons were produced in the same year [20].

#### 2.1.1 Portland cement

Portland cement is the most commonly used cement in the world. The material was firstly introduced in the early 19<sup>th</sup> century by an English bricklayer, Joseph Aspdin, when burning clay and powdered limestone [21]. Over the years, the cement has been ameliorated to the one we know today.

##### 2.1.1.1 *Manufacture of Portland cement*

The manufacturing of Portland cement can be divided in eight parts [21], [22]. The first step is quarrying the raw materials, which include limestone and clay. In recent years, some alternatives have been introduced to replace the raw materials, such as blast furnace slag and other industrial byproducts. This keeps them out of landfills and contributes to the circular economy.

After quarrying the materials, the rocks are crushed and some samples are sent to a laboratory for analysis to ensure the efficiency and quality of the production process. The third step is the mixing, grinding, and blending of the ingredients. The previously crushed rocks are now ground into a finer powder by use of a vertical roller mill, and mixed with the other ingredients.

Once the materials are mixed and blended together, they go through a preheating tower and travel from top to bottom. This makes the kiln process, that happens next in the manufacturing, more efficient, as heat is added to the raw materials and starts the chemical reactions. After the preheating tower, the kiln firing process starts. Here, the materials are heated up to 1450°C, which partially melts the mix of raw materials. Due to the heat, a series of reactions takes place which results in the formation of clinkers. Clinkers are grey balls the size of marbles.

The next step is the cooling of the clinker, which takes place in a clinker cooler. Heated air from the coolers can be recovered and returned to the kilns to save fuel and increase the burning efficiency.

After the cooling process, the clinker is put in a ball mill, mixed with some gypsum, and ground into a powder fine enough ( $< 90 \mu\text{m}$ ) to achieve the desired properties.

Once the cement is finished, it can be pumped into storage silos and packed in bags, or dispatched using bulk containers [23]. Figure 2.1 shows the whole manufacturing process of Portland cement.

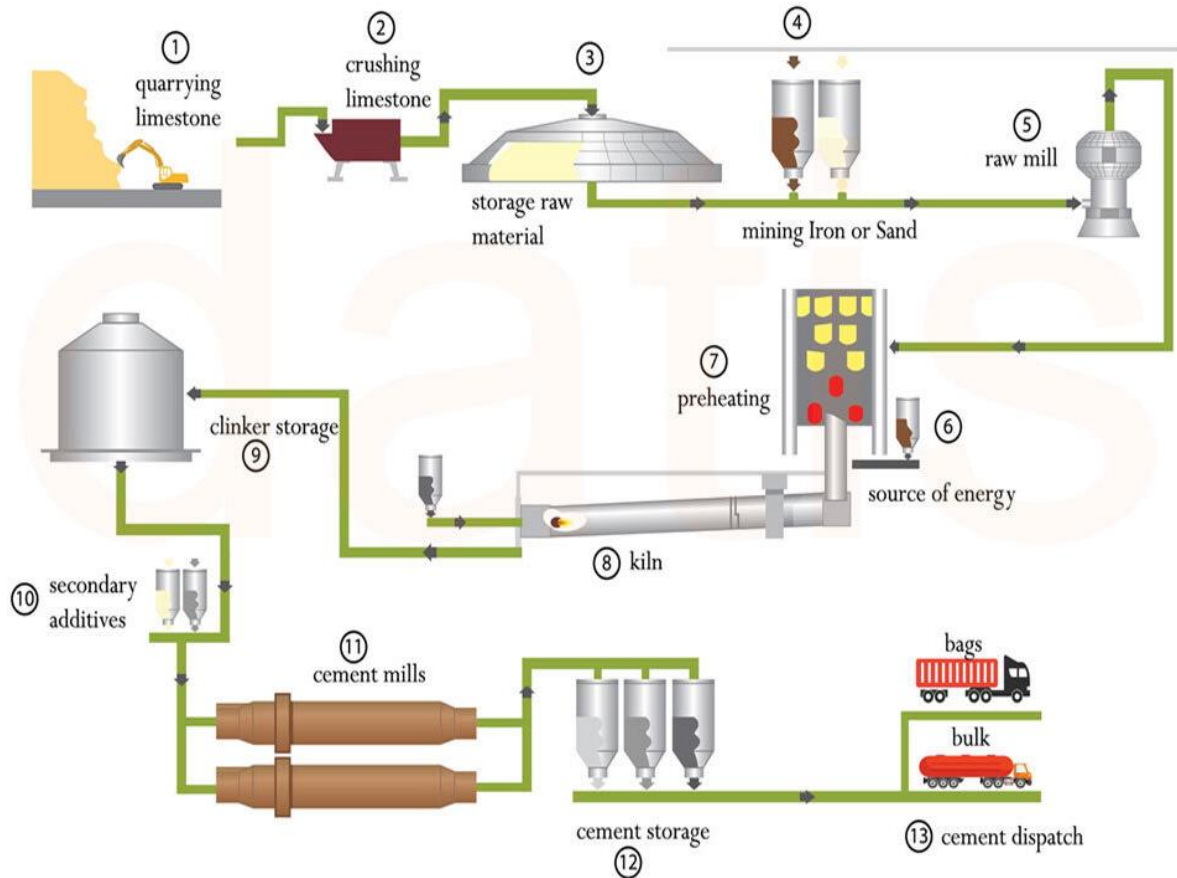


**Figure 2.1: Manufacture of Portland cement [24]**

The manufacturing procedure of Portland cement can be summarized in the following key steps:

- Quarrying the raw materials (limestone and clay)
- Crushing, grinding and blending
- Kiln firing process and clinker formation
- Clinker cooling
- Incorporation of gypsum + final grinding
- Storage and packaging

### **2.1.1.2 Chemical composition**

Portland cement is made of 4 principal components, and 5 secondary components [22], [23]. As principal components, there are tricalcium silicate ( $3\text{CaO}\cdot\text{SiO}_2$ ), dicalcium silicate ( $2\text{CaO}\cdot\text{SiO}_2$ ), tricalcium aluminate ( $3\text{CaO}\cdot\text{Al}_2\text{O}_3$ ), and tetracalcium aluminoferrite ( $4\text{CaO}\cdot\text{Al}_2\text{O}_3\cdot\text{Fe}_2\text{O}_3$ ). These compounds can also be written using an abbreviated notation, namely  $\text{C}_3\text{S}$ ,  $\text{C}_2\text{S}$ ,  $\text{C}_3\text{A}$  and  $\text{C}_4\text{AF}$  respectively. In this abbreviated notation, C stands for lime, S for silica, A for aluminate, and F for ferric oxide. Alite ( $\text{C}_3\text{S}$ ) and blite ( $\text{C}_2\text{S}$ ) form about 80%

of the total Portland cement compounds, while  $C_3A$  and  $C_4AF$  form about 20%.

These components are the result of the chemical reaction which took place during the kiln firing process, when limestone ( $CaO + CaCO_2$ ) and clay ( $SiO_2 + Al_2O_3 + Fe_2O_3$ ) are mixed and heated [22].

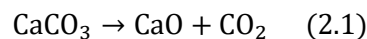
During this process, a small amount of secondary components are also formed, namely  $MgO$ ,  $TiO_2$ ,  $Mn_2O_3$ ,  $K_2O$  and  $Na_2O$ .

### **2.1.1.3 Hydration process**

For Portland cement to take up the role of a hydraulic binder, it needs to be mixed with water [22]. When mixing those elements together, hydration occurs, which is the chemical reaction between the main compounds of cement and water. The hydration of each of the compounds takes place independently of the others, as the hydration rate of the different compounds is different. There are three different hydration products, namely calcium silicate hydrate (C-S-H), calcium hydroxide ( $Ca(OH)_2$ ), and ettringite ( $3CaO \cdot Al_2O_3 \cdot 3CaSO_4 \cdot 32H_2O$ ).

## **2.1.2 The effect of cement on global warming**

Cement is known to be one of the key sources of global carbon dioxide ( $CO_2$ ) emissions, as it is responsible for about 8% of the world's total  $CO_2$  emissions [17]. This is mainly due to the cement production, as it requires high temperatures during the kiln firing phase to decompose limestone in calcium silicate and calcium aluminate [25], [26]. During the heating of limestone, it is decomposed according to the reaction shown in equation 2.1 and releases 0.78 tons  $CO_2$  per ton of  $CaO$  produced. This quantity of  $CO_2$  released is only due to the chemical reactions. The combustion of the fossil fuels releases additional carbon emissions.



Carbon dioxide is a greenhouse gas, which traps heat in the atmosphere by absorbing the sun's heat and preventing it from escaping into space [27]. The EU has plans to reduce the greenhouse gas emissions by legally binding targets: by 2030 the emissions should be 55% lower compared to 1990, and by 2050 the EU should reach net zero emissions.

One way to reduce the  $CO_2$  emissions in mortar or concrete, is to replace the cement by an alternative material, like alkali-activated materials (AAM) [25].

### **2.1.3 Cement mortar**

Mortar is a mixture of cement, sand and water, and, depending on the application, possible admixtures. The proportions of the ingredients may vary depending on the specific applications, such as masonry, floor screeds, plastering, and others.

## **2.2 Alkali-activated materials**

As stated before, cement is responsible for about 8% of the global carbon dioxide emissions. By replacing cement by an alkali-activated binder, the  $CO_2$  emissions originated from the construction industry can significantly be reduced.

Alkali-activated materials are defined as any binder system derived from the reaction between a precursor and an activator [25], [28]. The precursor is a solid aluminosilicate. This can be a calcium silicate or a more aluminosilicate-rich material like metallurgical slag, fly ash or natural pozzolan. The activator, on the other hand, can include alkali hydroxides, silicates, carbonates, sulfates, aluminates or oxides, as long as it can supply alkali metal cations, raise the pH level of the mixture and promote the dissolution of the solid precursor.

The reaction of an alkali source with an alumina- and silica-containing solid precursor was patented by a German chemist and engineer in 1908, as a means of forming a solid material comparable to hardened Portland cement.

Alkali-activated binders can be produced following two main pathways, namely the one-part mix system, where dry powder is combined with water, or the two-part mix system, using liquid activators. The two-part mix system is the most used pathways nowadays.

Geopolymers can be seen as a subclass of alkali-activated materials [25], [28]. This term was firstly introduced by Davidovits in the 1970s, and describes low-calcium alkali-activated aluminosilicate binders. For this research specifically, two of the three precursors used have a high-calcium content, making the term “geopolymer” unfit to describe these alkali-activated binders. Nevertheless, due to the flexible use of the term “geopolymer” within the construction industry, and the popularity of this term compared to “alkali-activated binder”, the term “geopolymer” will be used during this research as synonym to “alkali-activated binder”.

## **2.2.1 Precursors**

Different solid precursors are suitable for the production of alkali-activated materials [28]. Most aluminosilicate supplementary cementitious materials can be used. For this research, the two precursors that will be used for the making of geopolymer mortar are ground granulated blast furnace slag (GGBS) and construction and demolition waste (CDW)

### **2.2.1.1 *Ground granulated blast furnace slag***

Granulated blast furnace slag is a by-product of the steel and iron industry. As can be seen in Figure 2.2, the blast furnace runs up to 1500°C [29], [30], [31]. Molten iron and molten slag are created by supplying the blast furnace with a mixture of limestone, iron ore, and coke. The molten slag floats on top of the molten iron due to its lower density. The molten slag primarily consists of silicates and alumina derived from the original iron ore, along with some oxides contributed by the limestone. After cooling the slag using high-pressure water jets, the slag quenches rapidly, forming small granular particles (< 5 mm). The formation of larger crystals is prevented due to the rapid cooling, resulting in a granular material of about 95% non-crystalline calcium-aluminosilicates. In order to enhance the reactivity of the material, the slag is ground into fine powders, which are then called ground granulated blast furnace slag (GGBS).

# The Blast Furnace

Charge: iron ore, coke, limestone

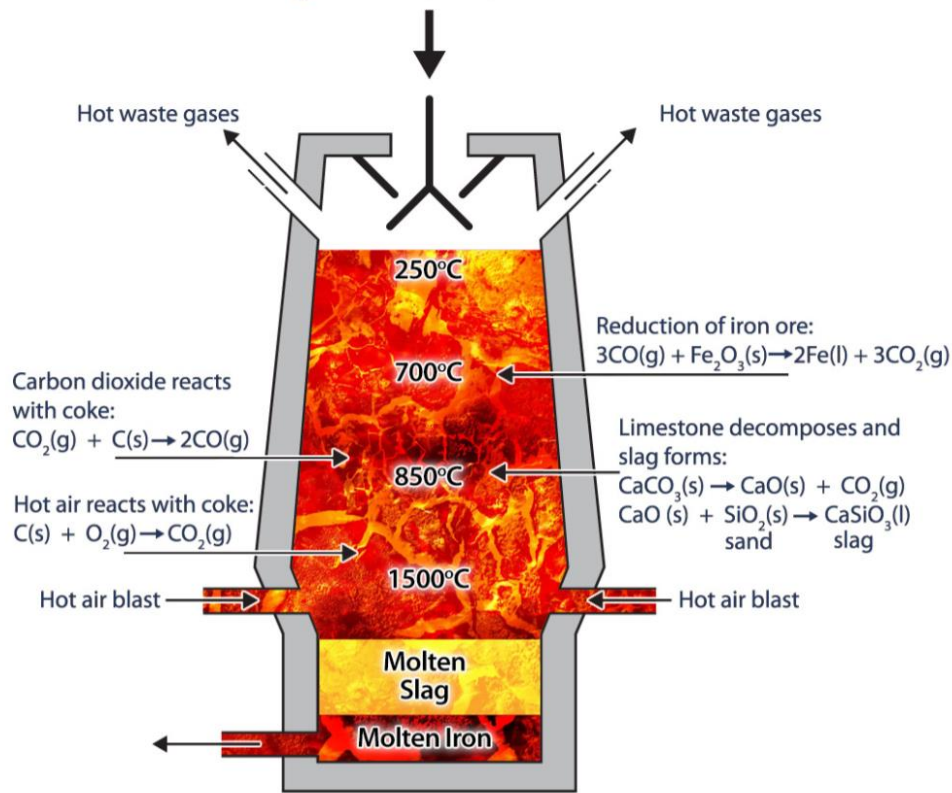


**Figure 2.2: Production process GGBS [32]**

GGBS can be used as binder due to its composition rich in amorphous calcium, silica and alumina [33], [34]. Several researchers have replaced ordinary Portland cement (OPC) on different levels with GGBS to analyze its effect on the workability and mechanical properties. By including GGBS, the workability of concretes can be enhanced. GGBS activated in alkali solution possesses a higher strength than OPC, and has a better resistance to chemicals. However, it also leads to a reduced setting time which increases the shrinkage and development of micro cracks, leading to a higher porosity and decrease in strength.

Using GGBS as precursor has proven to have other advantages as well, like reducing the energy consumption, decreasing the greenhouse gas emissions, and reducing reliance on raw materials [33].

## 2.2.1.2 Construction and demolition waste

Construction and demolition waste (CDW) includes any kind of waste generated during construction processes, such as concrete, bricks, wood, glass, et cetera. In the EU, around a third of all the waste generated comes from the construction sector, which reaches up to 450-500 million tons per year [12], [35], [36], [37]. From this waste, nearly 43% end up in landfills, which leads to environmental, societal, economical and public health challenges. By recycling and reusing these materials, the problems originated from CDW can significantly decrease, but the lack of confidence in the quality of the materials is still a major obstacle.

For this research, two kinds of CDW are used, namely recycled concrete powder (RCP) and recycled brick powder (RBP). These materials can be produced through different methods. The production process for the materials used in this research is as follows: RCP is obtained by crushing concrete blocks. During this process, fine particles are released and collected in a water basin, where they settle at the bottom. This sediment is then retrieved and dried, resulting in RCP, which is also referred to as filter cake. This process is visualized in Figure 2.3. By adding RCP to mortar, the compressive strength, flexural strength and resistance to chloride penetration is known to decrease, and the drying shrinkage will be reduced [38], [39]. By limiting the RCP content to 30% when combining it with OPC, the decrease in compressive strength is negligible.

The RBP used in this research, on the other hand, is produced from the cutting of fired clay bricks. This process is illustrated in Figure 2.4. Using RBP in the preparation of mortar can lead to a change in the compressive strength and flexural strength, but compared to mortars with RCP, the reduction of the compressive strength after 28 days is smaller [40]. For flexural strength, using RBP also leads to better results after 28 days, but when increasing the test period up to 180 days, RCP shows a clear improvement due to the secondary hydration process.



**Figure 2.3: RCP preparation process**



**Figure 2.4: RBP preparation process**

### **2.2.1.3 Chemical composition of CDW**

The above-mentioned CDW can also be described in terms of its chemical composition. RCP primarily consists of a mixture of materials from the original concrete mixture. These include fine particles such as sand, remnants of hydration products from the cement paste, and particles of limestone [41]. Sand is predominantly composed of silica ( $\text{SiO}_2$ ), in the form of quartz. In this form,  $\text{SiO}_2$  is considered chemically inert and does not contribute to the reactivity of RCP. The hydration products typically include calcium silicate hydrates (C-S-H) and portlandite ( $\text{Ca}(\text{OH})_2$ ). Among those,  $\text{Ca}(\text{OH})_2$  is the only chemically reactive component present in RCP, but since it is present in relatively small amounts, the overall reactivity of RCP is generally low. Additionally, calcium carbonate ( $\text{CaCO}_3$ ) is also found in RCP, originated both from the limestone and from the carbonation of portlandite.

RBP, on the other hand, is primarily composed of clay-rich materials. Its main oxides include silica ( $\text{SiO}_2$ ), alumina ( $\text{Al}_2\text{O}_3$ ) and ferric oxide ( $\text{Fe}_2\text{O}_3$ ). Unlike the quartz form of silica present in RCP, the silica in RBP can be reactive. The alumina present promotes the formation of calcium alumina and ameliorates the early-stage mechanical properties of cementitious systems [42].

When comparing both recycled brick powder and recycled concrete powder, recycled brick powder knows a higher reactivity as well as better early-stage mechanical properties when used in concrete mixtures.

The chemical composition of recycled bricks and waste concrete, together with other possible construction and demolition waste, are shown in the ternary diagram below (Figure 2.5).

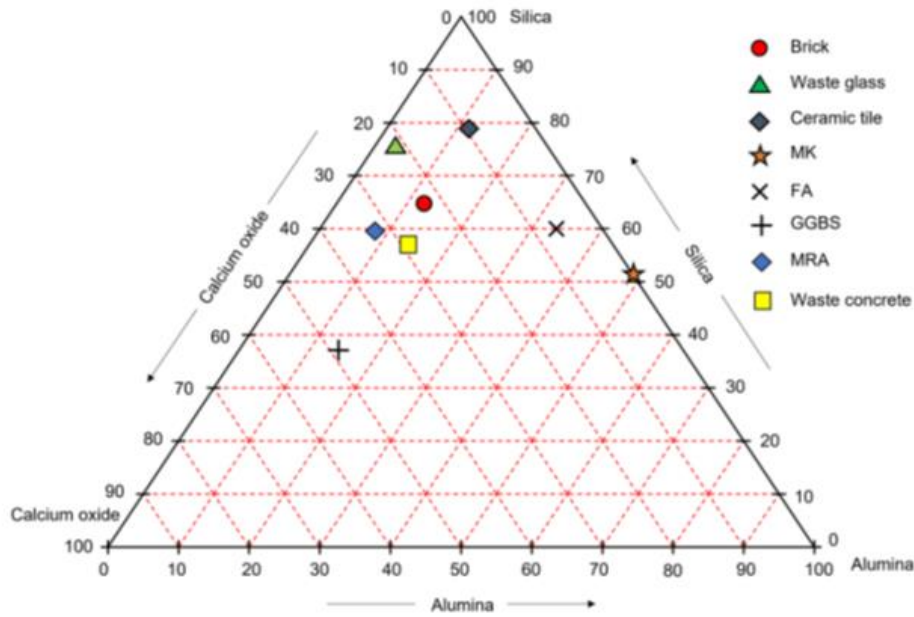


Figure 2.5: Ternary diagram of CDW

## 2.2.2 Alkali-activator

The most commonly used alkali-activators are NaOH,  $\text{Na}_2\text{SiO}_3$ , KOH and  $\text{K}_2\text{SiO}_3$  [28]. They are the ingredient in the geopolymer that initiates the pozzolanic reaction in aluminosilicate minerals [43]. A pozzolanic reaction can be defined as the chemical process in which a finely divided material, although not cementitious on its own, reacts with calcium hydroxide in the presence of a moisture [44]. This reaction produces calcium silicate hydrates (C-S-H).

In this research, a mixture of sodium hydroxide and sodium silicate will be used. These activators are known for their superior rheological performance and low cost. However, it is important to obtain the optimum Si/Na or  $\text{SiO}_2/\text{Na}_2\text{O}$  ratio based on the quantity of hydroxide and silicate, due to the consistent deflocculating activity in the particulate suspensions of sodium silicate. Increasing the Na ion in the solution promotes the dissolution of aluminosilicate minerals, due to their ability to hold the hydration layer of water molecules.

Based on research from Research Group RecyCon, the  $\text{SiO}_2/\text{Na}_2\text{O}$  ratio that is used in this study will be equal to 1.38 [36].

### 2.2.2.1 Sodium hydroxide

Sodium hydroxide, also known as caustic soda, is a white, translucent crystalline solution. The production of NaOH exists of three major steps, namely brine purification, electrolysis and product recovery. On Figure 2.6, the industrial production process of NaOH is shown. This process is also described below the figure.

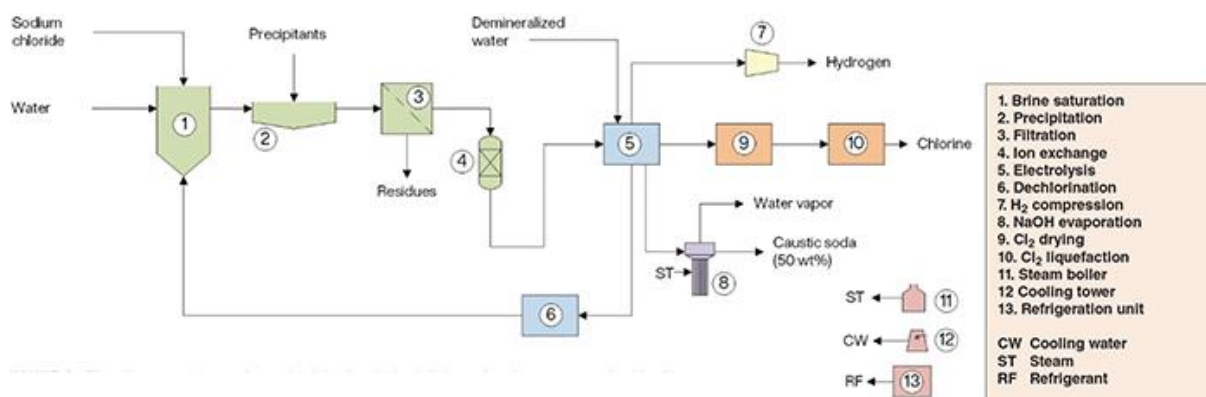


**Figure 2.6: Industrial production process of NaOH [45]**

Brine purification begins by mixing the recycled depleted brine with water, followed by re-saturating it using fresh NaCl. Heavy metal ions, such as  $\text{Ca}^{2+}$  and  $\text{Mg}^{2+}$ , present in the brine can damage the membrane. Because of this, precipitants are added to the brine, causing the metals to precipitate and from a sludge that is removed through settling in a clarifier. The clarifier solution is then filtered and further processed using ion-exchange resins to remove the residual hardness and reach acceptable quality levels.

The second step is the electrolysis. The electrolysis process primarily requires ultrapure brine and electricity. Brine is added into the anolyte compartments of the cells, which are separated from the catholyte compartments by cation-exchange membranes. At the anodes, chlorine gas is introduced, while sodium ions migrate through the membranes into the catholytes. The depleted brine from the anode compartments undergoes dichlorination before being recycled to the brine saturation stage. On the catholyte side, water is electrolyzed, resulting in the generation of hydrogen gas and hydroxyl ions. The membranes prevent hydroxyl ions from entering the anolyte compartments. This allows them to combine with sodium ions in the catholytes, resulting in the production of sodium hydroxide. Demineralized water is added to maintain the desired catholyte concentration.

The last step consists of the product recovery. Here, hydrogen generated during electrolysis is compressed and supplied to consumers. The sodium hydroxide solution is concentrated into a saturated 50 wt.% NaOH solution. Chlorine gas from the process goes to a drying system, where drying towers use concentrated sulfuric acid as a dehydrating agent. The dried chlorine gas is then compressed, liquified, and stored in dedicated storage vessels.

In this research, the sodium hydroxide solution is made from a mixture of commercialized sodium hydroxide pellets and water.

### 2.2.2.2 Sodium silicate

There are two main methods to produce sodium silicate in aqueous solution, namely the melting process and subsequent dissolution, and hydrothermal process [46], [47], [48]. Both methods involve the reaction of silica with a sodium, but they differ in the way the reaction is carried out.

The first method (Figure 2.7), being the melting process and subsequent dissolution method, involves the reaction of quartz ( $\text{SiO}_2$ ) and sodium carbonate ( $\text{Na}_2\text{CO}_3$ ) at a high temperature of  $1400^\circ\text{C}$  in special furnaces. This reaction results in the formation of anhydrous sodium silicate in molten form, along with the release of carbon dioxide. Rapidly cooling and breaking

the molten silicate results in a glossy sodium silicate, also known as waterglass. After hydrating and dissolving the glassy sodium silicate in water to the desired concentration, the solution can be purified, controlled and used. Those last steps take place in a high pressure and high temperature special autoclaves.

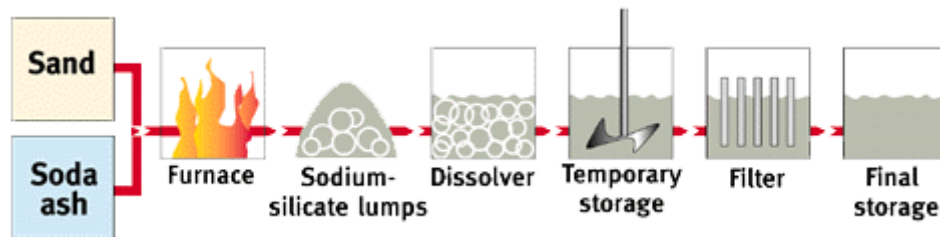


**Figure 2.7: Melting process and subsequent dissolution method [47]**

The second method is called the hydrothermal process. A visual representation of this method is given in Figure 2.8. This process makes direct production of sodium silicate possible in its hydrated and dissolved form, by letting quartz chemically react with sodium hydroxide in aqueous solution. This reaction takes place under high temperature and high pressure, and yields sodium silicate directly in its aqueous form, making a separate dissolution step unnecessary. After purifying and controlling the solution, the sodium silicate can be used.

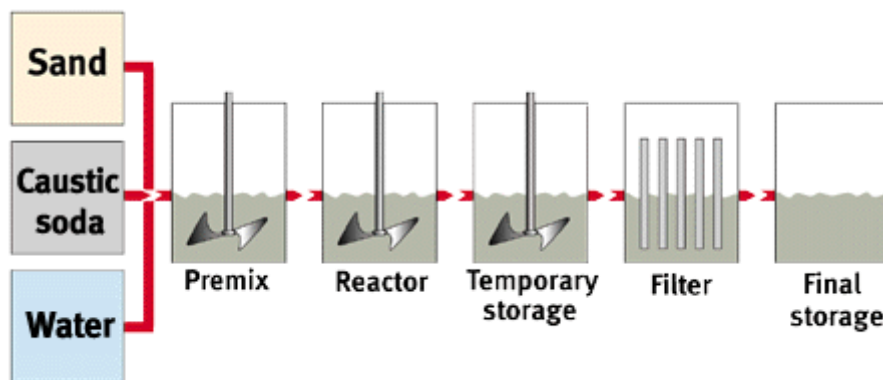


**Figure 2.8: Hydrothermal process [47]**

### 2.2.3 Alkaline activation reaction of geopolymers

The alkaline activation reaction of geopolymers can generally be divided into 4 main steps: dissolution, condensation, polycondensation and crystallization of the gels [49]. Those steps are schematically represented in Figure 2.9, and are explained below.

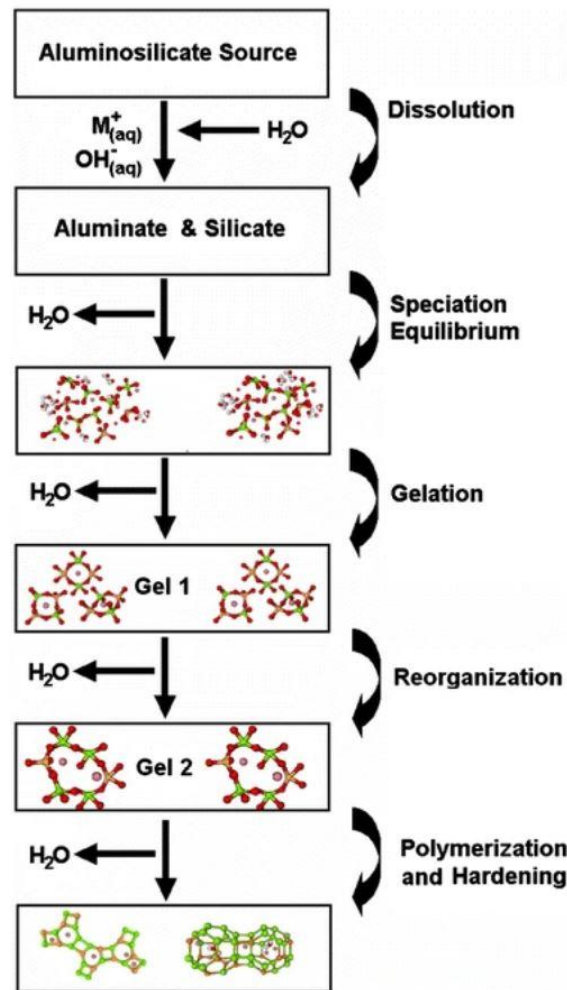


**Figure 2.9: Alkaline activation reaction of geopolymers [49]**

The first step in the reaction process is the dissolution of the aluminosilicate materials and the release of reactive silicate and aluminate monomers, represented as  $[\text{Si}(\text{OH})_4]^-$  and  $[\text{Al}(\text{OH})_4]^-$  respectively. This dissolution process breaks the covalent Si-O-Si and Al-O-Al bonds that form the structure of aluminosilicates. However, this bond breaking can only occur in a highly alkaline environment with a pH higher than 14, which is created by the activating solution. This dissolution process leads to the colloidal phase.

The colloidal phase then begins a process of water elimination through a nucleophilic substitution reaction. In this reaction, the negatively charged species  $[\text{Si}(\text{OH})_4]^-$  and  $[\text{Al}(\text{OH})_4]^-$  connect together due to the attraction between the hydroxyl (OH) groups on the silicate molecules and aluminum ions in the aluminate structure. This phase initiates the condensation step, which is a chemical equilibrium process during which intermediate compounds are formed. During this stage, an unstable aluminosilicate network takes shape, which leads to the release of water molecules.

This process continues with further water release and the initial gel formation. Although the system moves toward chemical equilibrium, load balancing cannot be fully achieved because both silicate and aluminate are negatively charged. This is why the presence of alkali metal ions, such as  $\text{Na}^+$  and  $\text{K}^+$ , is essential in the alkaline solution. These positive charged ions help to stabilize the negatively charged gels by balancing their overall charge. As a result, the

structure of the intermediate compounds reorganizes, leading to the development of more resistant final compound.

Finally, the polycondensation of the gels take place, which might undergo crystallization. This steps results in the formation of stable gels that make up the final structure of geopolymers. The amorphous gels are often referred to as N-A-S-H in the literature, meaning sodium silicate aluminate hydrate, while the crystalline or semi-crystalline phases are commonly identified as zeolites. At this stage, the material begins to harden, developing mechanical strength and other characteristic properties of alkali-activated materials.

The alkaline activation reaction of geopolymers can be summarized as follows:

1. **Dissolution:** aluminosilicate materials dissolve in a highly alkaline environment, breaking Si-O-Si and Al-O-Al bonds and **releasing silicate and aluminate monomers**.
2. **Condensation:** silicate and aluminate monomers react through **nucleophilic substitution**, forming an **unstable aluminosilicate network** and releasing water.
3. **Polycondensation:** further water release and **gel formation** takes place, requiring alkali metal ions to stabilize the negatively charged network.
4. **Crystallization:** **stable, amorphous N-A-S-H gels** are formed, leading to the development of the materials mechanical properties and durability.

#### 2.2.4 CDW-based geopolymers

Vitse, Zhang and Li [36] researched the effect of increasing the slag content in CDW-GGBS based geopolymer composites on the workability and mechanical properties. As precursors, GGBS and mixed recycled aggregate powder (MRAP) were used. A mixture of sodium hydroxide and sodium silicate were used as alkaline activators. During this study, the GGBS-to-MRAP ratio was varied from 50:50 to 80:20. When increasing the ratio from 50:50 to 70:20, a significant decrease in initial and final setting time was observed. By increasing the ratio even further, both the initial and final setting time increased slightly. An increase in GGBS content leads to a faster setting and accelerated polycondensation due to its higher CaO content. However, if the CaO content is excessively present, it will form calcium aluminate hydrates by reacting with the alkaline activator, leading to a delay in activation.

Furthermore, increasing the GGBS content leads to a decrease in flowability. The most notable decrease was observed when increasing the GGBS-to-MRAP ratio from 70:30 to 80:20. Due to the high surface area of GGBS, the particles absorb more water leading to a reduction in workability. These findings are visualized in Figure 2.10.

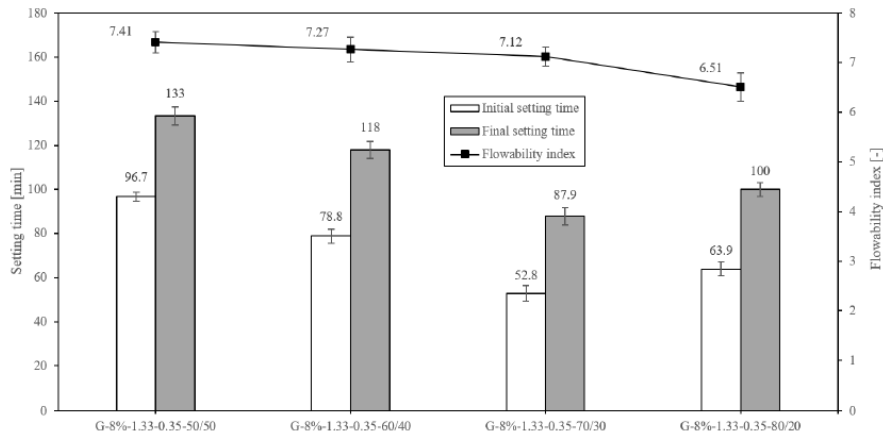


**Figure 2.10: GGBS-MRAP based geopolymer – workability [36]**

The mechanical properties of the GGBS-MRAP based geopolymers were also tested with varying ratios. Increasing the GGBS content led to an increase in compressive strength. The most notable increase was observed when increasing the ratio from 60:40 to 70:30. A further increase in GGBS content did not lead to any significant change regarding the compressive strength. This increase in strength is linked to the reactive amorphous silica and alumina present in GGBS, whereas MRAP contents of hydratable amorphous phases are rather low. The increased reactivity of GGBS leads to effective geopolymer gels formation, resulting in a stronger geopolymer matrix. The compressive strength at 1 day and 7 days is plotted in Figure 2.11.

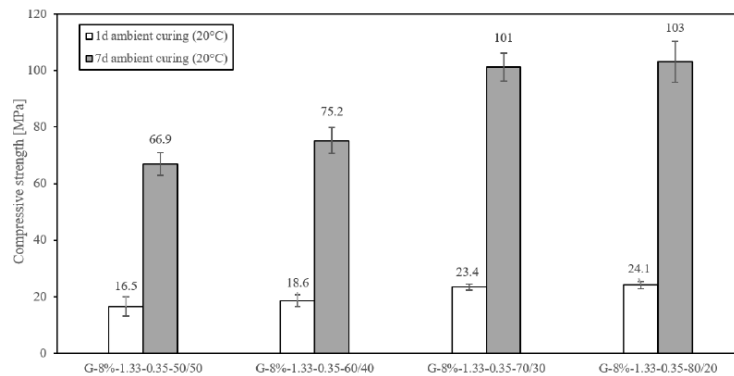


**Figure 2.11: GGBS-MRAP based geopolymer – compressive strength [36]**

Alhawat et al. [50] reviewed the properties of geopolymers sourced from CDW. When making geopolymer mortars using CDW, it is recommended to add supplementary cementitious materials. Recycled brick powder, for example, has a CaO shortage which can be covered by incorporating GGBS into the mixture. Furthermore, most CDW have a low calcium concentration and crystalline form, leading to a limited strength growth at early ages. This makes the activation process of CDW slow. If GGBS is present in the mixture, up to 60% RBP can be incorporated before noting a remarkable decrease in compressive strength thanks to the calcium present in GGBS.

When comparing RBP and RCP, RBP results in better mechanical performances. This is due to the higher silica and alumina content of bricks and ceramics compared to waste concrete. The mechanical performance of both CDW can be improved by reducing the particle fraction to sizes smaller than 75  $\mu\text{m}$ .

Furthermore, the mechanical properties of geopolymers can be improved by changing the molarity of sodium hydroxide as alkaline activator. The best performances have been obtained within a molarity range of 8 to 12 mol. Moreover, a mixture of sodium hydroxide and sodium silicate was reported to be the most effective activator for optimal mechanical properties for CDW-based geopolymers. The recommended sodium silicate-to-sodium hydroxide ratio is between 1.0 and 2.0. A higher sodium silicate content leads to a decrease in workability due to the high viscosity of the fluid. On the other hand, increasing the sodium hydroxide content prolongs the setting time of the geopolymer.

Saini, Singh and Kapoor [51] researched the strength and durability properties of geopolymer mortars made with varying concrete waste powder (CWP) content. As precursor, both GGBS and CWD were used. The CWP content was varied from 100% to 80%. A mixture of sodium silicate and sodium hydroxide (12M) were used as alkaline activator. The compressive strength of the mortars were analyzed for the three CWP contents. CWP alone proves to provide sufficient compressive strength. However, incorporating GGBS in the mixture increases the compressive strength, ameliorating the early stage strength gain. Their findings regarding the compressive strength are illustrated in Figure 2.12.

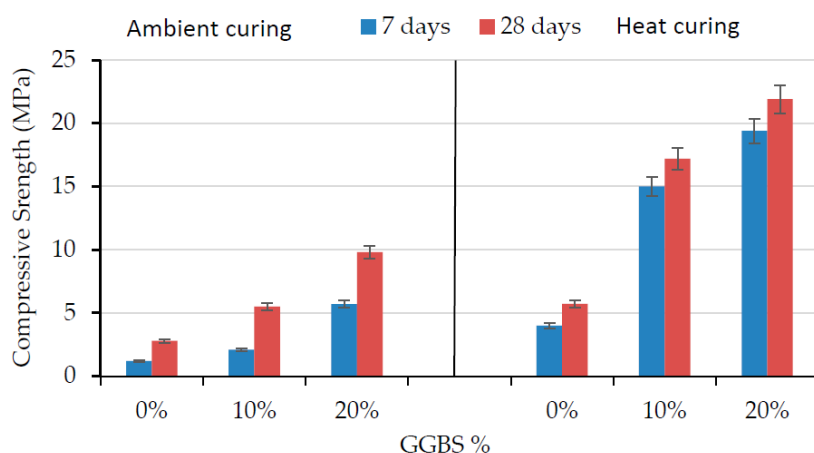


**Figure 2.12: GGBS-CWP based geopolymer – compressive strength [51]**

Furthermore, a decrease in porosity was noted when increasing the GGBS content. Due to the smaller particle size of GGBS, the material has better filling properties leading to smaller voids and less water absorption. Both the porosity and water absorption decreased up to 20% of the replacement level of CWP.

Zhang et al. [52] researched the effect of GGBS on RCP-based geopolymers. As precursor during this research, both RCP and GGBS were used. The GGBS replacement ratio varied from 0% up to 50%. A mixture of sodium hydroxide and sodium silicate were used as alkaline activator. The strength properties of the geopolymers were analyzed for each of the replacement ratios. Increasing the slag content led to an increase in compressive strength due to the accelerated reaction of calcium. When no GGBS was added, the geopolymer displayed low strength properties due to the low reactivity of the RCP. Figure 2.13 shows the compressive and flexural strength of the geopolymers at 3 days, 7 days and 28 days. The incorporation of GGBS in the mixture mainly promotes the development of the compressive

strength in the early ages. The flexural strength has a similar trend to that of the compressive strength.

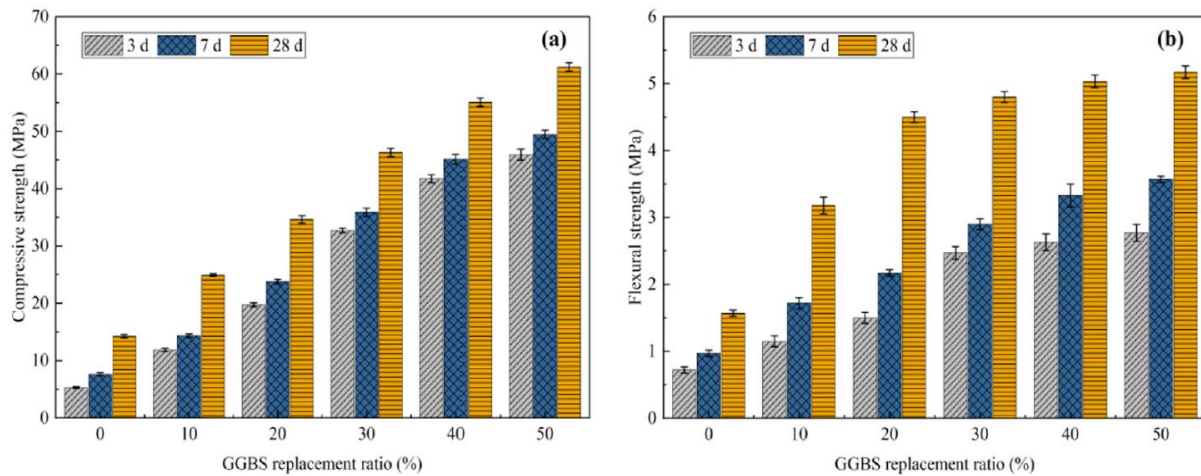


**Figure 2.13: GGBS-RCP based geopolymer – compressive and flexural strength [52]**

The study also researched the influence of the GGBS content on the porosity and water absorption of the geopolymer mixtures. Increasing the GGBS content leads to a reduction of porosity and water absorption. The geopolymer mixture is denser and more compacted, reducing the water permeability and porosity.

## 2.3 Sand

Sand plays a crucial role in both human society and the natural environment [53], [54]. While it is widely known for its use in the construction industry, sand also provides essential ecosystem services, such as protecting river deltas and coastal zones, and for maintaining biodiversity. Globally, around 50 billion metric tons of sand are consumed each year, making sand the second most extracted natural resource after water [55], [56], [57]. This amount is nearly three times higher as it was just two decades ago. However, even if sand may look abundantly present on earth, the actual resource is becoming increasingly scarce. Only around 19 billion metric ton of new sand are naturally generated each year, being less than half the amount of sand currently being consumed.

### 2.3.1 Types of sand

In Belgium, there are four main sources of supply of sand, namely land and rivers, import from abroad, secondary raw materials, and the North Sea [58].

Pit sand, also known as coarse sand, is a naturally occurring type of sand on land [59]. This sand has a gritty texture, and is used in various construction tasks, such as surface leveling, as base layer or as bedding material. However, as the extraction of sand on land has a negative impact on the environment, due to the noise, dust, traffic and mining activities, extraction on land has been restricted.

Another type of sand is river sand, which is directly sourced from riverbeds. This sand is known for its smooth and rounded particles, which increases the workability of construction materials like concrete and mortar. However, environmental concerns have also led to stricter

regulations on its extraction. In Belgium, dredging river sand for construction purposes has been firmly regulated since 1996, as excessive removal disrupts river flow and contributes to riverbank erosion [41], [53].

Instead of river sand, sea sand has widely been used in Belgium. This sand can be dredged from sea floors, beaches or tidal areas [60], [61]. Due to its proximity to seawater, sea sand often contains high levels of salts, particularly chlorides, which can lead to corrosion of reinforcement bars in concrete structures, leading to a decline of durability of the structure. Nevertheless, the use of sea sand also comes with certain advantages, such as its affordability and aesthetic appeal.

Another commonly used type is manufactured sand, also referred to as M-sand [59], [62]. This sand is artificially produced by crushing hard rocks into finer particles that are similar in size to naturally occurring sand. M-sand is characterized by its more angular shape, enhancing the mechanical bonding in concrete. One of the key advantages is its consistent particle size and quality, which can be precisely controlled during production. Moreover, the use of manufactured sand reduces reliance on natural sand sources, leading to a reduced environmental impact.

A more recent and increasingly studied source is recycled sand, produced from construction and demolition waste [63]. During the demolition and recycling process of CDW, including demolition, handling, transportation and production of coarse aggregates, around 50% of the resulting material consists of sand-sized particles. Based on grain size analysis, this fraction can be processed into recycled sand with a grading similar to that of the original sand present in the waste. Advanced crushing techniques, such as the use of a vertical shaft impact crusher, makes the production of lower porosity recycled sand is possible.

In summary, while natural sands such as pit, river, and sea sand have long been relied upon in construction, environmental limitations and increasing global demand have led to the growing demand of alternatives like manufactured and recycled sand. Each type of sand comes with its own set of properties, benefits, and challenges, making material selection a crucial factor depending on the specific requirements of the application.

## **2.3.2 Uses of sand**

Sand is one of the most versatile natural materials, and is used in a wide range of applications across various industries [64]. The construction sector is the perfect example, where sand is a key ingredient in concrete, mortar, and asphalt, serving as a fine aggregate that enhances strength and stability. Sand is also vital for road construction, land reclamation, and backfilling operations. Beyond construction, it is used in the glass industry, where the silica content (quartz) of sand is melted to produce glass products. Additionally, sand finds applications in water filtration systems, and even in recreational uses, such as in playgrounds and sports fields.

### **2.3.2.1 Sand in mortar**

Mortar is composed using cement, sand, water, and possible admixtures. The addition of sand to cement paste plays a crucial role in modifying the mortar's properties. Adding sand to the cement paste reduces the total porosity of the cement mortar, as its larger surface area leads to denser packing and a stronger bond to the cement paste [65], [66]. This helps control

shrinkage and reduces cracks. However, while sand is essential to the mixture, an excessive amount can decrease overall strength: the composite may become more compact and strengthen, but the bond at the interface weakens [67]. Additionally, too much sand decreases the workability of the mixture as well, resulting in a reduced strength once more. On the other hand, sand is generally less expensive than cement, making it a cost-effective component in mortar. Sand is also a great filler material, reducing the binder volume needed.

### 2.3.3 Requirements for sand in mortar

Aggregates added in mortars have to be according the standard NBN EN 13139 [68]. The aggregates may be of natural origin, manufactured or recycled, as long as they fulfill the requirements. The requirements described are for mortars meant for masonry, repair, plastering and other purposes, as further described in the standard itself.

The requirements can be divided into 3 main parts, being the geometrical requirements, the physical requirements and the chemical requirements. Starting with the geometrical requirements, the aggregates used should be of following sizes: 0/1 mm, 0/2 mm, 0/4 mm, 0/8 mm, 2/4 mm or 2/8 mm. As the aggregates used in this research will be smaller than 4 mm, the particle shape of the aggregates won't influence the behavior of the mortar. Additionally, the shell content does not have to be determined.

The fines content, being the maximum percentage passing through the 0.063 mm sieve by mass, should not exceed a certain value as depicted in the standard. Table 2.1 shows an overview of those limitations, divided by category. Examples of the categories as described in the standard are as follows: category 1 – floor screeds, sprayed, repair mortars, grouts (all aggregates); category 2 – rendering and plastering mortars (all aggregates); category 3 – masonry mortars (all aggregates except crushed rock); category 4 – masonry mortars (crushed rock).

**Table 2.1: Fines content [68]**

| Aggregate size [mm] | Maximum percentage passing 0,063 mm sieve by mass |            |            |            |            |
|---------------------|---------------------------------------------------|------------|------------|------------|------------|
|                     | Category 1                                        | Category 2 | Category 3 | Category 4 | Category 5 |
| 0/1                 | 3                                                 | 5          | 8          | 30         | >30        |
| 0/2                 | 3                                                 | 5          | 8          | 30         |            |
| 0/4; 2/4            | 3                                                 | 5          | 8          | 30         |            |
| 0/8; 2/8            | 3                                                 | 5          | 8          | 11         |            |

The physical properties of the aggregates must be tested if the particular application at the end use or if the origin of the aggregates require it. If required, following tests should be performed: particle density (EN 1097-6), water absorption (EN 1097-6), resistance to freezing and thawing (EN 1367-1).

Lastly, the chemical requirements only need to be tested if the application at end use or if the origin of the aggregates require it. The tests that, if required, should be carried out are as follows: water-soluble chloride ion content (EN 1744-1:1998), acid-soluble sulfate content (EN 1744-1:1998), total-sulfur content (EN 1744-1:1998), constituents which alter the rate of setting and hardening of mortar (EN 1744-1:1998).

### 2.3.4 Geopolymer mortars based on other types of precursors

Over the past decade, increasing research has focused on geopolymer mortars due to their excellent properties, making them a promising cement alternative. While studies specifically on GGBS-CDW-based geopolymer mortars are still limited, existing research regarding other types of geopolymer mortars provide a strong foundation for further investigation in this area.

#### 2.3.4.1 Fly ash based geopolymer mortars

Temuujin, van Riessen and MacKenzie [69] researched the physical and mechanical properties of fly ash based geopolymer mortars by varying the sand aggregate content from 10 wt.% to 50 wt.% (binder-to-sand ratio of 9:1 to 1:1). The sand used is described as bricklayer's sand, while the geopolymer itself was made from Collie fly ash from Western Australia as precursor, and a mixture of sodium silicate and sodium hydroxide (14M) as activator. The grading curve of the sand aggregate is shown in the figure below (Figure 2.14). No fineness modulus was calculated. The dry density of the sand was 1416 kg/m<sup>3</sup>. The sand was homogeneously distributed withing the geopolymer binder.

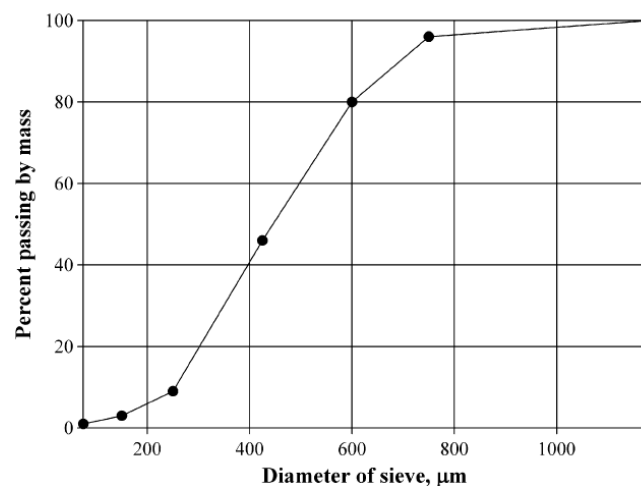


**Figure 2.14: Grading curve bricklayer's sand in fly ash based geopolymer mortar [69]**

The workability of the geopolymer mortars was analyzed, resulting in an acceptable flowability from 10 wt.% up to 30 wt.%. When increasing the sand content even more, the mortars were more stiff and difficult to pack.

The compressive strength of the mortar samples was tested after seven days, using an EZ-50 Universal testing machine (Lloyd Instruments) and the ASTM C39 standard as guide. After researching the compressive strength of the mortars, no significant change has been found with varying aggregate content. The compressive strength is depending on the strength of the geopolymer paste, the interfacial bonding between the geopolymer and the sand, and the sand aggregate itself. Even though the increase of sand content reduces the degree of geopolymerisation, the interfacial bonding strength of the geopolymer mortar remained comparable to that of the geopolymer paste. The values of the compressive strength after seven days can be found in Figure 2.15.

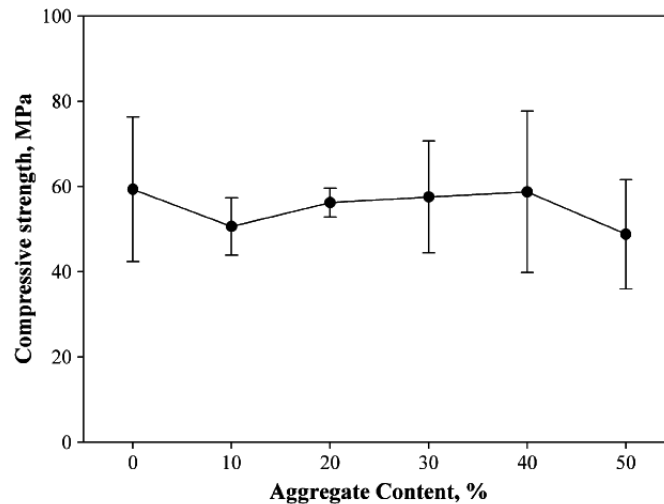


**Figure 2.15: Compressive strength of fly ash based geopolymer mortar samples [69]**

The aggregate level also has its influence on the porosity. The open porosity and density were measured using Archimedes principle. Increasing the aggregate content decreased the open porosity, and increased the density. For 50 wt.% sand, a decrease of 37.8% open porosity was found, while the density increased with 14.5%. This increase in density is due to the lower porosity, and due to density of quartz ( $2.65 \text{ g/cm}^3 > 2 \text{ g/cm}^3$  geopolymer paste).

Another study, by Zailani et al. [70] investigated the use of fly ash based geopolymer mortars with various binder-to-sand ratios as repair material. In this study, both the physical and mechanical properties of the geopolymer mortar were analyzed, and their performance as a repair material was assessed. For the geopolymer paste, fly ash (Manjung Power Plant in Lumit, Perak, Malaysia) was used as aluminosilicate source, and a mixture of sodium silicate and sodium hydroxide (12M) as the alkali activator solution. As sand aggregates, quartz river sand was procured by a local company. The particle size distribution curve of the used sand aggregates is shown in Figure 2.16. The lower and upper limit visible in the figure, are the lower and upper limit for fine aggregates according to the ASTM C33 standard. The aggregates were in saturated surface dry condition before adding to the mixture, to prevent absorption of alkali activator. The binder-to-sand ratio was varied from 1:4 to 4:1 (equal to 80% sand to 20% sand).

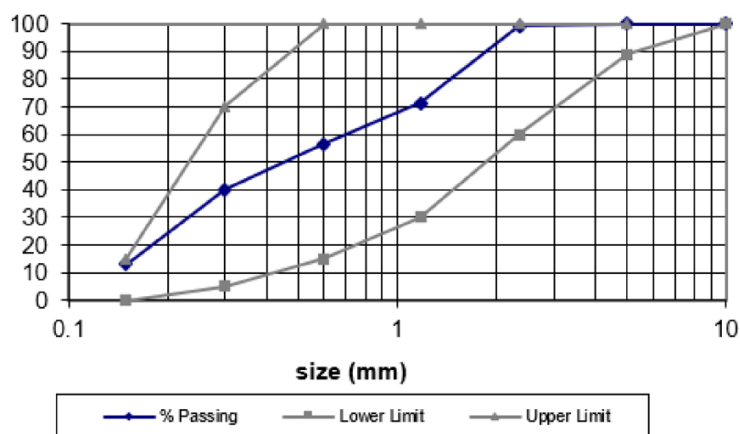


**Figure 2.16: Grading curve quartz river sand in fly ash based geopolymer mortar [70]**

The workability of the geopolymer mortars was tested using a flow table according to the ASTM C230 standard. According to the standard, the flow table has to be subjected to twenty-five jolts within 20 s. When using this method, the required flow of repair mortar is in between 90 mm and 150 mm. If the flow is higher than 150 mm, the mortar mixture is described as having a high fluidity. If the flow is smaller than 90 mm, the mixture is described as stiff. The results are illustrated in the table and figure below (Table 2.2 and Figure 2.17). For the mixture to be of adequate flowability for repair purposed, the binder-to-sand ratio should be in between 1:2 and 1:1 (equal to 66,7% sand to 50% sand)

**Table 2.2: Workability of fly ash based geopolymer mortar**

| Binder:<br>Sand | Characteristics                                                                                             | Flow<br>(mm) |
|-----------------|-------------------------------------------------------------------------------------------------------------|--------------|
| 1:4             | Very dry and not workable.<br>(Dry Flow)                                                                    | 70           |
| 1:3             | Insufficient binder and less workable.<br>(Dry Flow)                                                        | 75           |
| 1:2             | Easily placed into the mould.<br>Suitable for restoration of concrete spalling.<br>(Wet Flow)               | 92           |
| 1:1             | Uniformly fill the mould as it is placed without<br>segregating.<br>(Wet Flow)                              | 115          |
| 2:1             | Easy to handle but slurry.<br>(Wet Flow)                                                                    | 162          |
| 3:1             | Mixture is wet and has high workability. Need formwork<br>for the repair purposes.<br>(Wet Flow)            | 175          |
| 4:1             | Mixture is too wet, very high workability but is not<br>suitable for restoration of spalling.<br>(Wet Flow) | 210          |

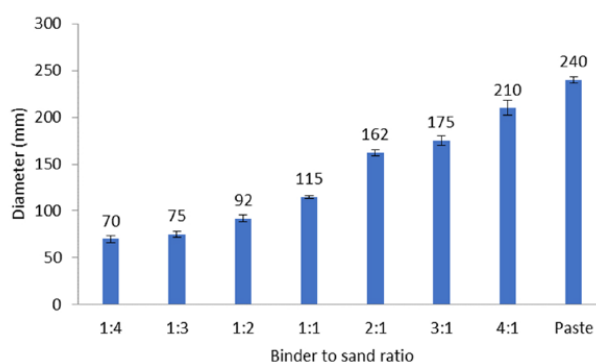


**Figure 2.17: Workability of fly ash based geopolymer mortar [70]**

The compressive strength of the geopolymer mortars was also analyzed. The compressive strength was tested after 3, 7, 14 and 28 days using an Instron machine series 5569 Mechanical Tester. The test was conducted according to the ASTM C109 standard. The results obtained from these tests are visualized in Figure 2.18. When reducing the binder-to-sand ratio from 1:4 to 1:2 (80% to 66.7%), the compressive strength increases, before decreasing up till a binder-to-sand ratio of 4:1 (20%). After 28 days, a binder-to-sand ratio of 1:2 leads to a compressive strength of 63.39 MPa. This increase in compressive strength may be due to the inclusion of a strong particle distribution thanks to the sand, leading to increased mechanical properties. A binder-to-sand ratio of 1:2 still has sufficient binder to bind the sand aggregates, and adding the right amount of sand can remarkably improve the strength of the material. The strength of the geopolymer mortar depends on the original strength of the geopolymer binder, as well as on the bonding between the geopolymer paste and the sand aggregates. With a

binder-to-sand ratio of 1:2, the compressive strength of the geopolymer paste can be increased up to 30 to 40% of its original value.

Too low binder-to-sand ratios (3:1 and 4:1) know a low compressive strength. A possible explanation for this phenomenon is the high moisture loss in low sand content, leading to drying shrinkage.

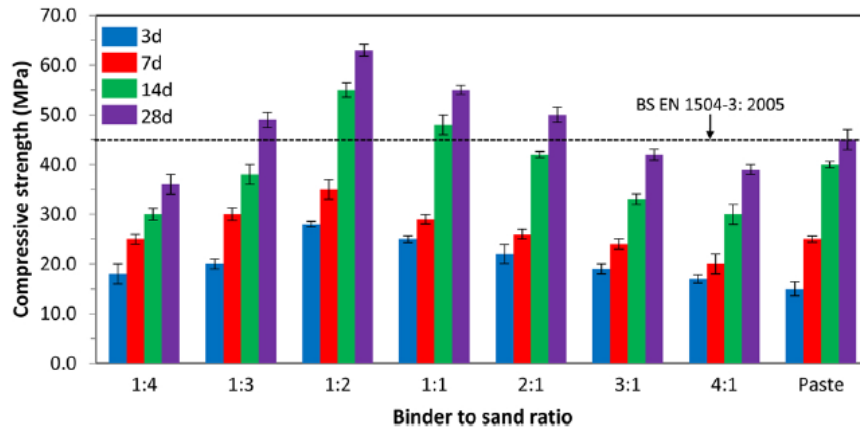


**Figure 2.18: Compressive strength of fly ash based geopolymer mortar [70]**

Lastly, the fresh density of the geopolymer mortars was analyzed. Increasing the sand content leads to an increase in density, as can be seen in Table 2.3. This effect is due to the higher density of quartz is sand aggregates.

**Table 2.3: Fresh density fly ash geopolymer mortar [70]**

| Binder: Sand, (wt. ratio) | Sand content (wt%) | Density (kg/m <sup>3</sup> ) |
|---------------------------|--------------------|------------------------------|
| 1:4                       | 80                 | 2230                         |
| 1:3                       | 75                 | 2210                         |
| 1:2                       | 67                 | 2190                         |
| 1:1                       | 50                 | 2160                         |
| 2:1                       | 33                 | 2040                         |
| 3:1                       | 25                 | 2010                         |
| 4:1                       | 20                 | 2000                         |
| Paste                     | -                  | 1940                         |

Guades [71] investigated the effect of the sand-to-fly ash ratio on the mechanical properties of geopolymer mortar. The precursor used in this study was Class F fly ash originated from Pozzolan Philippines, conform ASTM C-618. As alkaline activator solution, a mixture of sodium silicate and sodium hydroxide (14M) was used. For the sand aggregates, clean dry river sand 0.475/2 mm was selected. Although no grading curve was provided in this research, the grading was reported to be satisfactory according to the ASTM D 2487 standard. The alkaline activator-to-precursor ratio was set to 0.3, and a Na<sub>2</sub>SiO<sub>3</sub>/NaOH ratio of 1 was applied. The sand-to-fly ash ratio was varied from 0 to 6.

The mechanical properties of the geopolymer mortars were tested after 7, 14 and 28 days. The compressive tests were executed according to ASTM C873M, using a 2000 kN-capacity compressive testing machine. A visual representation of the effect of varying sand-to-fly ash ratios is given in Figure 2.19. A significant difference in compressive strength is noted between 7, 14 and 28 days of curing. Samples with sand-to-fly ash ratio of 4 and 6 did not harden until

14 days of curing, making their resulting strength negligible. After 28 days of curing, the compressive strength varied from 0.7 to 12.4 MPa. In comparison, cement-based mortars were tested. Their compressive strength varied from 2.3 to 5.9 MPa after 28 days. The compressive strength of the geopolymer mortars decreased with increasing sand content. An increase in workability (and decrease in flow value) leads to a decrease of strength in mortar, which might be one of the reasons for the drop in strength. A second reason is due to the decrease in formed gel in the geopolymerization process. Due to this, not all particles bind equally, leading to a reduction in strength.

The deformation curves of the specimens were also analyzed. It could be observed that the samples remain linear elastic during testing until failure occurs. A sudden drop in compressive loading shows the brittle behavior of the fly ash-based geopolymer mortar.

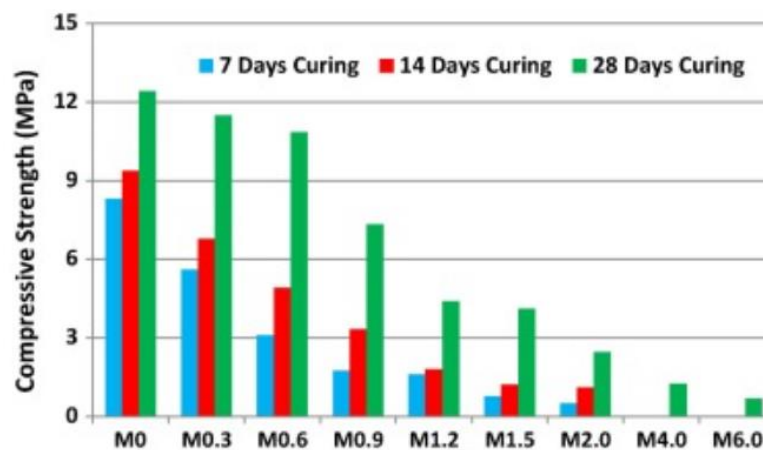


**Figure 2.19: Compressive strength of fly ash based geopolymer mortar [71]**

Moreover, the failure modes of the geopolymer mortars were analyzed. The most common failures were splitting, shear and conical failures, as is often the case in cement-based mortars under compression loading. Two of those failure modes in geopolymer mortars are visualized in Figure 2.20.



**Figure 2.20: Failure modes fly ash based geopolymer mortar [71]**

#### 2.3.4.2 Metakaolin and fly ash based geopolymer mortars

Zhang, Su, Goao, Zhang and Zhang [72] researched the effect of sand-precursor ratio on mechanical and durability properties of geopolymer mortar. The geopolymer paste was designed using a mix of metakaolin and fly ash originated from Luoyang power plant (China) as precursor. The mass ratio of fly ash to metakaolin is equal to 3:7. As alkaline activator, both sodium silicate and sodium hydroxide were used and a  $\text{SiO}_2/\text{Na}_2\text{O}$  ratio of 1.3 was synthesized. Manufactured sand was added to the mixture to make the geopolymer mortars. The sand aggregates were produced in Xinxiang (China), and knows a fineness modulus of 2.9. This manufactured sand was made from limestone particles, with 6% stone powder (particles < 0.075 mm). No grading curve was given in this research, but some supplementary information was the moisture content (4.5%) and the apparent density ( $1.820 \text{ kg/m}^3$ ). In this research, the sand to precursor (metakaolin and fly ash) ratio was varied from 1 to 5, while the activator content stayed equal.

The compressive strength after 28 days was analyzed, taking the Chinees JGJT70-2009 standard into account. In Figure 2.21, a visual representation of the compressive strengths is given. When increasing the sand-to-precursor ratio, the compressive strength gradually decreases. A maximal strength is reached at a sand-to-precursor ratio of 1, reaching a value of 40.2 MPa. This decrease in strength is due to the decrease in binder on contact surfaces between the sand and the geopolymer mortar. This leads to weaker interfacial transition zones and more micro-cracks.

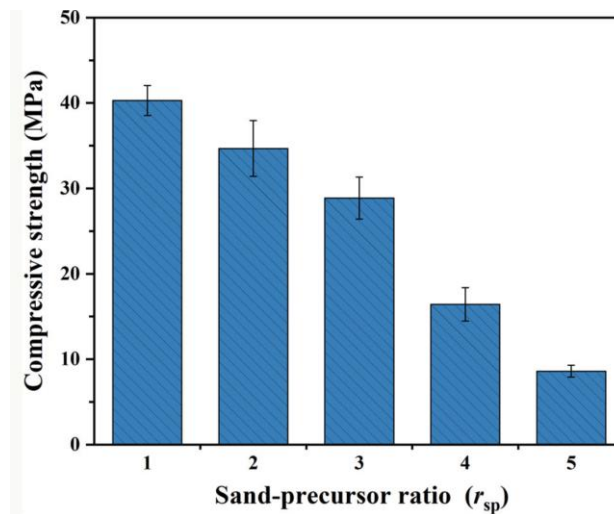


**Figure 2.21: Compressive strength of metakaolin and fly ash based geopolymer mortar [72]**

The failure modes of the geopolymer mortars are visualized in Figure 2.22. In the first picture, a sand-to-precursor ratio of 1 was used, following by 3 in the second picture, and 5 in the last picture.

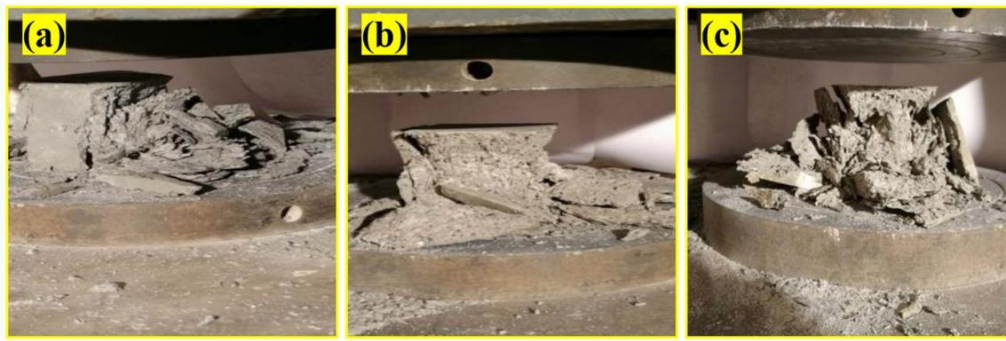


**Figure 2.22: Failure modes metakaolin and fly ash based geopolymer mortar [72]**

The flexural and splitting tensile strength was also studied during this research. The tests were conducted following the GB/T7897-2008 standard. The results regarding the flexural tests are illustrated in Figure 2.23. A gradual decrease of flexural strength is noted when increasing the sand-to-precursor ratio. The maximal flexural strength after 28 days is at a ratio of 1, leading to a value of 4.3 MPa. The splitting tensile strength results know a similar pattern, the maximal strength of 3.38 MPa was obtained at a ratio of 1. The decrease in flexural strength is also due to the insufficient binder between the geopolymer matrix and the sand aggregates. Moreover, an increase in sand aggregates will decrease the flow of the mortar, leading to a lower tensile strength.

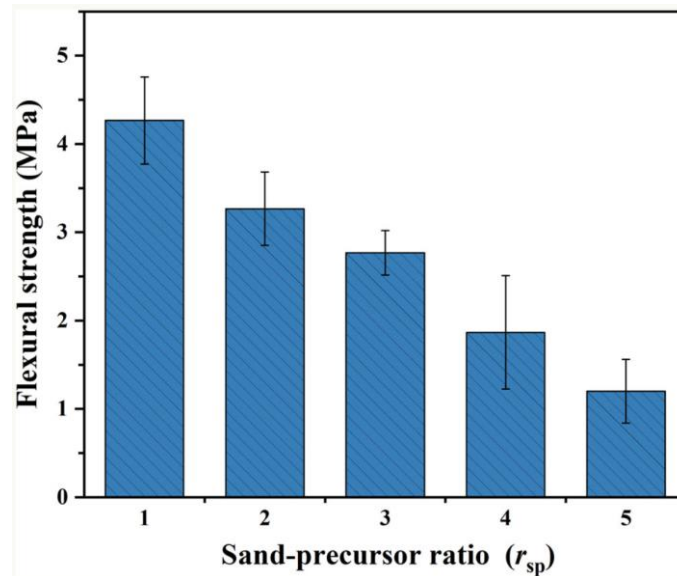


**Figure 2.23: Flexural strength of metakaolin and fly ash based geopolymer mortar [72]**

A relationship between the compressive strength and the flexural strength was found using the linear model of the regression equation. The linear model was considered to be the most consistent among the mechanical properties of the geopolymer mortars. This model gave the following relationship (2.2):

$$R_f = 0.09147R_c + 0.31595 \quad (2.2)$$

With:

$R_c$  = compressive strength [MPa];

$R_f$  = flexural strength [MPa].

The coefficient of determination  $R^2$  for this model is 0.91, specifying a good correlation between the two variables. This relationship is visualized in Figure 2.24.

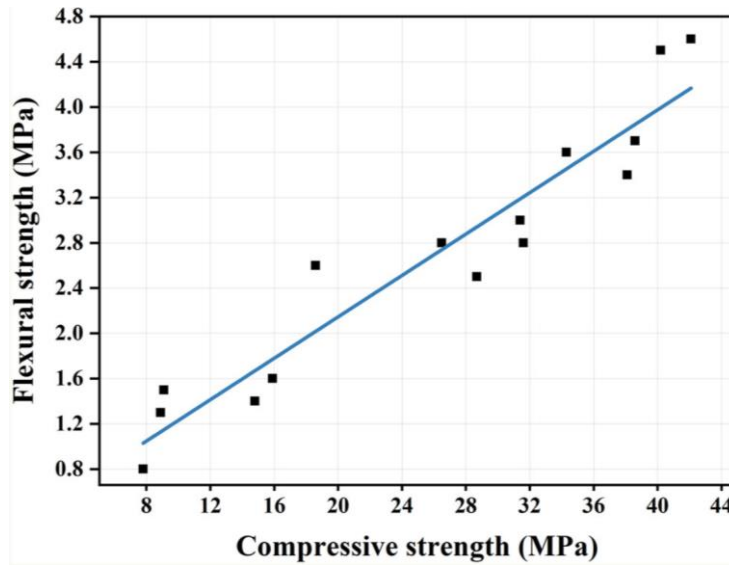


**Figure 2.24: Linear relationship compressive and flexural strength [72]**

A similar relationship is found between the compressive and the tensile strength, as discussed in more detail in the research of Zhang, Su, Goao, Zhang and Zhang [72].

#### **2.3.4.3 Metakaolin based geopolymer mortars**

Steinerova [73] researched the mechanical properties of metakaolin based geopolymer mortar with varying sand contents. In this study, metakaolinite was used as aluminosilicate source, originated from Sedlecky kaolin a.s. (Czech Republic). As activator solution, a mixture of sodium silicate and sodium hydroxide was made, obtaining a Si/Al ratio of 1.4, a Na/Al ratio of 1 and a  $H_2O/Na$  ratio of 7.14. To make the geopolymer mortars, ST 52 quartz sand derived from the Sklopisek Strelec mines (Czech Republic) was added. The grain size was in between 0.4 and 0.6 mm, as can be seen on the grading curve in Figure 2.25. The grains are described as having a rough surface. They are rather irregular, rounded and bumpy. Different amounts of sand aggregates were added to the mixture, varying from 0 wt.% up to 93 wt.%.

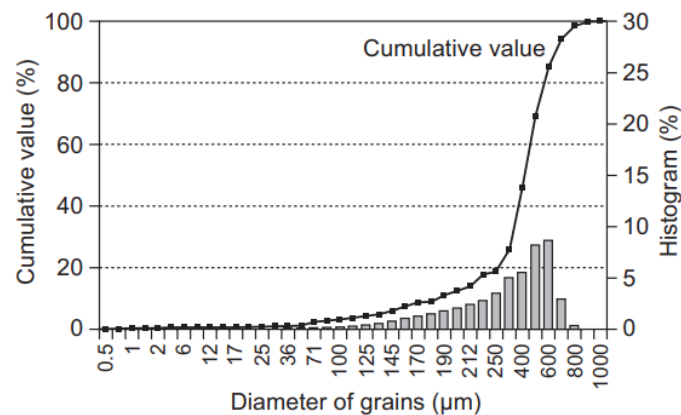


**Figure 2.25: Grading curve ST 52 sand in metakaolin based geopolymer mortars [73]**

During this study, the mechanical properties of the mortars were tested. The compressive and flexural strength were evaluated according to the EN 196-1 standard. To measure the compressive strength, the EU50 Load-testing machine (Werkstoffprüfmaschinen, VEB Leipzig, Germany) was used. For the flexural strength, the 3-point bending machine, FPZ100 Load-testing machine (Thüringen Industriewerk, VEB Rauenstein, Germany) was used. The results obtained from these tests after 28 days are illustrated in Figure 2.26.

A sand content of 78 wt.% achieves the highest compressive strength with a value of 70 MPa. The flexural strength reaches its peak at 78 wt.% as well, with a value of 11.7 MPa. Between 0 and 34 wt.%, the binder is abundantly present, minimizing the effect of the added sand. By increasing the sand content up to 60 wt.%, the strength starts increasing, reaching its optimal content between 74 to 78 wt.%. At 78 wt.%, the sand grains are still fully coated by the geopolymer binder, avoiding cracks and coarse pores. When increasing the sand content even more, the lack of binder leads to coarse-pore formation and cracks.

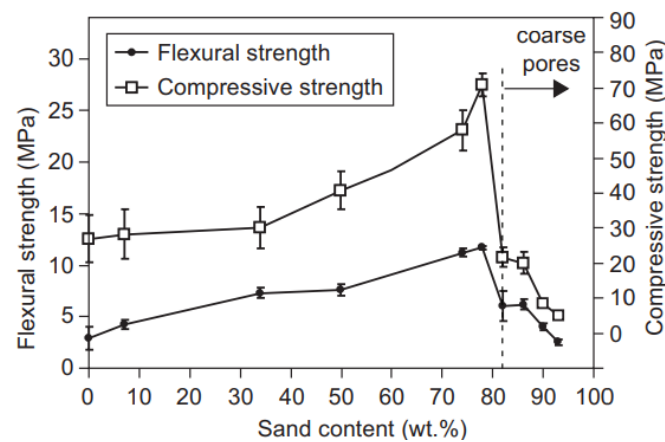


**Figure 2.26: Compressive and flexural strength - metakaolin based geopolymer mortars [73]**

Furthermore, the porosity and bulk density of the mortar samples were analyzed. The porosity was measured using Pascal 140 and Pascal 240 porosimeters by POROTEC, GmbH, Germany. As can be seen on Figure 2.27, the bulk density of the samples increases up till 78 wt.%, reaching a peak of 2.08 g/cm<sup>3</sup>. At this sand quantity, the maximal sand-grain compaction is reached.

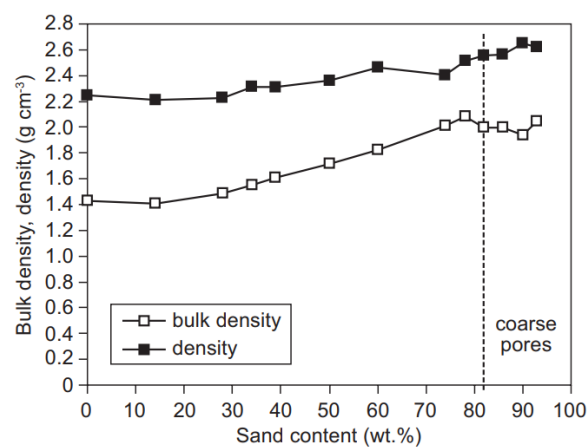


**Figure 2.27: Bulk density and density - metakaolin based geopolymer mortars [73]**

#### **2.3.4.4 Summary on geopolymer mortars based on other types of precursors**

From the studies analyzed above, different conclusions can be made. Firstly, increasing the sand content leads to an increase in density and decrease in porosity. In some researches, a peak in density is visible, leading to a decrease when an excess of sand is added. Moreover, the flowability of the geopolymer mortars decreases when increasing the sand content for all above mentioned studies. In terms of mechanical strengths, the flexural strength might decrease with the addition of sand. Other studies show an increase in flexural strength, followed by a peak value at the maximal density and minimal porosity. When more sand is incorporated, the flexural strength will decrease. For the compressive strength, different observations were made. Depending on the study, the addition of sand doesn't have a significant influence on the compressive strength of the geopolymer mortars. Based on other studies, increasing the sand content leads to an increase in compressive strength, followed by a peak at maximal density, and a decrease when an excess of sand is added. An increase in compressive strength will lead to an increase in flexural strength.

The optimal sand content for all the above mentioned researches are different due to the difference in geopolymer binder.

## 3 TEST PROGRAM

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In this section, the focus is laid on the methodology used during this research. The laboratory tests conducted to evaluate the quality, mechanical properties and workability of the geopolymer pastes and geopolymer mortar are emphasized.

The research in itself is divided in two main parts. Firstly, an optimal geopolymer paste is created based on the mechanical properties and workability of the material.

Afterwards, the optimal geopolymer paste is used to create geopolymer mortar. Different quantities and types of sand are tested to come to an optimal mortar. The mortars are rated based on the mechanical properties and workability.

### 3.1 Materials and preparation

#### 3.1.1 Materials

The materials used for the geopolymer paste can be divided in two main parts: the precursors and the alkali activators. The precursors and alkali activators have been extensively described in the literature study. The main precursor used in this research is GGBS from Ecocem Benelux B.V., Moerdijk, Netherlands. Additional precursors RCP and RBP are added to the mix. RCP has been acquired from AC Materials, Brugge, Belgium, while RBP has been purchased from Prefaxis-Ploegsteert, Komen-Waasten, Belgium. A pictures of the precursors is visible in Figure 3.1. The chemical composition of the used materials, according to X-ray fluorescence, can be found in Table 3.1. The particle size properties, based on laser particle size analysis, are given in Table 3.2. The particle size distribution itself is visualized in Figure 3.2.

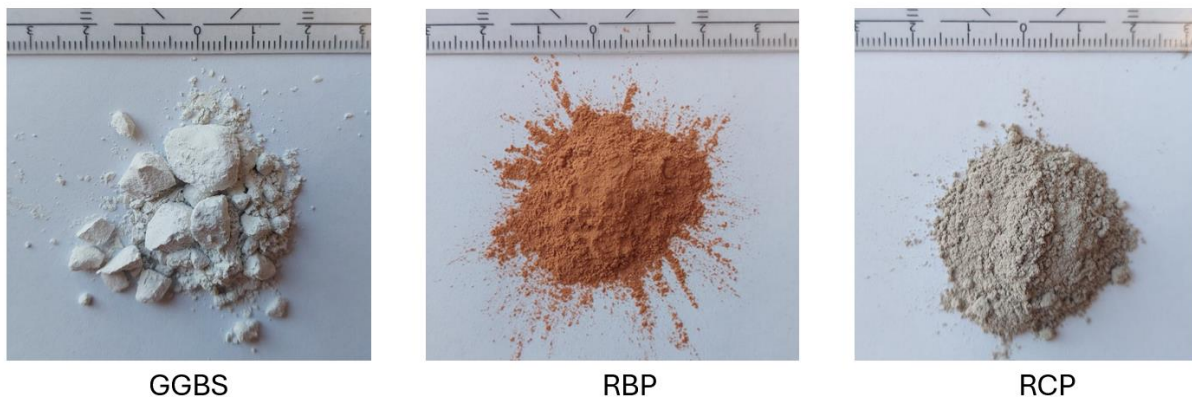


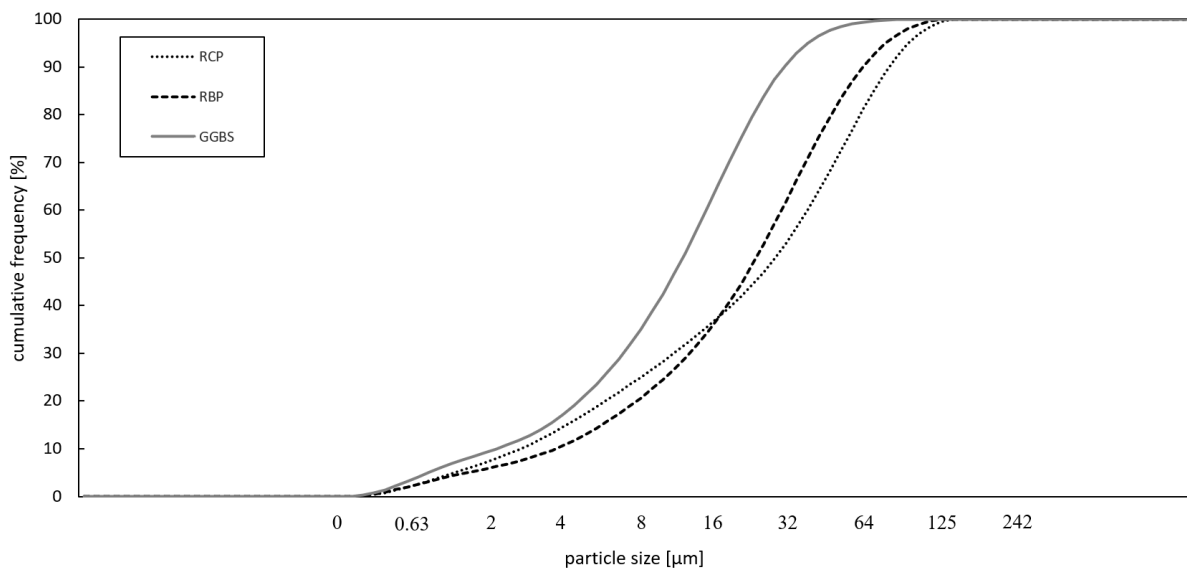
**Figure 3.1: Precursors**

**Table 3.1: Chemical composition of precursors (wt.%)**

| Precursors  | SiO <sub>2</sub> | Al <sub>2</sub> O <sub>3</sub> | Fe <sub>2</sub> O <sub>3</sub> | CaO  | MgO  | K <sub>2</sub> O | Na <sub>2</sub> O | Others |
|-------------|------------------|--------------------------------|--------------------------------|------|------|------------------|-------------------|--------|
| <b>GGBS</b> | 33.3             | 12.6                           | 0.41                           | 40.4 | 8.28 | 0.74             | 0.63              | 3.6    |
| <b>RBP</b>  | 63.2             | 13.0                           | 4.58                           | 10.8 | 1.83 | 2.72             | 1.89              | 2.0    |
| <b>RCP</b>  | 38.3             | 7.02                           | 5.41                           | 42.4 | 1.59 | 1.21             | 0.42              | 3.7    |

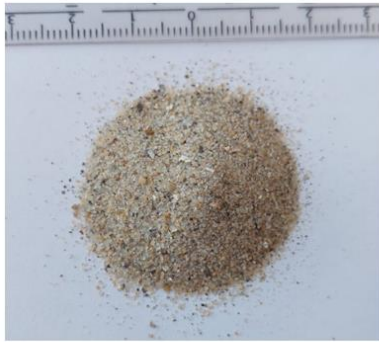
**Table 3.2: Precursor particle size properties**

| Precursors  | Specific surface [m <sup>2</sup> /g] | D10 [μm] | D50 [μm] | D90 [μm] |
|-------------|--------------------------------------|----------|----------|----------|
| <b>GGBS</b> | 1.48                                 | 1.60     | 11.0     | 31.3     |
| <b>RBP</b>  | 0.96                                 | 2.93     | 23.4     | 70.9     |
| <b>RCP</b>  | 1.07                                 | 2.04     | 28.5     | 92.9     |

**Figure 3.2: Particle size distribution – Precursors**

Sodium hydroxide and sodium silicate are used as alkali activators. The sodium silicate used during this research has a silica content of 25.9%, and a sodium oxide content of 7.9%. Sodium hydroxide pellets are mixed with water to obtain a concentration of 12 mol. The SiO<sub>2</sub>/ Na<sub>2</sub>O ratio is set on 1.38.

Sand is incorporated in the mixture for the making of geopolymer mortar. Three different types of sand will be analyzed in this research, namely sea sand 0/2 mm and 0/1 mm originated from the North Sea, and CEN Standard sand. The CEN sand used is CEN-normsand DIN EN 196-1 from Beckum, Germany. A picture of each of these sand types is visible in Figure 3.3. The particle size distribution of the sand aggregates are visualized in Figure 3.4, Figure 3.5 and Figure 3.6. These distributions have been made according to NBN EN 933-1, while the lower and upper limits of the particle size distribution for the CEN Standard sand are taken from NBN EN 196-1. Other particle characteristics are given in Table 3.3.



Sea sand 0/2 mm



Sea sand 0/1 mm



CEN Standard sand

**Figure 3.3: Sand types**

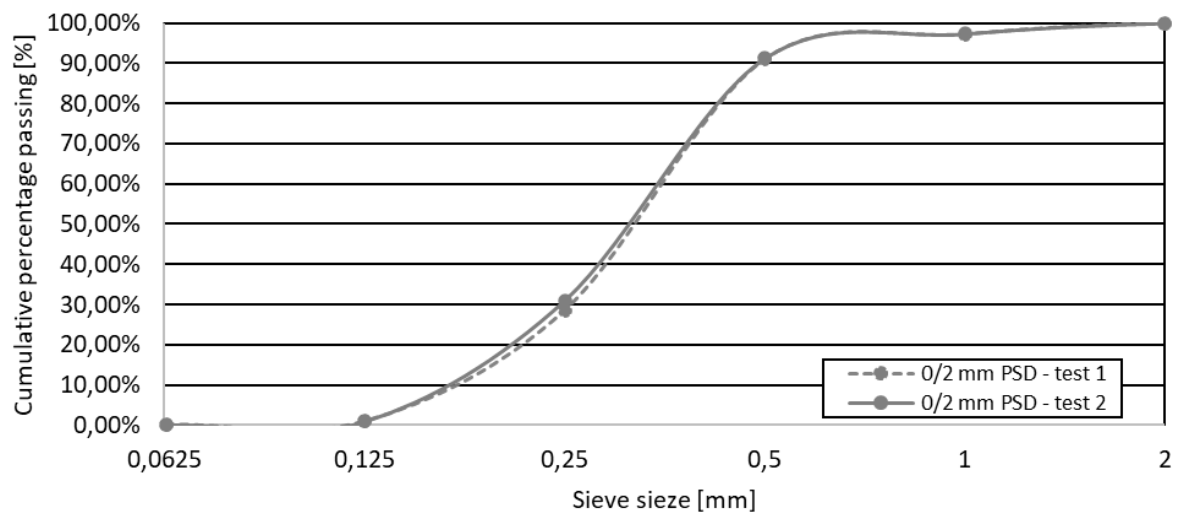


**Figure 3.4: Particle size distribution – Sea sand 0/2 mm**

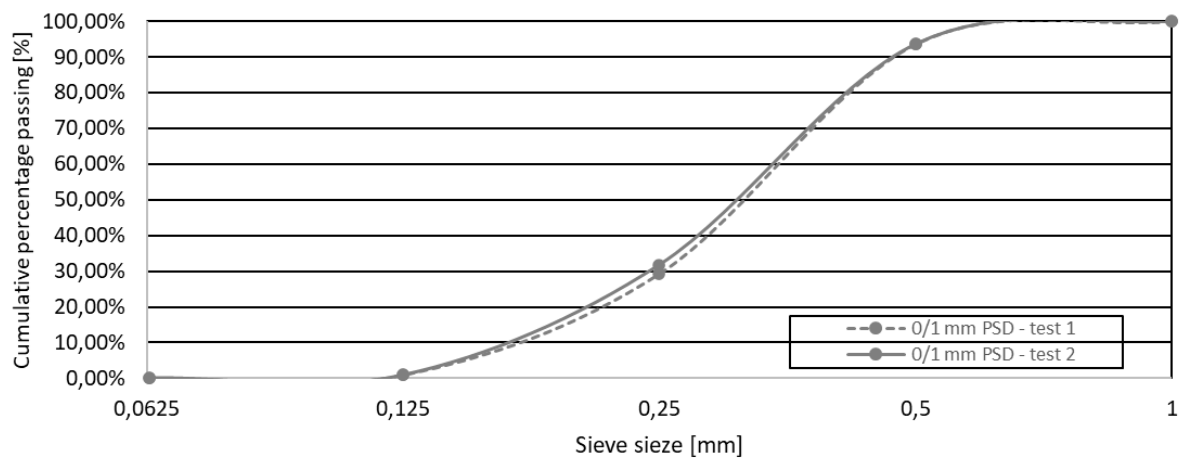


**Figure 3.5: Particle size distribution – Sea sand 0/1 mm**

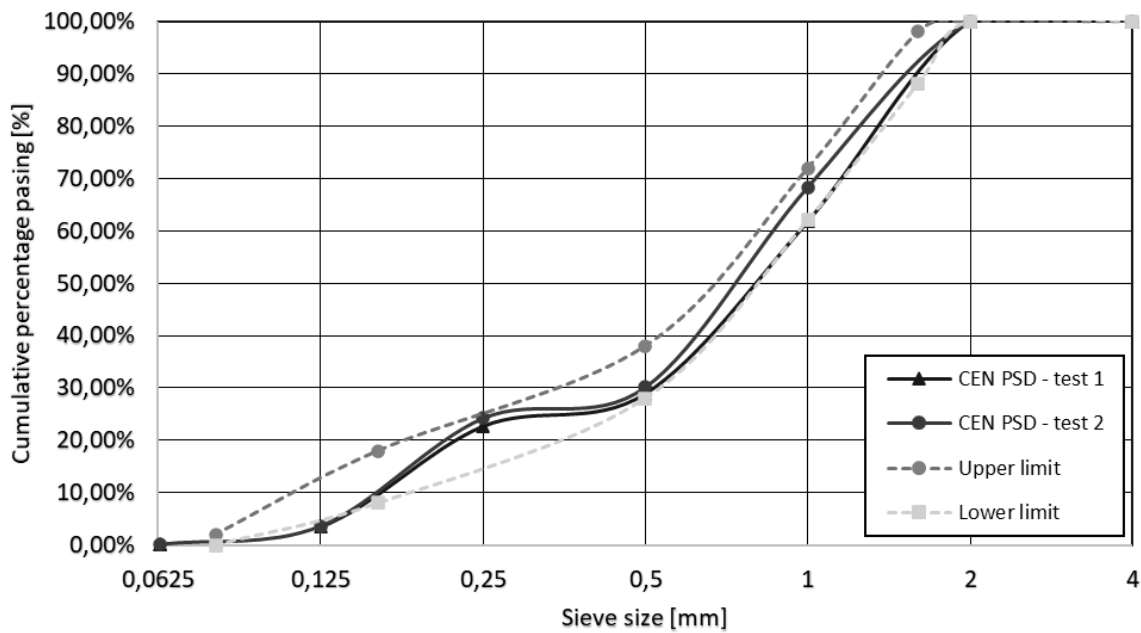


Figure 3.6: Particle size distribution – CEN Standard sand

Table 3.3: Grading characteristics of used sands

|                   | Fineness modulus | D10 [mm] | D50 [mm] | D90 [mm] |
|-------------------|------------------|----------|----------|----------|
| 0/2 mm            | 1,81             | 0,16     | 0,33     | 0,50     |
| 0/1 mm            | 1,75             | 0,16     | 0,33     | 0,49     |
| CEN Standard sand | 2,79             | 0,18     | 0,79     | 1,71     |

According to NBN EN 13139, the fineness of the sands can be classified based on their fineness modulus [68]. The 0/2 mm and 0/1 mm sands are classified as fine to medium graded sands, while the CEN Standard sand is defined as medium to coarse graded sand.

An overview of all the materials used during this research is visible in Figure 3.7.

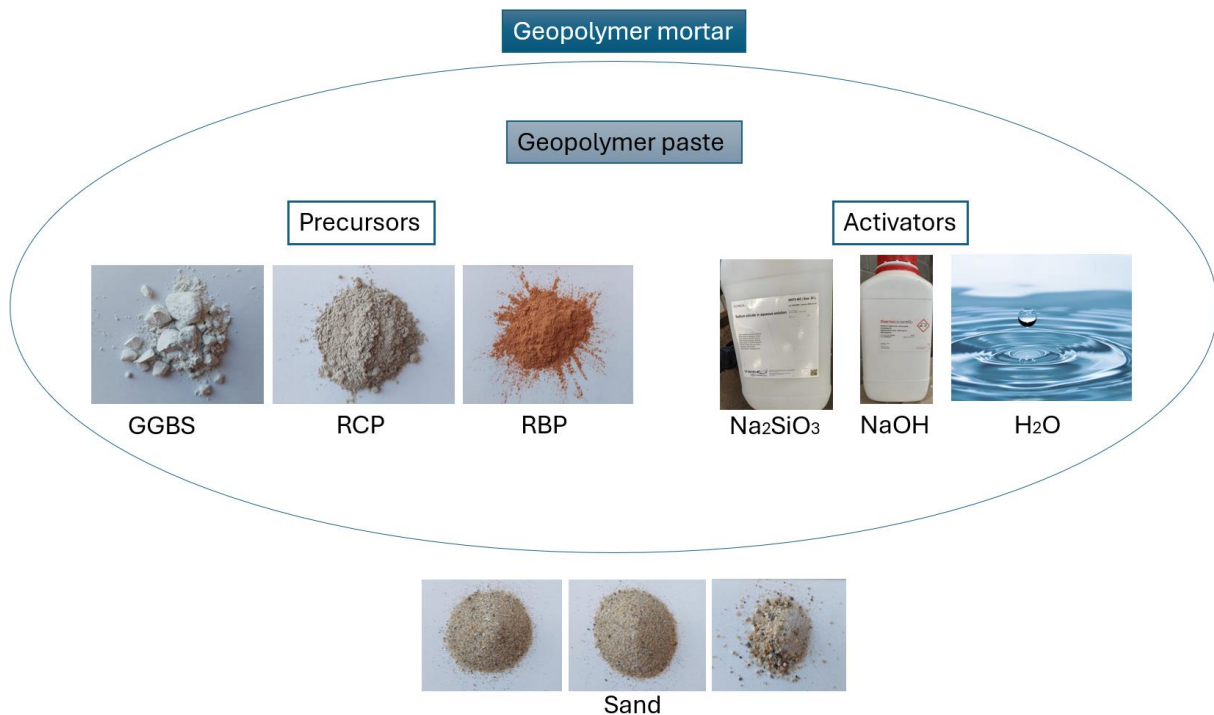


**Figure 3.7: Overview materials**

### 3.1.2 Mix design

#### 3.1.2.1 Geopolymer paste

Two stages of mix design are undertaken. The first stage is the mix design of the geopolymer paste. Different mixtures are tested with varying GGBS and CDW contents. The weighted percentage of GGBS is varied from 40 wt.% to 70 wt.%, as literature showed these contents to have the optimal results [36]. For each of these percentages, the RCP and RBP contents are varied to test different combinations.

The water to binder ratio stays constant for all the mixtures at a value of 0.40. Both the Na<sub>2</sub>O-to-binder ratio and the SiO<sub>2</sub>-to-Na<sub>2</sub>O ratio are also kept constant at 8% and 1.38 respectively.

The mix design of the different geopolymer pastes are added in Appendix A. The name of the mix design might need some clarification. The first mix design is G-8%-1,38-0,40. The G stands for geopolymer, 8% refers to Na<sub>2</sub>O/b, 1.38 stands for SiO<sub>2</sub>/ Na<sub>2</sub>O, and 0.40 is w/b.

The mass of sodium silicate (SS), sodium hydroxide (SH) and water (H<sub>2</sub>O) have also been calculated. The calculations are added in Appendix B.

#### 3.1.2.2 Geopolymer mortar

The second stage is the mix design of the geopolymer mortar. This mix design is based on the optimal geopolymer paste. How the optimal geopolymer paste is determined is discussed in Chapter 4: Results and discussion. Mixture 18 is set as optimal paste, with a GGBS content of 60%, a RCP content of 15% and a RBP content of 25%. The sand content is varied from 0 to 60%.

The mix design of the geopolymer mortars is visualized in Table 3.4.

**Table 3.4: Mix design – Geopolymer mortars**

| sand [%]  | sand [g] | geopolymer [%] | geopolymer [g] | GGBS [g] | RCP [g] | RBP [g] | activator [g] |
|-----------|----------|----------------|----------------|----------|---------|---------|---------------|
| <b>0</b>  | 0        | 100            | 2560,5         | 960      | 240     | 400     | 960,5         |
| <b>10</b> | 256,1    | 90             | 2304,5         | 864      | 216     | 360     | 864,5         |
| <b>20</b> | 512,1    | 80             | 2048,4         | 768      | 192     | 320     | 768,4         |
| <b>30</b> | 768,2    | 70             | 1792,4         | 672      | 168     | 280     | 672,4         |
| <b>40</b> | 1024,2   | 60             | 1536,3         | 576      | 144     | 240     | 576,3         |
| <b>50</b> | 1280,3   | 50             | 1280,3         | 480      | 120     | 200     | 480,3         |
| <b>60</b> | 1536,3   | 40             | 1024,2         | 384      | 96      | 160     | 384,2         |

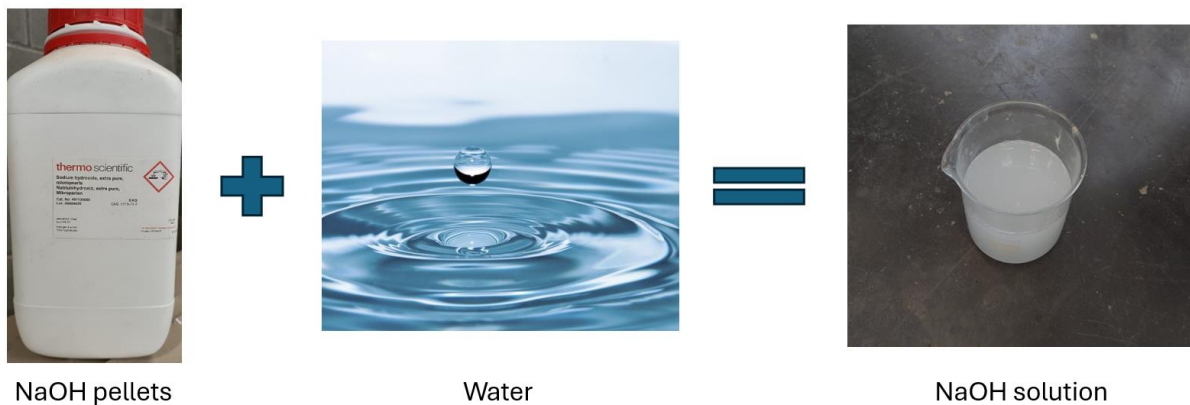
### 3.1.3 Preparation of samples

The preparation of the samples is carried out as shown in literature [36]. The performed steps are listed below.

#### Step 1: Preparation of NaOH solution

Sodium hydroxide pellets need to be dissolved in distilled water at least 24 hours before mixing with other elements to allow the solution to cool down and stabilize. The used NaOH pellets and the preparation process are shown in Figure 3.8. The optimal result is obtained by mixing the pellets into the water, and not inversed. Otherwise, all the pellets will react at the same time, causing too much heat production in a short amount of time.

Once the NaOH solution is created, the liquid needs to be stored in an airtight container to prevent evaporation.

**Figure 3.8: Preparation process NaOH**

#### Step 2: Alkali activator preparation

Once the sodium hydroxide solution has cooled down, it can be mixed with  $\text{Na}_2\text{SiO}_3$  to the predetermined ratio. This mixture is the activator solution. Before mixing this solution with the dry materials, it needs to stabilize and cool down during 24 hours due to the chemical reaction between sodium hydroxide and sodium silicate.

This preparation process is also visible in Figure 3.9.

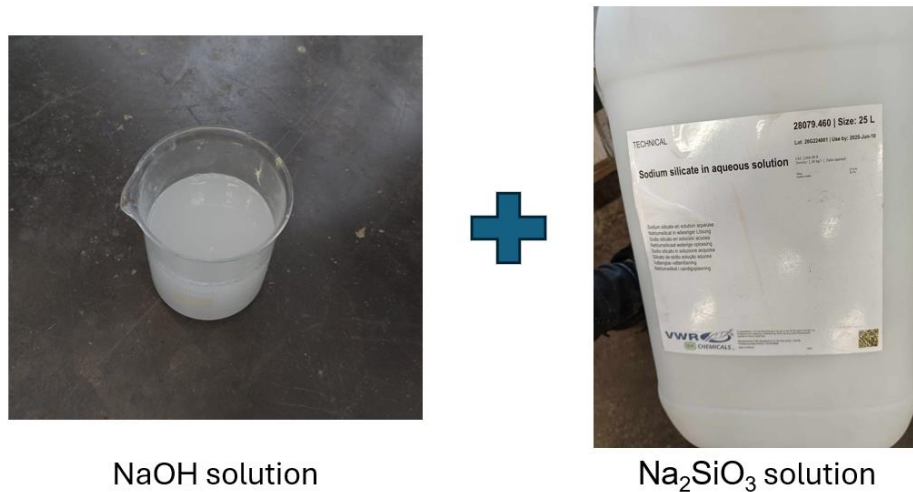


**Figure 3.9: Alkali activator preparation**

### **Step 3: Geopolymer paste**

#### **Step 3.1: Dry material mixture**

The dry materials, GGBS, RCP and RBP, are mixed based on their predetermined ratios. The three materials are added in an empty mixing pot and mixed during 2 minutes at low speed (140 rpm). The mixer used during this research is an E093N Automatic Planetary Mixer.

#### **Step 3.2: Addition of activators**

The alkali activator solution is gradually added to the dry mix while continuously mixing at low speed. After 2 minutes, the speed is switched to high speed (285 rpm) for 2 more minutes.

### **Step 4: Geopolymer mortar**

To prepare the geopolymer mortar, the sand is added to the geopolymer paste while continuously mixing at low speed. After 30 seconds, the speed is switched to high speed for 30 seconds. The mixing is thereafter stopped during 90 seconds. The mortar is scraped from the side of the mixing pot back to the middle during the first 30 seconds. Lastly, the mixture needs to be mixed at high speed for 1 more minute.

### **Step 5: Casting and compacting**

Both the geopolymer paste and geopolymer mortar need to be poured into moulds and compacted using a vibrating table to eliminate air voids. The compaction table is set on 1 jolt per second. The samples need to be stored in an ambient controlled room and the samples need to be covered with an impermeable material.

### Step 6: Demoulding

The demoulding is according to the standard NBN EN 196 [74]. For samples tested after 24 hours, the demoulding needs to take place maximum 20 minutes before testing. The sample needs to be covered with a damp cloth until testing takes place. For other tests, the demoulding needs to take place 20 to 24 hours after casting.

The preparation of the samples can be summarized as shown in Figure 3.10.

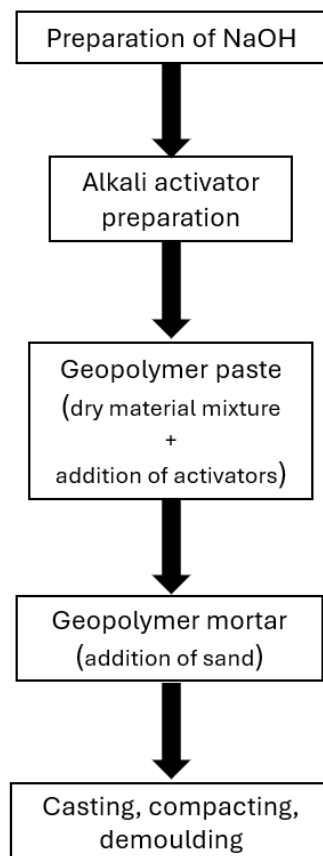


**Figure 3.10: Flowchart mixing procedure**

## 3.2 Test methods

The mixtures are rated based on their workability and mechanical properties. To analyze these properties, different laboratory tests are conducted. The tests listed below are executed for both the geopolymer pastes and geopolymer mortar, except for the Vicat test and flexural strength test. The Vicat test is only conducted for the geopolymer paste, while the flexural strength is tested to help determine the optimal mortar.

### 3.2.1 Dry bulk density of geopolymer mortars (NBN EN 12390-7)

The dry bulk density of hardened concrete is calculated in accordance to NBN EN 12390-7, by dividing the mass of a sample by its corresponding volume [75]. The bulk density of the

geopolymer mortars will be calculated using this standard. The volume of each sample is equal to the mold in which the geopolymer mortar is cast. The molds used are prismatic with the following dimensions: 40x40x160 mm<sup>3</sup>.

### 3.2.2 Workability tests

The workability of the geopolymer mortars is evaluated based on the flowability index of the mixtures. The optimal flowability index has internally been discussed and set to a value of 2.5. If the flowability index is lower, the mortar is not workable enough. This makes the mixture more stiff, and casting into molds more difficult. The flowability index is poor if the quantity of binder present is too low for the quantity of added sand, leading to an increase in pore formation.

#### 3.2.2.1 Mini slump test (NBN EN 1015-3)

The mini slump test is conducted according to NBN EN 1015-3 [76]. For this test, a flow table as seen on Figure 3.11 is needed, together with a truncated conical mould made of stainless steel. The mould has a height of 60 mm ± 0.5 mm, an internal diameter of 100 mm ± 0.5 mm at the bottom and 70 mm ± 0.5 mm at the top.



**Figure 3.11: Test set-up of mini slump test**

The flowability index can be calculated using the following formula (3.1) [77],

$$D = \frac{(d_1 \times d_2) - d_0^2}{d_0^2} \quad (3.1)$$

With:

- D = flowability index [-];
- d<sub>1</sub> = maximum spread diameter [mm];
- d<sub>2</sub> = diameter perpendicular to d<sub>1</sub> [mm];
- d<sub>0</sub> = diameter of the mini slump cone [mm].

A visualization of these dimensions is given in Figure 3.12.



**Figure 3.12: Measurement mini slump test**

### **3.2.2.2 Vicat test (NBN EN 196-3)**

The Vicat test is conducted as depicted in NBN EN 196-3 [78]. This test is used to calculate the initial and final setting time of a mixture. The Vicat apparatus used during this research is shown in Figure 3.13.



**Figure 3.13: Vicat apparatus**

### 3.2.3 Mechanical properties tests

#### 3.2.3.1 Compressive strength (NBN EN 196-1)

The compressive strength of the samples is determined as prescribed in NBN EN 196-1 [11]. The test specimen is tested at different ages, namely 24 h ± 15 min, 72 h ± 30 min, 7 d ± 2 h and 28 d ± 8 h.

The compressive strength is calculated using following formula (3.2),

$$R_c = \frac{F_c}{1600} \quad (3.2)$$

With:

$R_c$  = compressive strength [MPa];

$F_c$  = maximum load at fracture [N];

1600 = area [mm] (=40 mm x 40 mm).

#### 3.2.3.2 Flexural strength (NBN EN 196-1)

The flexural strength of the samples is determined as written in NBN EN 196-1 [11]. Only the geopolymer mortars are tested on their flexural strength. The test specimen are tested at different ages, equal to the ages of the compressive strength tests.

The flexural strength is calculated by using the following equation (3.3),

$$R_f = \frac{1.5 * F_f * l}{b^3} \quad (3.3)$$

With:

$R_f$  = flexural strength [MPa];

$b$  = side of square section prism [mm];

$F_f$  = load applied to the middle of the prism at fracture [N];

$l$  = distance between supports [mm].

Both the compressive and the flexural tests are executed using the MacBen Servo Plus Evolution (Figure 3.14).



Figure 3.14: MacBen Servo Plus Evolution

### 3.3 Statistical analysis

#### 3.3.1 Outliers

The outliers of the compressive tests are calculated according to NBN EN 196-1. The mean value of the six test results are taken. If one of the individual values varies by more than  $\pm 10\%$ , the value is considered an outlier and is discarded. If less than 5 values remain, the test needs to be redone.

#### 3.3.2 Standard deviation

The standard deviations of the tests are calculated and used as error bars for the graphs made during this research. These error bars show the reliability of the test data.

The sample standard deviation,  $s$ , is the positive square root of the sample variance  $s^2$  [79]. The sample variance is calculated using formula 3.4:

$$s^2 = \sum_{i=1}^n \frac{(x_i - \bar{x})^2}{n - 1} \quad (3.4)$$

With:

- $s^2$  = sample variance;
- $x_i$  = sample value;
- $\bar{x}$  = mean sample value.

## 4 RESULTS AND DISCUSSION

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### 4.1 Geopolymer pastes

The results regarding the geopolymer pastes are obtained from a collaborative study. From these results, the four mixtures with the highest compressive strengths after 7 days are retained, along with their respective initial and final setting time and flowability indices, as shown in Table 4.1.

To determine the optimal geopolymer paste for mortar production, the compressive strength, setting time, and flowability index must all be taken into consideration. Firstly, it is important to select a paste with a high compressive strength, as the incorporation of sand is not intended to enhance this property. Mixture 11, 16, 18 and 22 all meet this requirement. Secondly, the setting time should be sufficient to allow for incorporation of sand, but not excessively long, as the addition of sand isn't expected to significantly reduce the setting time. Lastly, the flowability index must be high enough to incorporate a substantial amount of sand, without compromising the workability or causing excessive pore formation.

Taking all these considerations into account, mixture 18 is selected as the optimal geopolymer paste, consisting of 60% GGBS, 15% RCP, and 25% RBP.

**Table 4.1: Results geopolymer pastes**

| Mixture | R <sub>c</sub> (7)<br>[MPa] | Initial setting time<br>[min] | Final setting time<br>[min] | D   |
|---------|-----------------------------|-------------------------------|-----------------------------|-----|
| 11      | 60,610                      | 95                            | 110                         | 6,7 |
| 16      | 68,397                      | 150                           | 160                         | 7,7 |
| 18      | 61,975                      | 90                            | 100                         | 7,4 |
| 22      | 63,586                      | 55                            | 65                          | 3,8 |

### 4.2 Geopolymer mortars

#### 4.2.1 Dry bulk density (NBN EN 12390-7)

The measured dry bulk density of the geopolymer mortars are plotted in Figure 4.1, Figure 4.2 and Figure 4.3. The standard deviation of the weight of the prisms is added in Appendix C. For each sand type, an increase in bulk density is noted up until a sand content of 50 wt.%. At 50 wt.% sand, the maximal density is reached. For sand contents exceeding 50 wt.%, a decrease in bulk density is observed. This decrease in bulk density is mainly due to the lack of binder for the higher sand quantities, leading to a loss of workability and bad compaction, resulting in pore formation.

A higher density results in a better compaction, leading to minimal porosity. According to the graphs obtained, a minimal porosity for each of the sand types should occur at 50 wt.% sand, which is equivalent to a binder-to-sand ratio of 1:1.

Furthermore, sand has generally a higher density than geopolymer mortar, leading to an increased density with increasing sand content.

Steinerova [73], who tested metakaolinite geopolymer mortars with varying sand contents, also noticed an increase in bulk density up until a certain sand content, before noting a decrease in density. The maximal bulk density occurred at 73 wt.% sand. This difference in sand content is due to the different binder used. An increased amount of sand content can be added to a binder with a higher flowability.

The pore formation could more accurately be discussed if high pressure mercury porosimetry was executed, or if SEM microscopy images were made of the samples. Based on the research results of Steinerova, the porosity of the samples decreases with an increase in sand content, up to 78 wt.% sand. Afterwards, the porosity increases again, indicating coarse pores. By viewing the SEM microscopy images, a lack of binder can be noted when increasing the sand content with more than 78 wt.%, resulting in pore formation.

Zailani et al. [70] researched the impact of binder-to-sand ratio of fly ash-based geopolymer mortars. When increasing the sand content up to 80 wt.% sand, the density of the geopolymer mortars increased as well. No decrease in density was found, noting the higher flowability of the geopolymer paste.

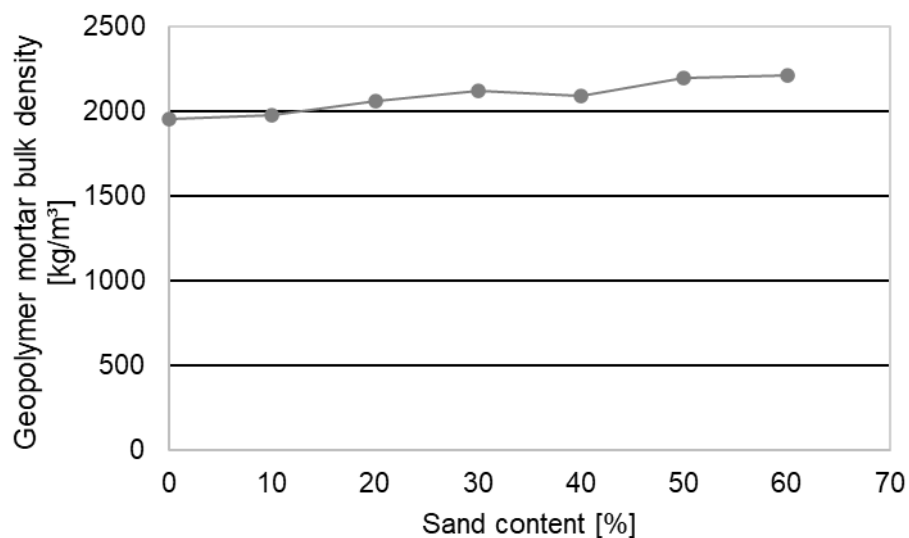


**Figure 4.1: Bulk density – Sea sand 0/2 mm**

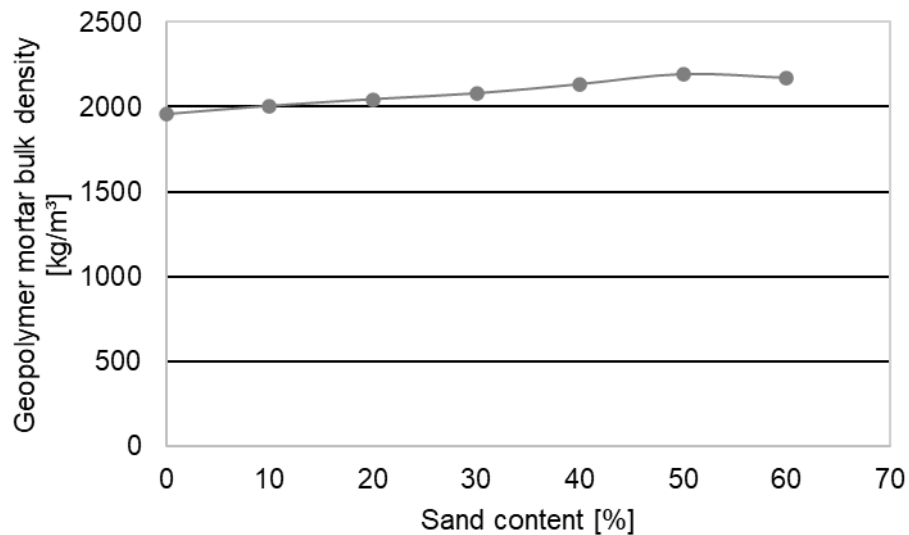


**Figure 4.2: Bulk density – Sea sand 0/1 mm**

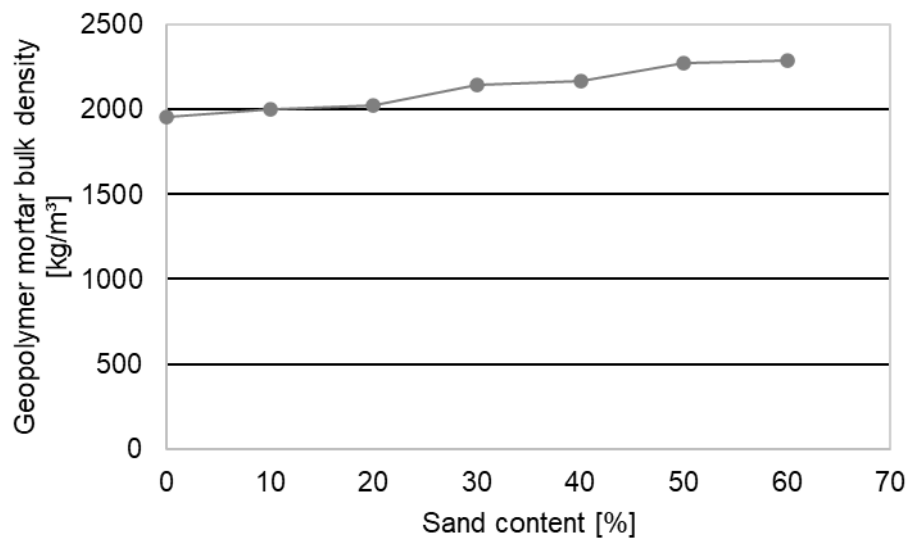


**Figure 4.3: Bulk density – CEN Standard sand**

#### 4.2.2 Cross section of geopolymer mortar samples

The cross sections of the geopolymer mortar samples, obtained after executing the flexural strength tests, are visible on Figure 4.5, Figure 4.6 and Figure 4.7. To be able to compare with the geopolymer paste, the cross section of a geopolymer paste sample has been added in Figure 4.4. Above each of the cross sections, the respective sand content has been added for clarification.

Based on the cross sections, it can be concluded that the sand is well distributed within each of the samples. Furthermore, at 60 wt.% sand a significant increase in pore formation is visible, which confirms the decrease in density.

The higher fineness modulus of the CEN Standard sand compared to the sea sand can also visually be confirmed by comparing Figure 4.7 with Figure 4.5 and Figure 4.6. The particles present in CEN Standard sand are coarser than the particles in sea sand.

0%

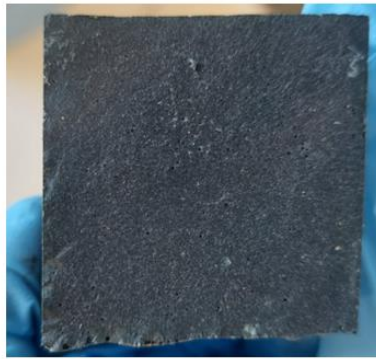


**Figure 4.4: Cross section – Geopolymer paste**

10%



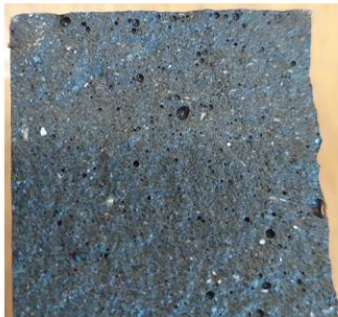
20%



30%



40%



50%



60%



**Figure 4.5: Cross section geopolymer mortars – Sea sand 0/2 mm**

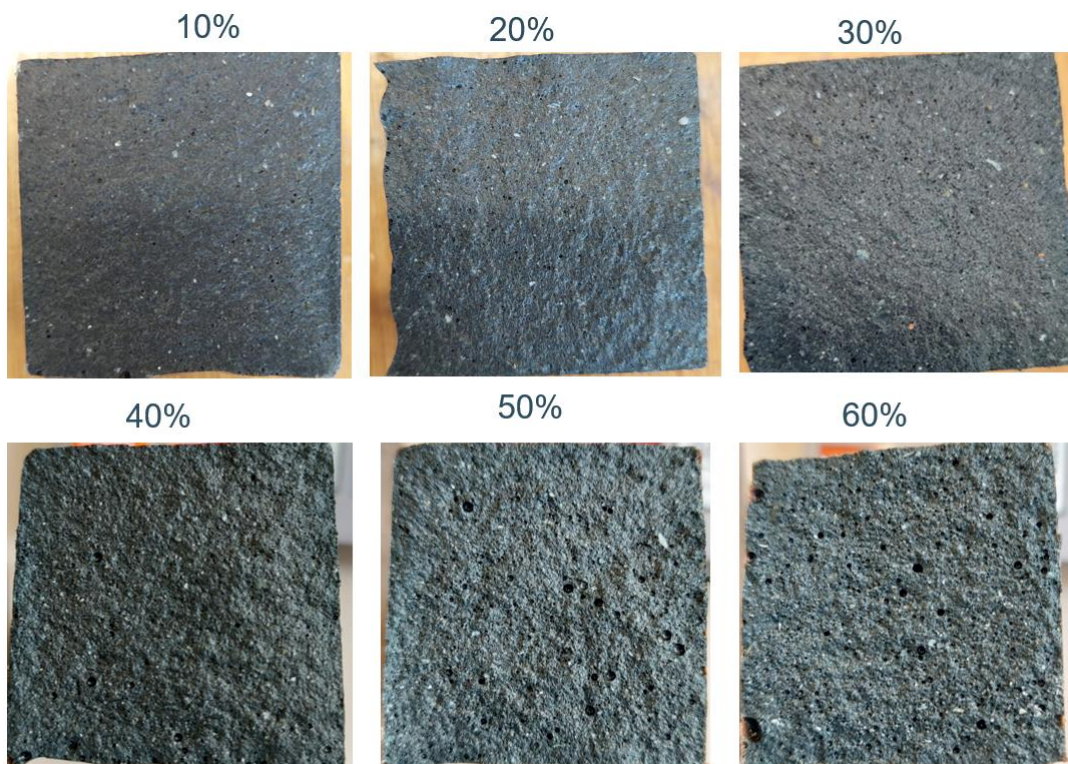


**Figure 4.6: Cross section geopolymer mortars – Sea sand 0/1 mm**

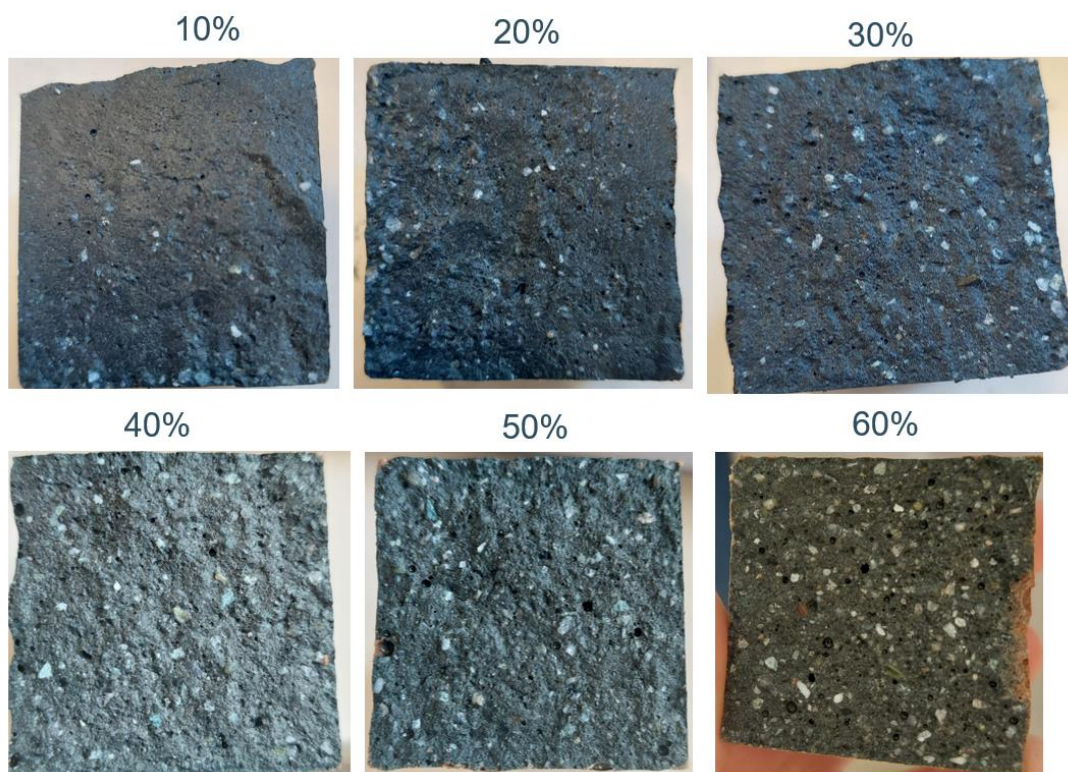


**Figure 4.7: Cross section geopolymer mortars – CEN Standard sand**

### 4.2.3 Workability (NBN EN 1015-3)

The flowability index for each sand content has been plotted on Figure 4.8 and Figure 4.9 for every type of sand. The flowability index as shown on the graphs are the mean values from two separate measurement. The individual measurements are added in Appendix D. As can be seen on both graphs, an increase in sand content leads to a decrease in flowability index. The fine graded sands, sea sand 0/2 mm and 0/1 mm, know a steeper decrease in flowability index than the coarse graded CEN Standard sand. Fine particles have a higher specific surface area than coarse particles, leading to an increased water absorption.

For an optimal flowability index of 2.5, a sand content of 50 to 55 wt.% could be used for every sand type. For coarse graded sands, the sand content could be increased up to 60 wt.%. The optimal binder-to-sand ratio would thus be around the 1:1.

Zailani [70] et al. researched the workability of fly ash-based geopolymer mortars for repairing properties. By increasing the sand content, a decrease in workability was also noted. An optimal sand content of 50 wt.% up to 67 wt. % was found to be suitable for the repairing works. If the flowability of the geopolymer paste is higher, the added sand content can be increased. Furthermore, if the sand particles used are coarse, more sand particles can be added to the mixture.

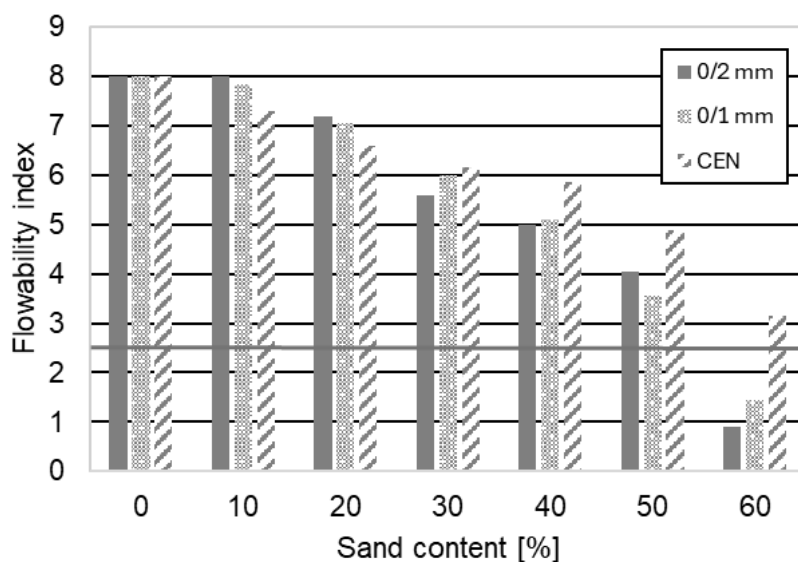


Figure 4.8: Flowability index – Graph 1

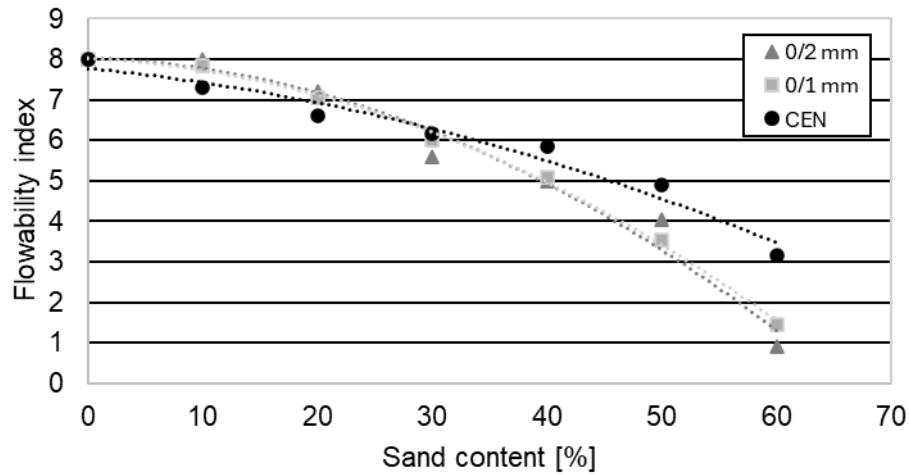


**Figure 4.9: Flowability index – Graph 2**

To be able to visualize the difference in flowability at 60 wt.% between sea sand 0/2 mm and CEN Standard sand, pictures taken during the mini slump test are added in Figure 4.10. The pictures on the left for each sand type have been taken before jolting the table, while the pictures on the right are the result of 15 jolts of the table. The compaction of 60 wt.% sea sand 0/2 mm is not optimal, as can be seen on the pictures.



**Figure 4.10: Photos mini slump test**

## 4.2.4 Mechanical properties

### 4.2.4.1 Flexural strength (NBN EN 196-1)

#### Sea sand 0/2 mm

The flexural strength of the geopolymer mortars made with sea sand 0/2 mm are plotted in Figure 4.11, Figure 4.12, Figure 4.13, Figure 4.14. After 1 day, an increase in sand content doesn't have a significant influence on the flexural strength. The bond between the paste and the sand is not yet strong enough. Between 3 and 28 days, an increase in sand content leads to an increase in flexural strength. The highest flexural strength after 28 days is  $8.7 \pm 0.7$  MPa.

This value occurs at 50 wt.% sand (binder-to-sand ratio = 1:1). The strength after 28 days is more than the double of the strength after 1 day.

Steinerova [73] researched the effect of sand content on the flexural strength of metakaolinite geopolymer mortars. An increase in sand content led to an increase in flexural strength, up until 78 wt.% sand. By increasing the sand content even further, the abundance of sand leads to a lack of binder, which causes coarse-pore formation. The mixture is not flowable enough, making compaction difficult, which causes air bubbles to stay in the mixture. This is similar to what is found in this research. The difference in optimal sand content is due to the difference in binder. A more workable binder can incorporate more sand.

Zhang, Su, Goao, Zhang and Zhang [72] researched the effect of the sand-precursor ratio on the flexural strength of metakaolin and fly ash-based geopolymer mortars. The sand-precursor ratio increased from 1 to 5, leading in a decrease of flexural strength. This progression in flexural strength knows a downward trend, as the optimal sand content has already been exceeded. There is insufficient binder for the sand aggregates to bond with the geopolymer matrix. The increase in sand leads to a reduction in flowability, increasing the air trapped within the mixture and increasing the pore formation.

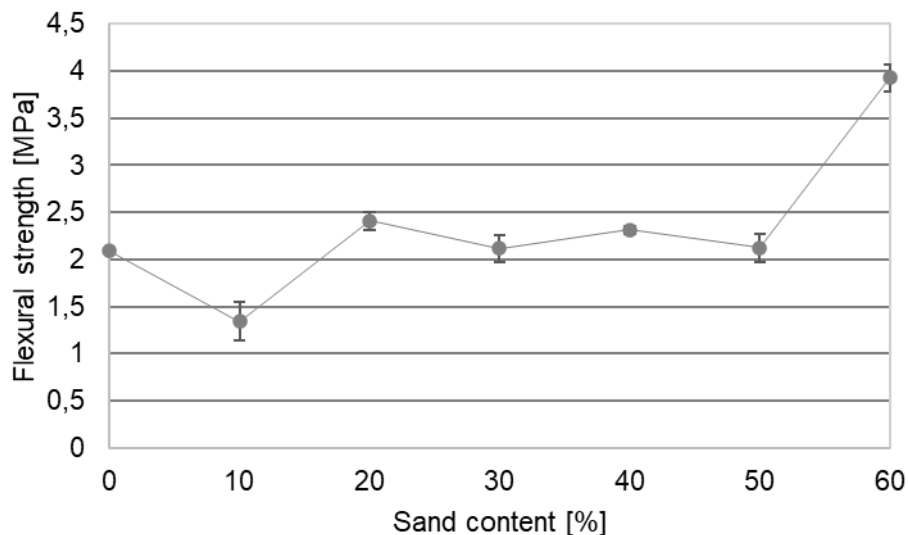


**Figure 4.11: Flexural strength 0/2 mm – 1 day**

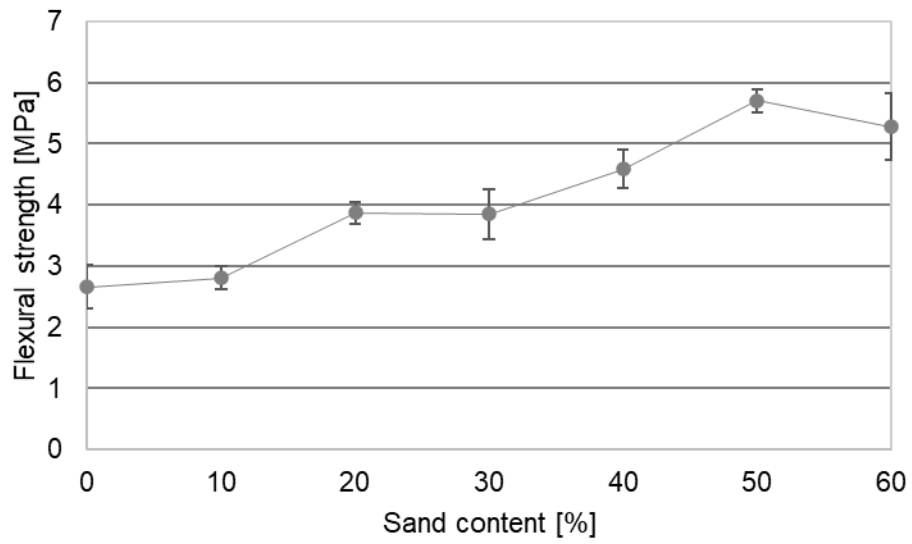


**Figure 4.12: Flexural strength 0/2 mm – 3 days**

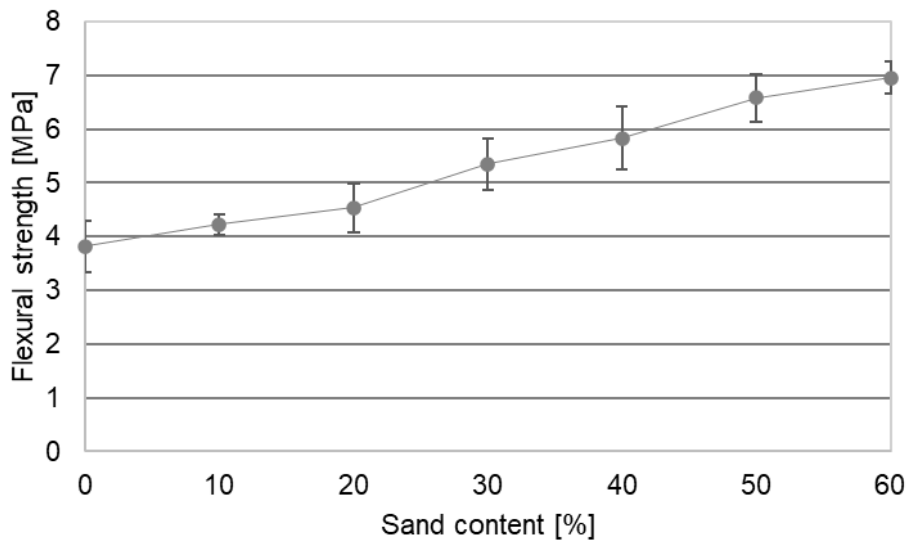


**Figure 4.13: Flexural strength 0/2 mm – 7 days**

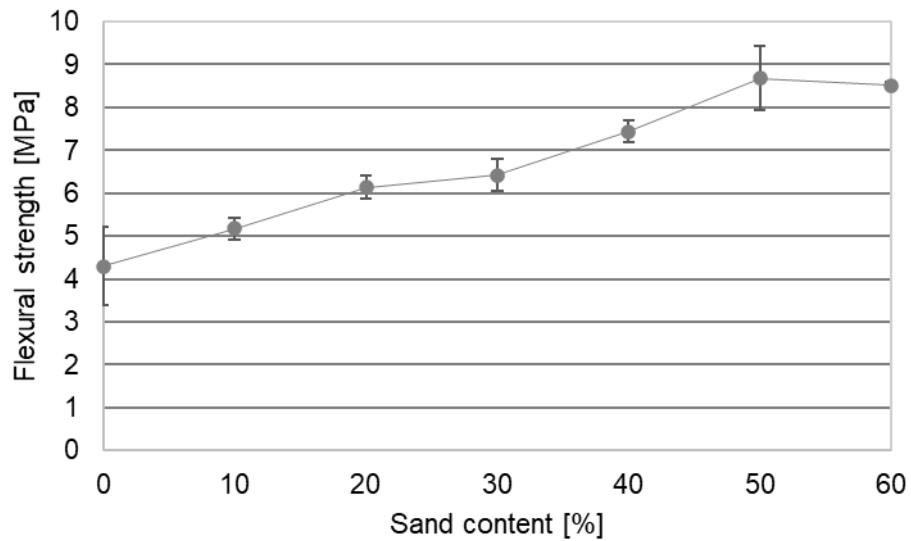


**Figure 4.14: Flexural strength 0/2 mm – 28 days**

Figure 4.15 shows the flexural strength for each sand content over time. From this figure can be concluded that the flexural strength increases over time. Furthermore, 50 wt. % knows the steepest increase in flexural strength over time.

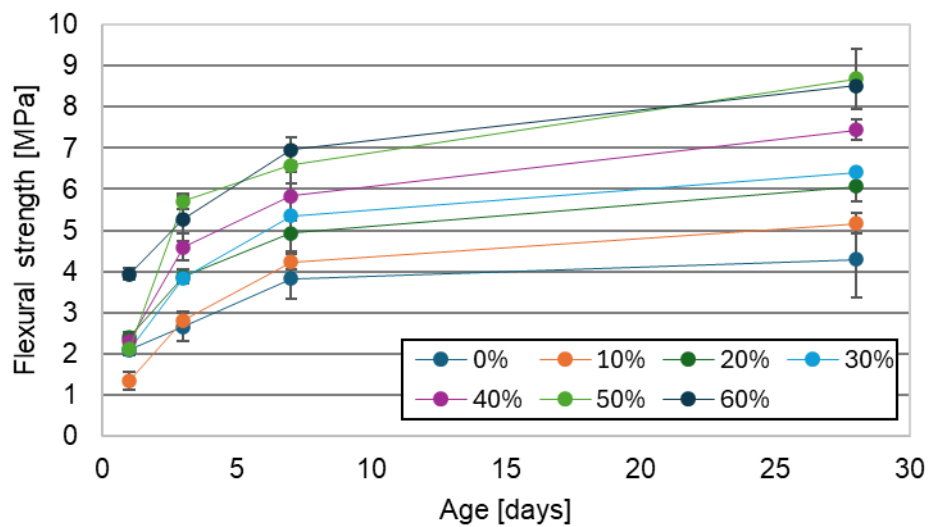


**Figure 4.15: Flexural strength over time – 0/2 mm**

By normalizing the curves obtained in Figure 4.15, the development of the flexural strength for each sand content can be analyzed for a common scale. Higher ratios refer to a higher development.

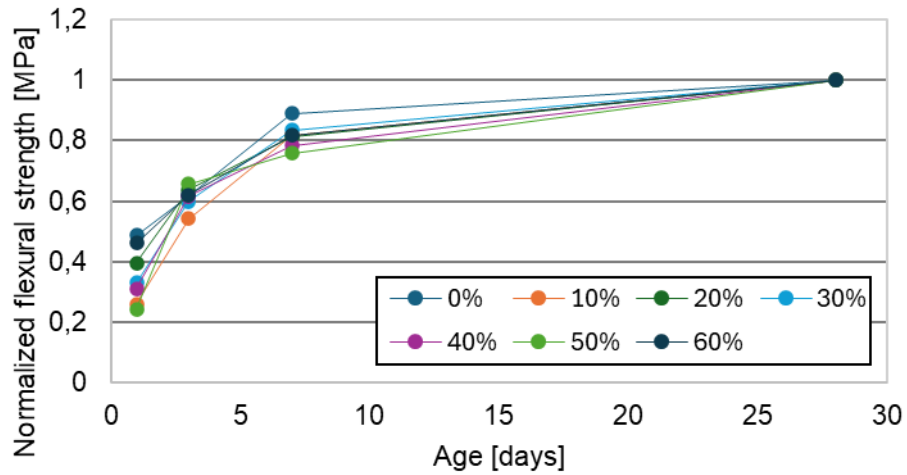


**Figure 4.16: Normalized flexural strength – 0/2 mm**

From this normalized graph (Figure 4.16), an estimation model is made, as shown in Figure 4.17. Following logarithmic relationship (4.1) is obtained:

$$R_{f,normalized} = 0.1946 * \ln(t) + 0.3857 \quad (4.1)$$

With:

$R_{f,normalized}$  = normalized flexural strength [-];

$t$  = time [days].

This relationship can be rewritten in function of the flexural strength at 28 days. This gives equation 4.2:

$$R_f(t) = [0.1946 * \ln(t) + 0.3857] * R_f(28) \quad (4.2)$$

With:

$R_f(t)$  = flexural strength at age  $t$  [MPa].

For this relationship, a coefficient of determination  $R^2$  of 0.9367 applies, specifying a good correlation between the two variables.

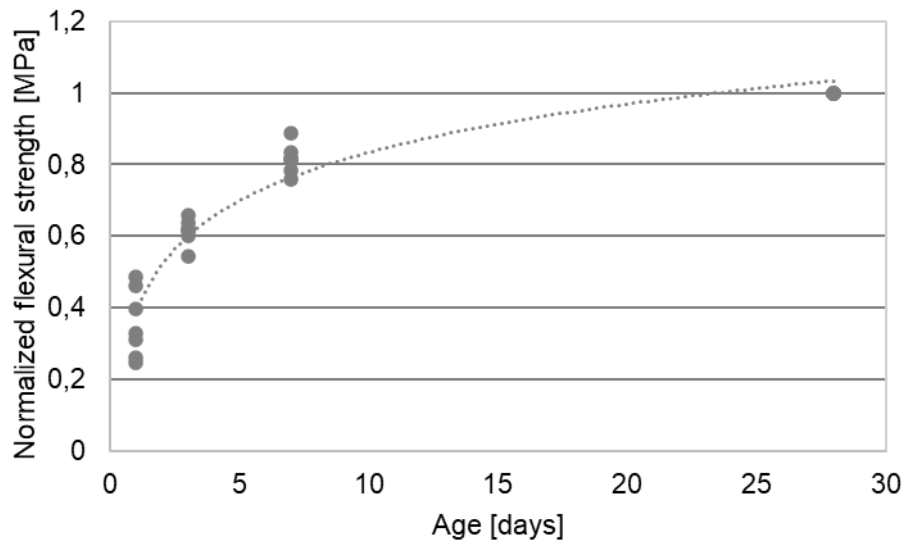


**Figure 4.17: Model estimation - Flexural strength 0/2 mm**

#### Sea sand 0/1 mm

The flexural strength of the geopolymer mortars made with sea sand 0/1 mm is plotted in Figure 4.18, Figure 4.19, Figure 4.20 and Figure 4.21. The curves show a similar progression to the geopolymer mortars made with sea sand 0/2 mm up to 7 days. After 1 day, an increase in sand content doesn't show a remarkable influence on the flexural strength. From 3 to 7 days, increasing the sand content leads to an increase in flexural strength. At 28 days, an increase in sand content increases the flexural strength, before stabilizing from 30 wt. % up to 60 wt.% sand. Due to the small size of the sand particles, the influence of the sand is restricted, which becomes visible when the bond gets strong enough. The flexural strength reaches up to  $7.8 \pm 0.4$  MPa after 28 days for an optimal sand content of 50% (b:s = 1:1).

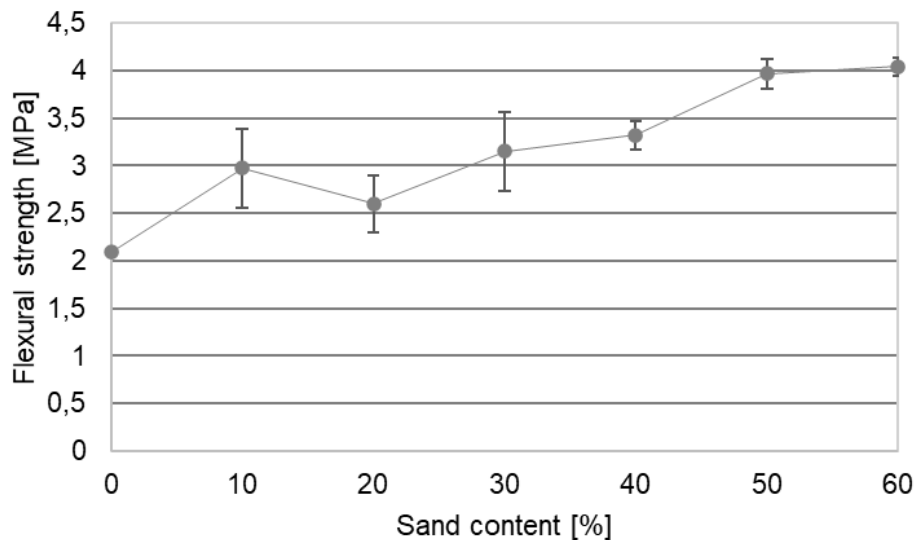


**Figure 4.18: Flexural strength 0/1 mm – 1 day**

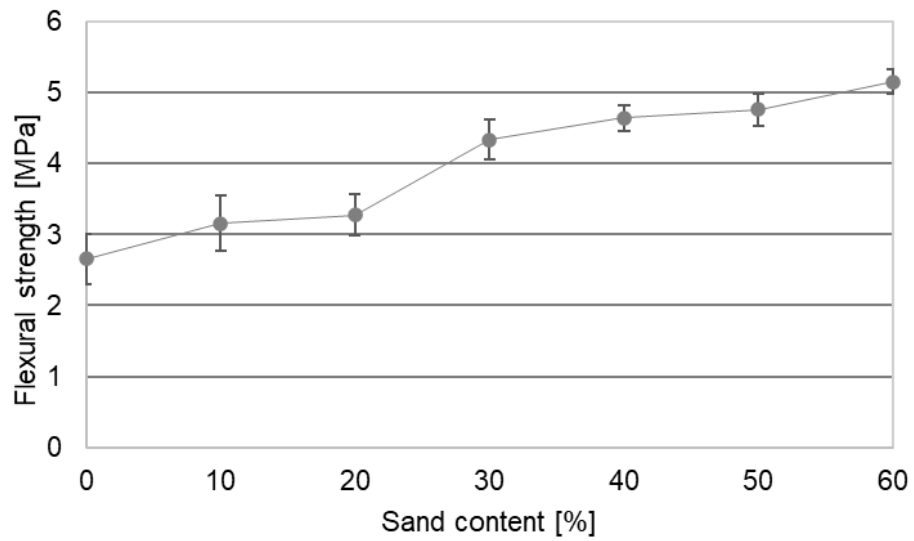


**Figure 4.19: Flexural strength 0/1 mm – 3 days**

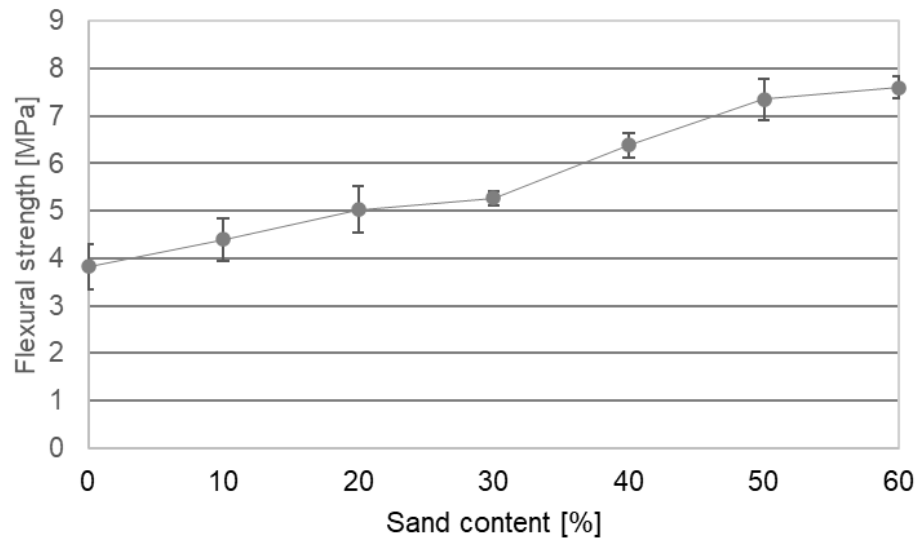


**Figure 4.20: Flexural strength 0/1 mm – 7 days**

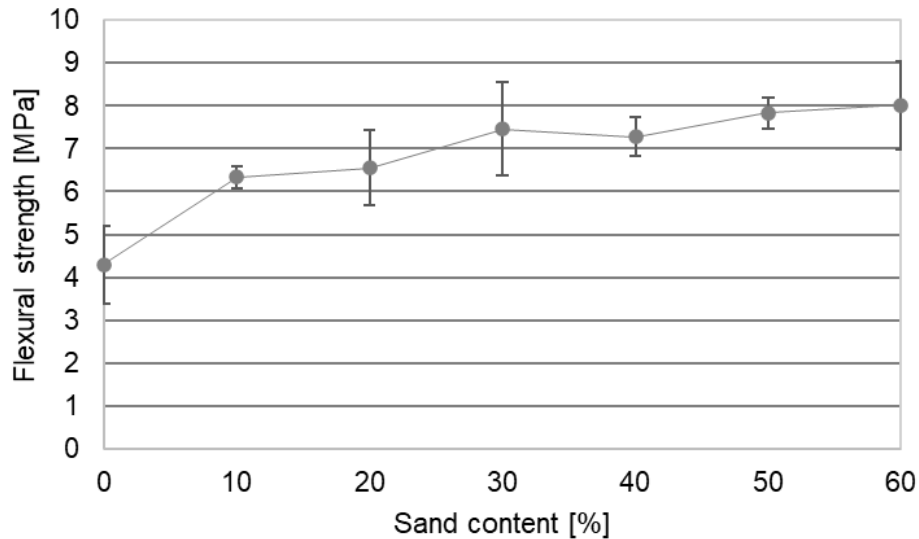


**Figure 4.21: Flexural strength 0/1 mm – 28 days**

The flexural strength has been plotted over time in Figure 4.22. From this graph, an increase in flexural strength can be noted over time for each sand content. The maximal flexural strength is almost reached after 7 days for higher sand contents, unlike with sea sand 0/2 mm. The sand particles are too small to influence the geopolymers mixture after 7 days.

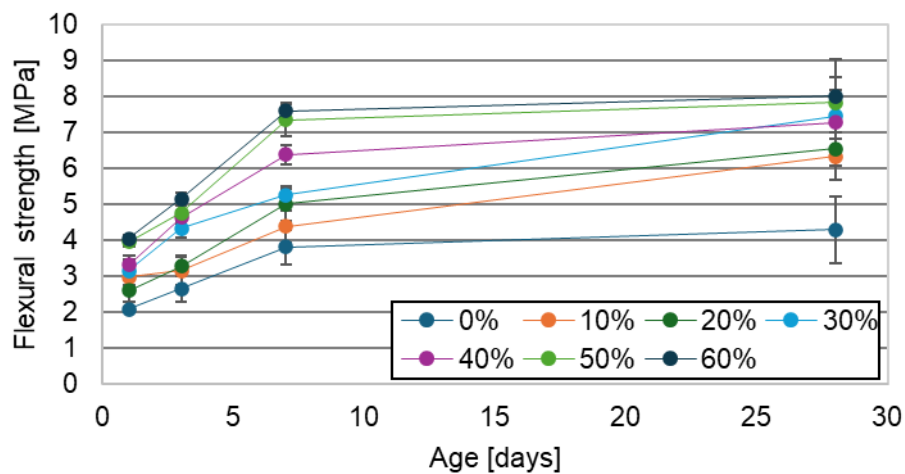


**Figure 4.22: Flexural strength over time – 0/1 mm**

The normalized flexural strength over time is plotted in Figure 4.23. This figure shows the development of the flexural strength, which knows the steepest increase for higher sand contents at low age.

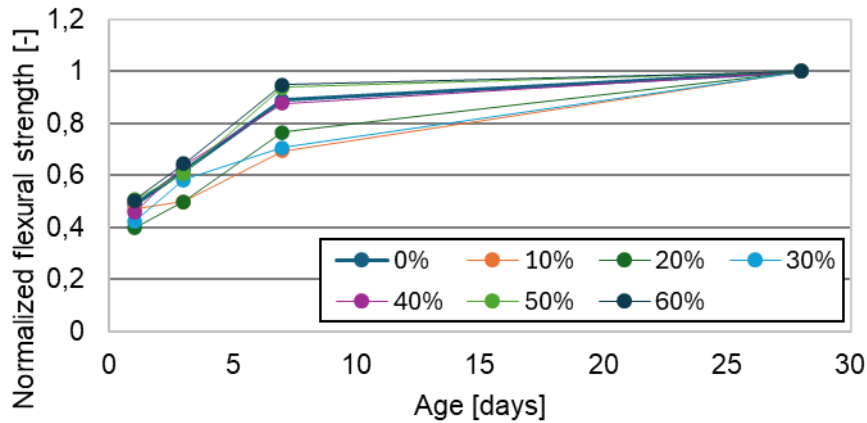


**Figure 4.23: Normalized flexural strength – 0/1 mm**

An estimation model is made for sea sand 0/1 mm in Figure 4.24. From this graph, following logarithmic relationship (4.3) is obtained:

$$R_{f,normalized} = 0.1691 * \ln(t) + 0.4499 \quad (4.3)$$

By rewriting this relationship in function of the flexural strength at 28 days, the following relationship (4.4) is obtained:

$$R_f(t) = [0.1691 * \ln(t) + 0.4499] * R_f(28) \quad (4.4)$$

A coefficient of determination  $R^2$  of 0.8926 applies for this relationship, which indicates a good correlation between the two variables.

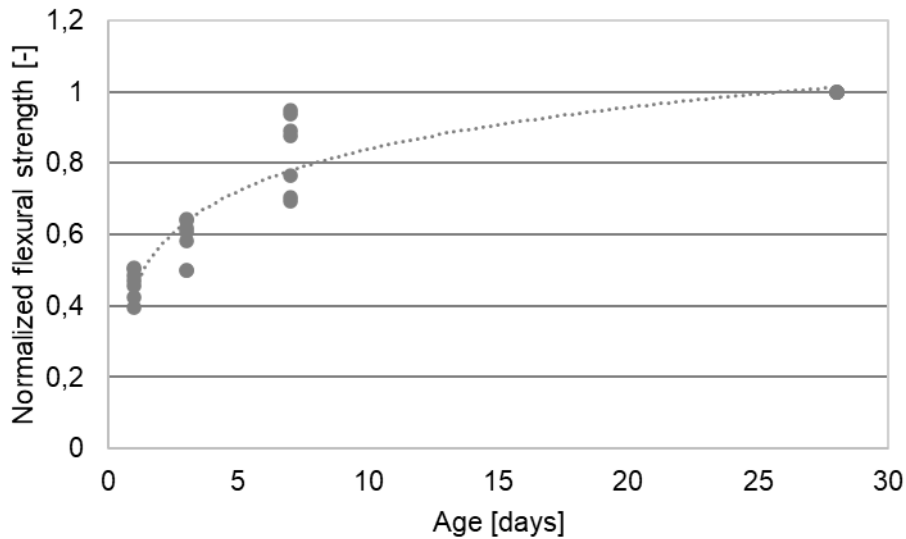


**Figure 4.24: Model estimation - Flexural strength 0/1 mm**

### CEN Standard sand

In Figure 4.25, Figure 4.26, Figure 4.27 and Figure 4.28, the flexural strength of the geopolymer mortars for different sand contents at varying ages can be seen. Unlike sea sand 0/2 mm and 0/1 mm, the coarser CEN sand particles know an increase in flexural strength from day 1 with an increase in sand content. Between 50 wt.% and 60 wt.%, the increase in flexural strength becomes less steep, noting the stabilization of the flexural strength at higher

sand contents. The optimal binder-to-sand ratio for CEN Standard sand can be increased from 1:1 (=50 wt.%) to 2:3 (= 60 wt.%) compared to sea sand 0/2 mm and 0/1 mm. At 28 days, a flexural strength of  $9.5 \pm 0.1$  MPa is reached with 60 wt.% sand.

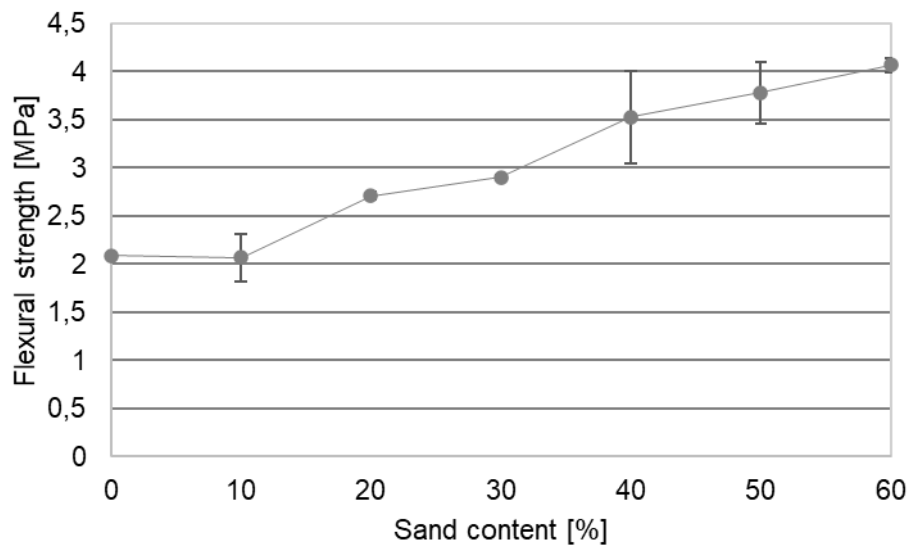


**Figure 4.25: Flexural strength CEN – 1 day**

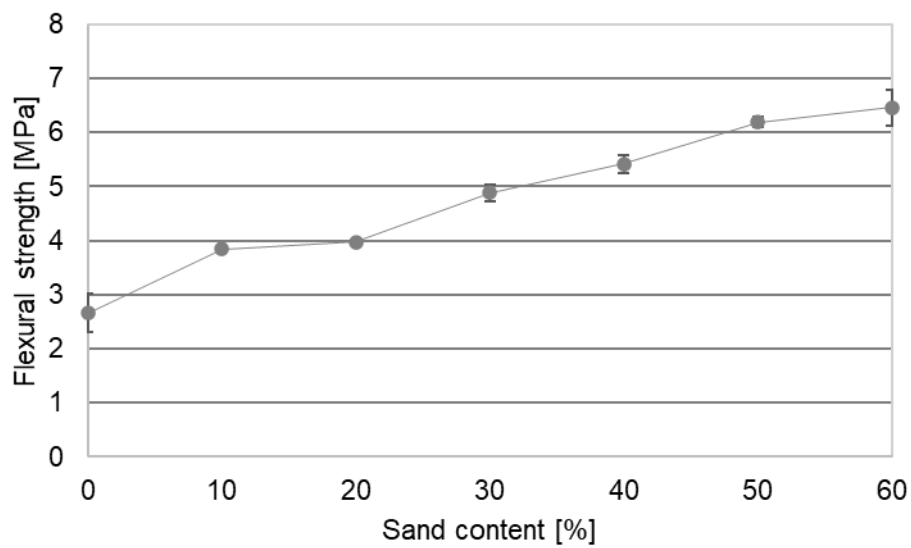


**Figure 4.26: Flexural strength CEN – 3 days**

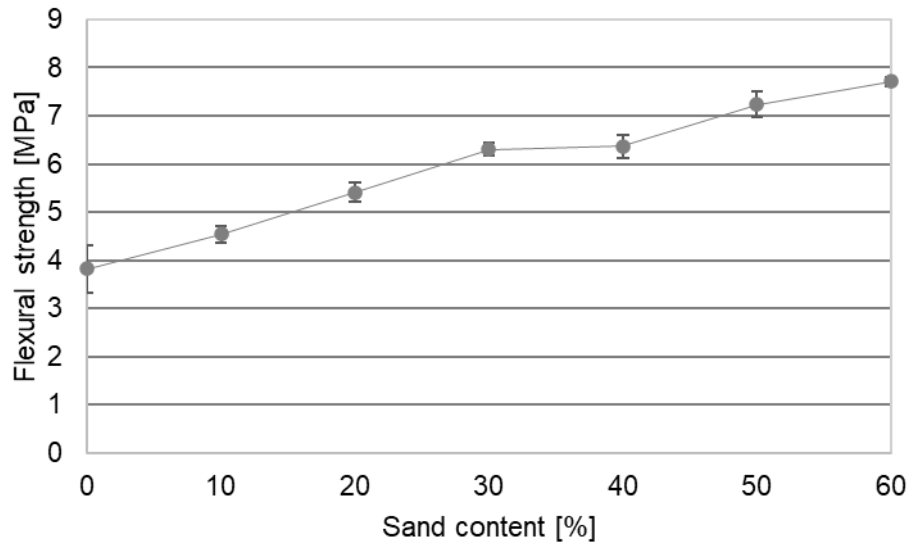


**Figure 4.27: Flexural strength CEN – 7 days**

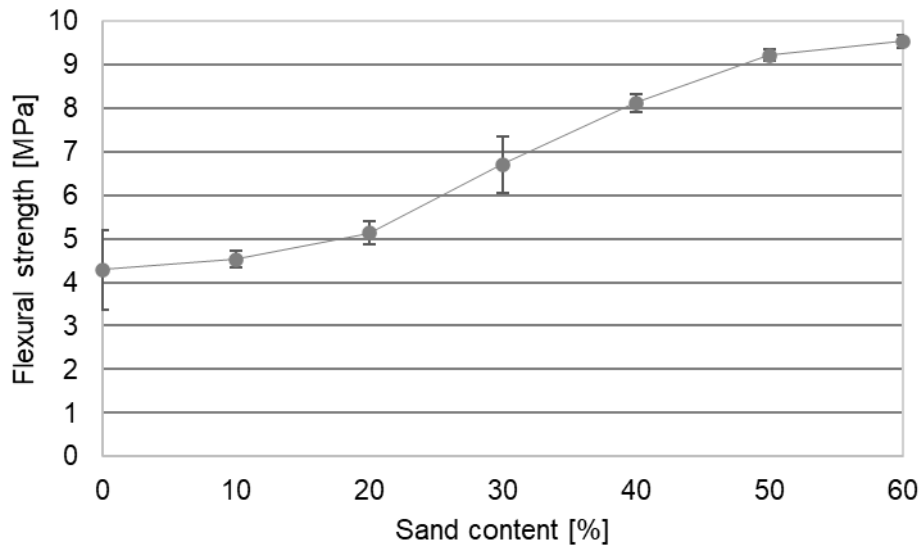


**Figure 4.28: Flexural strength CEN – 28 days**

Figure 4.29 plots the flexural strength over time for each sand content. An increase in flexural strength can be observed over time. The flexural strength increases with an increase in sand content as well, up to 50 wt.% sand before stabilizing.

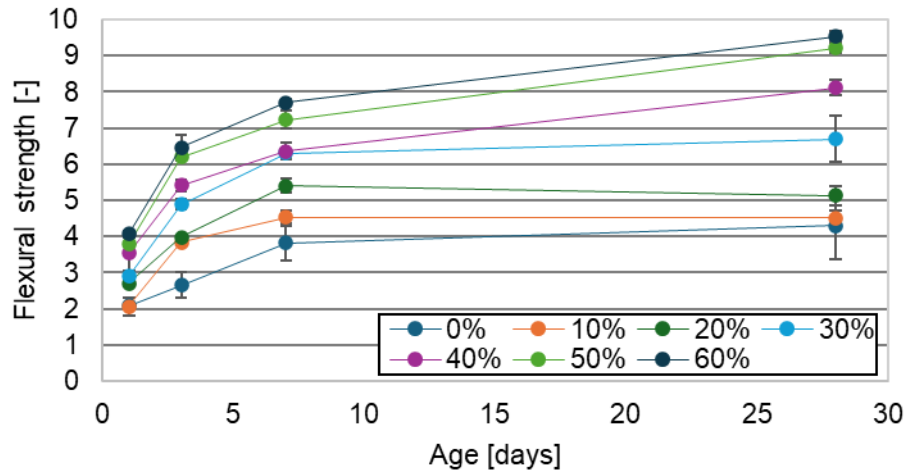


**Figure 4.29: Flexural strength over time – CEN**

In Figure 4.30 the normalized flexural strength over time is plotted. Figure 4.31 shows an estimation model made from the normalized flexural strength. Following logarithmic relationship (4.5) is obtained:

$$R_{f,normalized} = 0.167 * \ln(t) + 0.5012 \quad (4.5)$$

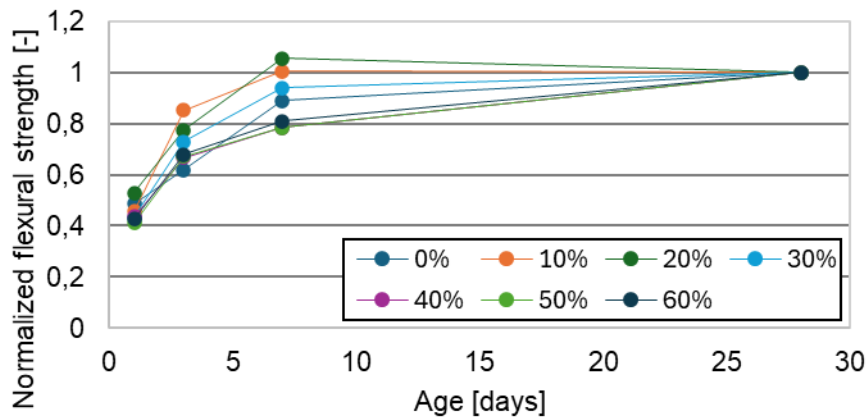


**Figure 4.30: Normalized flexural strength – CEN**

By rewriting relationship 4.5 in function of the flexural strength at 28 days, the following relationship (4.6) is obtained:

$$R_f(t) = [0.167 * \ln(t) + 0.5012] * R_f(28) \quad (4.6)$$

A coefficient of determination  $R^2$  of 0.848 applies for this relationship, which indicates an adequate correlation between the two variables.

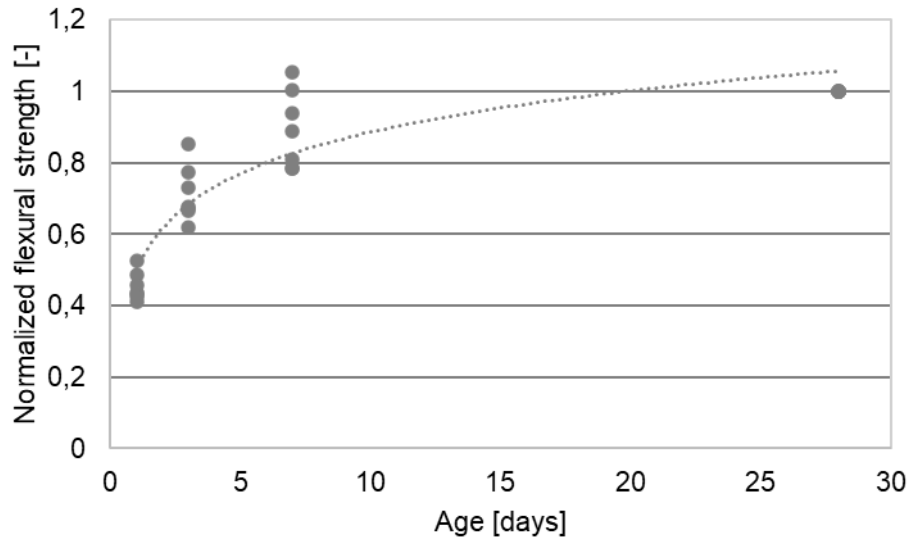


**Figure 4.31: Model estimation - Flexural strength CEN**

For sand contents between 30 wt.% and 60 wt.%, another logarithmic relationship might be more fitting, as demonstrated in Figure 4.32. Following formula (4.7) is obtained:

$$R_{f,normalized} = 0.1703 * \ln(t) + 0.4643 \quad (4.7)$$

With its subsequent coefficient of determination  $R^2$  of 0.9464.

By rewriting this relationship in terms of the flexural strength at 28 days, the following relationship (4.8) is obtained:

$$R_f(t) = [0.1703 * \ln(t) + 0.4643] * R_f(28) \quad (4.8)$$

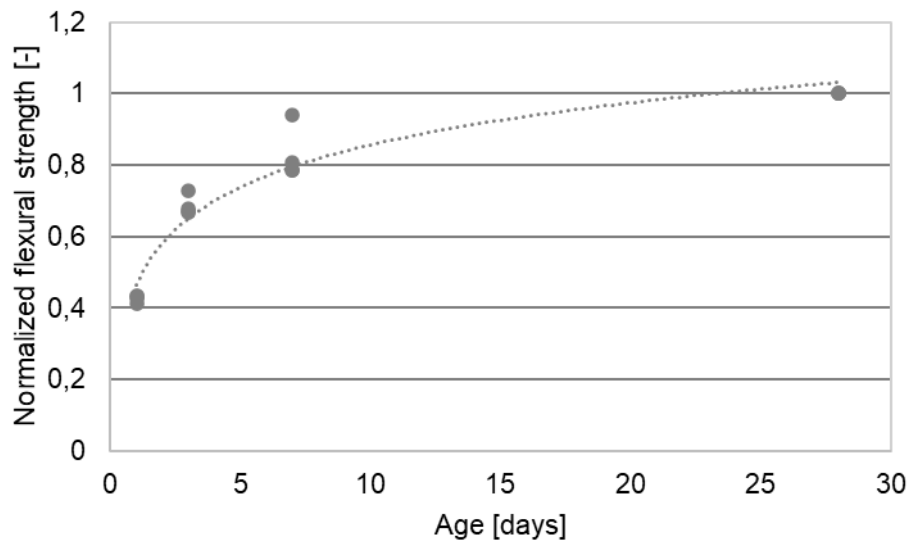


**Figure 4.32: Model estimation 30-60 wt.% - Flexural strength CEN**

### Flexural strength at 28 days

The flexural strength at 28 days has been plotted in Figure 4.33 for each type of sand. As can be seen on the graph, an increase in sand content leads to an increase in flexural strength for

all types of sand, before stabilizing at 50 wt.% of sand. The flexural strength at 28 days is different for each type of sand. The flexural strength obtained with CEN Standard sand, for example, is 5.4% higher than with 0/2 mm sea sand, and 15.2% higher than with 0/1 mm sea sand at 50 wt.% sand. The coarser CEN sand particles have a more positive influence on the flexural strength than the finer sea sand particles. There are different reasons for this phenomenon. Firstly, coarser particles are larger, making the bonding process with the geopolymer paste easier. Furthermore, coarser particles make the overall skeleton stronger. The coarser particles are in the way during the flexural strength test, hindering the rotation of the sample. This principle is illustrated in Figure 4.34.

Moreover, geopolymer mortars made with coarser aggregates, like CEN Standard sand, can have a higher sand content and a lower binder-to-sand ratio. Coarser particles absorb less water, making the geopolymer mortar more workable for the same sand content as finer sand aggregates.

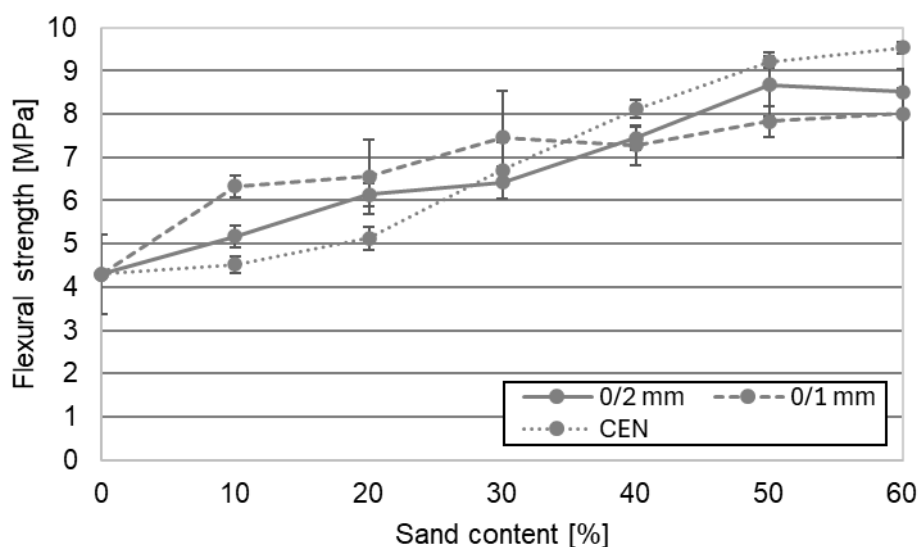


**Figure 4.33: Flexural strength at 28 days**

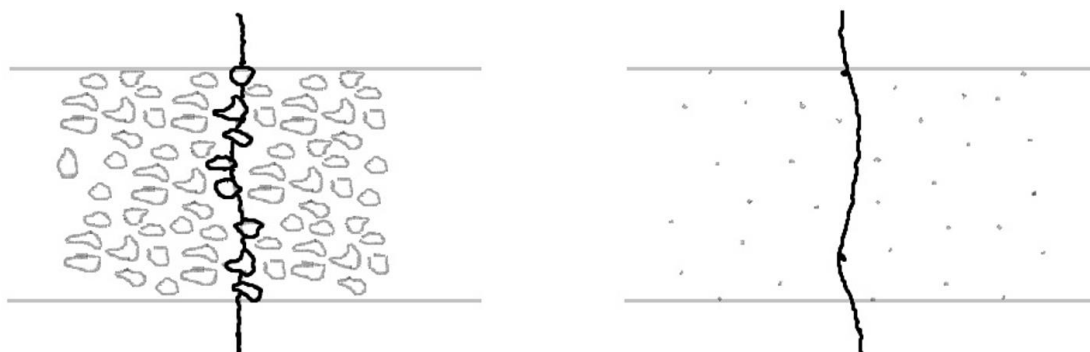


**Figure 4.34: Difference in failure mode when using coarse (left) and fine (right) particles**

## Comparison estimation models

The three estimation models are visualized in Figure 4.35. From this graph, and the equations 4.2, 4.4 and 4.6, the early strength development and strength gain over time can be compared for the three types of sand. The early-age strength ratio is the highest for CEN Standards sand, having reached 50.12% of its 28-day strength at 1 day. This high early-age strength is due to the elevated fineness modulus of CEN sand, increasing the bonding capacity of the sand particles with the geopolymer mortar. Finer sand particles have a lower initial strength, but a faster growth rate.

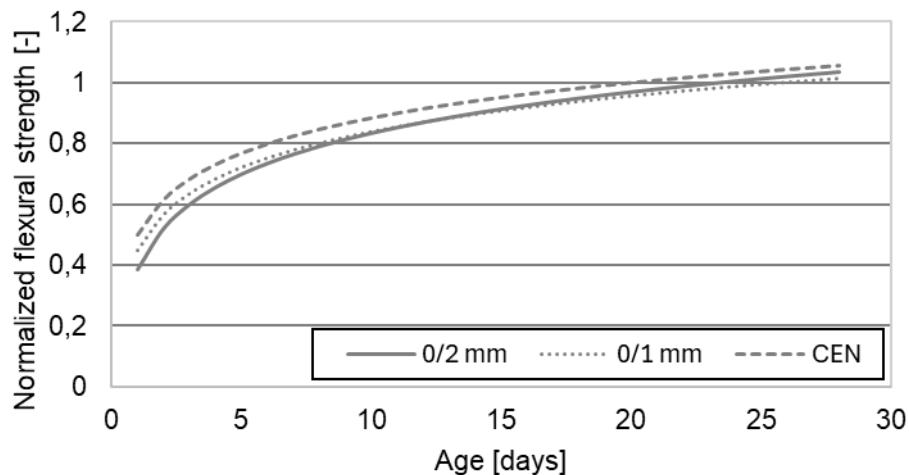


**Figure 4.35: Comparison estimation models - Flexural strength**

The fineness modulus of the used sands might have a relationship with the estimation models for the flexural strength, making an generalized flexural strength estimation model (4.9) possible.

$$R_f(t) = [(-0.0135 * FM + 0.2056) * \ln(x) + (0.075 * FM + 0.2773)] * R_f(28) \quad (4.9)$$

With:

$R_f(t)$  = flexural strength at age  $t$  [MPa];

FM = fineness modulus.

The early-age flexural strength factor shows a moderate linear correlation with the fineness modulus ( $R^2 = 0.64$ ). However, the logarithmic growth coefficient has a poor linear correlated, having a coefficient of determination  $R^2$  of only 0.26.

### 4.2.4.2 Compressive strength (NBN EN 196-1)

#### Sea sand 0/2 mm

The compressive strength for different sand contents has been plotted in Figure 4.36, Figure 4.37, Figure 4.38 and Figure 4.39 for samples aged of 1 day, 3 days, 7 days and 28 days respectively. After 1 day, the sand particles have a negative impact on the compressive strength. The bond between the geopolymer matrix and sand particles is not yet complete, leading to a decreasing trend. Between 3 and 28 days, increasing the sand content doesn't have a significant influence on the compressive strength. The compressive strength at 28 days reaches a value of  $80.5 \pm 1.5$  MPa for 50 wt.% sand. The compressive strength has more than quadrupled at 28 days compared to day 1.

Temuujin, van Riessen and MacKenzie [69] researched the compressive strength for fly ash-based geopolymer mortars with varying sand contents. No significant changes in compressive

strength were found either when varying the sand content from 0 wt.% up to 50 wt.%. The compressive strength of the mortars was mainly depending on the strength of the geopolymer paste, the bonding between the sand particles and the geopolymer paste, and the aggregates themselves. An increase in sand content led to a decrease in open porosity and an increase in density, as a better compaction could be achieved by incorporating sand into the mixture.

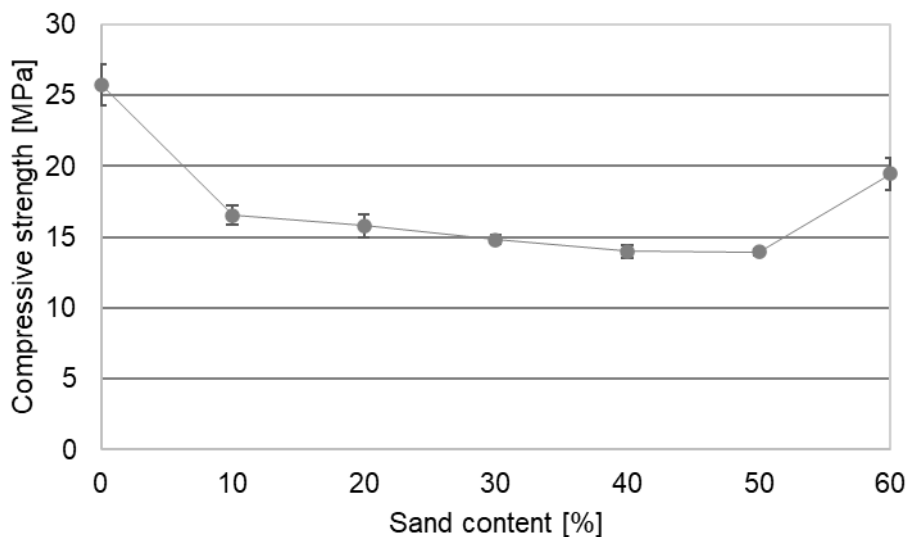


**Figure 4.36: Compressive strength 0/2 mm – 1 day**

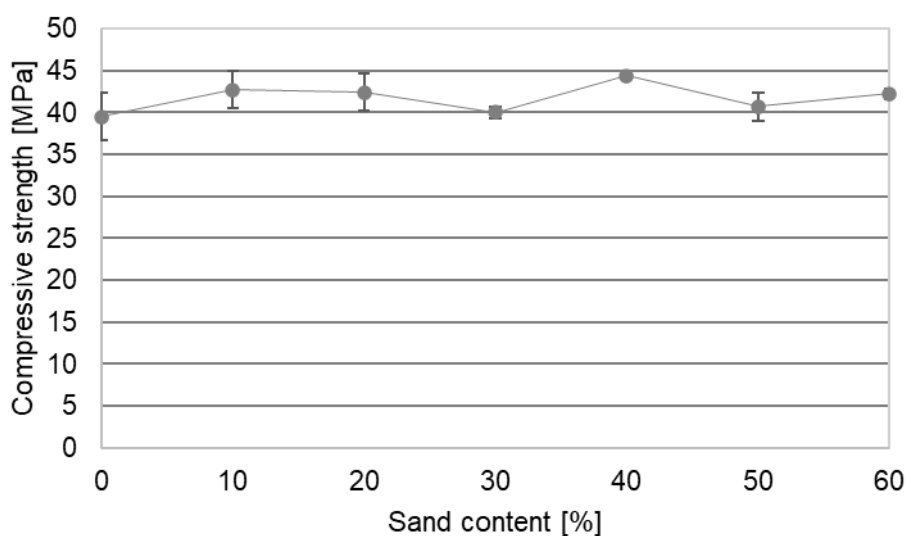


**Figure 4.37: Compressive strength 0/2 mm – 3 days**

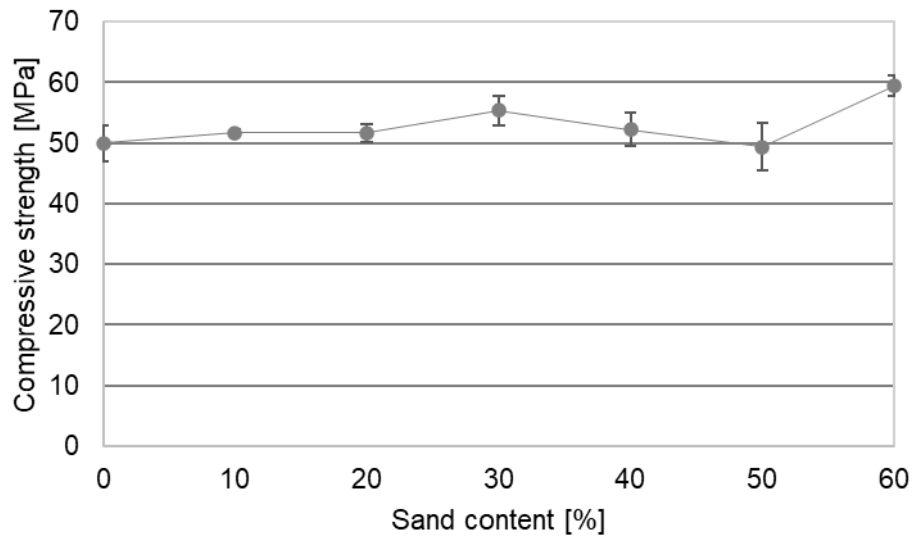


**Figure 4.38: Compressive strength 0/2 mm – 7 days**

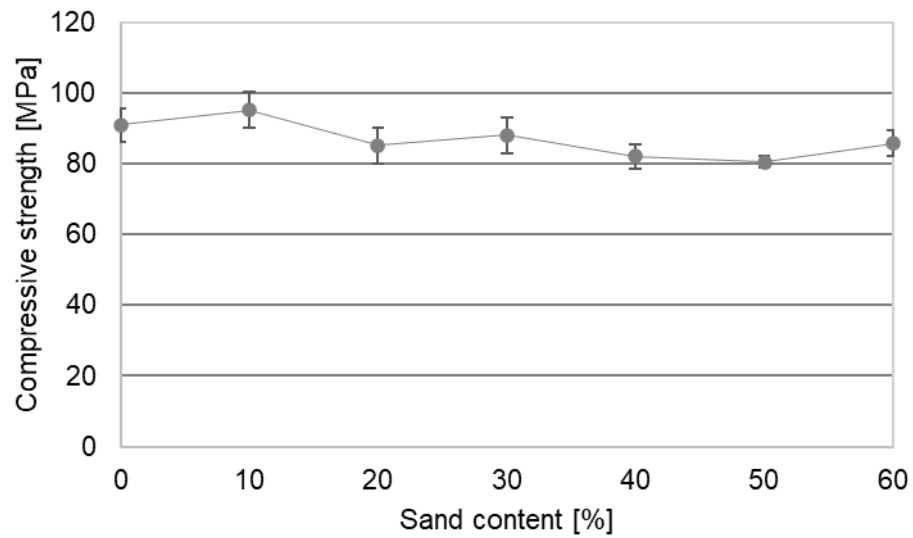


**Figure 4.39: Compressive strength 0/2 mm – 28 days**

The compressive strength over time has been plotted in Figure 4.40 for each sand content of sea sand 0/2 mm. As can be seen on the figure, the compressive strength increases over time for each sand content. The presence of sand particles in the mixture does not have a significant influence on the compressive strength of the geopolymer mortars.

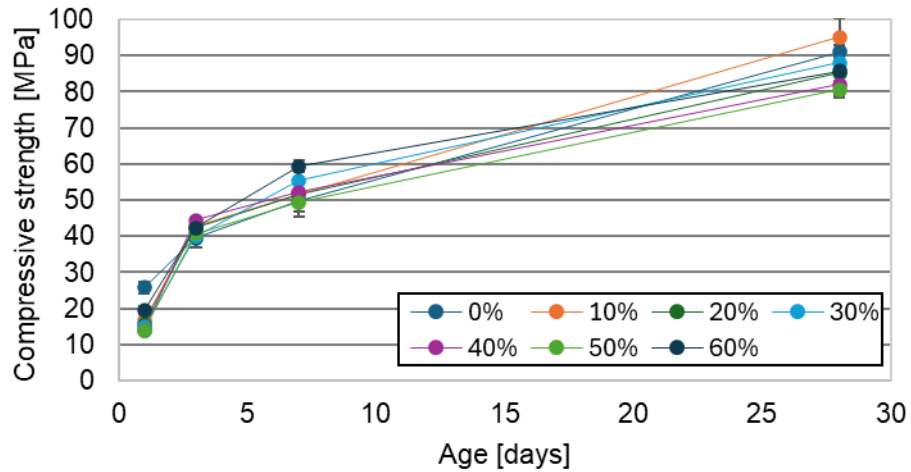


**Figure 4.40: Compressive strength over time – 0/2 mm**

The normalization of the above given graph is visible in Figure 4.41. From this curve, an estimation model is made for geopolimer mortars made with sea sand 0/2 mm, as shown in Figure 4.42. From this graph, the following logarithmic relationship (4.10) is obtained:

$$R_{c,normalized} = 0.2359 * \ln(t) + 0.1963 \quad (4.10)$$

With:

$$R_{c,normalized} = \text{normalized compressive strength [-]}.$$

This relationship can be rewritten in terms of the compressive strength at 28 days, which gives formula 4.11:

$$R_c(t) = [0.2359 * \ln(t) + 0.1963] * R_c(28) \quad (4.11)$$

The coefficient of determination  $R^2$  that matches with this relationship is 0.9758, which indicates a good correlation between the two variables.

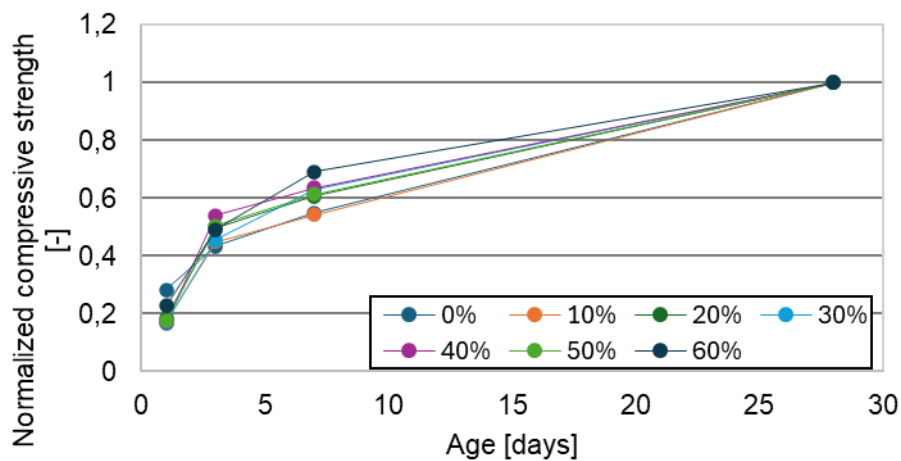


**Figure 4.41: Normalized compressive strength – 0/2 mm**

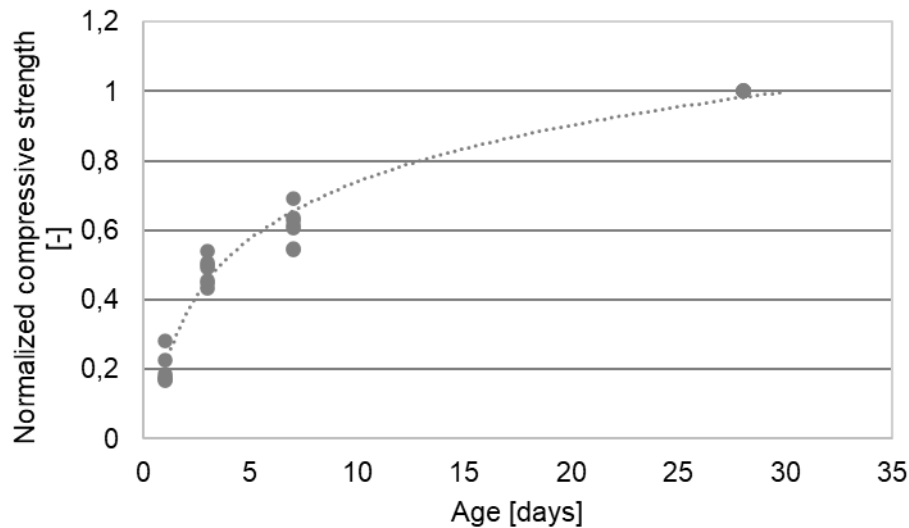


**Figure 4.42: Model estimation – Compressive strength 0/2 mm**

### Sea sand 0/1 mm

In Figure 4.43, Figure 4.44, Figure 4.45 and Figure 4.46 the compressive strength for different sand contents for sea sand 0/1 mm has been plotted for 1 day, 3 days, 7 days and 28 days respectively. As can be seen in the figures, increasing the sand content doesn't have a remarkable influence on the compressive strength from 1 day up to 7 days. At 28 days, the compressive strength decreases with an increase in sand content up to 20 wt.% sand. When increasing the sand content further, the compressive strength stabilizes. The drop in compressive strength is linked to the increased pore formation and air content in the mixture when working with 0/1 mm sand. Due to the small size of the particles, they absorb more water, leading to a bad workability and compaction.

The compressive strength at 28 days reaches  $59.9 \pm 3.1$  MPa for 50 wt.% sand, which is more than 20 MPa lower than when using 0/2 mm sea sand.

The compressive strength of fly ash-based geopolymer mortar was also researched by Zainali et al. [70]. By varying the sand content from 0 wt.% up to 80 wt.%, they were able to analyze the effect of the sand quantity on the strength of the mortars. Increasing the sand content up to 67 wt.% led to an increase in compressive strength. By incorporating more than 67 wt.% sand in the mixture, the compressive strength of the geopolymer mortars decreased. The compressive strength was found to depend on the compressive strength of the geopolymer binder itself, and the bonding between the binder and the sand aggregates. A higher sand content decreases the workability of the mixture, limiting the available binder and reducing the compacting abilities of the mixture. Pore-formation will occur, decreasing the overall strength of the matrix, which takes place in this research as well.

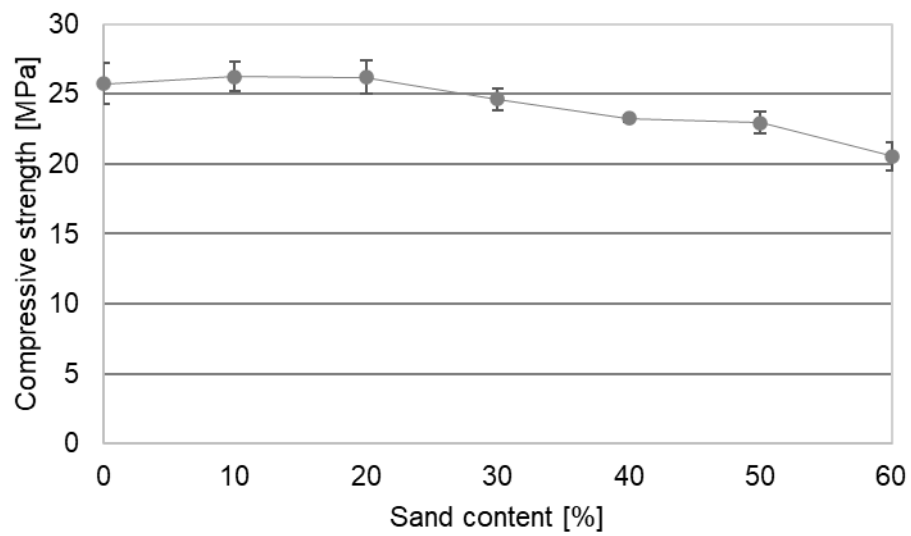


**Figure 4.43: Compressive strength 0/1 mm – 1 day**

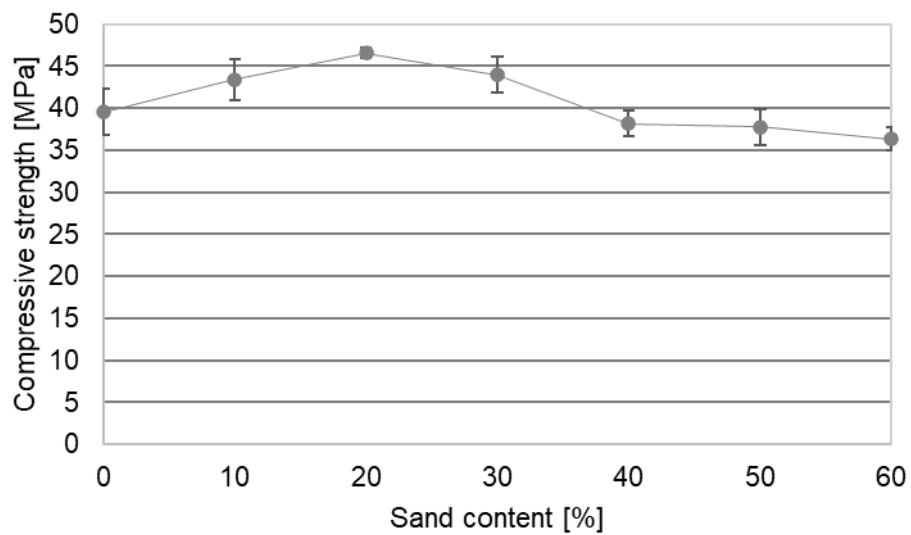


**Figure 4.44: Compressive strength 0/1 mm – 3 days**

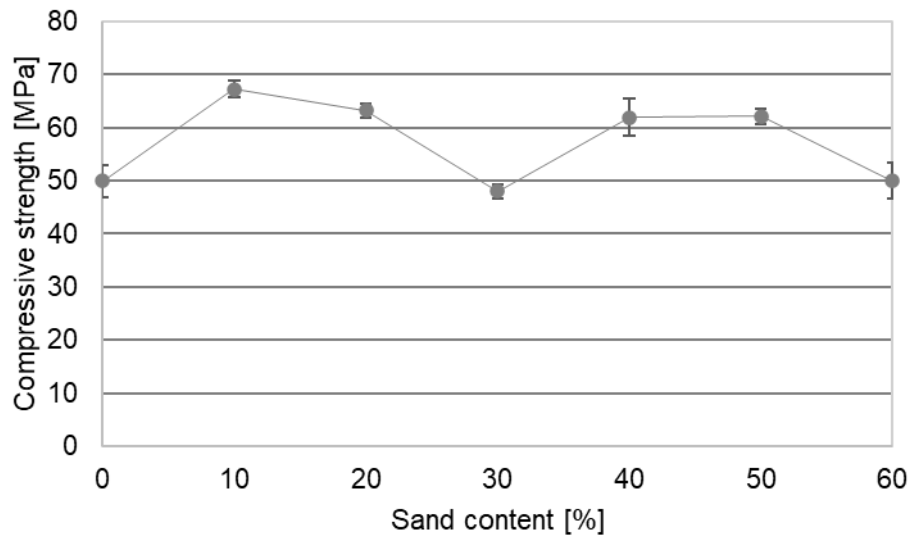


**Figure 4.45: Compressive strength 0/1 mm – 7 days**

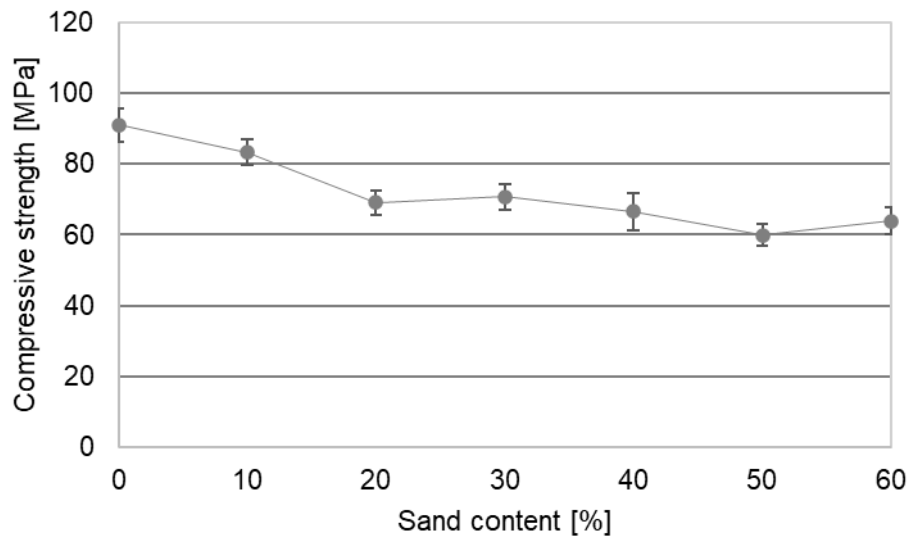


**Figure 4.46: Compressive strength 0/1 mm – 28 days**

The compressive strength is plotted over time in Figure 4.47. As can be seen on the figure, the compressive strength increases over time. An increase in sand content shows a decrease in compressive strength. Increasing the sand content results in less available binder to bond the sand particles with the geopolymer matrix, increasing the pore formation and decreasing the overall strength of the matrix.

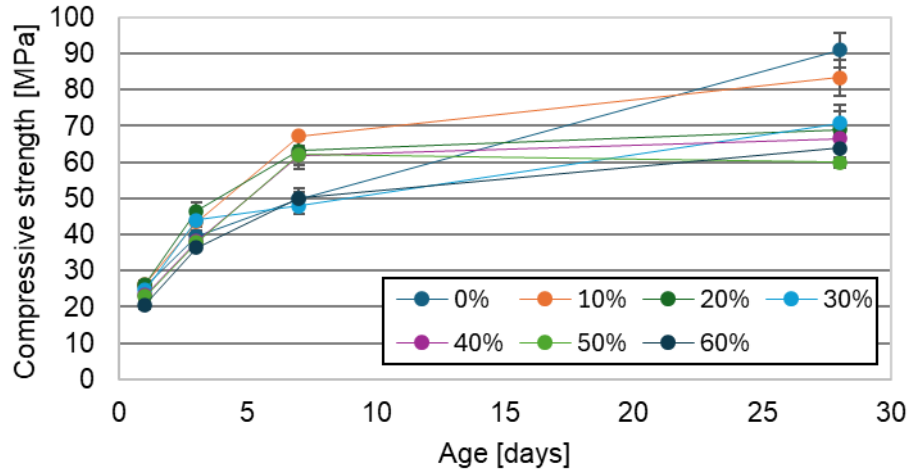


**Figure 4.47: Compressive strength over time – 0/1 mm**

The compressive strength over time has been normalized in Figure 4.48. The greater the change in ratio, the greater the development of the compressive strength. A higher sand content shows a greater initial development, before stabilizing from 7 to 28 days. When decreasing the sand content, the development happens more gradually. This development is similar to the flexural strength with 0/1 mm sea sand, the sand particles are too small to influence the geopolymer mixture after 7 days.

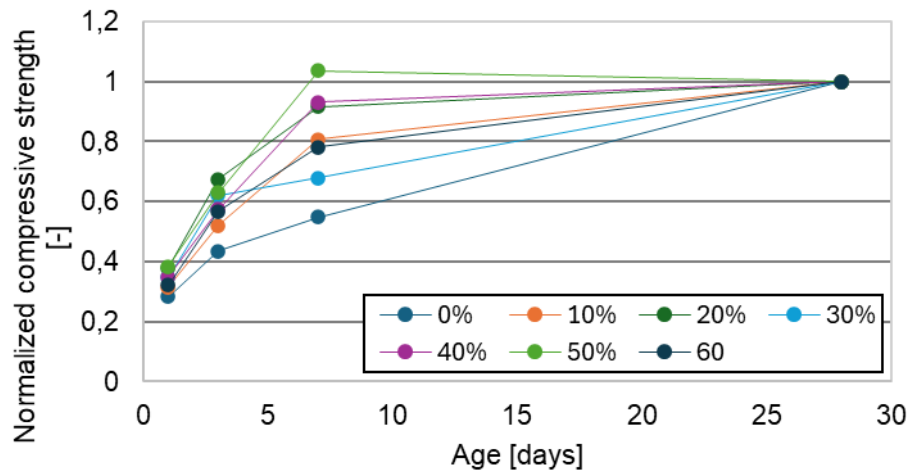


**Figure 4.48: Normalized compressive strength – 0/1 mm**

From this normalized graph, an estimation model is made for the compressive strength of geopolymer mortars made with sea sand 0/1 mm (Figure 4.49). Following logarithmic relationship (4.12) is obtained:

$$R_{c,normalized} = 0.2019 * \ln(t) + 0.3603 \quad (4.12)$$

By rewriting this relationship in function of the compressive strength at 28 days, formula 4.13 is obtained:

$$R_c(t) = [0.2019 * \ln(t) + 0.3603] * R_c(28) \quad (4.13)$$

This estimation model has a coefficient of determination  $R^2$  of 0.8734, which indicates an adequate correlation between the two variables.

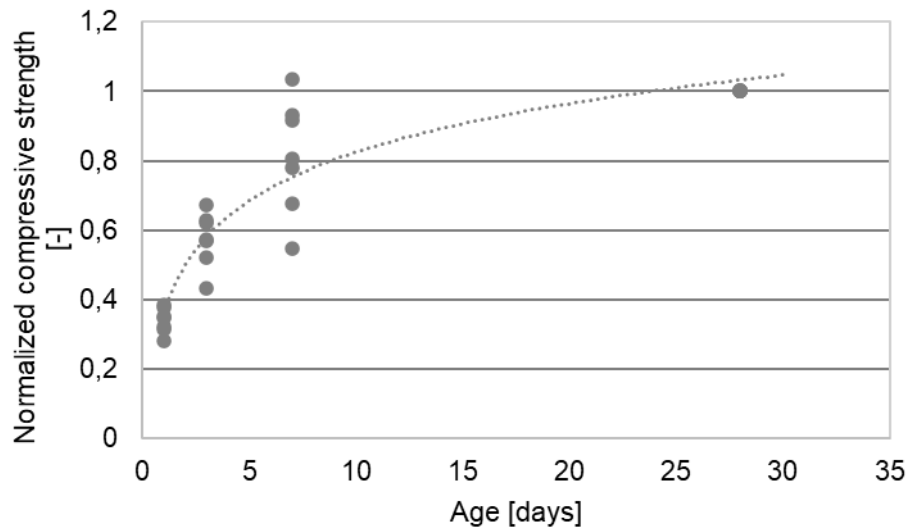


**Figure 4.49: Model estimation – Compressive strength 0/1 mm**

### **CEN Standard sand**

The compressive strength for different sand contents of CEN Standard sand is plotted after 1 day, 3 days, 7 days and 28 days on Figure 4.50, Figure 4.51, Figure 4.52 and Figure 4.53 respectively. For each of the sample ages, there is no significant influence in the compressive strength when increasing the sand content. Coarse sand particles absorb less water, making the mixture more workable and better compactable, limiting the amount of pores. The compressive strength after 28 days reaches a value of  $87.4 \pm 2.5$  MPa.

As was discussed in chapter 4.2.1, an increase in pore-formation takes place from 60 wt.% sand due to the bad workability and compactability of the mixture. Increasing the sand content even further would lead to an increase in pores, reducing the strength of the geopolymer matrix.

The optimal sand quantity is highly depending on the workability of the mixture and of grain size. An increased flowability of the geopolymer paste, and an increased grain size, leads to a higher optimal sand content.

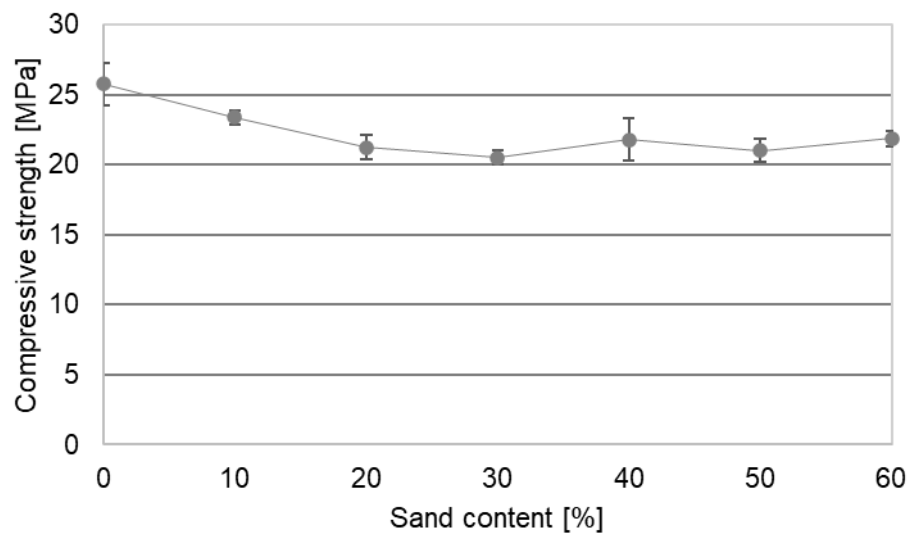


**Figure 4.50: Compressive strength CEN – 1 day**

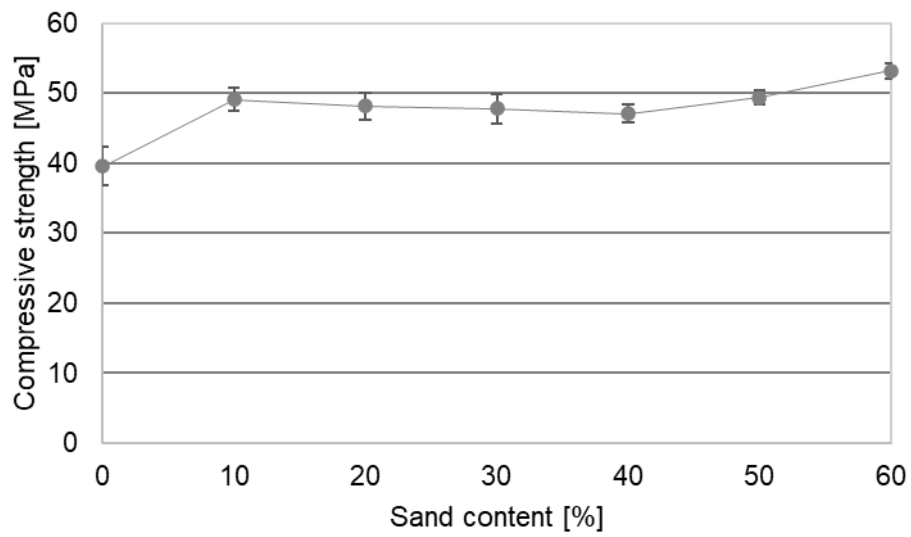


**Figure 4.51: Compressive strength CEN – 3 days**

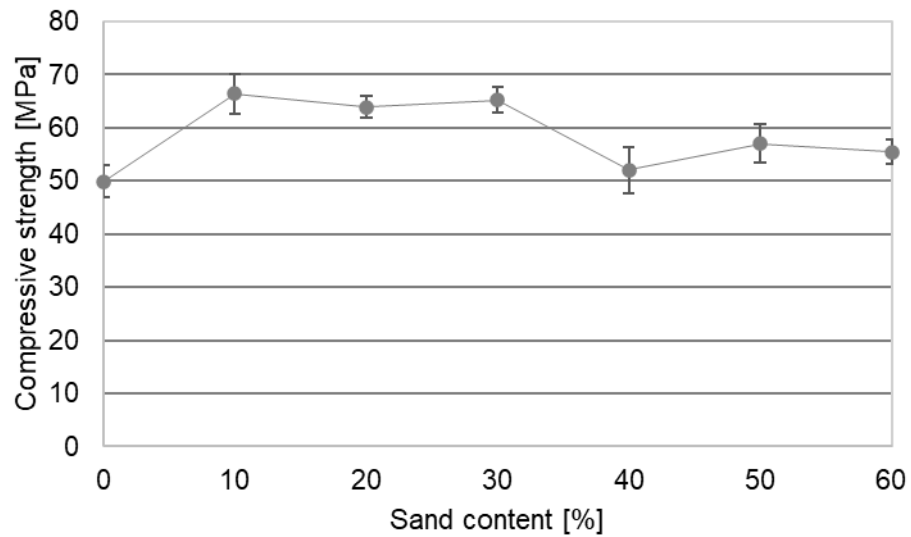


**Figure 4.52: Compressive strength CEN – 7 days**

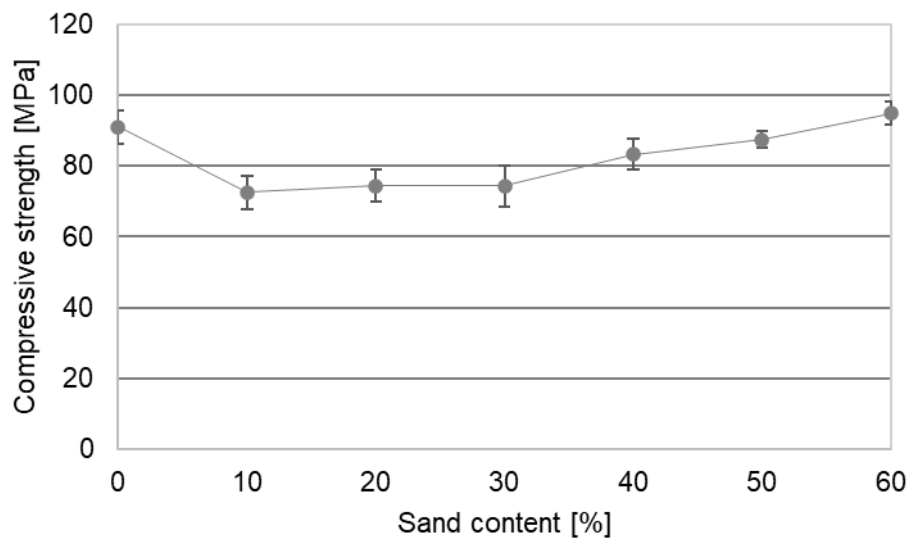


**Figure 4.53: Compressive strength CEN – 28 days**

The compressive strength over time is plotted for different sand contents in Figure 4.54. From this graph can be concluded that the compressive strength increases over time. Furthermore, an increase in sand content leads to an increase in compressive strength.

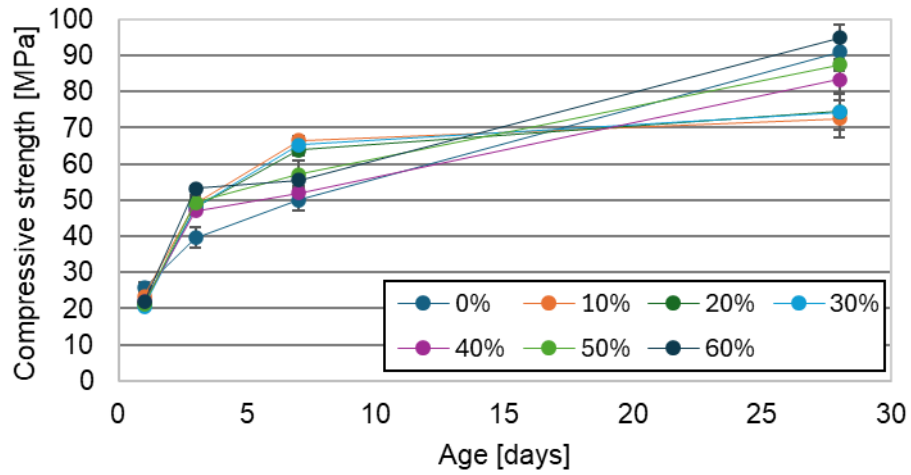


**Figure 4.54: Compressive strength over time – CEN**

By normalizing the compressive strength over time (Figure 4.55), the development of the strength can be seen in further detail.

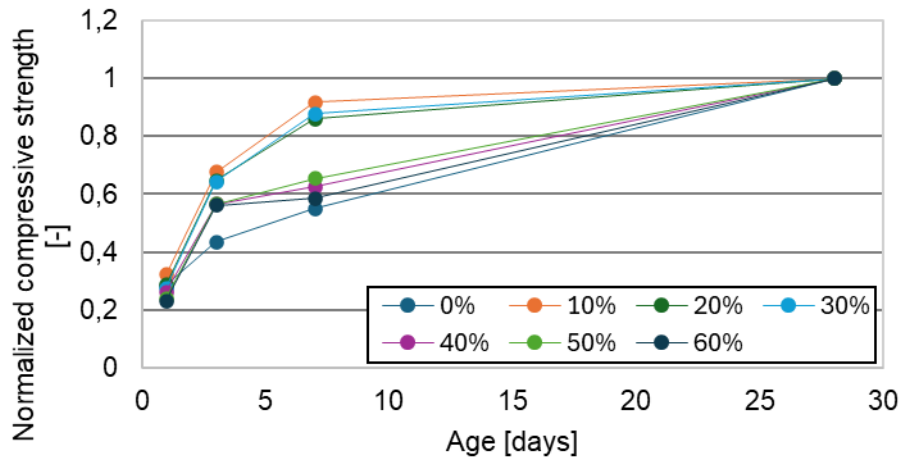


**Figure 4.55: Normalized compressive strength – CEN**

From the normalized curve, an estimation model is made. This model is visible in Figure 4.56. From this model, an estimation of the compressive strength over time can be made with following logarithmic relationship (4.14):

$$R_{c,normalized} = 0.2142 * \ln(t) + 0.3034 \quad (4.14)$$

This relationship can be rewritten in function of the compressive strength at 28 days, which gives the following formula (4.15):

$$R_c(t) = [0.2142 * \ln(t) + 0.3034] * R_c(28) \quad (4.15)$$

This estimation model has a coefficient of determination  $R^2$  of 0.8993, which indicates a good correlation between the two variables.

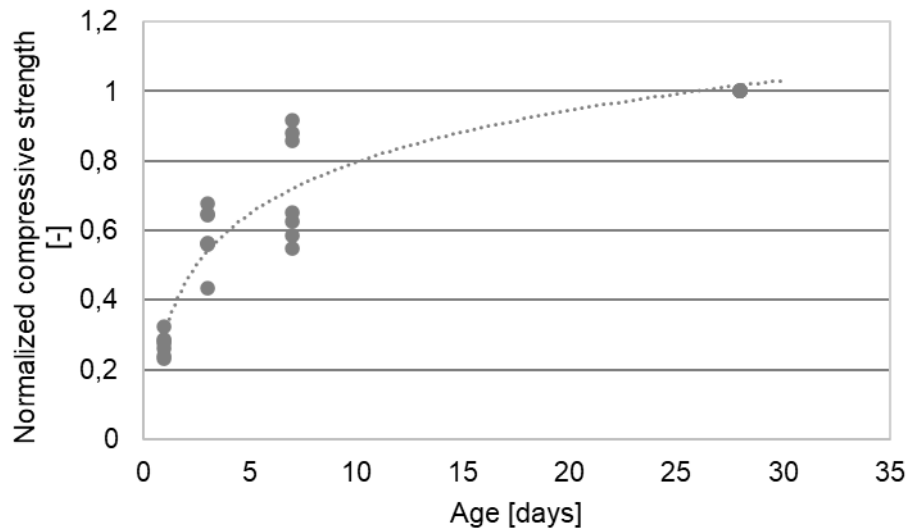


**Figure 4.56: Model estimation – Compressive strength CEN**

### Compressive strength at 28 days

On Figure 4.57, the compressive strength for different sand contents is visible for each type of sand. As can be seen on the figure, increasing the sand content doesn't have a significant influence on the compressive strength. The type of sand, however, plays an important role in the strength development. Finer sand particles have a negative influence on the compressive strength of the geopolymer mortars compared to coarser sand particles. Coarser particles absorb less water, leading to an ameliorated workability compared to finer particles. Mixtures with a better workability are easier to compact, decreasing the air content and pores within the mixture, thus improving the overall strength of the matrix. The compressive strength made with 50 wt.% CEN Standard sand is 7.9% higher than with 0/2 mm sea sand, and 31.5 % higher than with 0/1 mm sea sand.

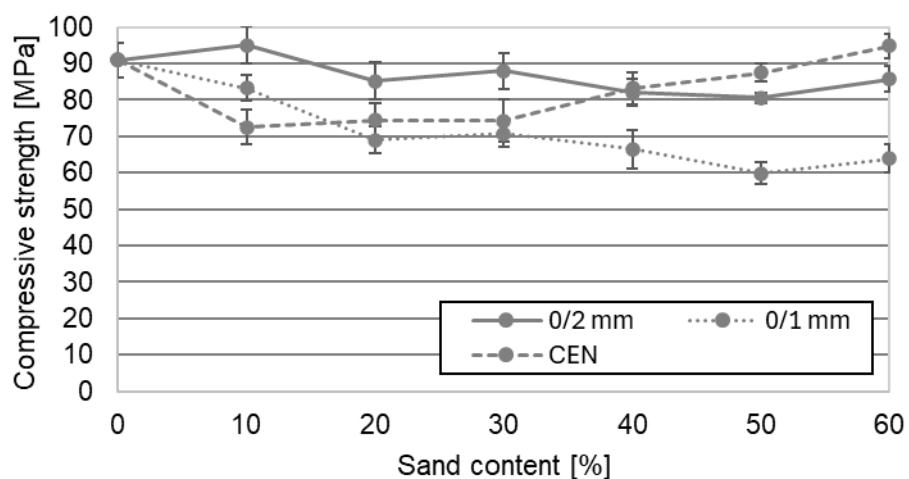


**Figure 4.57: Compressive strength at 28 days**

### Comparison estimation models

The three estimation models for the compressive strength are visualized in Figure 4.58. From this graph, together with the equations 4.11, 4.13 and 4.15, strength gain over time and the early strength development for the three types of sand can be analyzed. The early-age strength ratio is the highest for sea sand 0/1 mm, followed by CEN sand and sea sand 0/2 mm. Sea sand 0/1 mm has reached 36.03% of its 28-day strength at 1 day, while sea sand 0/2 mm reaches only 19.63% of its 28-day strength at 1 day. Sea sand 0/2 mm knows the highest growth rate, followed by CEN sand and sea sand 0/1 mm.

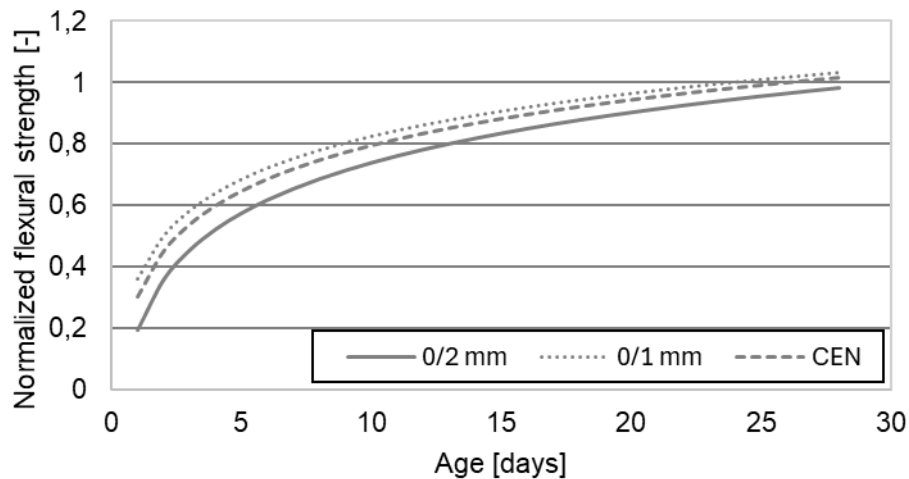


Figure 4.58: Comparison estimation models - Compressive strength

From Figure 4.58, no correlation between the fineness modulus of the used sands and the estimation models can be found. When looking for a linear correlation, both the early-age strength factor and the logarithmic growth coefficient have a coefficient of determination  $R^2$  around the 0.01.

#### 4.2.4.3 Compressive versus flexural strength

The compressive strength plotted against the flexural strength is visible in Figure 4.59, Figure 4.60 and Figure 4.61 for sea sand 0/2 mm, sea sand 0/1 mm and CEN Standard sand respectively. For the three sand types, an increase in compressive strength leads to an increase in flexural strength. Furthermore, an increase in sand content leads to an increase in flexural strength for the same compressive strength.

These findings are similar to the ones found in literature. Steinerova [73] and Zhang, Su, Goao, Zhang and Zhang [72] noted an increase in flexural strength when the compressive strength increased for geopolymer mortars with metakaolin.

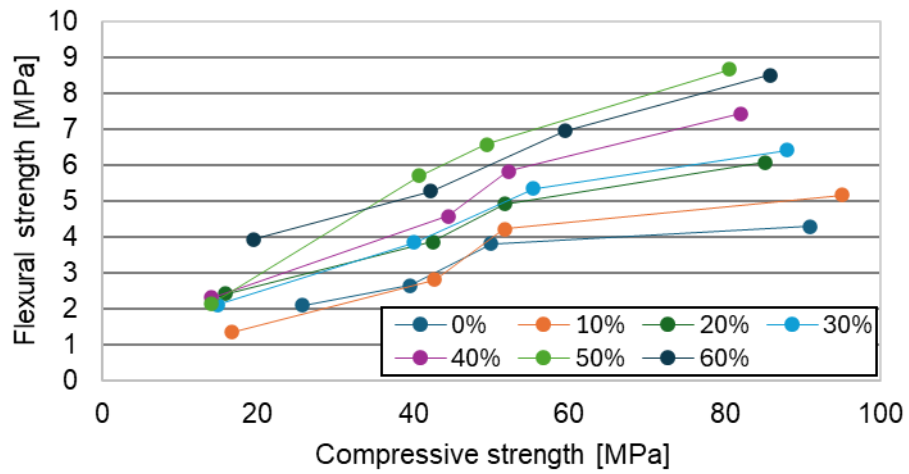


Figure 4.59: Compressive versus flexural strength - 0/2 mm

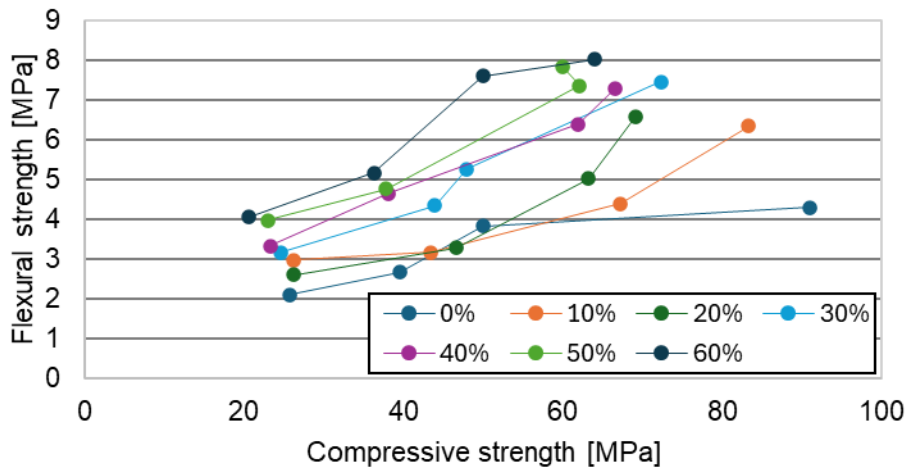


Figure 4.60: Compressive versus flexural strength - 0/1 mm

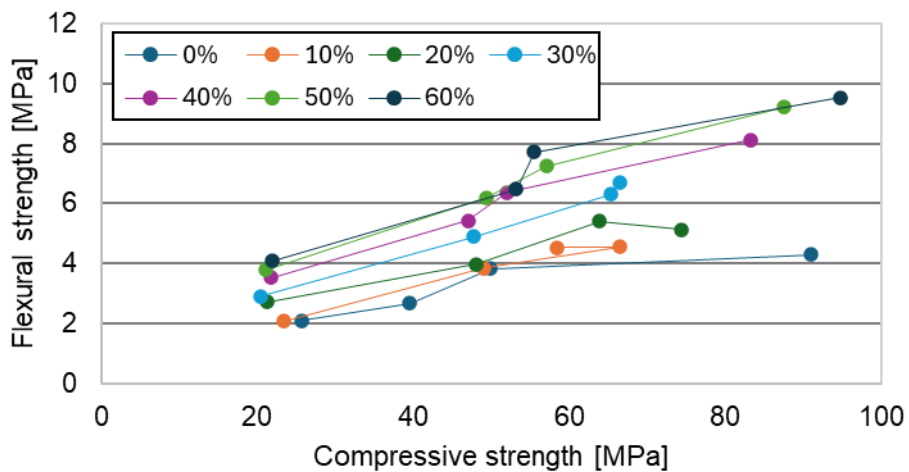


Figure 4.61: Compressive versus flexural strength - CEN

### 4.2.5 Temperature

The temperature of fresh mixtures has been measured for different sand contents, as can be seen on Figure 4.62. The temperature of the mixtures is highly dependent on the ambient temperature in the lab. However, an increase in temperature can be seen with an increased sand content. A higher sand content leads to a stiffer mix, requiring a higher mechanical energy input. This energy is partly released as heat. Moreover, the geopolymerization reaction itself is exothermic, which releases heat. Increasing the sand content decreases the thermal inertia of the mixture, limiting its ability to absorb and dissipate heat, leading to a temperature increase.

This aligns to findings in the literature regarding increased sand content in cement applications [80]. The specific heat of the mortar decreases with an increase in sand content, resulting in less heat being stored in the mixture and a more rapid heat release. The thermal conductivity increases, leading to an easier heat transfer.

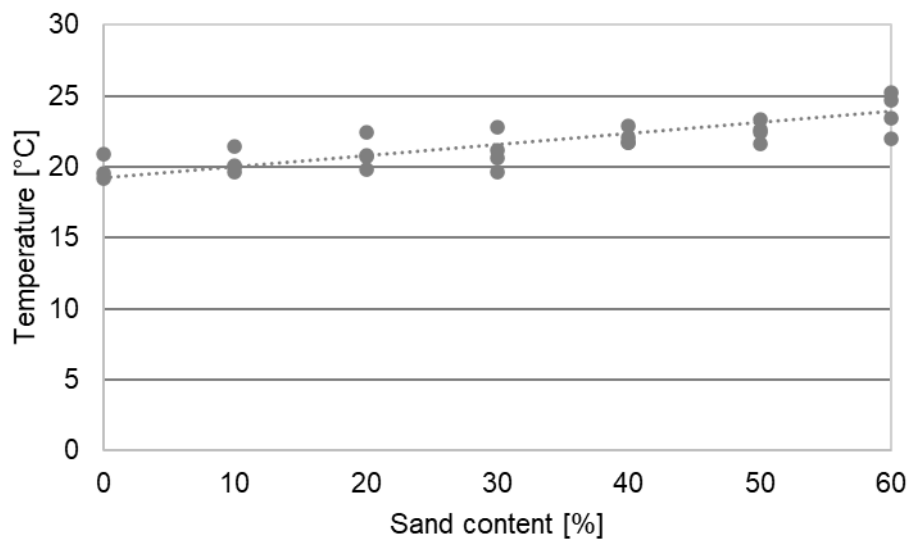


**Figure 4.62: Temperature for different sand contents**

## 5 CONCLUSION

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### 5.1 Research findings

This master's thesis investigates the effect of the binder-to-sand ratio on the workability and mechanical properties of GGBS-CDW based geopolymer mortars. A geopolymer mixture consisting of 60% GGBS, 15% RCP and 25% RBP is used. The geopolymer paste has a compressive strength of 62 MPa after 28 days, an initial and final setting time of 90 minutes and 100 minutes respectively, and a flowability index of 7.4. The geopolymer mortars were tested for three different types of sand by gradually increasing the sand content from 0 wt.% to 60 wt.%.

#### **Dry bulk density**

Increasing the sand content up to 50 wt.% leads to an increase in the dry bulk density of the mortars, before stabilizing and decreasing. A minimal total porosity is reached when the bulk density is at its maximum. Excessive sand results in poor workability and compaction due to the lack of binder paste, leading to increased pore formation. Based on the measured dry bulk density, an optimal binder-to-sand ratio of 1:1 is found for the three sand types. For coarser sand types, such as CEN sand, lower binder-to-sand ratios can be considered.

#### **Workability**

The workability of the geopolymer mortars is tested based on the flowability index. An increase in sand content results in a decrease in flowability index. For an optimal flowability index of 2.5, a sand content between 50 wt.% and 55 wt.% can be used. For coarser sand types, the sand content might be increased up to 60 wt.%.

#### **Flexural strength**

The mechanical properties of the geopolymer mortars is tested from 1 day up to 28 days. The flexural strength of the geopolymer mortar is dependent on the sand content and sand type. A higher sand content increases the flexural strength at 28 days up to an optimal sand content. Coarser sand types, such as CEN sand, reach values up to  $9.5 \pm 0.1$  MPa with 60 wt.%. Finer sand types, such as sea sand 0/2 mm and sea sand 0/1 mm, have their optimal value at 50 wt.% sand, reaching  $8.7 \pm 0.7$  MPa and  $7.8 \pm 0.4$  MPa respectively.

#### **Compressive strength**

The compressive strength of the geopolymer mortars is more dependent on the sand type than on the sand content. An increase in sand content does not have a significant influence on the compressive strength at 28 days for each sand type. For sea sand 0/1 mm, the compressive strength drops at 28 days up to 20 wt.% sand, before stabilizing. This decrease is due to the small size of the particles, absorbing more water and increasing the porosity of the mixture. Smaller sand particles results in lower compressive strengths, with sea sand 0/1 mm reaching a value of  $59.9 \pm 3.1$  MPa at 28 days for 50 wt.% sand. Sea sand 0/2 mm and CEN sand, on the other hand, reach values around  $80.5 \pm 1.5$  MPa and  $87.4 \pm 2.5$  MPa respectively.

## Summary

In a nutshell, the research findings can be summarized as shown in Table 5.1:

**Table 5.1: Summary research findings**

|                        | Dry bulk density | Workability | Flexural strength | Compressive strength |
|------------------------|------------------|-------------|-------------------|----------------------|
| Sand ↗ (up to 50 wt.%) | ↗                | ↘           | ↗                 | →                    |
| Sand ↗ (50 - 60 wt.%)  | →/↘              | ↘           | →                 | →                    |
| Coarseness ↗           | ↗                | ↗           | ↗                 | ↗                    |

## 5.2 Limitations of the research

There are different factors in this master's thesis that were not taken into account. Firstly, the workability of the geopolymer mortars was tested by only considering the flowability index. Even though the initial and final setting time of the geopolymer mortar was tested, no tests were conducted to evaluate the change in setting time based on the different sand contents.

Moreover, the porosity of the geopolymer samples was evaluated based on correlations with bulk density found in literature. A better correlation between the porosity and test results would be possible by executing high pressure mercury porosimetry, or if SEM microscopy images were made of the samples.

Furthermore, only three different types of sand were analyzed, with two of the sand types being sea sand. As sea sand is one of the most used types of sand in Belgium, this limitation is quite insubstantial.

Additionally, this research only focused on the workability and mechanical properties of the geopolymer mortars, not taking long-term durability aspects into account.

## 5.3 Suggestions for further research

As sea sand is becoming more scarce, it would be a great alternative to use recycled sand and evaluate the properties of varying binder-to-sand ratios on geopolymer mortars.

Furthermore, it might be interesting to investigate the long-term durability aspects of geopolymer mortars with varying binder-to-sand ratios, such as the resistance to freeze-thaw cycles, carbonation resistance and chemical resistance.

Geopolymers have a lower carbon footprint than cement, making it an environmental friendly alternative. However, the carbon dioxide emitted from geopolymers varies based on the precursors and activators used. Conducting embodied carbon calculations or an overall life cycle analysis (LCA) could evaluate the environmental benefits of the geopolymer mortars.

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## Appendix A: Mix design geopolymers paste

**Table A.1: Mix design geopolymers paste**

| Number | Mix design     | Precursor [g] | GGBS [%] | RCP [%] | RBP [%] | SS [g] | SH [g] | H <sub>2</sub> O [g] | Na <sub>2</sub> O/b | SiO <sub>2</sub> /Na <sub>2</sub> O | w/b  |
|--------|----------------|---------------|----------|---------|---------|--------|--------|----------------------|---------------------|-------------------------------------|------|
| 1      | G-8%-1,38-0,40 | 400           | 40       | 60      | -       | 164,7  | 24,5   | 50,9                 | 8                   | 1,38                                | 0,40 |
| 2      | G-8%-1,38-0,40 | 400           | 40       | -       | 60      | 164,7  | 24,5   | 50,9                 | 8                   | 1,38                                | 0,40 |
| 3      | G-8%-1,38-0,40 | 400           | 40       | 30      | 30      | 164,7  | 24,5   | 50,9                 | 8                   | 1,38                                | 0,40 |
| 4      | G-8%-1,38-0,40 | 400           | 40       | 20      | 40      | 164,7  | 24,5   | 50,9                 | 8                   | 1,38                                | 0,40 |
| 5      | G-8%-1,38-0,40 | 400           | 40       | 10      | 50      | 164,7  | 24,5   | 50,9                 | 8                   | 1,38                                | 0,40 |
| 6      | G-8%-1,38-0,40 | 400           | 40       | 40      | 20      | 164,7  | 24,5   | 50,9                 | 8                   | 1,38                                | 0,40 |
| 7      | G-8%-1,38-0,40 | 400           | 40       | 50      | 10      | 164,7  | 24,5   | 50,9                 | 8                   | 1,38                                | 0,40 |
| 8      | G-8%-1,38-0,40 | 400           | 50       | 50      | -       | 164,7  | 24,5   | 50,9                 | 8                   | 1,38                                | 0,40 |
| 9      | G-8%-1,38-0,40 | 400           | 50       | -       | 50      | 164,7  | 24,5   | 50,9                 | 8                   | 1,38                                | 0,40 |
| 10     | G-8%-1,38-0,40 | 400           | 50       | 25      | 25      | 164,7  | 24,5   | 50,9                 | 8                   | 1,38                                | 0,40 |
| 11     | G-8%-1,38-0,40 | 400           | 50       | 12,5    | 37,5    | 164,7  | 24,5   | 50,9                 | 8                   | 1,38                                | 0,40 |
| 12     | G-8%-1,38-0,40 | 400           | 50       | 6,3     | 43,8    | 164,7  | 24,5   | 50,9                 | 8                   | 1,38                                | 0,40 |
| 13     | G-8%-1,38-0,40 | 400           | 50       | 37,5    | 12,5    | 164,7  | 24,5   | 50,9                 | 8                   | 1,38                                | 0,40 |
| 14     | G-8%-1,38-0,40 | 400           | 50       | 43,8    | 6,3     | 164,7  | 24,5   | 50,9                 | 8                   | 1,38                                | 0,40 |
| 15     | G-8%-1,38-0,40 | 400           | 60       | 40      | -       | 164,7  | 24,5   | 50,9                 | 8                   | 1,38                                | 0,40 |
| 16     | G-8%-1,38-0,40 | 400           | 60       | -       | 40      | 164,7  | 24,5   | 50,9                 | 8                   | 1,38                                | 0,40 |
| 17     | G-8%-1,38-0,40 | 400           | 60       | 20      | 20      | 164,7  | 24,5   | 50,9                 | 8                   | 1,38                                | 0,40 |
| 18     | G-8%-1,38-0,40 | 400           | 60       | 15      | 25      | 164,7  | 24,5   | 50,9                 | 8                   | 1,38                                | 0,40 |
| 19     | G-8%-1,38-0,40 | 400           | 60       | 10      | 30      | 164,7  | 24,5   | 50,9                 | 8                   | 1,38                                | 0,40 |
| 20     | G-8%-1,38-0,40 | 400           | 60       | 25      | 15      | 164,7  | 24,5   | 50,9                 | 8                   | 1,38                                | 0,40 |
| 21     | G-8%-1,38-0,40 | 400           | 60       | 30      | 10      | 164,7  | 24,5   | 50,9                 | 8                   | 1,38                                | 0,40 |
| 22     | G-8%-1,38-0,40 | 400           | 70       | 30      | -       | 164,7  | 24,5   | 50,9                 | 8                   | 1,38                                | 0,40 |
| 23     | G-8%-1,38-0,40 | 400           | 70       | -       | 30      | 164,7  | 24,5   | 50,9                 | 8                   | 1,38                                | 0,40 |
| 24     | G-8%-1,38-0,40 | 400           | 70       | 15      | 15      | 164,7  | 24,5   | 50,9                 | 8                   | 1,38                                | 0,40 |
| 25     | G-8%-1,38-0,40 | 400           | 70       | 10      | 20      | 164,7  | 24,5   | 50,9                 | 8                   | 1,38                                | 0,40 |
| 26     | G-8%-1,38-0,40 | 400           | 70       | 5       | 25      | 164,7  | 24,5   | 50,9                 | 8                   | 1,38                                | 0,40 |
| 27     | G-8%-1,38-0,40 | 400           | 70       | 20      | 10      | 164,7  | 24,5   | 50,9                 | 8                   | 1,38                                | 0,40 |

## Appendix B: Calculations alkaline activator content

### Sodium silicate calculation

The calculation of the quantity of sodium silicate is done as follows:

- $\frac{Na_2O}{b}$  is set on 8%. For a binder quantity of 400 g, 32 g of  $Na_2O$  is obtained:  
$$\frac{Na_2O}{b} = 8\% \Leftrightarrow Na_2O = 8\% * b = 8\% * 400\text{ g} = 32\text{ g } Na_2O_{(t)}$$

By dividing this value with the molar mass of  $Na_2O$ , the quantity of mol  $Na_2O$  is calculated:

$$\frac{32\text{ g } Na_2O_{(t)}}{61,979\text{ g/mol}} = 0,516\text{ mol } Na_2O_{(t)}$$

- $\frac{n(SiO_2)}{n(Na_2O_{(t)})}$  is set on 1.38, this can be rewritten to obtain the mol for  $SiO_2$ :  
$$\frac{n(SiO_2)}{n(Na_2O_{(t)})} = \frac{n(SiO_2)}{0,516\text{ mol } Na_2O_{(t)}} = 1.38 \Leftrightarrow n(SiO_2) = 1.38 * 0,516\text{ mol } Na_2O_{(t)}$$
  
$$\Leftrightarrow n(SiO_2) = 0.712\text{ mol}$$
  
$$\Leftrightarrow m(SiO_2) = 0.712\text{ mol} * 60.08 \frac{\text{g}}{\text{mol}} = 42.77\text{ g } SiO_2$$
- 25.9%  $SiO_2$  is present in the sodium silicate aqueous solution that is used:  
$$42.77\text{ g } SiO_2 \cong 25.9\% \text{ SS} \Leftrightarrow 100\% \text{ SS} = 164.7\text{ g}$$

The total quantity of sodium silicate is equal to 164.7 g.

### Sodium hydroxide calculation

The quantity of sodium hydroxide is calculated as shown below.

- Firstly, the mol  $Na_2O$  of the sodium hydroxide solution is calculated:  
$$n(Na_2O_{(SH)}) = n(Na_2O_{(t)}) - n(Na_2O_{(SS)})$$
  
$$\Leftrightarrow n(Na_2O_{(SH)}) = 0,516\text{ mol } Na_2O_{(t)} - \frac{7.9\% * 164.7}{61,978} Na_2O_{(SS)}$$
  
In this equation, 7.9% is the quantity of  $Na_2O$  in the used sodium silicate solution, 61.98 is the molar mass of  $Na_2O$ , and 164.7 is the total mass of sodium silicate.  
$$\Leftrightarrow n(Na_2O_{(SH)}) = 0,306\text{ mol } Na_2O$$
- Knowing that following reaction takes place, the mol of sodium hydroxide can be calculated.  
$$2NaOH \xrightarrow{\text{equivalent}} Na_2O + H_2O$$
  
$$2 * n(NaOH) = n(Na_2O_{(SH)})$$
  
$$\Leftrightarrow 2 * 0.306\text{ mol } NaOH = 0,306\text{ mol } Na_2O$$
  
$$\Leftrightarrow 0,612\text{ mol } NaOH = 0,306\text{ mol } Na_2O$$
- By multiplying the mol of sodium hydroxide with its molar mass, the mass of sodium hydroxide is calculated.

$$SH = 0,612 \text{ mol} * 39,997 \frac{\text{g}}{\text{mol}} = 24,466 \text{ g}$$

The total quantity of the sodium hydroxide is 24.5 g.

### Water calculation

The quantity of water added to the mixture is calculated below.

- The water-to-binder ratio is equal to 0.4:

$$\frac{w}{b} = 0.4 \Leftrightarrow H_2O_{(t)} = 0.4 * binder = 0.4 * 400 \text{ g} = 160 \text{ g}$$

$$160 \text{ g } H_2O_{(t)} = H_2O_{(SS)} + H_2O_{(extra)}$$

- The mass of water originated from sodium silicate is calculated as follows,  
 $H_2O_{(SS)} = (1 - 0.079 - 0.259) * 164.7 \text{ g} = 109.1 \text{ g}$   
 with 0.079 being the sodium oxide content, and 0.259 the silica content.

- The extra water added to the mixture can now be calculated.

$$H_2O_{(extra)} = 160 \text{ g } H_2O_{(t)} - 109.1 \text{ g } H_2O_{(SS)} = 50.9 \text{ g}$$

The total quantity of water is 50.9 g.

## Appendix C: Measured dry bulk density

Table C.1: Measured dry bulk density – 0/2 mm

| Sand [mm] | Sand quantity [%] | Age [days] | Weight [g] | Mean [g] | s [g] |
|-----------|-------------------|------------|------------|----------|-------|
| -         | 0                 | 28         | 498,6      | 500,4    | 1,6   |
|           |                   |            | 500,8      |          |       |
|           |                   |            | 501,8      |          |       |
| 0/2       | 10                | 28         | 507,9      | 505,8    | 3,1   |
|           |                   |            | 502,3      |          |       |
|           |                   |            | 507,2      |          |       |
| 0/2       | 20                | 28         | 526        | 526,9    | 0,9   |
|           |                   |            | 527,8      |          |       |
|           |                   |            | 526,9      |          |       |
| 0/2       | 30                | 28         | 536,5      | 542,9    | 5,8   |
|           |                   |            | 544,3      |          |       |
|           |                   |            | 547,8      |          |       |
| 0/2       | 40                | 28         | 537,9      | 535,5    | 3,5   |
|           |                   |            | 531,5      |          |       |
|           |                   |            | 537        |          |       |
| 0/2       | 50                | 28         | 559,8      | 562,4    | 4,6   |
|           |                   |            | 559,7      |          |       |
|           |                   |            | 567,8      |          |       |
| 0/2       | 60                | 28         | 570,3      | 565,7    | 7,9   |
|           |                   |            | 570,3      |          |       |
|           |                   |            | 556,6      |          |       |

**Table C.2: Measured dry bulk density – 0/1 mm**

| Sand [mm] | Sand quantity [%] | Age [days] | Weight [g] | Mean [g] | s [g] |
|-----------|-------------------|------------|------------|----------|-------|
| -         | 0                 | 28         | 498,6      | 500,4    | 1,6   |
|           |                   |            | 500,8      |          |       |
|           |                   |            | 501,8      |          |       |
| 0/1       | 10                | 28         | 512,3      | 512,9    | 1,6   |
|           |                   |            | 511,7      |          |       |
|           |                   |            | 514,8      |          |       |
| 0/1       | 20                | 28         | 521,8      | 522,9    | 1,8   |
|           |                   |            | 522        |          |       |
|           |                   |            | 525        |          |       |
| 0/1       | 30                | 28         | 536,5      | 531,7    | 4,2   |
|           |                   |            | 530,1      |          |       |
|           |                   |            | 528,6      |          |       |
| 0/1       | 40                | 28         | 544,6      | 545,5    | 2,0   |
|           |                   |            | 547,8      |          |       |
|           |                   |            | 544        |          |       |
| 0/1       | 50                | 28         | 560,7      | 560,7    | 0,9   |
|           |                   |            | 559,8      |          |       |
|           |                   |            | 561,6      |          |       |
| 0/1       | 60                | 28         | 553,8      | 555,0    | 10,5  |
|           |                   |            | 566        |          |       |
|           |                   |            | 545,1      |          |       |

**Table C.3: Measured dry bulk density – CEN**

| Sand [mm] | Sand quantity [%] | Age [days] | Weight [g] | Mean [g] | s [g] |
|-----------|-------------------|------------|------------|----------|-------|
| -         | 0                 | 28         | 498,6      | 500,4    | 1,6   |
|           |                   |            | 500,8      |          |       |
|           |                   |            | 501,8      |          |       |
| CEN       | 10                | 28         | 512,2      | 512,4    | 3,7   |
|           |                   |            | 516,2      |          |       |
|           |                   |            | 508,9      |          |       |
| CEN       | 20                | 28         | 517,6      | 517,4    | 1,6   |
|           |                   |            | 518,8      |          |       |
|           |                   |            | 515,7      |          |       |
| CEN       | 30                | 28         | 548,3      | 548,4    | 2,5   |
|           |                   |            | 550,9      |          |       |
|           |                   |            | 546        |          |       |
| CEN       | 40                | 28         | 554        | 555,7    | 2,1   |
|           |                   |            | 555,1      |          |       |
|           |                   |            | 558        |          |       |
| CEN       | 50                | 28         | 579,4      | 581,6    | 3,1   |
|           |                   |            | 580,3      |          |       |
|           |                   |            | 585,2      |          |       |
| CEN       | 60                | 28         | 578,6      | 585,2    | 5,8   |
|           |                   |            | 589,7      |          |       |
|           |                   |            | 587,2      |          |       |

## Appendix D: Measured flowability index

**Table D.1: Measured flowability index – 0%**

| Sand [mm] | Sand quantity [%] | d1 [cm] | d2 [cm] | d2 [cm] | D   | D mean |
|-----------|-------------------|---------|---------|---------|-----|--------|
| -         | 0                 | 29,1    | 29,3    | 10,0    | 7,5 | 7,8    |
|           |                   | 29,3    | 30,7    | 10,0    | 8,0 |        |

**Table D.2: Measured flowability index – 0/2 mm**

| Sand [mm] | Sand quantity [%] | d1 [cm] | d2 [cm] | d2 [cm] | D   | D mean |
|-----------|-------------------|---------|---------|---------|-----|--------|
| 0/2       | 10,0              | 29,7    | 30,4    | 10,0    | 8,0 | 8,1    |
|           |                   | 30,9    | 29,5    | 10,0    | 8,1 |        |
| 0/2       | 20,0              | 28,3    | 28,9    | 10,0    | 7,2 | 7,2    |
|           |                   | 28,7    | 28,5    | 10      | 7,2 |        |
| 0/2       | 30,0              | 25,2    | 25,7    | 10,0    | 5,5 | 5,6    |
|           |                   | 25,6    | 26,1    | 10      | 5,7 |        |
| 0/2       | 40,0              | 24,6    | 24,3    | 10,0    | 5,0 | 5,0    |
|           |                   | 24,6    | 24,2    | 10      | 5,0 |        |
| 0/2       | 50,0              | 22,4    | 22,8    | 10,0    | 4,1 | 4,1    |
|           |                   | 22,1    | 22,6    | 10,0    | 4,0 |        |
| 0/2       | 60,0              | 14,3    | 14,4    | 10,0    | 1,1 | 0,9    |
|           |                   | 13,1    | 13      | 10,0    | 0,7 |        |

**Table D.3: Measured flowability index – 0/1 mm**

| Sand [mm] | Sand quantity [%] | d1 [cm] | d2 [cm] | d2 [cm] | D      | D mean |
|-----------|-------------------|---------|---------|---------|--------|--------|
| 0/1       | 10,0              | 30,0    | 29,7    | 10,0    | 7,9    | 7,9    |
|           |                   | 29,5    | 29,8    | 10,0    | 7,8    |        |
| 0/1       | 20,0              | 28,0    | 28,3    | 10,0    | 6,9    | 7,1    |
|           |                   | 28,9    | 28,4    | 10      | 7,2    |        |
| 0/1       | 30,0              | 26,2    | 26,7    | 10,0    | 6,0    | 6,0    |
|           |                   | 26,6    | 26,5    | 10      | 6,0    |        |
| 0/1       | 40,0              | 24,9    | 24,4    | 10,0    | 5,1    | 5,1    |
|           |                   | 24,9    | 24,7    | 10      | 5,1503 |        |
| 0/1       | 50,0              | 21,0    | 21,3    | 10,0    | 3,5    | 3,5    |
|           |                   | 21,5    | 21,5    | 10,0    | 3,6    |        |
| 0/1       | 60,0              | 15,5    | 15,5    | 10,0    | 1,4    | 1,5    |
|           |                   | 16,1    | 15,8    | 10,0    | 1,5    |        |

**Table D.4: : Measured flowability index – CEN**

| Sand [mm] | Sand quantity [%] | d1 [cm] | d2 [cm] | d2 [cm] | D   | D mean |
|-----------|-------------------|---------|---------|---------|-----|--------|
| CEN       | 10,0              | 28,9    | 28,5    | 10,0    | 7,2 | 7,3    |
|           |                   | 29,0    | 29      | 10,0    | 7,4 |        |
| CEN       | 20,0              | 27,5    | 27,5    | 10,0    | 6,6 | 6,6    |
|           |                   | 27,3    | 28      | 10      | 6,6 |        |
| CEN       | 30,0              | 26,0    | 26,5    | 10,0    | 5,9 | 6,2    |
|           |                   | 27      | 27,5    | 10      | 6,4 |        |
| CEN       | 40,0              | 27,0    | 26,8    | 10,0    | 6,2 | 5,9    |
|           |                   | 25,4    | 25,6    | 10      | 5,5 |        |
| CEN       | 50,0              | 24,5    | 24      | 10,0    | 4,9 | 4,9    |
|           |                   | 24,5    | 24,2    | 10,0    | 4,9 |        |
| CEN       | 60,0              | 21,0    | 20,3    | 10,0    | 3,3 | 3,2    |
|           |                   | 20,1    | 20,1    | 10,0    | 3,0 |        |

## Appendix E: Measured flexural strength

**Table E.1: Measured flexural strength – Geopolymer paste**

| Sand [mm] | Sand quantity [%] | Age [days] | Prism | R <sub>f</sub> [MPa] | R <sub>f,mean</sub> [MPa] | s [MPa] |
|-----------|-------------------|------------|-------|----------------------|---------------------------|---------|
| -         | 0                 | 1          | 1     | 2,088                | 2,1                       | 0,02    |
|           | 0                 | 1          | 2     | 2,108                |                           |         |
|           | 0                 | 1          | 3     | 2,066                |                           |         |
| -         | 0                 | 3          | 1     | 2,324                | 2,7                       | 0,4     |
|           | 0                 | 3          | 2     | 2,614                |                           |         |
|           | 0                 | 3          | 3     | 3,03                 |                           |         |
| -         | 0                 | 7          | 1     | 4,343                | 3,8                       | 0,5     |
|           | 0                 | 7          | 2     | 3,721                |                           |         |
|           | 0                 | 7          | 3     | 3,39                 |                           |         |
| -         | 0                 | 27         | 1     | 5,287                | 4,3                       | 0,9     |
|           | 0                 | 27         | 2     | 4,113                |                           |         |
|           | 0                 | 27         | 3     | 3,482                |                           |         |

**Table E.2: Measured flexural strength – 0/2 mm – 10%**

| Sand [mm] | Sand quantity [%] | Age [days] | Prism | R <sub>f</sub> [MPa] | R <sub>f,mean</sub> [MPa] | s [MPa] |
|-----------|-------------------|------------|-------|----------------------|---------------------------|---------|
| 0/2       | 10                | 1          | 1     | 1,579                | 1,3                       | 0,2     |
|           | 10                | 1          | 2     | 1,242                |                           |         |
|           | 10                | 1          | 3     | 1,204                |                           |         |
| 0/2       | 10                | 3          | 1     | 2,689                | 2,8                       | 0,2     |
|           | 10                | 3          | 2     | 3,019                |                           |         |
|           | 10                | 3          | 3     | 2,707                |                           |         |
| 0/2       | 10                | 7          | 1     | 4,16                 | 4,2                       | 0,2     |
|           | 10                | 7          | 2     | 4,435                |                           |         |
|           | 10                | 7          | 3     | 4,076                |                           |         |
| 0/2       | 10                | 28         | 1     | 4,984                | 5,2                       | 0,3     |
|           | 10                | 28         | 2     | 5,066                |                           |         |
|           | 10                | 28         | 3     | 5,468                |                           |         |

**Table E.3: Measured flexural strength – 0/2 mm – 20%**

| Sand [mm] | Sand quantity [%] | Age [days] | Prism | R <sub>f</sub> [MPa] | R <sub>f,mean</sub> [MPa] | s [MPa] |
|-----------|-------------------|------------|-------|----------------------|---------------------------|---------|
| 0/2       | 20                | 1          | 1     | 2,431                | 2,4                       | 0,1     |
|           | 20                | 1          | 2     | 2,304                |                           |         |
|           | 20                | 1          | 3     | 2,496                |                           |         |
| 0/2       | 20                | 3          | 1     | 4,071                | 3,9                       | 0,2     |
|           | 20                | 3          | 2     | 3,777                |                           |         |
|           | 20                | 3          | 3     | 3,763                |                           |         |
| 0/2       | 20                | 7          | 1     | 5,251                | 4,9                       | 0,4     |
|           | 20                | 7          | 2     | 4,432                |                           |         |
|           | 20                | 7          | 3     | 5,091                |                           |         |
| 0/2       | 20                | 28         | 1     | 7,461                | 7,2                       | 0,3     |
|           | 20                | 28         | 2     | 6,961                |                           |         |
|           | 20                | 28         | 3     | 7,06                 |                           |         |

**Table E.4: Measured flexural strength – 0/2 mm – 30%**

| Sand [mm] | Sand quantity [%] | Age [days] | Prism | R <sub>f</sub> [MPa] | R <sub>f,mean</sub> [MPa] | s [MPa] |
|-----------|-------------------|------------|-------|----------------------|---------------------------|---------|
| 0/2       | 30                | 1          | 1     | 2,262                | 2,1                       | 0,1     |
|           | 30                | 1          | 2     | 1,984                |                           |         |
|           | 30                | 1          | 3     | 2,097                |                           |         |
| 0/2       | 30                | 3          | 1     | 4,111                | 3,8                       | 0,4     |
|           | 30                | 3          | 2     | 4,056                |                           |         |
|           | 30                | 3          | 3     | 3,375                |                           |         |
| 0/2       | 30                | 7          | 1     | 5,62                 | 5,3                       | 0,5     |
|           | 30                | 7          | 2     | 4,79                 |                           |         |
|           | 30                | 7          | 3     | 5,635                |                           |         |
| 0/2       | 30                | 28         | 1     | 6,289                | 6,4                       | 0,4     |
|           | 30                | 28         | 2     | 6,124                |                           |         |
|           | 30                | 28         | 3     | 6,844                |                           |         |

**Table E.4: Measured flexural strength – 0/2 mm – 40%**

| Sand [mm] | Sand quantity [%] | Age [days] | Prism | R <sub>f</sub> [MPa] | R <sub>f,mean</sub> [MPa] | s [MPa] |
|-----------|-------------------|------------|-------|----------------------|---------------------------|---------|
| 0/2       | 40                | 1          | 1     | 2,269                | 2,3                       | 0,04    |
|           | 40                | 1          | 2     | 2,311                |                           |         |
|           | 40                | 1          | 3     | 2,355                |                           |         |
| 0/2       | 40                | 3          | 1     | 4,946                | 4,6                       | 0,3     |
|           | 40                | 3          | 2     | 4,488                |                           |         |
|           | 40                | 3          | 3     | 4,33                 |                           |         |
| 0/2       | 40                | 7          | 1     | 6,452                | 5,8                       | 0,6     |
|           | 40                | 7          | 2     | 5,7725               |                           |         |
|           | 40                | 7          | 3     | 5,28                 |                           |         |
| 0/2       | 40                | 28         | 1     | 7,737                | 7,4                       | 0,3     |
|           | 40                | 28         | 2     | 7,281                |                           |         |
|           | 40                | 28         | 3     | 7,305                |                           |         |

**Table E.5: Measured flexural strength – 0/2 mm – 50%**

| Sand [mm] | Sand quantity [%] | Age [days] | Prism | R <sub>f</sub> [MPa] | R <sub>f,mean</sub> [MPa] | s [MPa] |
|-----------|-------------------|------------|-------|----------------------|---------------------------|---------|
| 0/2       | 50                | 1          | 1     | 2,059                | 2,1                       | 0,1     |
|           | 50                | 1          | 2     | 2,289                |                           |         |
|           | 50                | 1          | 3     | 2,013                |                           |         |
| 0/2       | 50                | 3          | 1     | 5,581                | 5,7                       | 0,2     |
|           | 50                | 3          | 2     | 5,921                |                           |         |
|           | 50                | 3          | 3     | 5,609                |                           |         |
| 0/2       | 50                | 7          | 1     | 7,04                 | 6,6                       | 0,4     |
|           | 50                | 7          | 2     | 6,559                |                           |         |
|           | 50                | 7          | 3     | 6,155                |                           |         |
| 0/2       | 50                | 28         | 1     | 9,238                | 8,7                       | 0,7     |
|           | 50                | 28         | 2     | 8,971                |                           |         |
|           | 50                | 28         | 3     | 7,841                |                           |         |

**Table E.6: Measured flexural strength – 0/2 mm – 60%**

| Sand [mm] | Sand quantity [%] | Age [days] | Prism | R <sub>f</sub> [MPa] | R <sub>f,mean</sub> [MPa] | s [MPa] |
|-----------|-------------------|------------|-------|----------------------|---------------------------|---------|
| 0/2       | 60                | 1          | 1     | 3,937                | 3,9                       | 0,1     |
|           | 60                | 1          | 2     | 4,067                |                           |         |
|           | 60                | 1          | 3     | 3,783                |                           |         |
| 0/2       | 60                | 3          | 1     | 5,552                | 5,3                       | 0,5     |
|           | 60                | 3          | 2     | 5,64                 |                           |         |
|           | 60                | 3          | 3     | 4,651                |                           |         |
| 0/2       | 60                | 7          | 1     | 6,746                | 7,0                       | 0,3     |
|           | 60                | 7          | 2     | 7,292                |                           |         |
|           | 60                | 7          | 3     | 6,835                |                           |         |
| 0/2       | 60                | 28         | 1     | 8,444                | 8,5                       | 0,1     |
|           | 60                | 28         | 2     | 8,515                |                           |         |
|           | 60                | 28         | 3     | 8,582                |                           |         |

**Table E.7: Measured flexural strength – 0/1 mm – 10%**

| Sand [mm] | Sand quantity [%] | Age [days] | Prism | R <sub>f</sub> [MPa] | R <sub>f,mean</sub> [MPa] | s [MPa] |
|-----------|-------------------|------------|-------|----------------------|---------------------------|---------|
| 0/1       | 10                | 1          | 1     | 3,384                | 3,0                       | 0,4     |
|           | 10                | 1          | 2     | 2,567                |                           |         |
|           | 10                | 1          | 3     | 2,965                |                           |         |
| 0/1       | 10                | 3          | 1     | 3,052                | 3,2                       | 0,4     |
|           | 10                | 3          | 2     | 3,585                |                           |         |
|           | 10                | 3          | 3     | 2,825                |                           |         |
| 0/1       | 10                | 7          | 1     | 4,861                | 4,4                       | 0,4     |
|           | 10                | 7          | 2     | 3,973                |                           |         |
|           | 10                | 7          | 3     | 4,348                |                           |         |
| 0/1       | 10                | 28         | 1     | 6,592                | 6,3                       | 0,2     |
|           | 10                | 28         | 2     | 6,322                |                           |         |
|           | 10                | 28         | 3     | 6,093                |                           |         |

**Table E.8: Measured flexural strength – 0/1 mm – 20%**

| Sand [mm] | Sand quantity [%] | Age [days] | Prism | R <sub>f</sub> [MPa] | R <sub>f,mean</sub> [MPa] | s [MPa] |
|-----------|-------------------|------------|-------|----------------------|---------------------------|---------|
| 0/1       | 20                | 1          | 1     | 2,928                | 2,6                       | 0,3     |
|           | 20                | 1          | 2     | 2,525                |                           |         |
|           | 20                | 1          | 3     | 2,346                |                           |         |
| 0/1       | 20                | 3          | 1     | 2,979                | 3,3                       | 0,3     |
|           | 20                | 3          | 2     | 3,295                |                           |         |
|           | 20                | 3          | 3     | 3,553                |                           |         |
| 0/1       | 20                | 7          | 1     | 5,553                | 5,0                       | 0,5     |
|           | 20                | 7          | 2     | 4,93                 |                           |         |
|           | 20                | 7          | 3     | 4,58                 |                           |         |
| 0/1       | 20                | 28         | 1     | 5,771                | 6,6                       | 0,9     |
|           | 20                | 28         | 2     | 7,481                |                           |         |
|           | 20                | 28         | 3     | 6,421                |                           |         |

**Table E.9: Measured flexural strength – 0/1 mm – 30%**

| Sand [mm] | Sand quantity [%] | Age [days] | Prism | R <sub>f</sub> [MPa] | R <sub>f,mean</sub> [MPa] | s [MPa] |
|-----------|-------------------|------------|-------|----------------------|---------------------------|---------|
| 0/1       | 30                | 1          | 1     | 3,446                | 3,2                       | 0,4     |
|           | 30                | 1          | 2     | 3,337                |                           |         |
|           | 30                | 1          | 3     | 2,676                |                           |         |
| 0/1       | 30                | 3          | 1     | 4,647                | 4,3                       | 0,3     |
|           | 30                | 3          | 2     | 4,265                |                           |         |
|           | 30                | 3          | 3     | 4,104                |                           |         |
| 0/1       | 30                | 7          | 1     | 5,077                | 5,3                       | 0,2     |
|           | 30                | 7          | 2     | 5,367                |                           |         |
|           | 30                | 7          | 3     | 5,343                |                           |         |
| 0/1       | 30                | 28         | 1     | 8,989                | 8,0                       | 0,8     |
|           | 30                | 28         | 2     | 7,694                |                           |         |
|           | 30                | 28         | 3     | 7,396                |                           |         |

**Table E.9: Measured flexural strength – 0/1 mm – 40%**

| Sand [mm] | Sand quantity [%] | Age [days] | Prism | R <sub>f</sub> [MPa] | R <sub>f,mean</sub> [MPa] | s [MPa] |
|-----------|-------------------|------------|-------|----------------------|---------------------------|---------|
| 0/1       | 40                | 1          | 1     | 3,379                | 3,3                       | 0,2     |
|           | 40                | 1          | 2     | 3,44                 |                           |         |
|           | 40                | 1          | 3     | 3,154                |                           |         |
| 0/1       | 40                | 3          | 1     | 4,611                | 4,6                       | 0,2     |
|           | 40                | 3          | 2     | 4,839                |                           |         |
|           | 40                | 3          | 3     | 4,479                |                           |         |
| 0/1       | 40                | 7          | 1     | 6,612                | 6,4                       | 0,3     |
|           | 40                | 7          | 2     | 6,431                |                           |         |
|           | 40                | 7          | 3     | 6,11                 |                           |         |
| 0/1       | 40                | 28         | 1     | 7,34                 | 7,3                       | 0,5     |
|           | 40                | 28         | 2     | 7,71                 |                           |         |
|           | 40                | 28         | 3     | 6,797                |                           |         |

**Table E.10: Measured flexural strength – 0/1 mm – 50%**

| Sand [mm] | Sand quantity [%] | Age [days] | Prism | R <sub>f</sub> [MPa] | R <sub>f,mean</sub> [MPa] | s [MPa] |
|-----------|-------------------|------------|-------|----------------------|---------------------------|---------|
| 0/1       | 50                | 1          | 1     | 4,129                | 4,0                       | 0,2     |
|           | 50                | 1          | 2     | 3,942                |                           |         |
|           | 50                | 1          | 3     | 3,828                |                           |         |
| 0/1       | 50                | 3          | 1     | 5,022                | 4,8                       | 0,2     |
|           | 50                | 3          | 2     | 4,607                |                           |         |
|           | 50                | 3          | 3     | 4,651                |                           |         |
| 0/1       | 50                | 7          | 1     | 6,893                | 7,4                       | 0,4     |
|           | 50                | 7          | 2     | 7,407                |                           |         |
|           | 50                | 7          | 3     | 7,759                |                           |         |
| 0/1       | 50                | 28         | 1     | 7,73                 | 7,8                       | 0,4     |
|           | 50                | 28         | 2     | 8,237                |                           |         |
|           | 50                | 28         | 3     | 7,543                |                           |         |

**Table E.11: Measured flexural strength – 0/1 mm – 60%**

| Sand [mm] | Sand quantity [%] | Age [days] | Prism | R <sub>f</sub> [MPa] | R <sub>f,mean</sub> [MPa] | s [MPa] |
|-----------|-------------------|------------|-------|----------------------|---------------------------|---------|
| 0/1       | 60                | 1          | 1     | 4,066                | 4,0                       | 0,1     |
|           | 60                | 1          | 2     | 4,129                |                           |         |
|           | 60                | 1          | 3     | 3,942                |                           |         |
| 0/1       | 60                | 3          | 1     | 5,309                | 5,2                       | 0,2     |
|           | 60                | 3          | 2     | 5,187                |                           |         |
|           | 60                | 3          | 3     | 4,97                 |                           |         |
| 0/1       | 60                | 7          | 1     | 7,325                | 7,6                       | 0,2     |
|           | 60                | 7          | 2     | 7,759                |                           |         |
|           | 60                | 7          | 3     | 7,708                |                           |         |
| 0/1       | 60                | 28         | 1     | 8,215                | 8,0                       | 1,0     |
|           | 60                | 28         | 2     | 8,924                |                           |         |
|           | 60                | 28         | 3     | 6,911                |                           |         |

**Table E.12: Measured flexural strength – CEN – 10%**

| Sand | Sand quantity [%] | Age [days] | Prism | R <sub>f</sub> [MPa] | R <sub>f,mean</sub> [MPa] | s [MPa] |
|------|-------------------|------------|-------|----------------------|---------------------------|---------|
| CEN  | 10                | 1          | 1     | 2,07                 | 2,1                       | 0,2     |
|      | 10                | 1          | 2     | 2,313                |                           |         |
|      | 10                | 1          | 3     | 1,816                |                           |         |
| CEN  | 10                | 3          | 1     | 3,902                | 3,8                       | 0,05    |
|      | 10                | 3          | 2     | 3,826                |                           |         |
|      | 10                | 3          | 3     | 3,812                |                           |         |
| CEN  | 10                | 7          | 1     | 4,734                | 4,5                       | 0,2     |
|      | 10                | 7          | 2     | 4,414                |                           |         |
|      | 10                | 7          | 3     | 4,462                |                           |         |
| CEN  | 10                | 28         | 1     | 5,231                | 5,0                       | 0,3     |
|      | 10                | 28         | 2     | 5,033                |                           |         |
|      | 10                | 28         | 3     | 4,6                  |                           |         |

**Table E.13: Measured flexural strength – CEN – 20%**

| Sand | Sand quantity [%] | Age [days] | Prism | R <sub>f</sub> [MPa] | R <sub>f,mean</sub> [MPa] | s [MPa] |
|------|-------------------|------------|-------|----------------------|---------------------------|---------|
| CEN  | 20                | 1          | 1     | 2,727                | 2,7                       | 0,04    |
|      | 20                | 1          | 2     | 2,736                |                           |         |
|      | 20                | 1          | 3     | 2,66                 |                           |         |
| CEN  | 20                | 3          | 1     | 3,966                | 4,0                       | 0,01    |
|      | 20                | 3          | 2     | 3,973                |                           |         |
|      | 20                | 3          | 3     | 3,977                |                           |         |
| CEN  | 20                | 7          | 1     | 5,307                | 5,4                       | 0,2     |
|      | 20                | 7          | 2     | 5,273                |                           |         |
|      | 20                | 7          | 3     | 5,639                |                           |         |
| CEN  | 20                | 28         | 1     | 5,432                | 5,1                       | 0,3     |
|      | 20                | 28         | 2     | 4,921                |                           |         |
|      | 20                | 28         | 3     | 5,044                |                           |         |

**Table E.14: Measured flexural strength – CEN – 30%**

| Sand | Sand quantity [%] | Age [days] | Prism | R <sub>f</sub> [MPa] | R <sub>f,mean</sub> [MPa] | s [MPa] |
|------|-------------------|------------|-------|----------------------|---------------------------|---------|
| CEN  | 30                | 1          | 1     | 2,916                | 2,9                       | 0,03    |
|      | 30                | 1          | 2     | 2,872                |                           |         |
|      | 30                | 1          | 3     | 2,923                |                           |         |
| CEN  | 30                | 3          | 1     | 4,832                | 4,9                       | 0,2     |
|      | 30                | 3          | 2     | 4,772                |                           |         |
|      | 30                | 3          | 3     | 5,057                |                           |         |
| CEN  | 30                | 7          | 1     | 6,447                | 6,3                       | 0,1     |
|      | 30                | 7          | 2     | 6,266                |                           |         |
|      | 30                | 7          | 3     | 6,186                |                           |         |
| CEN  | 30                | 28         | 1     | 7,603                | 7,1                       | 0,4     |
|      | 30                | 28         | 2     | 6,922                |                           |         |
|      | 30                | 28         | 3     | 6,798                |                           |         |

**Table E.15: Measured flexural strength – CEN – 40%**

| Sand | Sand quantity [%] | Age [days] | Prism | R <sub>f</sub> [MPa] | R <sub>f,mean</sub> [MPa] | s [MPa] |
|------|-------------------|------------|-------|----------------------|---------------------------|---------|
| CEN  | 40                | 1          | 1     | 4,071                | 3,5                       | 0,5     |
|      | 40                | 1          | 2     | 3,154                |                           |         |
|      | 40                | 1          | 3     | 3,368                |                           |         |
| CEN  | 40                | 3          | 1     | 5,595                | 5,4                       | 0,2     |
|      | 40                | 3          | 2     | 5,349                |                           |         |
|      | 40                | 3          | 3     | 5,3                  |                           |         |
| CEN  | 40                | 7          | 1     | 6,476                | 6,4                       | 0,2     |
|      | 40                | 7          | 2     | 6,088                |                           |         |
|      | 40                | 7          | 3     | 6,537                |                           |         |
| CEN  | 40                | 28         | 1     | 8,074                | 8,1                       | 0,2     |
|      | 40                | 28         | 2     | 7,93                 |                           |         |
|      | 40                | 28         | 3     | 8,339                |                           |         |

**Table E.16: Measured flexural strength – CEN – 50%**

| Sand | Sand quantity [%] | Age [days] | Prism | R <sub>f</sub> [MPa] | R <sub>f,mean</sub> [MPa] | s [MPa] |
|------|-------------------|------------|-------|----------------------|---------------------------|---------|
| CEN  | 50                | 1          | 1     | 4,1                  | 3,8                       | 0,3     |
|      | 50                | 1          | 2     | 3,46                 |                           |         |
|      | 50                | 1          | 3     | 3,788                |                           |         |
| CEN  | 50                | 3          | 1     | 6,202                | 6,2                       | 0,1     |
|      | 50                | 3          | 2     | 6,287                |                           |         |
|      | 50                | 3          | 3     | 6,095                |                           |         |
| CEN  | 50                | 7          | 1     | 7,495                | 7,2                       | 0,3     |
|      | 50                | 7          | 2     | 7,249                |                           |         |
|      | 50                | 7          | 3     | 6,965                |                           |         |
| CEN  | 50                | 28         | 1     | 9,113                | 9,2                       | 0,1     |
|      | 50                | 28         | 2     | 9,367                |                           |         |
|      | 50                | 28         | 3     | 9,165                |                           |         |

**Table E.17: Measured flexural strength – CEN – 60%**

| Sand | Sand quantity [%] | Age [days] | Prism | R <sub>f</sub> [MPa] | R <sub>f,mean</sub> [MPa] | s [MPa] |
|------|-------------------|------------|-------|----------------------|---------------------------|---------|
| CEN  | 60                | 1          | 1     | 4,131                | 4,1                       | 0,1     |
|      | 60                | 1          | 2     | 3,98                 |                           |         |
|      | 60                | 1          | 3     | 4,087                |                           |         |
| CEN  | 60                | 3          | 1     | 6,749                | 6,5                       | 0,3     |
|      | 60                | 3          | 2     | 6,093                |                           |         |
|      | 60                | 3          | 3     | 6,548                |                           |         |
| CEN  | 60                | 7          | 1     | 7,768                | 7,7                       | 0,1     |
|      | 60                | 7          | 2     | 7,752                |                           |         |
|      | 60                | 7          | 3     | 7,607                |                           |         |
| CEN  | 60                | 28         | 1     | 9,536                | 9,5                       | 0,1     |
|      | 60                | 28         | 2     | 9,678                |                           |         |
|      | 60                | 28         | 3     | 9,393                |                           |         |

## Appendix F: Measured compressive strength

The measured values of the compressive strength are visible in Appendix F. The values visualized in red are outliers, which are not taken into account for the calculation of the mean value. The upper and lower values indicate which values are seen as outliers. The standard deviation is calculated from the remaining values.

**Tabel F.1: Measured compressive strength – Geopolymer paste**

| Sand | Sand quantity<br>[%] | Age<br>[days] | Cube | Rc<br>[MPa] | Rc,mean<br>[MPa] | Upper<br>limit<br>[MPa] | Lower<br>limit<br>[MPa] | s<br>[MPa] |
|------|----------------------|---------------|------|-------------|------------------|-------------------------|-------------------------|------------|
| -    | 0                    | 1             | 1    | 29,471      | 25,7             | 28,3                    | 23,2                    | 1,5        |
|      | 0                    | 1             | 2    | 24,256      |                  |                         |                         |            |
|      | 0                    | 1             | 3    | 26,485      |                  |                         |                         |            |
|      | 0                    | 1             | 4    | 27,697      |                  |                         |                         |            |
|      | 0                    | 1             | 5    | 24,255      |                  |                         |                         |            |
|      | 0                    | 1             | 6    | 26,005      |                  |                         |                         |            |
| -    | 0                    | 3             | 1    | 49,434      | 39,5             | 43,5                    | 35,6                    | 2,8        |
|      | 0                    | 3             | 2    | 41,05       |                  |                         |                         |            |
|      | 0                    | 3             | 3    | 37,903      |                  |                         |                         |            |
|      | 0                    | 3             | 4    | 43,645      |                  |                         |                         |            |
|      | 0                    | 3             | 5    | 36,960      |                  |                         |                         |            |
|      | 0                    | 3             | 6    | 38,063      |                  |                         |                         |            |
| -    | 0                    | 7             | 1    | 44,855      | 49,9             | 54,9                    | 44,9                    | 3,0        |
|      | 0                    | 7             | 2    | 50,141      |                  |                         |                         |            |
|      | 0                    | 7             | 3    | 52,443      |                  |                         |                         |            |
|      | 0                    | 7             | 4    | 51,146      |                  |                         |                         |            |
|      | 0                    | 7             | 5    | 42,927      |                  |                         |                         |            |
|      | 0                    | 7             | 6    | 51,116      |                  |                         |                         |            |
| -    | 0                    | 28            | 1    | 98,289      | 91,0             | 100,1                   | 81,9                    | 4,8        |
|      | 0                    | 28            | 2    | 89,792      |                  |                         |                         |            |
|      | 0                    | 28            | 3    | 90,637      |                  |                         |                         |            |
|      | 0                    | 28            | 4    | 91,235      |                  |                         |                         |            |
|      | 0                    | 28            | 5    | 66,156      |                  |                         |                         |            |
|      | 0                    | 28            | 6    | 84,883      |                  |                         |                         |            |

**Tabel F.2: Measured compressive strength – 0/2 mm – 10%**

| Sand<br>[mm] | Sand quantity<br>[%] | Age<br>[days] | Cube | Rc<br>[MPa] | Rc,mean<br>[MPa] | Upper<br>limit<br>[MPa] | Lower<br>limit<br>[MPa] | s<br>[MPa] |
|--------------|----------------------|---------------|------|-------------|------------------|-------------------------|-------------------------|------------|
| 0/2          | 10                   | 1             | 1    | 17,065      | 16,5             | 18,2                    | 14,9                    | 0,7        |
|              | 10                   | 1             | 2    | 16,318      |                  |                         |                         |            |
|              | 10                   | 1             | 3    | 16,882      |                  |                         |                         |            |
|              | 10                   | 1             | 4    | 16,243      |                  |                         |                         |            |
|              | 10                   | 1             | 5    | 15,394      |                  |                         |                         |            |
|              | 10                   | 1             | 6    | 17,309      |                  |                         |                         |            |
| 0/2          | 10                   | 3             | 1    | 40,131      | 42,7             | 47,0                    | 38,4                    | 2,2        |
|              | 10                   | 3             | 2    | 44,168      |                  |                         |                         |            |
|              | 10                   | 3             | 3    | 44,771      |                  |                         |                         |            |
|              | 10                   | 3             | 4    | 39,671      |                  |                         |                         |            |
|              | 10                   | 3             | 5    | 44,030      |                  |                         |                         |            |
|              | 10                   | 3             | 6    | 43,404      |                  |                         |                         |            |
| 0/2          | 10                   | 7             | 1    | 51,789      | 51,7             | 56,8                    | 46,5                    | 0,5        |
|              | 10                   | 7             | 2    | 51,788      |                  |                         |                         |            |
|              | 10                   | 7             | 3    | 51,995      |                  |                         |                         |            |
|              | 10                   | 7             | 4    | 51,358      |                  |                         |                         |            |
|              | 10                   | 7             | 5    | 52,225      |                  |                         |                         |            |
|              | 10                   | 7             | 6    | 50,755      |                  |                         |                         |            |
| 0/2          | 10                   | 28            | 1    | 97,418      | 95,1             | 104,6                   | 85,6                    | 5,1        |
|              | 10                   | 28            | 2    | 95,693      |                  |                         |                         |            |
|              | 10                   | 28            | 3    | 86,229      |                  |                         |                         |            |
|              | 10                   | 28            | 4    | 94,857      |                  |                         |                         |            |
|              | 10                   | 28            | 5    | 94,501      |                  |                         |                         |            |
|              | 10                   | 28            | 6    | 101,767     |                  |                         |                         |            |

**Tabel F.3: Measured compressive strength – 0/2 mm – 20%**

| Sand<br>[mm] | Sand<br>quantity<br>[%] | Age<br>[days] | Cube | Rc<br>[MPa] | Rc,mean<br>[MPa] | Upper<br>limit<br>[MPa] | Lower<br>limit<br>[MPa] | s<br>[MPa] |
|--------------|-------------------------|---------------|------|-------------|------------------|-------------------------|-------------------------|------------|
| 0/2          | 20                      | 1             | 1    | 15,725      | 15,8             | 17,4                    | 14,2                    | 0,8        |
|              | 20                      | 1             | 2    | 13,713      |                  |                         |                         |            |
|              | 20                      | 1             | 3    | 16,101      |                  |                         |                         |            |
|              | 20                      | 1             | 4    | 16,254      |                  |                         |                         |            |
|              | 20                      | 1             | 5    | 14,368      |                  |                         |                         |            |
|              | 20                      | 1             | 6    | 16,517      |                  |                         |                         |            |
| 0/2          | 20                      | 3             | 1    | 45,494      | 42,4             | 46,7                    | 38,2                    | 2,2        |
|              | 20                      | 3             | 2    | 41,526      |                  |                         |                         |            |
|              | 20                      | 3             | 3    | 40,165      |                  |                         |                         |            |
|              | 20                      | 3             | 4    | 42,198      |                  |                         |                         |            |
|              | 20                      | 3             | 5    | 40,584      |                  |                         |                         |            |
|              | 20                      | 3             | 6    | 44,593      |                  |                         |                         |            |
| 0/2          | 20                      | 7             | 1    | 53,873      | 52,0             | 57,2                    | 46,8                    | 1,4        |
|              | 20                      | 7             | 2    | 50,186      |                  |                         |                         |            |
|              | 20                      | 7             | 3    | 49,997      |                  |                         |                         |            |
|              | 20                      | 7             | 4    | 51,656      |                  |                         |                         |            |
|              | 20                      | 7             | 5    | 51,863      |                  |                         |                         |            |
|              | 20                      | 7             | 6    | 52,420      |                  |                         |                         |            |
| 0/2          | 20                      | 28            | 1    | 84,883      | 85,2             | 93,7                    | 76,7                    | 5,1        |
|              | 20                      | 28            | 2    | 92,405      |                  |                         |                         |            |
|              | 20                      | 28            | 3    | 83,788      |                  |                         |                         |            |
|              | 20                      | 28            | 4    | 77,937      |                  |                         |                         |            |
|              | 20                      | 28            | 5    | 89,502      |                  |                         |                         |            |
|              | 20                      | 28            | 6    | 82,659      |                  |                         |                         |            |

**Tabel F.4: Measured compressive strength – 0/2 mm – 30%**

| Sand<br>[mm] | Sand<br>quantity<br>[%] | Age<br>[days] | Cube | Rc<br>[MPa] | Rc,mean<br>[MPa] | Upper<br>limit<br>[MPa] | Lower<br>limit<br>[MPa] | s<br>[MPa] |
|--------------|-------------------------|---------------|------|-------------|------------------|-------------------------|-------------------------|------------|
| 0/2          | 30                      | 1             | 1    | 14,602      | 14,8             | 16,3                    | 13,3                    | 0,3        |
|              | 30                      | 1             | 2    | 14,434      |                  |                         |                         |            |
|              | 30                      | 1             | 3    | 15,012      |                  |                         |                         |            |
|              | 30                      | 1             | 4    | 15,252      |                  |                         |                         |            |
|              | 30                      | 1             | 5    | 14,793      |                  |                         |                         |            |
|              | 30                      | 1             | 6    | 16,694      |                  |                         |                         |            |
| 0/2          | 30                      | 3             | 1    | 40,820      | 40,1             | 44,1                    | 36,0                    | 0,7        |
|              | 30                      | 3             | 2    | 39,172      |                  |                         |                         |            |
|              | 30                      | 3             | 3    | 40,665      |                  |                         |                         |            |
|              | 30                      | 3             | 4    | 33,687      |                  |                         |                         |            |
|              | 30                      | 3             | 5    | 39,789      |                  |                         |                         |            |
|              | 30                      | 3             | 6    | 39,826      |                  |                         |                         |            |
| 0/2          | 30                      | 7             | 1    | 57,847      | 55,3             | 60,9                    | 49,8                    | 2,4        |
|              | 30                      | 7             | 2    | 53,172      |                  |                         |                         |            |
|              | 30                      | 7             | 3    | 54,378      |                  |                         |                         |            |
|              | 30                      | 7             | 4    | 53,414      |                  |                         |                         |            |
|              | 30                      | 7             | 5    | 54,252      |                  |                         |                         |            |
|              | 30                      | 7             | 6    | 58,915      |                  |                         |                         |            |
| 0/2          | 30                      | 28            | 1    | 93,522      | 88,0             | 96,8                    | 79,2                    | 4,9        |
|              | 30                      | 28            | 2    | 92,137      |                  |                         |                         |            |
|              | 30                      | 28            | 3    | 88,099      |                  |                         |                         |            |
|              | 30                      | 28            | 4    | 89,474      |                  |                         |                         |            |
|              | 30                      | 28            | 5    | 84,519      |                  |                         |                         |            |
|              | 30                      | 28            | 6    | 80,224      |                  |                         |                         |            |

**Tabel F.5: Measured compressive strength – 0/2 mm – 40%**

| Sand<br>[mm] | Sand<br>quantity<br>[%] | Age<br>[days] | Cube | Rc<br>[MPa] | Rc,mean<br>[MPa] | Upper<br>limit<br>[MPa] | Lower<br>limit<br>[MPa] | s<br>[MPa] |
|--------------|-------------------------|---------------|------|-------------|------------------|-------------------------|-------------------------|------------|
| 0/2          | 40                      | 1             | 1    | 14,084      | 14,0             | 15,4                    | 12,6                    | 0,4        |
|              | 40                      | 1             | 2    | 13,719      |                  |                         |                         |            |
|              | 40                      | 1             | 3    | 14,357      |                  |                         |                         |            |
|              | 40                      | 1             | 4    | 14,049      |                  |                         |                         |            |
|              | 40                      | 1             | 5    | 14,482      |                  |                         |                         |            |
|              | 40                      | 1             | 6    | 13,291      |                  |                         |                         |            |
| 0/2          | 40                      | 3             | 1    | 44,208      | 44,4             | 48,8                    | 40,0                    | 0,3        |
|              | 40                      | 3             | 2    | 44,042      |                  |                         |                         |            |
|              | 40                      | 3             | 3    | 44,788      |                  |                         |                         |            |
|              | 40                      | 3             | 4    | 44,576      |                  |                         |                         |            |
|              | 40                      | 3             | 5    | 44,346      |                  |                         |                         |            |
|              | 40                      | 3             | 6    | 44,461      |                  |                         |                         |            |
| 0/2          | 40                      | 7             | 1    | 54,683      | 52,2             | 57,4                    | 46,9                    | 2,8        |
|              | 40                      | 7             | 2    | 51,272      |                  |                         |                         |            |
|              | 40                      | 7             | 3    | 53,419      |                  |                         |                         |            |
|              | 40                      | 7             | 4    | 49,807      |                  |                         |                         |            |
|              | 40                      | 7             | 5    | 55,315      |                  |                         |                         |            |
|              | 40                      | 7             | 6    | 48,463      |                  |                         |                         |            |
| 0/2          | 40                      | 28            | 1    | 83,914      | 82,0             | 90,2                    | 73,8                    | 3,6        |
|              | 40                      | 28            | 2    | 83,549      |                  |                         |                         |            |
|              | 40                      | 28            | 3    | 84,079      |                  |                         |                         |            |
|              | 40                      | 28            | 4    | 84,650      |                  |                         |                         |            |
|              | 40                      | 28            | 5    | 75,229      |                  |                         |                         |            |
|              | 40                      | 28            | 6    | 80,743      |                  |                         |                         |            |

**Tabel F.6: Measured compressive strength – 0/2 mm – 50%**

| Sand<br>[mm] | Sand<br>quantity<br>[%] | Age<br>[days] | Cube | Rc<br>[MPa] | Rc,mean<br>[MPa] | Upper<br>limit<br>[MPa] | Lower<br>limit<br>[MPa] | s<br>[MPa] |
|--------------|-------------------------|---------------|------|-------------|------------------|-------------------------|-------------------------|------------|
| 0/2          | 50                      | 1             | 1    | 14,038      | 13,9             | 15,3                    | 12,5                    | 0,2        |
|              | 50                      | 1             | 2    | 13,718      |                  |                         |                         |            |
|              | 50                      | 1             | 3    | 14,186      |                  |                         |                         |            |
|              | 50                      | 1             | 4    | 14,146      |                  |                         |                         |            |
|              | 50                      | 1             | 5    | 13,958      |                  |                         |                         |            |
|              | 50                      | 1             | 6    | 13,610      |                  |                         |                         |            |
| 0/2          | 50                      | 3             | 1    | 39,620      | 40,7             | 44,8                    | 36,6                    | 1,7        |
|              | 50                      | 3             | 2    | 41,480      |                  |                         |                         |            |
|              | 50                      | 3             | 3    | 43,582      |                  |                         |                         |            |
|              | 50                      | 3             | 4    | 41,038      |                  |                         |                         |            |
|              | 50                      | 3             | 5    | 39,683      |                  |                         |                         |            |
|              | 50                      | 3             | 6    | 38,856      |                  |                         |                         |            |
| 0/2          | 50                      | 7             | 1    | 45,661      | 48,3             | 53,2                    | 43,5                    | 3,4        |
|              | 50                      | 7             | 2    | 44,536      |                  |                         |                         |            |
|              | 50                      | 7             | 3    | 47,780      |                  |                         |                         |            |
|              | 50                      | 7             | 4    | 51,220      |                  |                         |                         |            |
|              | 50                      | 7             | 5    | 52,437      |                  |                         |                         |            |
|              | 50                      | 7             | 6    | 54,591      |                  |                         |                         |            |
| 0/2          | 50                      | 28            | 1    | 80,937      | 80,5             | 88,6                    | 72,5                    | 1,5        |
|              | 50                      | 28            | 2    | 82,185      |                  |                         |                         |            |
|              | 50                      | 28            | 3    | 81,410      |                  |                         |                         |            |
|              | 50                      | 28            | 4    | 78,257      |                  |                         |                         |            |
|              | 50                      | 28            | 5    | 81,462      |                  |                         |                         |            |
|              | 50                      | 28            | 6    | 79,021      |                  |                         |                         |            |

**Tabel F.7: Measured compressive strength – 0/2 mm – 60%**

| Sand<br>[mm] | Sand<br>quantity<br>[%] | Age<br>[days] | Cube | Rc<br>[MPa] | Rc,mean<br>[MPa] | Upper<br>limit<br>[MPa] | Lower<br>limit<br>[MPa] | s<br>[MPa] |
|--------------|-------------------------|---------------|------|-------------|------------------|-------------------------|-------------------------|------------|
| 0/2          | 60                      | 1             | 1    | 21,112      | 19,5             | 21,4                    | 17,5                    | 1,1        |
|              | 60                      | 1             | 2    | 18,101      |                  |                         |                         |            |
|              | 60                      | 1             | 3    | 19,202      |                  |                         |                         |            |
|              | 60                      | 1             | 4    | 19,980      |                  |                         |                         |            |
|              | 60                      | 1             | 5    | 18,420      |                  |                         |                         |            |
|              | 60                      | 1             | 6    | 19,968      |                  |                         |                         |            |
| 0/2          | 60                      | 3             | 1    | 41,859      | 42,2             | 46,4                    | 38,0                    | 0,6        |
|              | 60                      | 3             | 2    | 42,359      |                  |                         |                         |            |
|              | 60                      | 3             | 3    | 41,463      |                  |                         |                         |            |
|              | 60                      | 3             | 4    | 42,922      |                  |                         |                         |            |
|              | 60                      | 3             | 5    | 42,962      |                  |                         |                         |            |
|              | 60                      | 3             | 6    | 41,733      |                  |                         |                         |            |
| 0/2          | 60                      | 7             | 1    | 60,724      | 59,4             | 65,3                    | 53,5                    | 1,7        |
|              | 60                      | 7             | 2    | 59,983      |                  |                         |                         |            |
|              | 60                      | 7             | 3    | 61,006      |                  |                         |                         |            |
|              | 60                      | 7             | 4    | 58,089      |                  |                         |                         |            |
|              | 60                      | 7             | 5    | 57,164      |                  |                         |                         |            |
|              | 60                      | 7             | 6    | 46,040      |                  |                         |                         |            |
| 0/2          | 60                      | 28            | 1    | 86,902      | 85,2             | 93,7                    | 76,7                    | 3,6        |
|              | 60                      | 28            | 2    | 89,701      |                  |                         |                         |            |
|              | 60                      | 28            | 3    | 84,871      |                  |                         |                         |            |
|              | 60                      | 28            | 4    | 79,699      |                  |                         |                         |            |
|              | 60                      | 28            | 5    | 84,667      |                  |                         |                         |            |
|              | 60                      | 28            | 6    | 88,835      |                  |                         |                         |            |

**Tabel F.8: Measured compressive strength – 0/1 mm – 10%**

| Sand<br>[mm] | Sand<br>quantity<br>[%] | Age<br>[days] | Cube | Rc<br>[MPa] | Rc,mean<br>[MPa] | Upper<br>limit<br>[MPa] | Lower<br>limit<br>[MPa] | s<br>[MPa] |
|--------------|-------------------------|---------------|------|-------------|------------------|-------------------------|-------------------------|------------|
| 0/1          | 10                      | 1             | 1    | 22,546      | 26,2             | 28,9                    | 23,6                    | 1,0        |
|              | 10                      | 1             | 2    | 26,245      |                  |                         |                         |            |
|              | 10                      | 1             | 3    | 26,051      |                  |                         |                         |            |
|              | 10                      | 1             | 4    | 24,924      |                  |                         |                         |            |
|              | 10                      | 1             | 5    | 26,228      |                  |                         |                         |            |
|              | 10                      | 1             | 6    | 27,800      |                  |                         |                         |            |
| 0/1          | 10                      | 3             | 1    | 40,435      | 43,4             | 47,8                    | 39,1                    | 2,4        |
|              | 10                      | 3             | 2    | 45,104      |                  |                         |                         |            |
|              | 10                      | 3             | 3    | 41,549      |                  |                         |                         |            |
|              | 10                      | 3             | 4    | 44,300      |                  |                         |                         |            |
|              | 10                      | 3             | 5    | 42,284      |                  |                         |                         |            |
|              | 10                      | 3             | 6    | 46,913      |                  |                         |                         |            |
| 0/1          | 10                      | 7             | 1    | 67,891      | 67,2             | 73,9                    | 60,5                    | 1,6        |
|              | 10                      | 7             | 2    | 64,997      |                  |                         |                         |            |
|              | 10                      | 7             | 3    | 67,673      |                  |                         |                         |            |
|              | 10                      | 7             | 4    | 68,304      |                  |                         |                         |            |
|              | 10                      | 7             | 5    | 68,867      |                  |                         |                         |            |
|              | 10                      | 7             | 6    | 65,468      |                  |                         |                         |            |
| 0/1          | 10                      | 28            | 1    | 87,717      | 83,3             | 91,7                    | 75,0                    | 3,5        |
|              | 10                      | 28            | 2    | 78,428      |                  |                         |                         |            |
|              | 10                      | 28            | 3    | 86,901      |                  |                         |                         |            |
|              | 10                      | 28            | 4    | 83,149      |                  |                         |                         |            |
|              | 10                      | 28            | 5    | 81,826      |                  |                         |                         |            |
|              | 10                      | 28            | 6    | 81,951      |                  |                         |                         |            |

**Tabel F.9: Measured compressive strength – 0/1 mm – 20%**

| Sand<br>[mm] | Sand<br>quantity<br>[%] | Age<br>[days] | Cube | Rc<br>[MPa] | Rc,mean<br>[MPa] | Upper<br>limit<br>[MPa] | Lower<br>limit<br>[MPa] | s<br>[MPa] |
|--------------|-------------------------|---------------|------|-------------|------------------|-------------------------|-------------------------|------------|
| 0/1          | 20                      | 1             | 1    | 25,262      | 26,2             | 28,9                    | 23,6                    | 1,2        |
|              | 20                      | 1             | 2    | 25,993      |                  |                         |                         |            |
|              | 20                      | 1             | 3    | 24,673      |                  |                         |                         |            |
|              | 20                      | 1             | 4    | 27,508      |                  |                         |                         |            |
|              | 20                      | 1             | 5    | 26,016      |                  |                         |                         |            |
|              | 20                      | 1             | 6    | 27,725      |                  |                         |                         |            |
| 0/1          | 20                      | 3             | 1    | 46,620      | 46,6             | 51,2                    | 41,9                    | 0,6        |
|              | 20                      | 3             | 2    | 45,469      |                  |                         |                         |            |
|              | 20                      | 3             | 3    | 47,102      |                  |                         |                         |            |
|              | 20                      | 3             | 4    | 46,735      |                  |                         |                         |            |
|              | 20                      | 3             | 5    | 46,901      |                  |                         |                         |            |
|              | 20                      | 3             | 6    | 46,580      |                  |                         |                         |            |
| 0/1          | 20                      | 7             | 1    | 62,562      | 63,0             | 69,3                    | 56,7                    | 1,4        |
|              | 20                      | 7             | 2    | 64,359      |                  |                         |                         |            |
|              | 20                      | 7             | 3    | 62,389      |                  |                         |                         |            |
|              | 20                      | 7             | 4    | 64,462      |                  |                         |                         |            |
|              | 20                      | 7             | 5    | 64,313      |                  |                         |                         |            |
|              | 20                      | 7             | 6    | 61,189      |                  |                         |                         |            |
| 0/1          | 20                      | 28            | 1    | 73,599      | 69,1             | 76,0                    | 62,2                    | 3,6        |
|              | 20                      | 28            | 2    | 66,943      |                  |                         |                         |            |
|              | 20                      | 28            | 3    | 70,050      |                  |                         |                         |            |
|              | 20                      | 28            | 4    | 70,469      |                  |                         |                         |            |
|              | 20                      | 28            | 5    | 64,295      |                  |                         |                         |            |
|              | 20                      | 28            | 6    | 55,446      |                  |                         |                         |            |

**Tabel F.10: Measured compressive strength – 0/1 mm – 30%**

| Sand<br>[mm] | Sand<br>quantity<br>[%] | Age<br>[days] | Cube | Rc<br>[MPa] | Rc,mean<br>[MPa] | Upper<br>limit<br>[MPa] | Lower<br>limit<br>[MPa] | s<br>[MPa] |
|--------------|-------------------------|---------------|------|-------------|------------------|-------------------------|-------------------------|------------|
| 0/1          | 30                      | 1             | 1    | 24,261      | 24,4             | 26,8                    | 22,0                    | 0,8        |
|              | 30                      | 1             | 2    | 23,541      |                  |                         |                         |            |
|              | 30                      | 1             | 3    | 24,513      |                  |                         |                         |            |
|              | 30                      | 1             | 4    | 24,267      |                  |                         |                         |            |
|              | 30                      | 1             | 5    | 25,410      |                  |                         |                         |            |
|              | 30                      | 1             | 6    | 25,679      |                  |                         |                         |            |
| 0/1          | 30                      | 3             | 1    | 47,349      | 44,2             | 48,7                    | 39,8                    | 2,2        |
|              | 30                      | 3             | 2    | 45,885      |                  |                         |                         |            |
|              | 30                      | 3             | 3    | 42,284      |                  |                         |                         |            |
|              | 30                      | 3             | 4    | 42,393      |                  |                         |                         |            |
|              | 30                      | 3             | 5    | 43,220      |                  |                         |                         |            |
|              | 30                      | 3             | 6    | 42,491      |                  |                         |                         |            |
| 0/1          | 30                      | 7             | 1    | 47,022      | 48,0             | 52,8                    | 43,2                    | 1,4        |
|              | 30                      | 7             | 2    | 55,136      |                  |                         |                         |            |
|              | 30                      | 7             | 3    | 47,332      |                  |                         |                         |            |
|              | 30                      | 7             | 4    | 47,257      |                  |                         |                         |            |
|              | 30                      | 7             | 5    | 47,819      |                  |                         |                         |            |
|              | 30                      | 7             | 6    | 50,392      |                  |                         |                         |            |
| 0/1          | 30                      | 28            | 1    | 75,297      | 70,7             | 77,8                    | 63,7                    | 3,6        |
|              | 30                      | 28            | 2    | 66,501      |                  |                         |                         |            |
|              | 30                      | 28            | 3    | 73,346      |                  |                         |                         |            |
|              | 30                      | 28            | 4    | 68,069      |                  |                         |                         |            |
|              | 30                      | 28            | 5    | 53,580      |                  |                         |                         |            |
|              | 30                      | 28            | 6    | 70,400      |                  |                         |                         |            |

**Tabel F.11: Measured compressive strength – 0/1 mm – 40%**

| Sand<br>[mm] | Sand<br>quantity<br>[%] | Age<br>[days] | Cube | Rc<br>[MPa] | Rc,mean<br>[MPa] | Upper<br>limit<br>[MPa] | Lower<br>limit<br>[MPa] | s<br>[MPa] |
|--------------|-------------------------|---------------|------|-------------|------------------|-------------------------|-------------------------|------------|
| 0/1          | 40                      | 1             | 1    | 23,644      | 23,3             | 25,6                    | 20,9                    | 0,2        |
|              | 40                      | 1             | 2    | 23,410      |                  |                         |                         |            |
|              | 40                      | 1             | 3    | 23,204      |                  |                         |                         |            |
|              | 40                      | 1             | 4    | 23,141      |                  |                         |                         |            |
|              | 40                      | 1             | 5    | 22,987      |                  |                         |                         |            |
|              | 40                      | 1             | 6    | 23,227      |                  |                         |                         |            |
| 0/1          | 40                      | 3             | 1    | 40,073      | 38,1             | 41,9                    | 34,3                    | 1,5        |
|              | 40                      | 3             | 2    | 35,626      |                  |                         |                         |            |
|              | 40                      | 3             | 3    | 37,500      |                  |                         |                         |            |
|              | 40                      | 3             | 4    | 38,178      |                  |                         |                         |            |
|              | 40                      | 3             | 5    | 39,086      |                  |                         |                         |            |
|              | 40                      | 3             | 6    | 38,322      |                  |                         |                         |            |
| 0/1          | 40                      | 7             | 1    | 56,842      | 61,9             | 68,1                    | 55,7                    | 3,4        |
|              | 40                      | 7             | 2    | 60,557      |                  |                         |                         |            |
|              | 40                      | 7             | 3    | 65,152      |                  |                         |                         |            |
|              | 40                      | 7             | 4    | 59,897      |                  |                         |                         |            |
|              | 40                      | 7             | 5    | 62,981      |                  |                         |                         |            |
|              | 40                      | 7             | 6    | 65,927      |                  |                         |                         |            |
| 0/1          | 40                      | 28            | 1    | 71,497      | 66,5             | 73,1                    | 59,8                    | 5,3        |
|              | 40                      | 28            | 2    | 72,951      |                  |                         |                         |            |
|              | 40                      | 28            | 3    | 61,189      |                  |                         |                         |            |
|              | 40                      | 28            | 4    | 69,103      |                  |                         |                         |            |
|              | 40                      | 28            | 5    | 61,402      |                  |                         |                         |            |
|              | 40                      | 28            | 6    | 62,855      |                  |                         |                         |            |

**Tabel F.12: Measured compressive strength – 0/1 mm – 50%**

| Sand<br>[mm] | Sand<br>quantity<br>[%] | Age<br>[days] | Cube | Rc<br>[MPa] | Rc,mean<br>[MPa] | Upper<br>limit<br>[MPa] | Lower<br>limit<br>[MPa] | s<br>[MPa] |
|--------------|-------------------------|---------------|------|-------------|------------------|-------------------------|-------------------------|------------|
| 0/1          | 50                      | 1             | 1    | 22,181      | 23,0             | 25,3                    | 20,7                    | 0,8        |
|              | 50                      | 1             | 2    | 22,478      |                  |                         |                         |            |
|              | 50                      | 1             | 3    | 22,872      |                  |                         |                         |            |
|              | 50                      | 1             | 4    | 22,301      |                  |                         |                         |            |
|              | 50                      | 1             | 5    | 24,170      |                  |                         |                         |            |
|              | 50                      | 1             | 6    | 23,735      |                  |                         |                         |            |
| 0/1          | 50                      | 3             | 1    | 36,948      | 37,8             | 41,5                    | 34,0                    | 2,1        |
|              | 50                      | 3             | 2    | 35,804      |                  |                         |                         |            |
|              | 50                      | 3             | 3    | 37,012      |                  |                         |                         |            |
|              | 50                      | 3             | 4    | 40,492      |                  |                         |                         |            |
|              | 50                      | 3             | 5    | 40,406      |                  |                         |                         |            |
|              | 50                      | 3             | 6    | 35,896      |                  |                         |                         |            |
| 0/1          | 50                      | 7             | 1    | 62,383      | 62,1             | 68,3                    | 55,9                    | 1,4        |
|              | 50                      | 7             | 2    | 61,516      |                  |                         |                         |            |
|              | 50                      | 7             | 3    | 63,406      |                  |                         |                         |            |
|              | 50                      | 7             | 4    | 61,214      |                  |                         |                         |            |
|              | 50                      | 7             | 5    | 60,161      |                  |                         |                         |            |
|              | 50                      | 7             | 6    | 63,848      |                  |                         |                         |            |
| 0/1          | 50                      | 28            | 1    | 50,651      | 59,9             | 65,9                    | 53,9                    | 3,1        |
|              | 50                      | 28            | 2    | 60,534      |                  |                         |                         |            |
|              | 50                      | 28            | 3    | 63,923      |                  |                         |                         |            |
|              | 50                      | 28            | 4    | 60,121      |                  |                         |                         |            |
|              | 50                      | 28            | 5    | 55,303      |                  |                         |                         |            |
|              | 50                      | 28            | 6    | 59,650      |                  |                         |                         |            |

**Tabel F.13: Measured compressive strength – 0/1 mm – 60%**

| Sand<br>[mm] | Sand<br>quantity<br>[%] | Age<br>[days] | Cube | Rc<br>[MPa] | Rc,mean<br>[MPa] | Upper<br>limit<br>[MPa] | Lower<br>limit<br>[MPa] | s<br>[MPa] |
|--------------|-------------------------|---------------|------|-------------|------------------|-------------------------|-------------------------|------------|
| 0/1          | 60                      | 1             | 1    | 21,317      | 20,5             | 22,6                    | 18,5                    | 1,0        |
|              | 60                      | 1             | 2    | 22,009      |                  |                         |                         |            |
|              | 60                      | 1             | 3    | 19,803      |                  |                         |                         |            |
|              | 60                      | 1             | 4    | 20,065      |                  |                         |                         |            |
|              | 60                      | 1             | 5    | 19,191      |                  |                         |                         |            |
|              | 60                      | 1             | 6    | 20,831      |                  |                         |                         |            |
| 0/1          | 60                      | 3             | 1    | 36,045      | 36,3             | 39,9                    | 32,7                    | 1,4        |
|              | 60                      | 3             | 2    | 37,253      |                  |                         |                         |            |
|              | 60                      | 3             | 3    | 35,982      |                  |                         |                         |            |
|              | 60                      | 3             | 4    | 37,581      |                  |                         |                         |            |
|              | 60                      | 3             | 5    | 33,808      |                  |                         |                         |            |
|              | 60                      | 3             | 6    | 37,161      |                  |                         |                         |            |
| 0/1          | 60                      | 7             | 1    | 49,922      | 50,0             | 54,9                    | 45,0                    | 3,3        |
|              | 60                      | 7             | 2    | 49,021      |                  |                         |                         |            |
|              | 60                      | 7             | 3    | 53,322      |                  |                         |                         |            |
|              | 60                      | 7             | 4    | 44,927      |                  |                         |                         |            |
|              | 60                      | 7             | 5    | 52,569      |                  |                         |                         |            |
|              | 60                      | 7             | 6    | 40,918      |                  |                         |                         |            |
| 0/1          | 60                      | 28            | 1    | 64,106      | 63,9             | 70,3                    | 57,5                    | 3,9        |
|              | 60                      | 28            | 2    | 58,525      |                  |                         |                         |            |
|              | 60                      | 28            | 3    | 59,863      |                  |                         |                         |            |
|              | 60                      | 28            | 4    | 66,892      |                  |                         |                         |            |
|              | 60                      | 28            | 5    | 66,260      |                  |                         |                         |            |
|              | 60                      | 28            | 6    | 67,897      |                  |                         |                         |            |

**Tabel F.14: Measured compressive strength – CEN – 10%**

| Sand | Sand quantity [%] | Age [days] | Cube | Rc [MPa] | Rc,mean [MPa] | Upper limit [MPa] | Lower limit [MPa] | s [MPa] |
|------|-------------------|------------|------|----------|---------------|-------------------|-------------------|---------|
| CEN  | 10                | 1          | 1    | 24,056   | 23,4          | 25,7              | 21,0              | 0,5     |
|      | 10                | 1          | 2    | 22,684   |               |                   |                   |         |
|      | 10                | 1          | 3    | 23,501   |               |                   |                   |         |
|      | 10                | 1          | 4    | 22,969   |               |                   |                   |         |
|      | 10                | 1          | 5    | 23,450   |               |                   |                   |         |
|      | 10                | 1          | 6    | 23,587   |               |                   |                   |         |
| CEN  | 10                | 3          | 1    | 47,740   | 49,0          | 54,0              | 44,1              | 1,7     |
|      | 10                | 3          | 2    | 51,409   |               |                   |                   |         |
|      | 10                | 3          | 3    | 49,170   |               |                   |                   |         |
|      | 10                | 3          | 4    | 46,649   |               |                   |                   |         |
|      | 10                | 3          | 5    | 50,054   |               |                   |                   |         |
|      | 10                | 3          | 6    | 49,256   |               |                   |                   |         |
| CEN  | 10                | 7          | 1    | 60,155   | 66,5          | 73,1              | 59,8              | 3,7     |
|      | 10                | 7          | 2    | 56,532   |               |                   |                   |         |
|      | 10                | 7          | 3    | 67,064   |               |                   |                   |         |
|      | 10                | 7          | 4    | 70,119   |               |                   |                   |         |
|      | 10                | 7          | 5    | 67,914   |               |                   |                   |         |
|      | 10                | 7          | 6    | 67,057   |               |                   |                   |         |
| CEN  | 10                | 28         | 1    | 53,246   | 72,5          | 79,7              | 65,2              | 4,8     |
|      | 10                | 28         | 2    | 79,733   |               |                   |                   |         |
|      | 10                | 28         | 3    | 68,890   |               |                   |                   |         |
|      | 10                | 28         | 4    | 74,914   |               |                   |                   |         |
|      | 10                | 28         | 5    | 70,434   |               |                   |                   |         |
|      | 10                | 28         | 6    | 68,419   |               |                   |                   |         |

**Tabel F.15: Measured compressive strength – CEN – 20%**

| Sand | Sand quantity [%] | Age [days] | Cube | Rc [MPa] | Rc,mean [MPa] | Upper limit [MPa] | Lower limit [MPa] | s [MPa] |
|------|-------------------|------------|------|----------|---------------|-------------------|-------------------|---------|
| CEN  | 20                | 1          | 1    | 20,586   | 21,4          | 23,5              | 19,2              | 0,9     |
|      | 20                | 1          | 2    | 20,552   |               |                   |                   |         |
|      | 20                | 1          | 3    | 20,620   |               |                   |                   |         |
|      | 20                | 1          | 4    | 20,906   |               |                   |                   |         |
|      | 20                | 1          | 5    | 22,135   |               |                   |                   |         |
|      | 20                | 1          | 6    | 22,546   |               |                   |                   |         |
| CEN  | 20                | 3          | 1    | 48,337   | 48,1          | 52,9              | 43,3              | 1,9     |
|      | 20                | 3          | 2    | 47,091   |               |                   |                   |         |
|      | 20                | 3          | 3    | 47,625   |               |                   |                   |         |
|      | 20                | 3          | 4    | 45,512   |               |                   |                   |         |
|      | 20                | 3          | 5    | 51,260   |               |                   |                   |         |
|      | 20                | 3          | 6    | 48,819   |               |                   |                   |         |
| CEN  | 20                | 7          | 1    | 66,105   | 64,1          | 70,5              | 57,7              | 2,1     |
|      | 20                | 7          | 2    | 62,786   |               |                   |                   |         |
|      | 20                | 7          | 3    | 63,349   |               |                   |                   |         |
|      | 20                | 7          | 4    | 61,304   |               |                   |                   |         |
|      | 20                | 7          | 5    | 66,800   |               |                   |                   |         |
|      | 20                | 7          | 6    | 63,073   |               |                   |                   |         |
| CEN  | 20                | 28         | 1    | 72,209   | 74,4          | 81,9              | 67,0              | 4,5     |
|      | 20                | 28         | 2    | 78,011   |               |                   |                   |         |
|      | 20                | 28         | 3    | 71,331   |               |                   |                   |         |
|      | 20                | 28         | 4    | 80,486   |               |                   |                   |         |
|      | 20                | 28         | 5    | 56,044   |               |                   |                   |         |
|      | 20                | 28         | 6    | 70,102   |               |                   |                   |         |

**Tabel F.16: Measured compressive strength – CEN – 30%**

| Sand | Sand quantity [%] | Age [days] | Cube | Rc [MPa] | Rc,mean [MPa] | Upper limit [MPa] | Lower limit [MPa] | s [MPa] |
|------|-------------------|------------|------|----------|---------------|-------------------|-------------------|---------|
| CEN  | 30                | 1          | 1    | 20,660   | 20,4          | 22,4              | 18,4              | 0,5     |
|      | 30                | 1          | 2    | 20,712   |               |                   |                   |         |
|      | 30                | 1          | 3    | 20,288   |               |                   |                   |         |
|      | 30                | 1          | 4    | 19,528   |               |                   |                   |         |
|      | 30                | 1          | 5    | 20,769   |               |                   |                   |         |
|      | 30                | 1          | 6    | 21,106   |               |                   |                   |         |
| CEN  | 30                | 3          | 1    | 44,553   | 48,0          | 52,8              | 43,2              | 2,1     |
|      | 30                | 3          | 2    | 50,261   |               |                   |                   |         |
|      | 30                | 3          | 3    | 46,918   |               |                   |                   |         |
|      | 30                | 3          | 4    | 46,850   |               |                   |                   |         |
|      | 30                | 3          | 5    | 49,486   |               |                   |                   |         |
|      | 30                | 3          | 6    | 48,733   |               |                   |                   |         |
| CEN  | 30                | 7          | 1    | 67,449   | 65,3          | 71,8              | 58,7              | 2,3     |
|      | 30                | 7          | 2    | 67,478   |               |                   |                   |         |
|      | 30                | 7          | 3    | 61,293   |               |                   |                   |         |
|      | 30                | 7          | 4    | 65,967   |               |                   |                   |         |
|      | 30                | 7          | 5    | 64,865   |               |                   |                   |         |
|      | 30                | 7          | 6    | 64,566   |               |                   |                   |         |
| CEN  | 30                | 28         | 1    | 70,538   | 74,3          | 81,8              | 66,9              | 5,9     |
|      | 30                | 28         | 2    | 79,460   |               |                   |                   |         |
|      | 30                | 28         | 3    | 73,892   |               |                   |                   |         |
|      | 30                | 28         | 4    | 66,934   |               |                   |                   |         |
|      | 30                | 28         | 5    | 60,869   |               |                   |                   |         |
|      | 30                | 28         | 6    | 80,772   |               |                   |                   |         |

**Tabel F.17: Measured compressive strength – CEN – 40%**

| Sand | Sand quantity [%] | Age [days] | Cube | Rc [MPa] | Rc,mean [MPa] | Upper limit [MPa] | Lower limit [MPa] | s [MPa] |
|------|-------------------|------------|------|----------|---------------|-------------------|-------------------|---------|
| CEN  | 40                | 1          | 1    | 21,117   | 21,8          | 23,9              | 19,6              | 1,5     |
|      | 40                | 1          | 2    | 23,45    |               |                   |                   |         |
|      | 40                | 1          | 3    | 20,997   |               |                   |                   |         |
|      | 40                | 1          | 4    | 20,111   |               |                   |                   |         |
|      | 40                | 1          | 5    | 21,043   |               |                   |                   |         |
|      | 40                | 1          | 6    | 23,861   |               |                   |                   |         |
| CEN  | 40                | 3          | 1    | 45,592   | 47,0          | 51,7              | 42,3              | 1,2     |
|      | 40                | 3          | 2    | 45,839   |               |                   |                   |         |
|      | 40                | 3          | 3    | 48,67    |               |                   |                   |         |
|      | 40                | 3          | 4    | 46,626   |               |                   |                   |         |
|      | 40                | 3          | 5    | 47,332   |               |                   |                   |         |
|      | 40                | 3          | 6    | 48,182   |               |                   |                   |         |
| CEN  | 40                | 7          | 1    | 49,371   | 53,7          | 59,1              | 48,4              | 4,2     |
|      | 40                | 7          | 2    | 48,43    |               |                   |                   |         |
|      | 40                | 7          | 3    | 58,995   |               |                   |                   |         |
|      | 40                | 7          | 4    | 50,364   |               |                   |                   |         |
|      | 40                | 7          | 5    | 52,874   |               |                   |                   |         |
|      | 40                | 7          | 6    | 62,315   |               |                   |                   |         |
| CEN  | 40                | 28         | 1    | 83,777   | 83,3          | 91,6              | 74,9              | 4,4     |
|      | 40                | 28         | 2    | 83,953   |               |                   |                   |         |
|      | 40                | 28         | 3    | 75,434   |               |                   |                   |         |
|      | 40                | 28         | 4    | 82,830   |               |                   |                   |         |
|      | 40                | 28         | 5    | 84,912   |               |                   |                   |         |
|      | 40                | 28         | 6    | 88,738   |               |                   |                   |         |

**Tabel F.18: Measured compressive strength – CEN – 50%**

| Sand | Sand quantity [%] | Age [days] | Cube | Rc [MPa] | Rc,mean [MPa] | Upper limit [MPa] | Lower limit [MPa] | s [MPa] |
|------|-------------------|------------|------|----------|---------------|-------------------|-------------------|---------|
| CEN  | 50                | 1          | 1    | 21,289   | 21,0          | 23,1              | 18,9              | 0,8     |
|      | 50                | 1          | 2    | 20,117   |               |                   |                   |         |
|      | 50                | 1          | 3    | 20,306   |               |                   |                   |         |
|      | 50                | 1          | 4    | 21,615   |               |                   |                   |         |
|      | 50                | 1          | 5    | 20,649   |               |                   |                   |         |
|      | 50                | 1          | 6    | 22,101   |               |                   |                   |         |
| CEN  | 50                | 3          | 1    | 48,257   | 49,4          | 54,3              | 44,4              | 1,0     |
|      | 50                | 3          | 2    | 49,669   |               |                   |                   |         |
|      | 50                | 3          | 3    | 49,244   |               |                   |                   |         |
|      | 50                | 3          | 4    | 50,123   |               |                   |                   |         |
|      | 50                | 3          | 5    | 50,651   |               |                   |                   |         |
|      | 50                | 3          | 6    | 48,291   |               |                   |                   |         |
| CEN  | 50                | 7          | 1    | 54,177   | 57,1          | 62,8              | 51,4              | 3,7     |
|      | 50                | 7          | 2    | 60,874   |               |                   |                   |         |
|      | 50                | 7          | 3    | 62,390   |               |                   |                   |         |
|      | 50                | 7          | 4    | 54,235   |               |                   |                   |         |
|      | 50                | 7          | 5    | 56,469   |               |                   |                   |         |
|      | 50                | 7          | 6    | 54,281   |               |                   |                   |         |
| CEN  | 50                | 28         | 1    | 86,286   | 87,4          | 96,2              | 78,7              | 2,5     |
|      | 50                | 28         | 2    | 86,252   |               |                   |                   |         |
|      | 50                | 28         | 3    | 90,848   |               |                   |                   |         |
|      | 50                | 28         | 4    | 89,941   |               |                   |                   |         |
|      | 50                | 28         | 5    | 84,381   |               |                   |                   |         |
|      | 50                | 28         | 6    | 86,896   |               |                   |                   |         |

**Tabel F.19: Measured compressive strength – CEN – 60%**

| Sand | Sand quantity [%] | Age [days] | Cube | Rc [MPa] | Rc,mean [MPa] | Upper limit [MPa] | Lower limit [MPa] | s [MPa] |
|------|-------------------|------------|------|----------|---------------|-------------------|-------------------|---------|
| CEN  | 60                | 1          | 1    | 21,512   | 21,9          | 24,1              | 19,7              | 0,6     |
|      | 60                | 1          | 2    | 22,249   |               |                   |                   |         |
|      | 60                | 1          | 3    | 22,215   |               |                   |                   |         |
|      | 60                | 1          | 4    | 21,283   |               |                   |                   |         |
|      | 60                | 1          | 5    | 21,335   |               |                   |                   |         |
|      | 60                | 1          | 6    | 22,592   |               |                   |                   |         |
| CEN  | 60                | 3          | 1    | 51,737   | 53,2          | 58,5              | 47,8              | 1,0     |
|      | 60                | 3          | 2    | 37,167   |               |                   |                   |         |
|      | 60                | 3          | 3    | 52,546   |               |                   |                   |         |
|      | 60                | 3          | 4    | 54,447   |               |                   |                   |         |
|      | 60                | 3          | 5    | 53,506   |               |                   |                   |         |
|      | 60                | 3          | 6    | 53,534   |               |                   |                   |         |
| CEN  | 60                | 7          | 1    | 52,363   | 55,5          | 61,0              | 49,9              | 2,4     |
|      | 60                | 7          | 2    | 56,119   |               |                   |                   |         |
|      | 60                | 7          | 3    | 54,063   |               |                   |                   |         |
|      | 60                | 7          | 4    | 54,086   |               |                   |                   |         |
|      | 60                | 7          | 5    | 58,404   |               |                   |                   |         |
|      | 60                | 7          | 6    | 57,744   |               |                   |                   |         |
| CEN  | 60                | 28         | 1    | 96,409   | 94,8          | 104,3             | 85,3              | 3,2     |
|      | 60                | 28         | 2    | 91,082   |               |                   |                   |         |
|      | 60                | 28         | 3    | 95,08    |               |                   |                   |         |
|      | 60                | 28         | 4    | 98,214   |               |                   |                   |         |
|      | 60                | 28         | 5    | 97,326   |               |                   |                   |         |
|      | 60                | 28         | 6    | 90,534   |               |                   |                   |         |

## Appendix G: Measured temperature of raw mixtures

Tabel G.1: Measured temperature of raw mixtures

| Sand [%]  | Temperature raw mixtures<br>[°C] |               |               |               |
|-----------|----------------------------------|---------------|---------------|---------------|
|           | Measurement 1                    | Measurement 2 | Measurement 3 | Measurement 4 |
| <b>0</b>  | 19,2                             | 20,9          | 19,7          | 19,5          |
| <b>10</b> | 19,6                             | 21,4          | 20            | 20,1          |
| <b>20</b> | 19,8                             | 22,4          | 20,8          | 20,7          |
| <b>30</b> | 19,6                             | 22,8          | 20,6          | 21,2          |
| <b>40</b> | 21,7                             | 22,9          | 21,7          | 22,1          |
| <b>50</b> | 22,4                             | 23,3          | 21,6          | 22,6          |
| <b>60</b> | 23,4                             | 25,2          | 22            | 24,7          |

