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MASTER THESIS

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IN COLLABORATION WITH Mapei AS	CONTACT PERSON Thomas Beck

SUMMARY
This study is conducted as part of Mapei Re-Con Zero project with the aim to optimize the water-to-binder ratio (W/B) and binder mix design using 100% environmentally friendly binders, mainly mortar waste, Cement Kiln Dust (CKD), and Microfil. The goal is to achieve higher strength for binder made with waste sludges for effective recycling through the developed Re-ConZero approach. Experimental results showed that 40% CKD, 40% Microfil, and 20% mortar waste mixed at a W/B of 0.6 exhibited a 16% decrease in flowability while maintaining 84% of the 28 day-compressive strength relative to the binder made of 100% Portland cement. The findings of this project demonstrated the feasibility of using environmentally friendly binder to recycle waste sludge, offering promising opportunities for the Re-Con Zero initiative to promote waste recycling.

KEYWORDS
Re-Con Zero Technology
Sludge Waste Management
Supplementary Cementitious Materials

Preface

This master's thesis is written by Trygve Holth and Thea Kvale as the final project of our master's degree program in Structural Engineering and Building Technology at the Department of Civil Engineering and Energy Technology, Faculty of Technology, Arts and Design at Oslo Metropolitan University.

We would like to express our gratitude to the contributors who disposed their time and insights, enabling this research to be conducted. In particular, we would like to thank our internal supervisor at OsloMet, Sarra Drissi, for guidance throughout the semester. We also want to thank Thomas Beck, our external supervisor from Mapei AS, for sharing his invaluable expertise and providing the necessary resources to complete this project. In addition, we would like to thank Mapei and the laboratory staff at Mapei for assistance for letting us get access to the laboratory and the equipment needed.

Further, we would like to thank family and friends for their support and understanding throughout this semester.

It is our sincere hope that this master thesis will contribute to the existing knowledge within the building sector and inspire future research in this area. We respectfully present this work to the academic community and anyone with an interest in the subject matter, with hope that it will lead to a deeper understanding and research of the subject.

Oslo, 25th of May 2023

Trygve Holth   Thea Kvale

Abstract

Concrete ready mix plant manufacturers face the dual challenges of managing returned concrete and the water required for cleaning the delivery track, as well as the disposal of waste generated during the washing process. To overcome those challenges, Mapei AS has developed an environmentally friendly and innovative solution known as Re-Con Zero (RCZ). This technology consists of using a two-component powder additive to dry-clean concrete trucks and recycle the returned concrete into aggregates that could be used to replace natural aggregates in the production of concrete. Upon the successful implementation of this approach, Mapei is eager now to extend the application of RCZ to other type of waste, including waste sludge. Transforming this waste into aggregates was hindered by their non-hydraulic nature. The aggregates made of sludge failed to dry or gain strength over time. To solve this issue, this study aims to suggest an optimized binder mix design that facilitates recycling of waste sludge by RCZ.

Considering the environmental challenges associated with cement production, this work proposed the use of 100% waste materials, such as mortar waste, Cement Kiln Dust (CKD), and microfil. The effectiveness of the binders was evaluated based on their impact on the flowability, hardened density and the compressive strength development over time. A total of 15 mixes, varying in binders' content and water to binder ratio (W/B) were investigated to determine the optimal mix design combination for recycling sludge by RCZ.

Experimental results showed that the increase in CKD content and a decrease in microfil content in the mixtures resulted in a diminished performance. Furthermore, a high W/B ratio, above 1.0, resulted in a watery mixture with negligible strength. The most optimal mixture consisted of 40% CKD, 40% microfil, and 20% mortar waste, with a W/B ratio of 0.6. This mixture exhibited 16% lower flowability compared to the reference sample made of 100% Portland cement, but still achieved 84% of the 28 day-compressive strength of the reference sample. The reduced flowability reflects the ability of this binder to dry faster, which is crucial for the production of aggregates with RCZ.

The improvement of sludge properties by the incorporation of the suggested alternative binder expands the possibilities of using RCZ for recycling other wastes.

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Abbreviations

ACC	Accelerated Carbonation Curing
$Ca(OH)_2$	Calcium Hydroxide
C-A-H	Calcium Aluminate Hydrate
CKD	Cement Kiln Dust
CO_2	Carbon Dioxide
C-S-H	Calcium Silicate Hydrates
EEA	European Environment Agency
EPAs	Environmental Protection Agency
GHG	Greenhouse Gas
kN	Kilonewton
MPa	Megapascal
OPC	Ordinary Portland Cement
RC	Returned Concrete
RCA	Recycled Concrete Aggregate
RCZ	Re-Con Zero
RMC	Ready-Mixed Concrete
SCMs	Supplementary Cementitious Materials
SNL	Société Nouvelle du Littoral
SSB	Statistics Norway
W/B	Water/Binder
W/C	Water/Cement

Chapter 1 Introduction

As the most used construction material, concrete is responsible for a significant portion of global CO_2 emissions, with cement production being a major contributor, accounting for up to 8% (1). Additionally, the building construction industry generates for approximately 40% of the global waste, consumes nearly 40% of raw material and contributes approximately 25% of global CO_2 emissions (2,3). These statistics correspond with the unsustainable "take-make-dispose" model, often termed as the linear economy. Within the construction sector, concrete waste constitutes 50% of the overall construction and demolition waste (4). While hardened concrete is not the main source of hazard waste, the disposal of fresh concrete can pose risks, including damage to water and soil and the potential to cause burns on human skin (5).

The high consumption of natural resources in its creation only highlights the current sustainability issue. In Europe, between 1 and 4% of ready-mix concrete (RMC) is wasted (6). Disposal of this waste primarily occurs in landfills, and in some countries, it is lack of designated areas for concrete waste disposal which adversely affects both costs and the environment (7).

A fully loaded 8 m^3 truck of concrete carries around 32 tons of RMC (8). After delivery, the truck returns to the manufacturer. An “empty” truck contains approximately 100 kg of concrete attached to the drum. Each cleaning process requires between 500-1000 liters of water, resulting in the creation of concrete sludge, which is classified as waste (8,9). The high water consumption is particular concerning given the current global water scarcity issues, as UNESCO reports that between two and three billion people experience water shortages for one month each year (10). Considering the concrete industry’s heavy dependence on water for production and cleaning operations, there is a growing demand for efficient cleaning methods that minimize water usage. Addressing these challenges, Mapei has developed Re-Con Zero (RCZ), a two-component powder additive for cleaning concrete trucks and recycling returned concrete (RC). This technology consists of adding the powder into the concrete trucks in order to reduce water usage and improve the consistency of the remaining sludge during waste management (11).

In addition to optimizing the concrete production process, it is worth investigating the potential combination of the RCZ-technology with other types of waste sludges. When tunnels or mines are excavated, large amounts of industrial waste are produced including sludge (12). Unlike the concrete sludges from concrete trucks, these excavated sludges do not contain any binders. Due to the harmful effects of sludge disposal on landfills and the environment, it is essential to further explore the afterlife of sludge and develop proper recycling methods to reduce negative environmental impacts (8).

Mapei has already experimented by combining sludge with Ordinary Portland Cement (OPC) and RCZ powder, with success. However, due to the environmental concern associated with cement, other alternative binders should be used. Therefore, this study aims to suggest an optimized green binder mix design that facilitates recycling of waste sludge by RCZ. Since sludge typically includes significant amounts of water, the tests will be conducted using mortar mixtures with high water/binder (W/B) ratios than usual. The objective is to determine whether more environmentally friendly SCMs can substitute cement while maintaining competitive properties. This study will examine three SCMs:

- Mortar waste
- Cement Kiln Dust (CKD)
- Microfil 750 DOS, hereafter Microfil

Additionally, the testing will involve various W/B ratios to determine when the material properties are comparable with OPC mortar mixtures.

1.1 Social Perspective

Increased population and over-exploitation of natural resources bring both ecological and environmental difficulties (13). Slightly less than 3 billion people live in and around cities worldwide where there is need of a huge amounts of materials for construction of houses, bridges, roads, commercial buildings, to name a few examples (14). Today, the largest manufactured building material by volume is concrete, with an average global consumption of roughly 11 billion tons (13,14). OPC is a crucial component in the production of concrete and has a significant influence on the environment (14). Utilizing more environmentally friendly SCMs in concrete mixtures is important to reduce or replace OPC in concrete production.

Figure 1.1 demonstrates that the building sector is responsible for approximately 40% of global energy consumption (15). This highlights the requirements for sustainable practices in the industry, particularly the concrete production. Efforts towards environmentally friendly concrete sector could significantly reduce the sector's energy use and GHG emissions. In this context, exploring and integrating sustainable alternatives into construction processes becomes crucial.

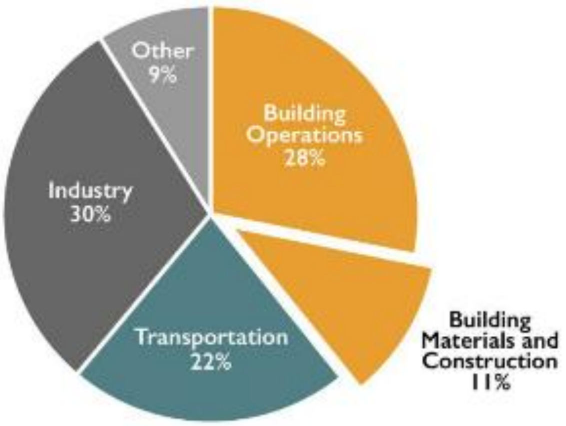

Figure 1.1 Percentages of emission in the building industry *(15)*

1.2 Objectives

To allow extending Mapei’s technology to other waste, in particular sludge, this thesis aims to:

1. Find the appropriate binder mixture that would allow competitive properties compared to cement.
2. Examine the effect of different W/B ratios on the flowability and compressive strength.

1.3 Thesis outline

This thesis is divided into three parts to ensure a methodical master's thesis. Each part serves an essential role in the investigation and contributes to the overall quality of the research. As a preliminary step, Chapter 2 displays a thorough literature review to establish a comprehensive understanding of the subject. Secondly, laboratory experiments were designed and executed with guidance from Mapei. The laboratory experiments, described in Chapter 3 were carried out at Mapei's Norwegian and Baltic headquarters located in Nord-Odal, which provided access to facilities and equipment essential for the successful execution of experiments. Finally, the findings from both laboratory experiments and literature review are presented in Chapter 4 to justify for the research objectives. This approach allowed us to assess the results and draw stronger and more informed conclusions.

1.3.1 Literature review

ScienceDirect has been used in the collection of published articles and papers in order to form an overview and an understanding of the subject itself, but also to acknowledge what kind of research that has already been completed prior to this study. Additionally, we have used theory provided by Mapei.

Using a dataset limited to 100 articles, a VOSviewer analysis was conducted to understand the research landscape of SCMs with a focus on articles containing "SCMs concrete" in their titles, abstracts, or keywords from ScienceDirect. The term "concrete" was favored over "mortar" in this study, despite “mortar” having a higher suitability. This is simply because the usage of "mortar" resulted in fewer research findings, given its less common appearance in SCM research. The obtained results provided valuable insights on current SCMs research.

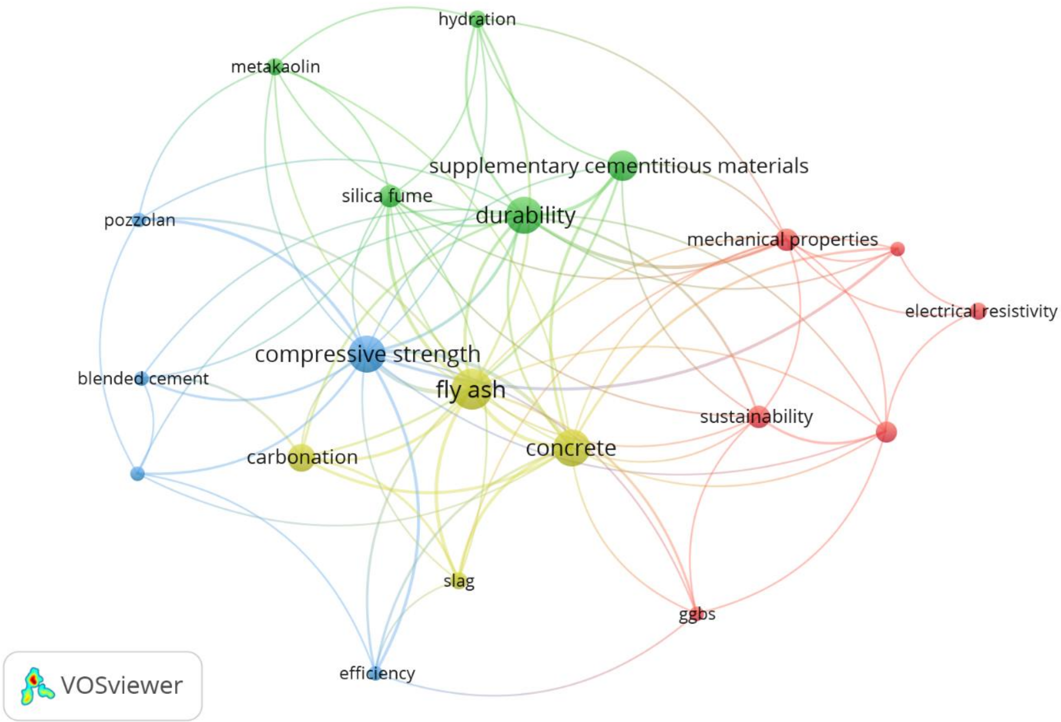

Figure 1.2 VOSviewer analysis

The VOS viewer analysis conducted on the field of construction materials science revealed interesting results. It appears that there has been a considerable amount of research done on alternative binders in concrete, with fly ash and silica fume partly being the primary focus, as Figure 1.2 illustrates. The majority of this research has centered on the properties of these mixtures, with less attention given to the influence and presence of water in SCMs mixtures. Although some studies have explored the relationship between W/B ratios and compressive strength, the completed VOSviewer analysis suggests that this line of research has not been properly investigated. This emphasizes the demand for more investigation into the influence of W/B ratios on the performance of alternative binders in both concrete and mortar, to gain a broader understanding of their properties and behavior.

1.4 Novelty and Contribution to the Field

In recent years, there has been a growing interest in exploring alternative binders as an intervention for reducing the environmental impact of concrete production. However, a large part of the existing research has focused on the use of these binders in combination with traditional cement. Incorporation of waste material into concrete and mortar mixtures can improve mechanical properties in the material and reduce environmental impact simultaneously. This study takes a different approach by exclusively replacing cement with a combination of waste-SCMs, particularly CKD, Microfil, and mortar waste, to produce a binder combination that would allow the recycling of sludge through the use of RCZ-technology. Additionally, this approach can provide a new life cycle for waste materials that might otherwise end up in landfills, polluting the environment. While this is still an emerging field of research, further research is needed to optimize the use of SCMs as binders in concrete and mortar mixtures and to assess their long-term durability and environmental impact.

1.5 Limitations

Due to time constraints, this study does not address the effect of the binder on the aggregation process and the characteristics of the subsequent aggregates. All experiments focused on investigating the flowability of the mixture and creating prismatic samples from it to evaluate their compressive strength. Further research is necessary to verify the reliability of our findings when utilizing RCZ-technology to produce aggregates from the same materials.

Drilling through various rock types, including limestone, or using certain explosives can affect the pH of the created sludge. Before the sludge can be safely released into the environment or be recycled, it needs to be treated to adjust the pH level. The pH values of the sludge are not something this thesis will be exploring, as it aims to find an adequate SCM mixture based of waste materials.

While the economic aspects of a chosen concrete mixture are crucial in real-world applications, this study sets aside such considerations. One limitation is therefore the exclusive focus on the mixture's structural attributes and performance, disregarding the cost implications of the selected SCMs. This could affect the practical applicability of the research findings when considering budget constraints in actual construction scenarios.

Chapter 2 Re-Con Zero and Concrete Waste Management

2.1 Introduction

This chapter will carry out findings from the comprehensive literature review. The purpose of this chapter is to shape and improve the general understanding of the subject of industrial waste management.

2.2 Concrete waste generation in concrete production and delivery industry

Each year, approximately 25 billion tons of concrete are produced, with an estimated 120 million tons being returned (16). Therefore, it is necessary to develop efficient, sustainable, and effective recycling and reuse methods to minimize concrete waste. Kazaz and Ulubeyli (5) highlighted in their study that one method for processing RC involves discharging it at a particular location until it hardens, followed by crushing and recycling it as aggregates. However, this method involves risk to water and soil and may not be an ideal approach. Other methods of managing RC includes the production of concrete block or retaining walls and reclamation systems where the ingredients are separated and reused (16). These methods are limited to local block production needs, capital investment requirements, and proper implementation.

Concrete batching plants that produce 1000 m^3 of concrete per day can generate a significant amount of waste, typically ranging from 8 to 10 tons of leftover material daily (16). This waste consists mainly of concrete that remains or adheres to the inside of the drum. It is crucial to distinguish and consider the potential risks associated with concrete waste, as it can have significant environmental impacts and pose hazards to human health. Concrete manufacturers face the challenge of managing large quantities of waste products, including concrete waste, requiring the adoption of sustainable waste management practices to minimize environmental impacts and promote a circular economy within the industry (5).

2.2.1 Treatment Strategies for Returned Concrete

Figure 2.1 provides a visual representation of various potential treatments strategies for RC. When concrete is returned to the manufacturer, it can be managed in different ways, including disposal in landfills, reuse in new concrete, or recycling for other applications (5).

Zhao et al. (17) conducted a literature review to explore various methods for utilizing RC in batching plants, with the aim of mitigation environmental damage caused by fresh concrete waste. Different types of RC were examined, and existing methods were reviewed one by one. The literature review highlighted the disposal method as the most commonly used strategy for concrete waste globally. However, it also acknowledged alternative strategies such as matching with suitable customers, blending with subsequent batches, discharging into settling basins or onto the ground, producing precast components, recycling mechanically, and utilizing hardened slurry cake in concrete and partition wall blocks. The research suggests that selecting appropriate methods for processing RC can enhance environmental sustainability and have positive societal impact (17).

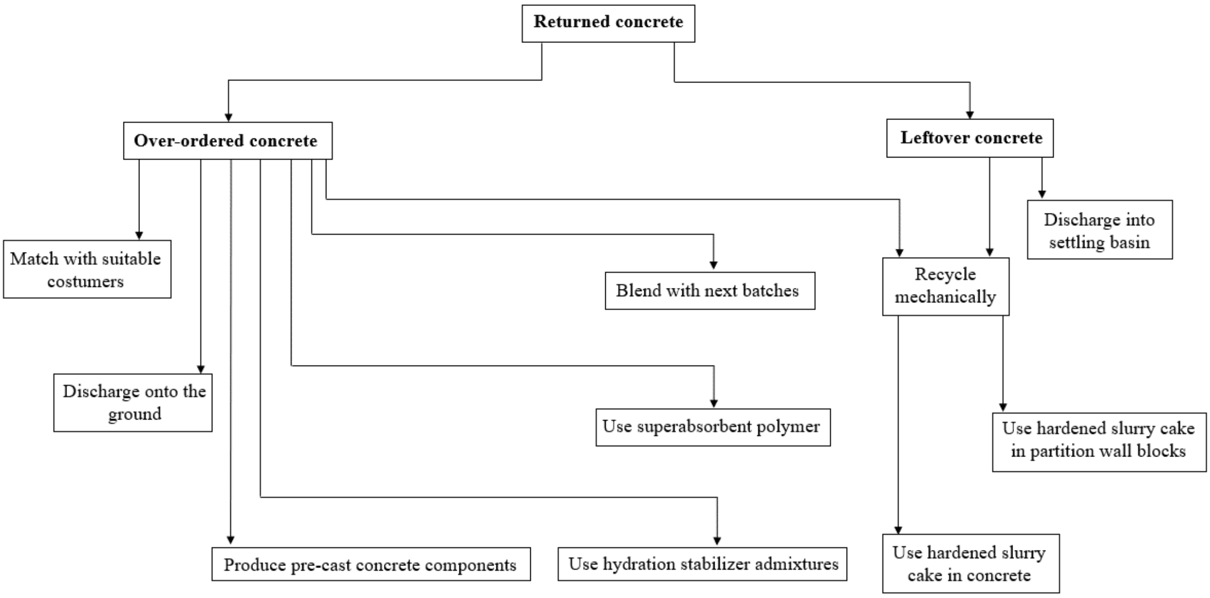

Figure 2.1 The most used alternatives for RC globally *(5)*

2.2.2 Overview of Concrete Waste Disposal in Norway

Table 2.1 offers a detailed overview of the total amount of concrete, brick, and other heavy building materials disposed of in Norway in 2021. Concrete and mortar are typically classified as either "lightly contaminated brick and concrete" or "concrete, brick, and other heavy building materials" (18). It is important to note that the Norwegian building industry faced significant challenges due to the COVID-19 pandemic in 2021, which makes it challenging to draw direct comparisons to previous years. Nonetheless, the distribution of waste materials produced remains highly relevant, emphasizing the need for sustainable waste management practices and promoting a circular economy in the concrete industry. An additional argument is the uncertainty surrounding the treatment and quantity of construction and demolishing waste, particularly the recycling of materials, due to the lack of reliable data reported in final project reports (19). This poses a significant challenge in achieving sustainable waste management practices, as accurate and transparent data collection systems are necessary.

Table 2.1 Concrete disposal Norway from 2021 *(18)*

Treatment Method	Concrete, brick and other heavy building materials [tonne (%)]	Lightly contaminated brick and concrete [tonne]
Recycled into Material	486 633 (70)	159 567

Deposit	187 821 (27)	0
Recycled into Energy	0	0
Other treatment/unspecified	21 001 (3)	0
Total	695 455	159 567

2.2.3 Challenges Associated with Conventional Disposal of Concrete Waste

The conventional disposal method of concrete waste involves the removal of waste concrete from construction sites and its transportation to landfills or dumpsites for disposal (5). Typically, the hardened concrete waste is broken into smaller pieces and loaded onto trucks for transportation. Once it arrives at the landfill or dumpsite, the waste concrete is dumped and left to decompose naturally over time. This disposal method presents several challenges, including significant environmental impact, land polluting, depletion of valuable resources, and an increasing demand for suitable landfill space (20).

According to the European Environment Agency (EEA), the landfilling rate from concrete waste in the EU decreased from 38% in 2004 to 24% in 2018 (21). This reduction can be attributed to improve waste management practices, increased recycling and composting rates. The implementation of waste reduction policies at the EU level, but the disposal of concrete waste remains a challenge globally.

The challenge of low demand for recycled concrete materials in the construction industry is another issue related to the increasing number of landfills. Hasan et al. (22) discuss this challenge and attribute the low demand for recycled concrete to the preferred virgin materials in construction. Concerns regarding quality, durability, and perceived risks associated with recycled concrete contribute to this market preference. Limited awareness among industry professionals, including engineers and architects, regarding the technical specifications and benefits of recycled concrete further prevents its adoption. To increase demand for recycled concrete, engineers and researchers need to develop innovative techniques, methodologies, and technologies that enhance the performance and reliability of recycled concrete. By doing so, Table 2.1 can include more options, and the amount of concrete in landfills can be reduced.

2.2.4 Recycling of Returned Concrete

The disposal and management of excess concrete pose significant challenges within the construction industry. Two main types of RC can be identified: over-ordered concrete, which occurs when contractors order a larger quantity of concrete than needed, and leftover concrete, which refers to concrete that remains in the truck after delivery (5), (23). The primary cause of this is overproduction, necessitation the development of effective procedures for handling and reusing the remaining material.

Xuan et al. (24) conducted a review where the focus was on the management on the current waste process for RMC. The authors reported that washing-out systems, which is a temporary station for contaminated water and slurry from cleaning concrete trucks, has been used at several concrete batching plants in recent years. However, the further recycling process system face several challenges, including increased cost, strict regulations locally, and poor product performance. The review concludes that there are need for mechanical aggregate and water reclaiming system installations in order to reduce disposal from RMC plants (24).

Another aspect of concrete waste management is the disposal of wastewater resulting from the cleaning of concrete truck drums on a daily basis. This wastewater, which can be classified as sludge, consumes a significant amount of water, with approximately 150-300 gallons being used every day for each concrete truck (25). Wastewater contains sand, gravel, fine cement particles, and chemical admixtures, resulting in a high pH value and meeting the Environmental Protection Agency (EPAs) definition of corrosivity, thereby being classified as hazardous (26). In an effort to address this issue, Chini and Mbwambo conducted a study on environmentally friendly solutions for disposal of concrete wastewater. Their findings indicate that by reusing wastewater, the consumption of fresh water in the production of one cubic yard of fresh-mixed concrete can be reduced from 20 to 5 gallons (25).

2.2.5 Separation and Reuse of Concrete Constituents

In cases where the reuse of RMC is not practical, an alternative approach can be separation and reusing of concrete constituents. Mulder et al. (27) acknowledges the Closed Cycle Construction method in a study, where the concept is to reuse materials while maintaining their original quality level. The primary objective of this approach is to minimize waste generation and conserve resources by reusing materials instead of disposing them as waste (27,28). A representation of this concept, illustrates the steps from deconstruction and component separation to manufacturing of construction products, is visualized in Figure 2.2 (27). For example, cement can be reused in order to be grounded down and used to make new cement for other construction projects, whilst sand and gravel can be used as a base material for roads or other construction projects (27). Through this process, the concrete material is effectively diverted from wasteful disposal, and its individual constituents are provided renewed purpose, thereby reducing the overall waste generated during the demolition process.

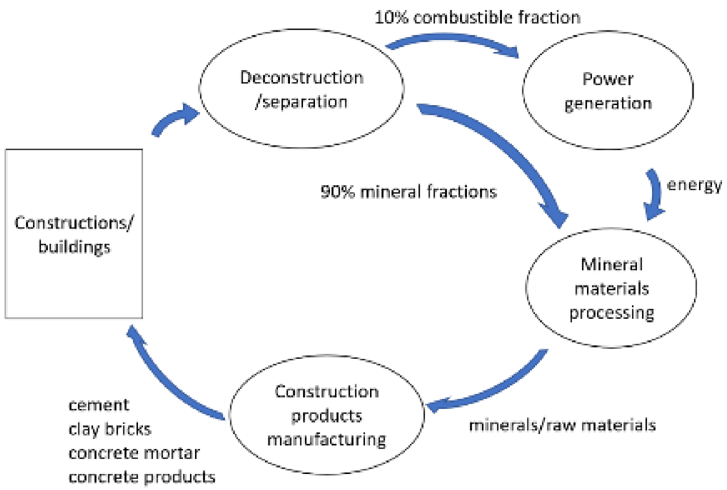

Figure 2.2 An example representation of Closed Cycle Construction concept *(27)*

Filter Press

A filter press, illustrated in Figure 2.3, is a machine designed to separate solid particles from liquid substances in concrete mixtures or concrete sludges. This process is important when recycling and reusing sludges (29). The filter press works by using pressure to force the sludge into a series of filters that hold back the solid particles while allowing the liquid components, usually water and cement, to pass through. (29–31). The device makes it possible to adjust the W/B ratio in waste sludges by extracting excess water, reducing waste volume, and reclaiming usable cement or other materials (31). Despite its utility, filter presses are not often used at construction sites or during tunnel excavations due to their substantial size, challenging mobility between projects, and considerable cost (32). In such scenarios, alternatives like dewatering bags or sedimentation tanks are preferred for separating solid and liquid components from excavation materials.

Figure 2.3 Filter press *(30)*

2.2.6 Recycled Solids

The European Union (EU) has set a binding target that mandates reusing or recycling a minimum of 70% of construction and demolition waste by 2020 (19). Latest calculations from Statistics Norway (SSB) show that the proportion of construction and demolition waste that is recycled or prepared for reuse experienced a considerable leap, rising from 56% in 2020 to 80% in 2021, as illustrated in Figure 2.4. The rise in the recycling rate is attributed primarily to the increased use of concrete and brick for filling and covering materials (19). This progression highlights EUs strategic commitment towards creating a circular economy, by focusing on waste reduction, reuse, and recycling.

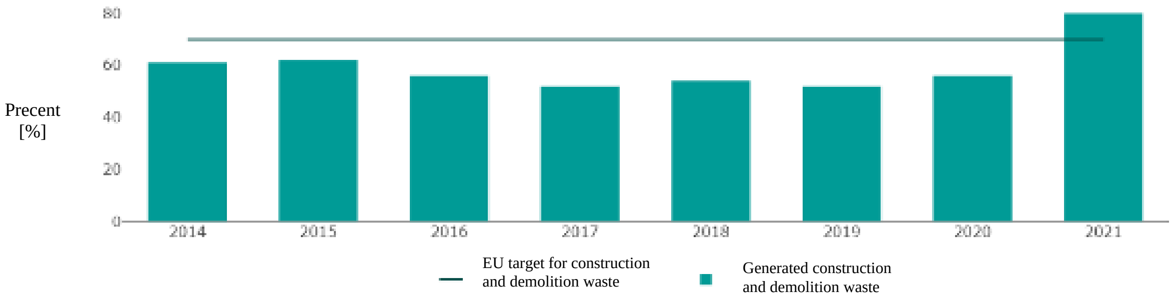

Figure 2.4 Material recycling of construction and demolition waste *(19)*

Recycling concrete is a heavily researched field within the construction waste research. Sangyong Kim et al. (33) published in 2013 a study where they used generated algorithms to find the optimal amount of RCA in concrete mixtures. In this article, the authors used artificial neural networks to optimize the percentage of RCA in concrete mixes. The study involved preparing concrete mixes with different percentages of RCA, ranging from 0 to 100%, and testing their compressive strength. The results show that it is possible to optimize the amount of RCA in concrete in order to keep the mechanical properties. This example shows how researchers are working on finding the optimal mixture of RCA and natural aggregates. Recycling of solid concrete is today commonly used in two different ways, either by being crushed and used as RCA or used as filling material for new construction projects (33).

An article completed by Abdollahnejad et al. (34) states that one of the main challenges related to RCA containing high moisture content is the reduction of compressive strength. Figure 2.5, presents a phenomenon labelled "internal curing”, which occurs if the moisture content of the RCA is higher than the fresh concrete. This can be advantageous as it can transfer moisture to the cementitious particles. Abdollahnejad et al. (34) also addresses the opposing effect, specifically by RCAs increased porosity compared to natural aggregates, absorbs moisture over time. The absorbed moisture in these highly porous aggregates can cause chemical reactions within the concrete, leading to potential structural weakening. This may include an alkali-silica reaction, carbonation, or freezing of absorbed water, each contributing to the deterioration of the concrete over time. As a conclusion Abdollahnejad et al. (34) highlight the necessity for careful consideration when using RCA in concrete.

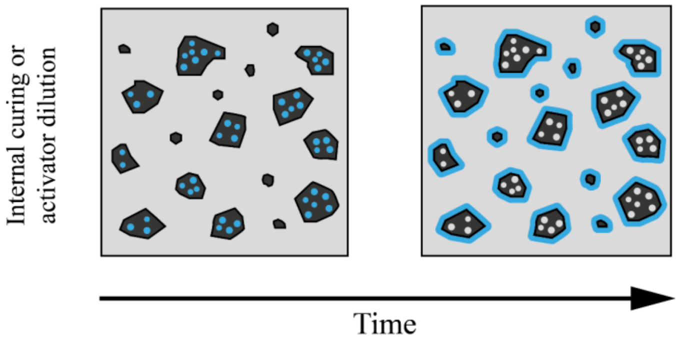

Figure 2.5 Saturated RCA performance over time *(34)*

2.3 Mapei: Innovation and Challenges

Mapei is a worldwide leader in manufacturing adhesives, sealants, and chemical products for the construction industry, with a particular emphasis on the production of concrete solutions (35). They are developing innovative construction chemicals that improves the performance, durability, and sustainability of concrete products. Mapei's global network include a total of 31 research centres in 20 different countries including the United States, Italy, and China, with their Nordic and Baltic headquarter being stationed in Sagstua, Norway (35).

2.3.1 Re-Con Zero

Mapei AS has developed a two-component powder additive for recycling fresh concrete waste from concrete trucks, called RCZ. Through their research, Mapei AS identified a specific combination of chemicals that, when added to the residual concrete in the concrete trucks, effectively recycles the residual. This by-product can then be effectively utilized in the production of new concrete and the method makes it possible to reduce concrete waste and improve its environmental impact (11). The RCZ technology consists of three different components: Component A, Component B, and Booster, as illustrated in Figure 2.6.

Figure 2.6 RCZ components *(11)*

2.3.2 Re-Con Zero as a Sustainable Solution for Managing Sludge

The management of wet concrete sludges poses significant challenges and financial implications for companies operating within the construction industry. Traditional methods of managing these sludges often require extensive containment measures, such as expensive containers or transportation equipment. These methods are not only costly, but they also pose a risk of environmental spillage. However, the use of RCZ offers an innovative and effective solution to this challenge. This innovative technology improves the porosity of wet concrete sludges, enabling them to absorb more water and thereby making them more manageable. As a result, companies can significantly reduce the containment measures required, leading to considerable cost savings. Simultaneously, this also considerably mitigates the risk for increased environmental footprint associated with managing wet concrete sludges, proving RCZ as a sustainable alternative. Figure 2.7 exemplifies how RCZ technology changes the sludge properties from a wet sludge(A) into a more controllable sludge with a thicker consistency (B) (9).

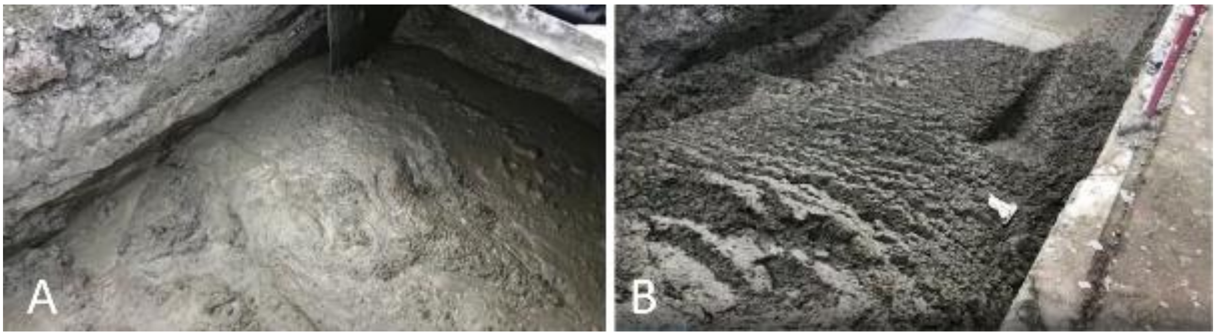

Figure 2.7 RCZ usage in sludge *(9)*

2.3.3 Cleaning concrete truck the green way: A look into Re-Con Zero-aggregates system

Fresh concrete attaches to the inner surface of the drum causing buildup after the truck returns to the manufacturer, this requires extensive water for cleaning purposes. This cleaning process creates a sludge that is considered waste. The RCZ technology allows for transformation of this waste into a useful and valuable material that can be reused in new concrete. This innovative solution not only minimizes environmental impact but also provides a valuable resource for sustainable construction practices (9).

Figure 2.8 provides a flow chart simplifying how Recycled Concrete Aggregate (RCA) is created from the RC through the usage of RCZ. The whole process occurs inside the concrete drum, where the RCZ components are added directly. The crushing process of the RCA is necessary because the aggregates can glue themselves to each other and create larger pieces. Mapei has had success using an “allu transformer shower”, to crush the glued aggregates into singular aggregates, other crushers might also be beneficial (9).

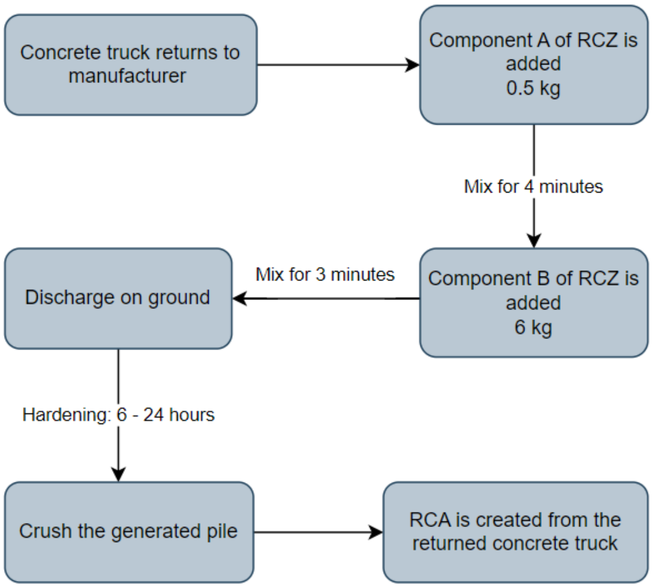

Figure 2.8 Flow chart of the creation of RCA with RCZ (9)

Figure 2.9 illustrates the finalised RCA created by the process described in the displayed flow chart. These aggregates have been tested and compared to other RCAs, and according to Norwegian standard NS-EN 206 it is just as usable as other RCAs. Table 2.2 contains properties of the RCZ aggregates delivered by Mapei and compares RCZ created aggregates with Mapei’s own crushed natural aggregates 4/8 mm. One important property in the table is the flakiness index. The flakiness index is a measure of the particle shape of aggregates, where a higher index value indicates a greater proportion of elongated or flake-like aggregates that may negatively affect the workability and strength of concrete. Table 2.2 explains that the flakiness index of RCZ aggregates is significantly lower compared to regular aggregates, mainly because of its smooth and round appearance, as illustrated in Figure 2.9. Although the RCA have a higher porosity than natural aggregates the flakiness of the aggregates gives it an improved workability (8).

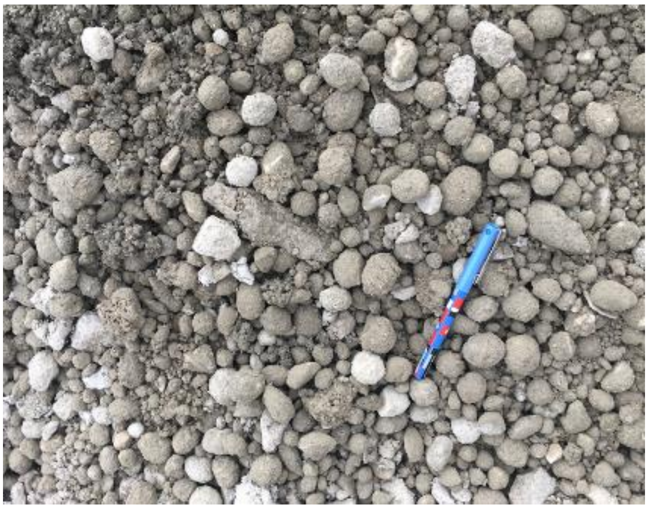

Figure 2.9 RCA created from RCZ *(36)*

Table 2.2 Properties of RCA according to NS-EN 12620

Category	Normal crushed aggregates 4/8 mm	Re-Con Zero Evo aggregates
Grain density [Mg/m^3]	2.78	2.66
Water absorption [%]	0.2	8
Los Angeles Index	Decl. LA_{15}	22-27
Micro-Deval MD	Not tested	31
Flakiness index	7	2

The cleaning process not only reduces the amount of waste but also generates a reusable product. Furthermore, during the production of RCZ-aggregates, a chemical reaction attracts CO_2 from the air and stores it inside the aggregates (carbonation), effectively capturing it. Mapei is currently working on calculating the amount of carbonation that is stored (9). Carbonation of concrete is currently a popular topic among researchers, as emissions and environmental footprint have increased in popularity in terms of research. Mapei calculates that RCZ absorbs up to 90% of the concrete on the inside of the drum and creates 2.3 kg of aggregates pr m^3 RC. This indicates that one truck produces under 10 kg of sludge with RCZ technology instead of the original 100 kg (8). However, it's worth noting that approximately 10% of the concrete remains on the drum surface after dry washing and needs to be removed using water. A comparison between the resulting sludge from the RCZ process and the created sludge from traditional washing methods is therefore interesting to explore further.

Figure 2.10 illustrates two samples that compares the sludge from a RCZ dry washed drum (A) and a sludge from the regular cleaning of a concrete drum (B). Sample A indicates that the usage of RCZ attracts a large amount of the particles, and the created sludge is therefore cleaner than the regular sample (B). The use of RCA in the sludge production process makes it more predictable and reduces the environmental hazards. As a result, managing the sludge becomes more predictable and more efficient.

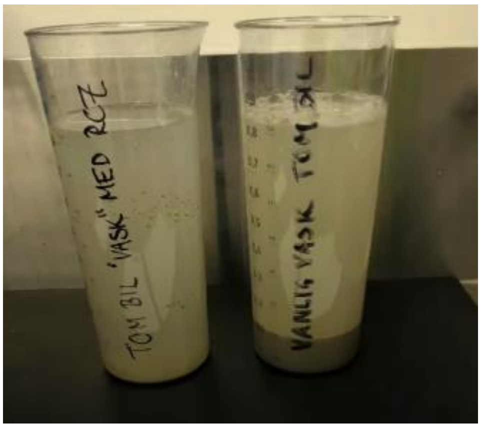

Figure 2.10 Comparison of sludge from washing drum *(9)*

The RCAs produced through RCZ technology possesses further possibilities. As detailed in Figure 2.11, the aggregates originally produced from the dry washing process can be added in the cleaning of additional concrete drums. This can be achieved by introducing a mixture of RCA aggregates, generated from RCZ, along with an additional 0.5 kg of RCZ component into the drum. This approach results in the original RCAs attracting more concrete, enhancing the efficiency of the cleaning process, and contributing to less RCZ powder per cleaning. Mapei explains that the created RCAs can be used in the cleaning process 2 to 3 times, before being used as RCA in new concrete.

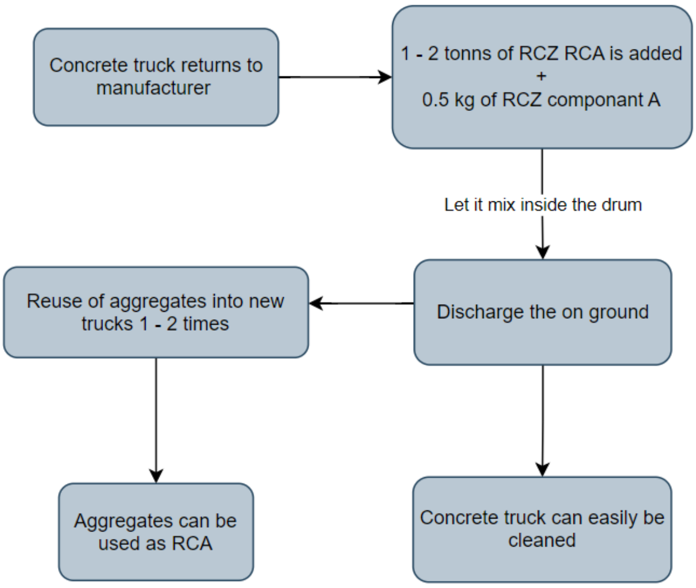

Figure 2.11 Flow chart how created RCZ aggregates is reused *(9)*

2.4 Effect of Water-to-Binder Ratio on Structural Development

The W/B ratio determines the permeability and compressive strength of a concrete batch. Concrete permeability refers to the ability of water or other fluids to penetrate through the pores and capillaries of concrete (37). There has been performed several studies to gain knowledge of the optimal W/B ratio to increase durability and lifespan of concrete structures. Kenneth C. Hover (38) did research on "*The influence of water on the performance of concrete*", a scientific review where he presented Figure 2.12. This figure shows a graph where water-to-cement (W/C), average 28 days compressive strength and permeability are considered. As the graph illustrates, the average compressive strength decreases as the W/C ratio increases conversely to the permeability that increases with a higher W/C ratio.

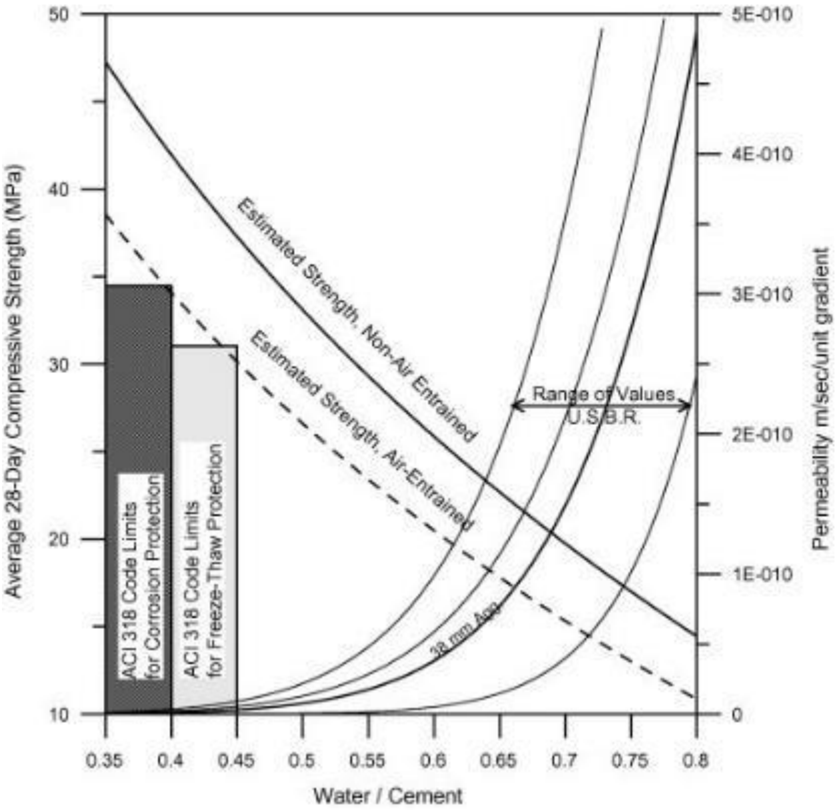

Figure 2.12 Concrete properties related to different W/C ratios *(38)*

In his research, Hover argues that the behavior of concrete is closely associated with water, as it is essential for hydration but also contributes to the creation of pores. He describes that the presence of these pores can lead to various forms of deterioration. Therefore, both strength and shrinkage, which are critical characteristics of concrete, are influenced by water (38).

Shaojun Zheng et al. (39) examinates in their study how the porosity of concrete evolves with different W/C ratios. Engaging microstructure analysis, they reveal the microstructure of concrete development. As previously explained, the presence of water ratios in the concrete mixture results in an escalated presence of pores within the concrete's structure. Exploring this phenomenon further, Zheng et al. (39) detail that when water is added to a concrete mixture, it combines with cement to form a paste that binds the aggregates together. However, if the W/B ratio is increased beyond the optimal point, there won't be enough cement particles to effectively utilize the excess water in the hydration process. The remaining water then stays in the mix as voids, increasing the space between the solid particles and leading to a higher degree of porosity (39). This dynamic is represented in Figure 2.13, where three different W/B ratios has been tested.

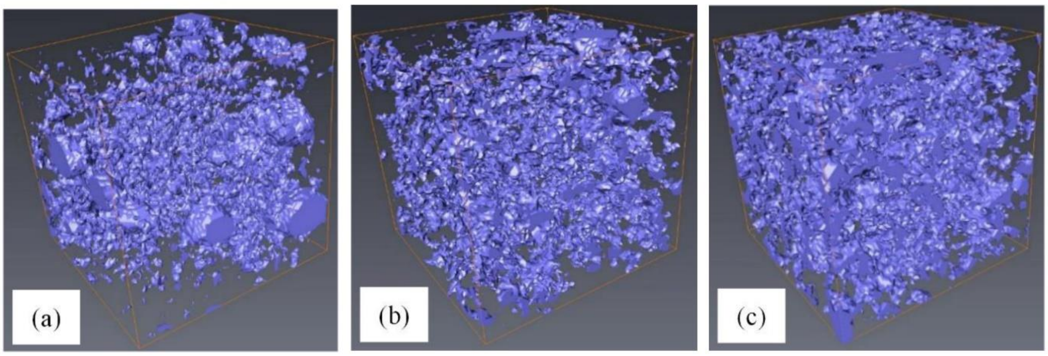

Figure 2.13 Pore structure of cement sample 28D W/B = (a) 0.40; (b) 0.44; (c) 0.50. *(39)*

2.5 SCMs Performance in Different W/B Ratios

This subchapter will investigate the performance of the selected SCMs, specifically CKD, Microfil, and mortar waste, in comparison to OPC in concrete or mortar mixtures with varying W/B ratios. The focus will be on the compressive strength and water absorption properties of the selected mixtures exclusively.

2.5.1 Effect of Using Mortar Waste

Usage of mortar waste as a binder replacement in concrete is a promising approach towards sustainable production line in mortar production. While it has potential to reduce the carbon footprint of concrete production by repurposing a waste material, it also presents challenges in terms of properties and performance of the resulting concrete. Research studies investigating the application of mortar waste as an OPC replacement are not commonly found in the existing literature. This suggests that this field is relatively unexplored, presenting opportunities for additional studies.

An article published by Yaprak et al. (40) explores the use of fine recycled concrete aggregate waste, as a partial replacement natural fine sand in concrete mixtures to evaluate their effect on the compressive strength of concrete. Figure 2.14 illustrates how the different mixtures performed compared to the reference test with 100% natural aggregates. The mixture design consists of a reference using 0% waste and increasingly increased amounts of waste up to 100% cement replacement. Based on the illustrated test results, the study found that using mortar waste at a ratio of up to 10% is suitable for producing C30 concrete, while ratios between 20 to 50% are within the requirements for producing C25 concrete (40). This article highlights the significant variability in properties of mortar waste, which can lead to substantial differences in outcomes across mixture designs. The article states that water absorption increase as recycled concrete waste was added. Because of the increased porosity in mortar waste compared to natural aggregates it is not surprising that the recycled aggregates had improved water absorption abilities.

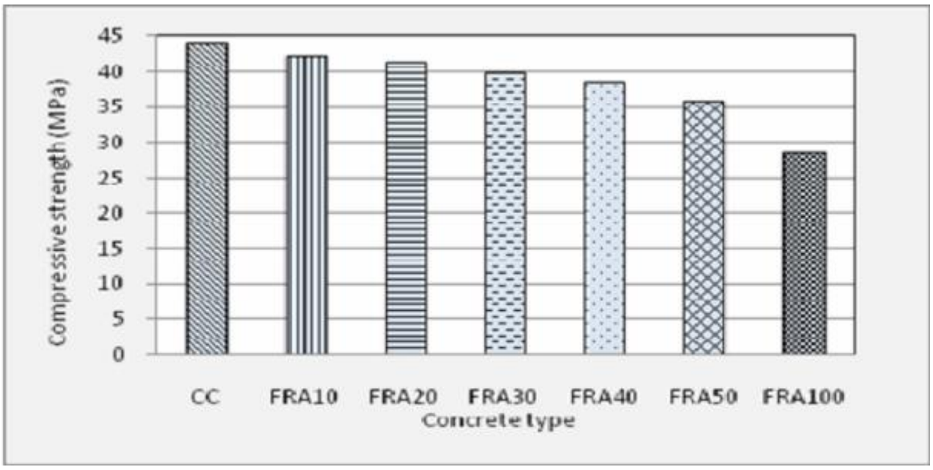

Figure 2.14 Compressive strength compared to mortar waste *(40)*

Yaprak et al. (40) emphasize a crucial factor in their article that needs to be considered when utilizing mortar waste. One of the main challenges of using mortar waste in concrete mixtures is determining the properties of the waste, as it is commonly collected without composition analysis. Since the incorporation of mortar waste in the building industry is a relatively new practice, there has not yet been registered any material properties (40).

2.5.2 Effect of using Cement Kiln Dust

Around 0,6-0,7 tons of CKD are generated for each ton of cement produced (41). Incorporating CKD in concrete mixtures considers sustainability by recycling industrial waste, reducing the demand for raw materials.

Research completed by Ali S Al-Harthy et al. (42) in 2003 examined the effect of CKD on the properties of mortar and concrete. The study used five different mortar mixtures: a reference mixture without CKD, and four with different CKD contents in their mixtures, ranging from 0% to 30% by weight of cement. Results showed that as the percentage of CKD increased, the compressive strength of the mortar and concrete decreased. The authors also reported that the decrease in performance as more CKD was added, it was discovered to be larger differences as the W/B ratio was raised. The decrease in compressive strength was mainly attributed the number of unreactive components in CKD. Not all of the components in CKD are contributing to strength in the mixture. As the proportion of CKD is increased, these unreactive components also increased as illustrated in Figure 2.15 (42).

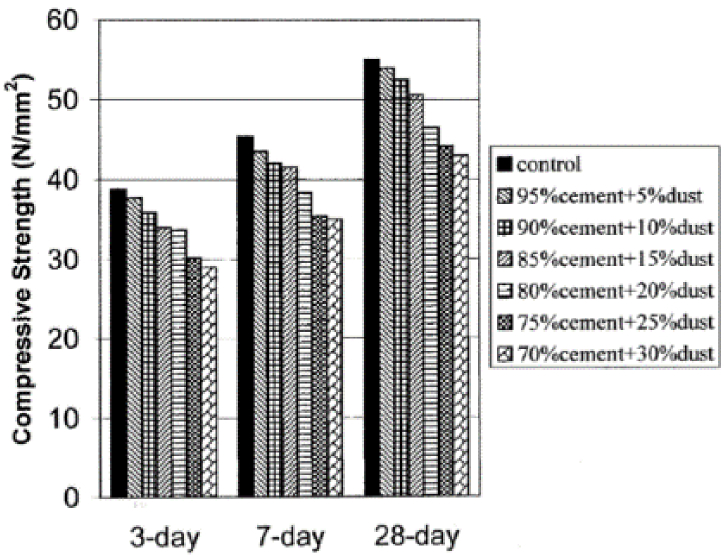

Figure 2.15 Compressive strength relation to added CKD *(42)*

The study found that increasing the CKD content in the mixtures led to a increase in water absorption. This could be because particle size of CKD and also CKDs ability to create a lower porosity, according to the report (42). Therefore, according to Ali S Al-Harthy et al. (42), the use of CKD in concrete mixtures should be carefully controlled, as high amounts can significantly reduce the strength and durability of the mixture.

2.5.3 Effect of using Microfil

Microfil are a type of SCM that are added to concrete to improve its properties. They are called "micro" because their particles are very small, with a diameter of less than 10 micrometers. This small particle size allows them to fill the spaces between larger cement particles. Fly ash and microsilica are common examples of Microfil (43).

Sharma et al. (44) conducted research on the effects of microsilica on the compressive strength of concrete. Microsilica, also known as silica fume, is a type of Microfil that is made of fine particles of amorphous silica (44). In their study, Sharma et al. (44) highlights the important physical and chemical properties of micro-silica and its contribution in improving the qualities of concrete. They found that the addition of microsilica led to a significant increase in the compressive strength of concrete. Sharma et al. (44) also describes Microfil's small particle size and fill voids and reduce capillary. This could be an explanation to why Microfil has the ability to improve concretes water absorption.

Sharma et al. (44) also referred to particle packing, which is the ability of small particles, in this case Microfil, to occupy the spaces between larger binder particles and aggregates, resulting in a more compact structure. Particle packing is similar to the filler effect mentioned, but the filler effect fills voids within the cementitious matrix, while particle packing fills spaces between larger particles

Portlandite

Through the hydration of cement hydration, calcium hydroxide ($Ca(OH)_2$) is created as a residue (45). When $Ca(OH)_2$ is created in cement hydration it is normally referred to as portlandite. In a cementitious reaction portlandite will attract oxygen and be transported to the concrete surface, where it will carbonate and lower the PH-value of the concrete. Therefore, the presence of portlandite in cementitious concrete mixtures will increase the risk of corrosion (46). Microfil contains Amorf Silica (SiO), which has the ability to react with $Ca(OH)_2$ (47):

$$3\,Ca(OH)_2 + 2\,SiO + 3H_2O = (3CaO * 2SiO * 3H_2O) = \mathrm{C3S2H3} \qquad [1]$$

C3S2H3 is a product that improves concrete strength (47). Therefore the presence of Microfil in cementitious reaction will react with Portlandite, a corrosion threat, and create C3S2H3, which will improve strength (47,48). The beneficial strength improvement from Microfil's reaction is why many companies include Microfil, typically 3-5%, in all of their concrete mixtures (48).

2.5.4 Pozzolanic reaction

A pozzolanic reaction is a chemical reaction between a pozzolan and calcium hydroxide $Ca(OH)_2$ that occurs in the presence of water. This results in the development of calcium silicate hydrates (C-S-H) and calcium aluminate hydrates (C-A-H), which are two primary binding components in concrete (49). Pozzolans are materials that are finely divided and chemically reactive, such as fly ash, silica fume, metakaolin, and calcined clay. These materials are typically added to concrete mixes as supplementary cementitious materials to enhance its strength and durability while reducing the amount of cement used (50).

During the pozzolanic reaction, the finely divided pozzolan particles react with calcium hydroxide released by the hydration of cement, forming additional C-S-H and C-A-H, which fill the spaces between cement particles and contribute to the strength and durability of the concrete (49). The reaction also reduces the amount of unreacted calcium hydroxide, which can improve the long-term durability of concrete by reducing its vulnerability to attack by environmental factors such as acid rain, sulphates, and chlorides (51).

2.5.5 Combination of CKD and Microfil

CKD contains calcium oxide (CaO), and when CaO reacts with water it creates:

$$CaO + H2O = Ca(OH)_2 \qquad [2]$$

Microfil contains amorphous silica (SiO) which when reacting with $Ca(OH)_2$ from the CKD creates calcium-silicate-hydrate. The reaction between SiO and $Ca(OH)_2$ is similar to the reaction between Microfil and cement. The pozzolanic reaction occurs when a pozzolanic material, such as Microfil or CKD, is added to a mixture that contains $Ca(OH)_2$ and water.

The reaction between Microfil and CKD is therefore considered pozzolanic because both materials contain silica and alumina, which are highly reactive components. Pozzolanic reactions, like the combination of CKD and Microfil, because they require time and moisture for the reaction between the pozzolan material and calcium hydroxide to occur, and the rate of the reaction depends on several factors, such as the fineness of the pozzolanic material and the temperature, which can delay the reaction under certain conditions (51).

Chapter 3 Materials and Methods

This chapter will present the selection of materials and the methods used related to our results. It will detail the specific laboratory procedures followed and provide an explanation for any necessary changes that were made.

3.1 Materials selection

The binders that will be examined are: mortar waste from Mapei’s own mortar plants in Sagstua in Norway, CKD from Heidelberg Materials, and Microfil 750 DOS from Elkem. Further subchapters will describe the properties to the components more detailed and account for why these binders were chosen.

3.1.1 Ordinary Portland Cement

OPC, specifically Standardsement FA produced by Heidelberg Materials in Oslo, was used as a reference in our laboratory work. This cement is tailored for Norwegian conditions. Standardsement FA meets the requirements of NS-EN 197-1:2011 for Portland composite cement CEM II/B-M(V-L) 42.5 R. OPC is the established binder in concrete and mortar production and will in this study be used as a reference when comparing different SCMs binders. Figure 3.1 illustrates the OPC that has been used in the concrete mixtures. Further information can be found in the datasheet in Appendix A.1.

Figure 3.1 OPC

3.1.2 Mortar waste

Mortar waste from Mapei's production line in Sagstua was used to see if it is possible to reuse the cementitious particles in the waste and therefore utilize the mortar further. It is essential to mention that technical datasheets for mortar waste do not exist, not only because of its low market demand, but also due to challenges in identifying the waste's sources. Mortar waste may origin from various sources, such as changes in production methods or instances where the mortar fails to meet quality standards. Mapei's mortar products include a range of types, such as repair mortars, masonry mortars, dry shot mortars, and more. These products share common components, primarily sand and binder. The mortar waste used in our laboratory work is illustrated in Figure 3.2.

Figure 3.2 Mortar waste

3.1.3 Cement Kiln Dust

The selected CKD was produced by Heidelberg Materials, the same factory as the selected OPC, in Oslo. The technical datasheet for the product is attached in appendix A.2. CKD look similar to Portland cement as a fine powder material with large variations in particle sizes. CKD is composed of Portland cement clinker phases, calcium oxide, calcium carbonate, alkali sulfates, and alkali chlorides, and is illustrated in Figure 3.3. CKD is a by-product from manufacturing OPC which makes it an interesting waste material to examine.

Figure 3.3 CKD

3.1.4 Microfil 750 DOS

The laboratory experiments were carried out using Microfil 750 DOS, illustrated in Figure 3.4. The selected Microfil is an off-spec microsilica produced by Elkem's Bjølvefossen plant in Ålvik, Hardanger. The plant primarily produces ferro-silicon alloys for the metal industry, and during this process, microsilica is filtered out from the waste product. However, some of the microsilica does not meet the specifications and cannot be used in concrete applications. Mapei has obtained CE-marking for this product as Microfil as a stabilizing admixture for concrete, in accordance with EN 934-2 Table 13, and supplies this product in bulk to concrete producers. The data sheet for Microfil can be found in Appendix A4. Despite the existing demand, there remains a significant volume of Microfil available, making it a potential component for the binder system in recycling mineral-based sludge, and this is also why it was selected during these laboratory experiments.

Figure 3.4 Microfil 750 DOS

3.1.5 Fine Aggregates

A high-quality sand aggregate named "standard sand" produced by Société Nouvelle du Littoral (SNL), a French manufacturer, was selected in the laboratory experiments. The sand is certified as Standard Sand in accordance with EN 196-1, ensuring it meets the necessary quality and consistency requirements for the laboratory work (52). Mapei's research and development laboratory uses this sand in all their tests on mortar or smaller concrete batches. CEN Standard Sand, also known as ISO Standard Sand, is a natural siliceous sand, characterized by its clean, isometric, and rounded particles, particularly in its finest fractions. The aggregates have a size between 0,08-2,00 mm, illustrated in Figure 3.5, where each bag contains 1350±5 g aggregate. Table 3.1 provides information about the particle size distribution. For example, approximately 99% of the sand particles are larger than 0.08 mm, while 67% of the particles are larger than 0.50 mm, and 0% of the particles are larger than 2.00 mm.

Figure 3.5 Standard sand

Table 3.1 Aggregate particle size composition *(52)*

Sieve mesh opening [mm]	Cumulative refusals [%]
0,08	99±1
0,16	87±5
0,50	67±5
1,00	33±5
1,60	7±5
2,00	0

3.1.6 Viscostar 6K

Viscostar 6K, a chemical additive produced by Mapei, was used in the laboratory work to adjust the properties of the mortar in some of the mixtures with higher W/B ratio. The product is designed to address specific challenges in concrete mixtures, such as improving pumpability, preventing separation, and reducing the risk of concrete bleeding. It is therefore considered a good option when mixing wet mortar mixtures. In mixtures that separated Viscostar 6K was added. The technical datasheet for Viscostar 6K can be found in appendix A.3 and Viscostar 6K is illustrated in Figure 3.6.

Figure 3.6 Viscostar 6K

3.2 Mixture Design

Table 3.2 illustrates the mixture design that has been used for the laboratory work. For three different W/B ratios (0.6, 1.0 and 1.3), five mixtures have been tested. The reference mixture consists of 100% OPC as binder. The goal is to compare the results of SCM mixtures with the reference for better understanding. Varying percentages of mortar waste, CKD, and Microfil have been incorporated as alternative binders in each of the following mixtures. The matrixes were carefully designed and suggested by Mapei.

Table 3.2 Mixture design

ID	0.6-REF	0.60 - 1	0.60 - 2	0.60 -3	0.60 - 4
Percent binder [%]:					
Reference OPC - CEM I	100	0	0	0	0
Mortar waste	0	20	20	20	40
CKD	0	40	50	60	50
Microfil	0	40	30	20	10
ID	**1.0-REF**	**1.00 - 1**	**1.00 - 2**	**1.00 -3**	**1.00 - 4**
Percent binder [%]:					
Reference OPC - CEM I	100	0	0	0	0
Mortar waste	0	20	20	20	40
CKD	0	40	50	60	50
Microfil	0	40	30	20	10
ID	**1.3-REF**	**1.30 - 1**	**1.30 - 2**	**1.30 -3**	**1.30 - 4**
Percent binder [%]:					
Reference OPC - CEM I	100	0	0	0	0
Mortar waste	0	20	20	20	40
CKD	0	40	50	60	50
Microfil	0	40	30	20	10

The amount of water differs from each mixture design depending on the W/B ratio. Considering the fact that each batch uses 450 g of binder. A W/B ratio of 0.60 therefore equals 270 g of water. W/B ratio at 1.00 should have 450 g of water, and finally a W/B ratio of 1.30 should have 585 g of water in the mortar mixtures.

3.3 Mixture procedure

The selected mixing procedure was designed according to NS-EN 196-1:2016, a procedure that is used on mortar mixtures. Table 3.3 details each step in the mixture process, including time and speed. The mixing speed was originally set at 281 rpm in parts of the procedure, but after completed mixtures obtaining W/B ratio of 1.3 resulting in spilled mortar out of the bowl, we decided together with Mapei to reduce it to 136 rpm for all of the mixtures. In order to get consistency in the mixing procedure, the mixtures, mixed initially at 281 rpm, were remixed for four minutes at 136 rpm. It is important to replicate the mixing process to prevent any inconsistencies.

Table 3.3 Mixture procedure

Time [min] from-to	Steps	Speed [rpm]
0.00	Before starting, pour water into the mixer.	136
0.00-0.30 (30 sec)	Slowly pour mixture of binders from the plastic bag.	136
0.30-1.00 (30 sec)	Slowly pour aggregates	136
1.00-1.30 (30 sec)	Mix for 30 sec	136
1.30-2.00 (30 sec)	Detach the arm and remove leftovers from the sides.	0
2.00-3.00 (60 sec)	Let the mixture rest	0
3.00-4.00 (60 sec)	Mix for 1 minute	136
4.00	Stop Pour mixture into molds	0

3.4 Laboratory work

A total of 30 compressive strength tests were carried out according to EN 12390-3. Each compressive strength test was completed twice on each end of the specimen. The cross section of each specimen mold size was respectively 40 x 40 mm. Additionally, flowability tests and density measurements were completed to examine the workability of the mortar.

3.4.1 Equipment list

Throughout the laboratory work, a range of equipment was used. Table 3.4 presents the equipment list and Figure 3.7 illustrates the mixing table. Appendix C includes a complete overview of all the equipment used, including visual representations of each item.

Table 3.4 Equipment list

Equipment list	
Mixer	Plastic cups
Mixing beater	Aggregates (1350 g)
Stopwatch	Water (20°C)

Sample mould	Binder mixture (450 g)
Weight	Viscostar 6K
Compressive strength test machine	Curing tank (20°C)

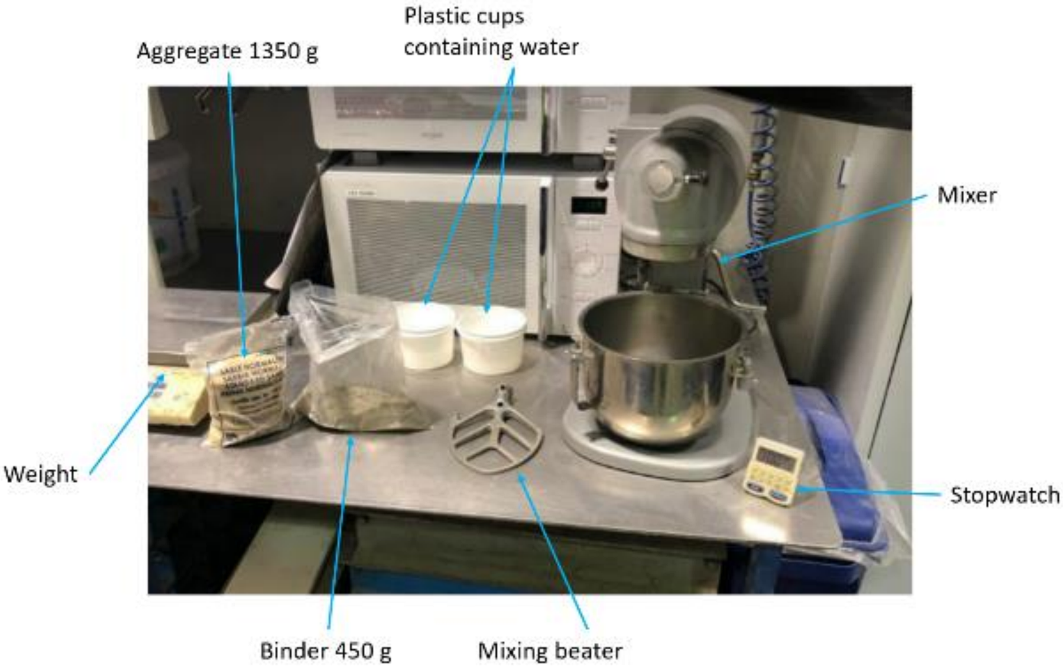

Figure 3.7 Mixing table

3.4.2 Laboratory methods

All laboratory procedures were conducted with guidance from Mapei. The study was carried out at Mapei's specialized laboratory for research and development, where a team of experienced laboratory technicians provided valuable assistance in executing our experimental protocols with precision and accuracy.

In order to ensure consistency between each mixture, it was essential to replicate the mixing procedure as closely as possible. To achieve this, each mixing process was completed by pre-mixing the components, as illustrated in Figure 3.7, and ensuring that every component was easily accessible before beginning the mixing stage. A scale with two decimal places was used, providing accurate measurement of components with precision. During the mixing process, both group members were assigned specific responsibilities and all mixtures were prepared using identical procedures to maintain uniformity. Binders or aggregates were seen to have a tendency of sticking to the interior of the mixing bowl, potentially changing the composition of subsequent mixtures. To prevent this issue, it was essential to ensure that all leftover materials were thoroughly incorporated into the mixture. Following the preparation of each mixture, all components were thoroughly cleaned to ensure the absence of any residual materials and to prepare for the next batch. Cleaning was carried out using water at 20ºC to prevent any inconsistencies in component temperature that could affect the subsequent mixture. During the mixing process, valuable information was acquired regarding the behaviour of these mixtures and the approaches to address any potential issues. The laboratory technicians and us as students had limited expertise in handling mortar mixtures with very high W/B ratios, similar to the ones used in our work. Therefore, it required time and experience to develop an understanding of the optimal methods for producing consistent mixtures.

For each batch it was performed flowability tests to acquire slump and spread information of each mortar mixtures. Flowability tests were performed according to ASTM C1437-07. Usage of this method includes a flow table with jolts, but since the mortar mixtures that are performed in this study has a higher W/B ratio than normal jolts was not a part of the procedure, as the jolts would make the mixture spill of the table.

The mixture was later poured into three molds, as illustrated in Figure 3.8. To determine whether the samples were ready to be removed from the mould, a slight pressure with our fingers was applied onto the surface of the mortar. When the samples had acquired sufficient strength to be removed, each sample was placed in a curing tank set to a room temperature of 20ºC until testing. These tanks provide a controlled environment with optimal temperature and moisture conditions that facilitates the hardening and development of strength. Prior to conducting the compressive strength tests, each specimen was removed from the curing tank to dry.

Figure 3.8 Sample mortar mold

Through our experiences, we learned that W/B ratios of 1.0 and 1.3 involve risk of segregation. Viscostar 6K was used in mixtures where segregation was observed, in order to create homogeneous results. In mixtures containing Viscostar 6K, it was added at the initial step of the mixing procedure, simultaneously with water. To determine the optimal amount of Viscostar 6K, several tests had to be repeated multiple times. This was necessary to find the dosage and achieve a homogeneous mixture. Viscostar 6K consists of 94% water, therefore the amount of water had to be subtracted in relation to the amount of Viscostar 6K added, in order to keep the correct W/B ratio.

Testing dates

Depicts in Table 3.5 are the dates of the compressive strength testes as well as the mixing dates.

Table 3.5 Testing dates for compressive strength testing

ID	Mixed	24H	7D	28D
0.6-REF	14.02.23	15.02.23	21.02.23	14.03.23
0.6-1	14.02.23	15.02.23	21.02.23	14.03.23
0.6-2	14.02.23	15.02.23	21.02.23	14.03.23
0.6-3	14.02.23	15.02.23	21.02.23	14.03.23
0.6-4	14.02.23	15.02.23	21.02.23	14.03.23
1.0-REF	15.02.23	16.02.23	22.02.23	15.03.23
1.0-1	15.02.23	16.02.23	22.02.23	15.03.23
1.0-2	15.02.23	16.02.23	22.02.23	15.03.23
1.0-3	15.02.23	16.02.23	22.02.23	15.03.23
1.0-4	15.02.23	16.02.23	22.02.23	15.03.23
1.3-REF	10.02.23	11.02.23	17.02.23	10.03.23
1.3-1	08.02.23	09.02.23	15.02.23	08.03.23
1.3-2	08.02.23	09.02.23	15.02.23	08.03.23
1.3-3	08.02.23	09.02.23	15.02.23	08.03.23
1.3-4	08.02.23	09.02.23	15.02.23	08.03.23

3.4.3 Testing

Flowability test

The mortar flow test, commonly referred to as the slump test, is a widely used technique for evaluating the workability of mortar. This test involves measuring the flow and deformation characteristics of freshly mixed mortar, providing a reliable indicator of its workability. The result reflects the ease with which the mortar can be transported, placed, and finished, while avoiding segregation or excessive hardening. The flow tests were conducted in accordance with ASTM C1437-07, which is the standard test method for the flow of hydraulic cement mortar. These tests will be performed as a slump cone test, where a sample of fresh mortar is placed into a metal cone, and when the cone is removed the mortar will flow and settle, according to the described ASTM standard. The height of the settled mortar is measured and compared to the height of the cone and will be the slump value in mm. Figure 3.9 shows the principle of the flow test. In addition to measure the slump we will also measure two diagonals per test which indicates the fluidity of the mortar mixtures.

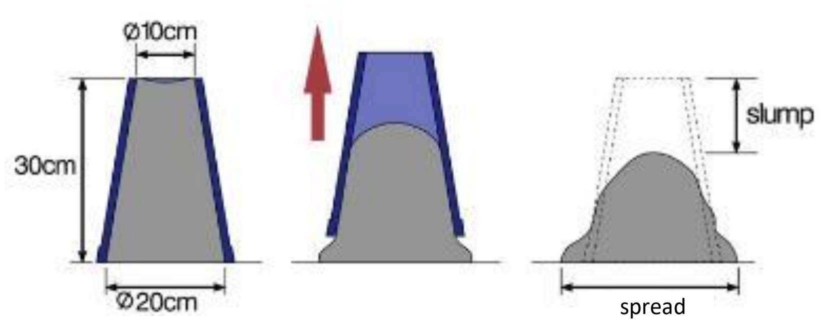

Figure 3.9 Flow test slump value (53)

Accurate workability will ensure a mortar mixture that flow easily into wanted molds, fully encapsulate eventual reinforcement, and fills all voids, leading to a mortar mixture with good quality and durability.

Compressive strength test

Compressive testing was conducted in accordance with EN 12390-3, which mandates testing each sample twice and selecting the average as the result. This approach is essential for eliminating minor irregularities in the specimen and assessing the consistency of the specimen's performance, the difference in testing results will be highlighted through the usage of error bars. Figure 3.10 illustrates how the compressive tests were conducted using an Automax compressive strength testing machine, supplied by Controls. The machine was specifically configured to test 40 x 40 mm surface specimens and is therefore capable of providing results in both MPa and the total amount of kN applied.

Figure 3.10 Compressive strength test

Density

Prior to the compressive strength testing, the weighing of each specimen followed the established practice outlined in EN 12390-3. This standardized approach involved evaluating the weight of mortar specimens both before and after the hardening process, enabling the calculation of density. Given the lack of experience on the properties of the SCM combinations, understanding the hardening process through density development holds significant importance.

Chapter 4 Results and Discussions of Laboratory Results

4.1 Flowability test

Table 4.1 present results of each mortar mixture's flowability. Slump was measured as the difference between the height of the cone and the mortar's highest point after the cone was removed. Furthermore, the spread values are the average of two measured diagonals from above where diagonals that differed by 90º were used as a benchmark. The table includes the following information: ID, added Viscostar 6K in %, slump in mm, and average spread in %.

Table 4.1 Flowability tests

ID	Viscostar 6K [%]	Slump [mm]	Spread [%]
0.6-REF	0.0	28	41
0.6-1	0.0	0	0
0.6-2	0.0	0	0
0.6-3	0.0	0	0
0.6-4	0.0	11	15
1.0-REF	1.0	49	146
1.0-1	1.0	23	44
1.0-2	1.0	31	97
1.0-3	1.0	36	135
1.0-4	1.0	17	130
1.3-REF	2.7	42	219
1.3-1	2.0	40	238
1.3-2	2.0	32	245
1.3-3	2.0	40	259
1.3-4	2.7	25	338

Table 4.1 demonstrates a trend where test number 1 appears to absorb more water in terms of spread and slump at W/B ratios of 0.6 and 1.0, while W/B ratio 1.3 deviates from this trend. A potential explanation for test number 1 exhibiting lower flow compared to other completed mixtures at W/B ratios of 0.6 and 1.0 could be attributed to the amount of Microfil present. Test number 1 contains 40% Microfil, which gradually decreases to 10% in test number 4. Previously presented research by Sharma et al (54) in page 20, highlights the ability of Microfil to utilize its small particle sizes and fill pores and voids that other binders may not be able to occupy. This creates a larger surface area for water to contact with. As a result, the Microfil allows a higher capacity to absorb water. Figure 4.1 further reveals how

this effect correlates with the performance of our mixtures. Test 1.0-1 the lowest flow both in terms of slump and spread, reduced flow in mortar mixtures generally results in improved workability, reduced segregation, and enhanced bonding, leading to superior construction quality and performance. This will be evaluated in the compressive strength test.

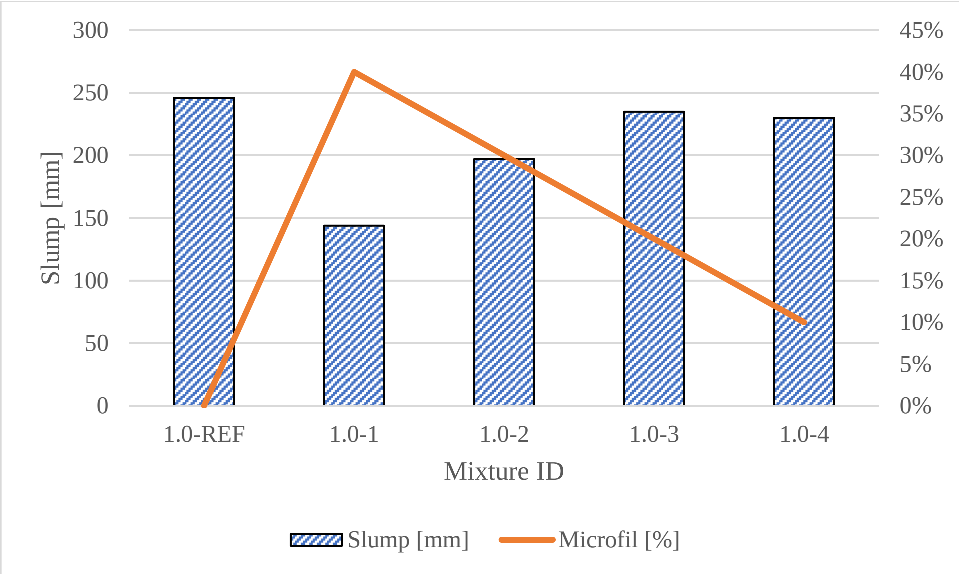

Figure 4.1 Slumps relation to amount of Microfil

The observed trend where reduced flow in increased Microfil content appears inconsistent in the case of W/B ratio 1.3, suggesting a possible influence of SCMs. It is possible that, at this specific W/B ratio, the SCM mixtures have reached their maximum water absorption capacity, potentially affecting the flow properties of the overall mixture. This saturation point may explain the improved flow performance of OPC compared to mixtures with saturated SCMs, leading to separation in W/B ratio 1.3, as illustrated in appendix B. Once the SCMs has reached saturation, the dominant characteristics of OPC may outperform the SCMs mixture, resulting in higher flow. The addition of Viscostar to these SCM mixtures provides supporting evidence for the influence of SCMs and their saturation point.

Figure 4.2 presents the flowability tests results from mixtures with W/B ratio 1.0. These tests provide insights into the flowability characteristics of each mixture with varying moisture content.

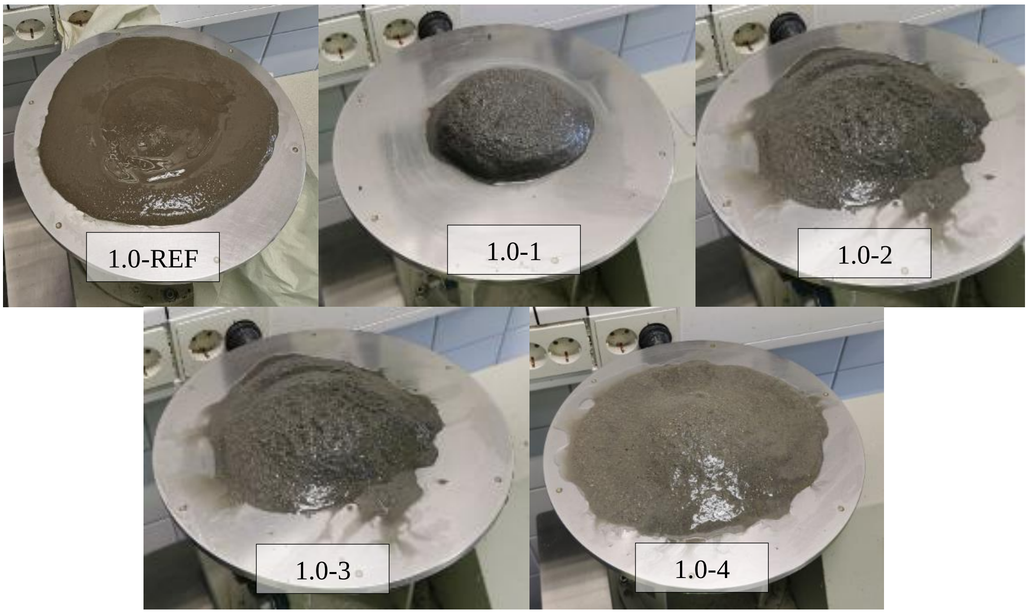

Figure 4.2 Flowability test for mixture 1.0-REF, 1.0-1, 1.0-2, 1.0-3, and 1.0-4

In the comparison represented in Figure 4.2, test 1.0-1 appears as the strongest performer, exhibiting reduced bleeding and a homogeneous appearance. As previously explained, this particular sample contains the highest proportion of Microfil, which is an explanation for the differential appearance. Test 4 negatively standout among the performed test, which includes 40% mortar waste compared to the 20% in other SCM mixtures. The increased amount of mortar waste looks to negatively affect the water absorption abilities of the mixture. Figure 4.3 presents a chart where mixture number 1 appears to linearly increase its slump as the W/B ratio increases. Note that it is difficult to draw comparisons in the flowability of mixtures containing W/B ratio of 1.3, since these suffer from separation, illustrated in appendix B, additionally they include different amounts of Viscostar.

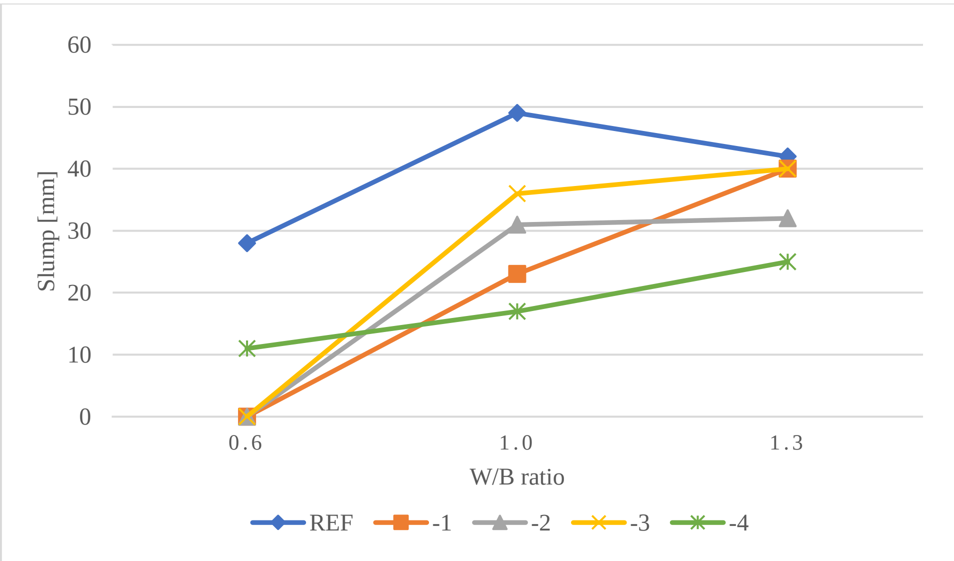

Figure 4.3 Line chart of slump in mm considering W/B ratio

The average spread of each mortar mixture is presented in Figure 4.4. The spread is higher where there is a higher water content in the concrete mixtures. Figure 4.3 represent a larger variation in results than Figure 4.4, which shows a more consistent increase in spread. These charts are made from the results presented in Table 4.1.

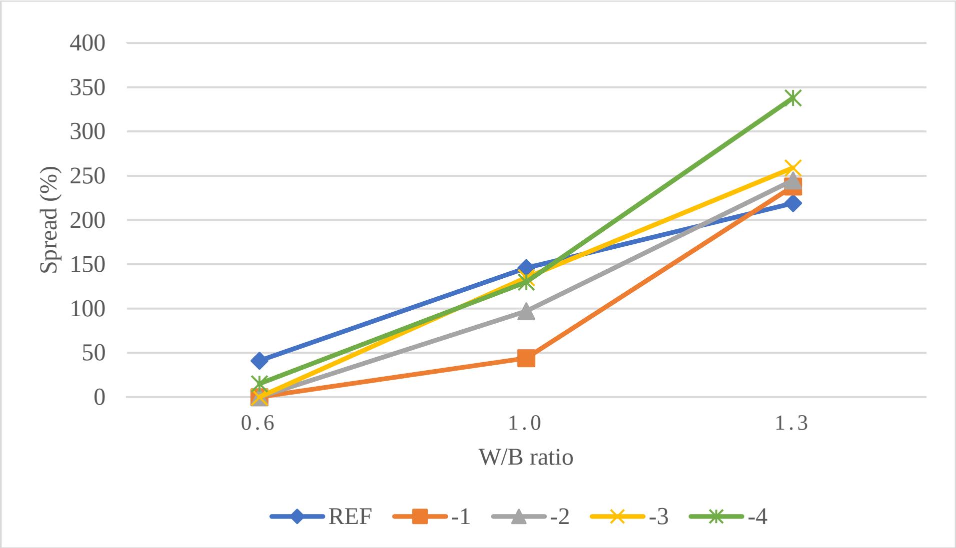

Figure 4.4 Line chart of spread in mm considering W/B ratio

The flowability test demonstrates that, each mixture's flowability increases in correlation with the W/B ratio. The charts reveal similar to the pictures on Figure 4.2 that test number 1 and 4 seems to generally stand out as the best and worst performer in the completed tests.

4.2 Compressive strength tests

An updated testing plan, presented in Table 4.2, was implemented after reviewing our initial approach to compressive testing on mortar samples. Typically, these tests are conducted at 24 hours, 7 days, and 28 days, as explained. However, our first mortar batch, tested at 24 hours, gave compressive strength results below 1 MPa. Values below 1 MPa are typically disregarded in compressive strength analysis as they are considered too low to provide reliable or meaningful results. Consequently, in consultation with our external supervisor from Mapei's office, we made the decision to discard the 24-hour test results. Instead, we proceeded with 7-day, 28-day, and additional 56-day tests for the remaining concrete specimens. Performing the 24-hour tests provided valuable results on the compressive strength development of SCM mixtures in high W/B ratios, highlighting that these mixtures require extended hardening time.

Table 4.2 Updated testing plan

ID	Mixed	7D	28D	56D
0.6-REF	14.02.23	21.02.23	14.03.23	11.04.23
0.6-1	14.02.23	21.02.23	14.03.23	11.04.23

0.6-2	14.02.23	21.02.23	14.03.23	11.04.23
0.6-3	14.02.23	21.02.23	14.03.23	11.04.23
0.6-4	14.02.23	21.02.23	14.03.23	11.04.23
1.0-REF	15.02.23	22.02.23	15.03.23	12.04.23
1.0-1	15.02.23	22.02.23	15.03.23	12.04.23
1.0-2	15.02.23	22.02.23	15.03.23	12.04.23
1.0-3	15.02.23	22.02.23	15.03.23	12.04.23
1.0-4	15.02.23	22.02.23	15.03.23	12.04.23
1.3-REF	10.02.23	17.02.23	10.03.23	07.04.23
1.3-1	08.02.23	15.02.23	08.03.23	05.04.23
1.3-2	08.02.23	15.02.23	08.03.23	05.04.23
1.3-3	08.02.23	15.02.23	08.03.23	05.04.23
1.3-4	08.02.23	15.02.23	08.03.23	05.04.23

Table 4.3 presents the compressive strength results from 7 days, 28 days, and 56 days testing for each mortar mixture. The tables also contain the date of testing, and their weight in gram before each testing.

Table 4.3 Compressive strength results

		7D		**28D**		**56D**	
ID	**Date**	**Weight [g]**	**MPa**	**Weight [g]**	**MPa**	**Weight [g]**	**MPa**
0.6-REF	14.02.23	561.0	22.87	562.4	38.52	568.8	44.20
0.6-1	14.02.23	544.5	17.68	544.0	32.39	549.5	37.07
0.6-2	14.02.23	542.6	12.06	552.6	25.79	562.0	31.87
0.6-3	14.02.23	548.2	8.93	538.1	17.54	552.7	22.22
0.6-4	14.02.23	541.0	3.78	537.3	8.47	540.7	11.32
1.0-REF	15.02.23	528.6	8.94	515.10	12.585	508.4	14.80
1.0-1	15.02.23	505.9	1.50	490.80	4.79	496.1	6.47
1.0-2	15.02.23	514.8	0.69	517.30	2.24	515.9	3.34
1.0-3	15.02.23	523.8	0.53	503.50	1.61	504.2	2.24
1.0-4	15.02.23	535.1	0.41	522.80	1.27	529.2	2.11
1.3-REF	10.02.23	515.8	5.28	524.50	7.37	496.7	10.06
1.3-1	08.02.23	490.3	0.16	498.80	0.96	475.5	0.97
1.3-2	08.02.23	493.8	0.13	499.40	0.44	498.4	0.77

1.3-3	08.02.23	495.7	0.12	509.00	0.46	501.7	0.83
1.3-4	08.02.23	522.6	0.12	524.30	0.52	524.7	1.00

Figure 4.5 displays a column chart of the compressive strength of the mortar mixtures after 28 days, with blue columns representing W/B ratio 0.6, orange columns representing W/B ratio 1.0, and grey columns representing W/B ratio 1.3. The vertical axis represents compressive strength values [MPa], while the horizontal axis represents the five mixture designs.

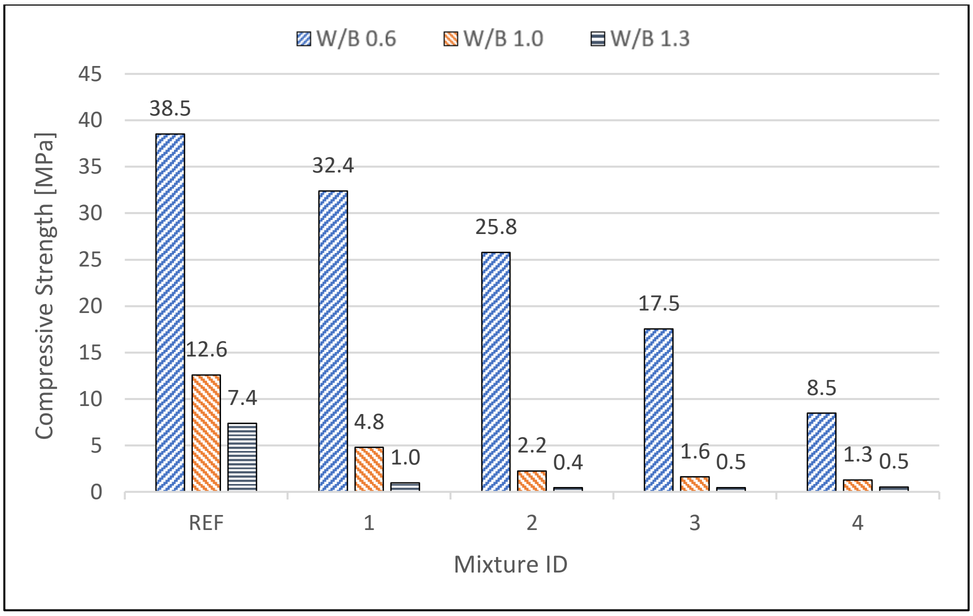

Figure 4.5 Compressive strength column chart 28D

Presented in the column chart, the mortar mixtures with a W/B ratio of 0.6 exhibit superior compressive strength in comparison to W/B ratios of 1.0 and 1.3. The reference mixtures demonstrate, as expected, the highest compressive strength. Surprisingly 0.6-1 mixture demonstrates a compressive strength of 6.13 MPa lower than the reference, this equates to approximately a 16% decrease. The mortar mixtures with a W/B ratio of 0.6 are noteworthy for their superior performance, significantly outperforming other mixtures with higher W/B ratios. The SCM mixtures exhibited less compressive strength at W/B ratios of 1.0 and 1.3, yielding some results under 2 MPa. Such low compressive strength values offer valuable information on the saturation point of the SCMs and their water absorption abilities. However, the compressive strength values below 2 MPa pose a challenge when it comes to drawing reliable conclusions or establishing comparisons between each SCMs sample.

Remarkably, the mixture labeled 0.6-1, achieved 84% of the compressive strength compared to 0.6-REF. Test number 1, which consists of 40% CKD, 40% Microfil, and 20% mortar waste, stands out as the outperformer in terms of compressive strength. This balance of SCMs seems to contribute well to each other. The portion of Microfil, due to its small particle size, contributes by filling gaps and voids that are unreachable by other binders. CKD contributes with chemical reactivity particle size distribution, contributing to the development of strength. Although accounting for only 20% of the mixture, mortar waste utilizes its cementitious hydrates to create strength. These effects combined appears to achieve a harmonious balance among the binders compared to tests number the SCMs compositions in test 2-4. It is therefore interesting to further evaluate the compressive strength to each of the SCMs.

Figure 4.6 presents the compressive strength development of mixes compared to each W/B ratio. It illustrates a trend where the reference test using OPC is performing stronger compared to the SCM mixtures as the W/B ratio increases.

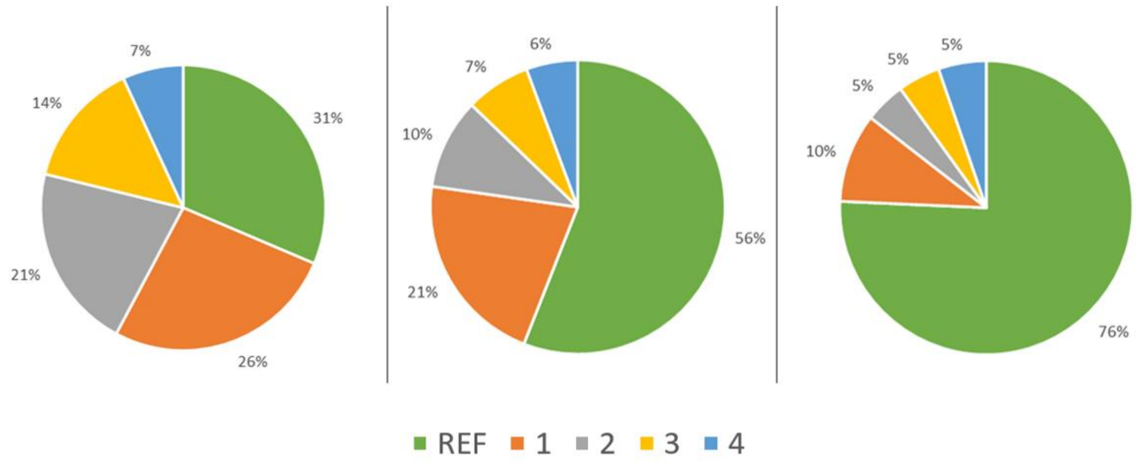

Figure 4.6 Comparison of compressive strength performances in pie chart

This trend could be explained by the effectiveness of the hydration products of each mixture in different W/B ratios. OPC is known to effectively create a strong network of strong connections as water amounts are increased. When increasing the W/B ratio, the SCM mixtures could potentially create fewer and weaker bonds, which may explain the SCMs observed decrease in strength compared to OPC, represented in Figure 4.6.

Another explanation could be that the maximum water absorption for the SCM mixtures, as explained in the discussion of flowability where SCM mixtures appears to separate earlier compared to the reference. The water absorption capacity of cementitious materials is a critical factor influencing their hydration efficiency and the resulting compressive strength of the mixes. Microfil, CKD and mortar waste may exhibit a lower water absorption capacity compared to OPC due to their natural physical and chemical properties. The variation of particle size in CKD may limit their ability to absorb and effectively utilize additional water for hydration. This could result in an earlier saturation compared to OPC. When the water content exceeds this saturation point, the additional water may not contribute to further beneficial hydration reactions but could instead lead to increased porosity, which can negatively impact compressive strength. This could explain why OPC performs better than the SCM mixtures in higher W/B ratios. Figure 4.7 shows the compressive strength relation to time for W/B 0.6, Figure 4.8 shows results for W/B 1.0 and further, Figure 4.9 shows results for W/B ratio 1.3.

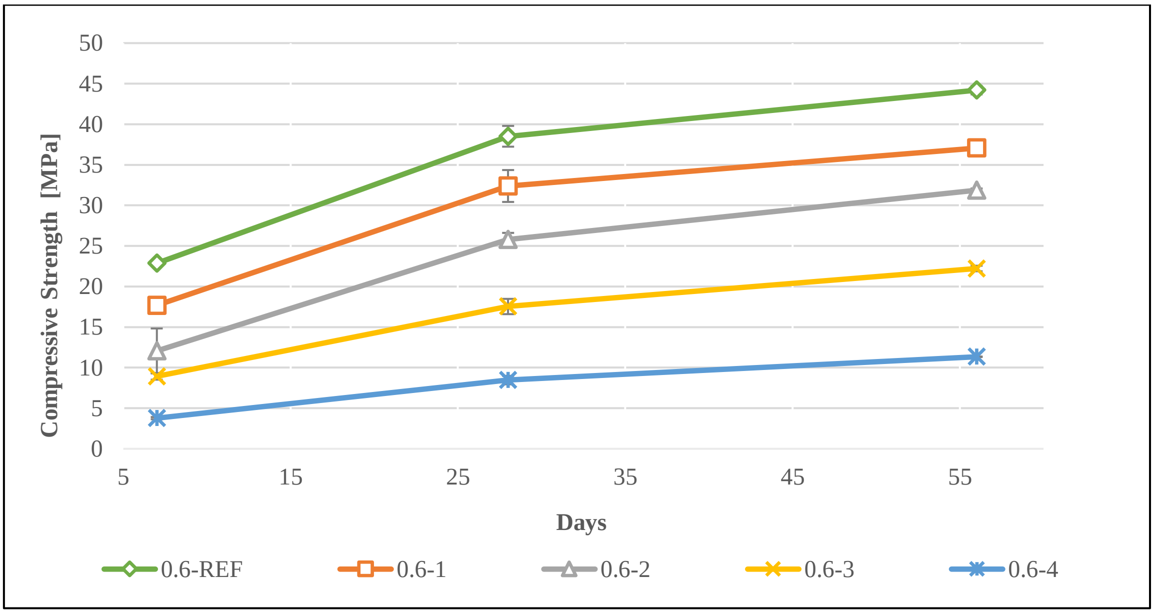

Figure 4.7 Compressive strength line chart W/B 0.6

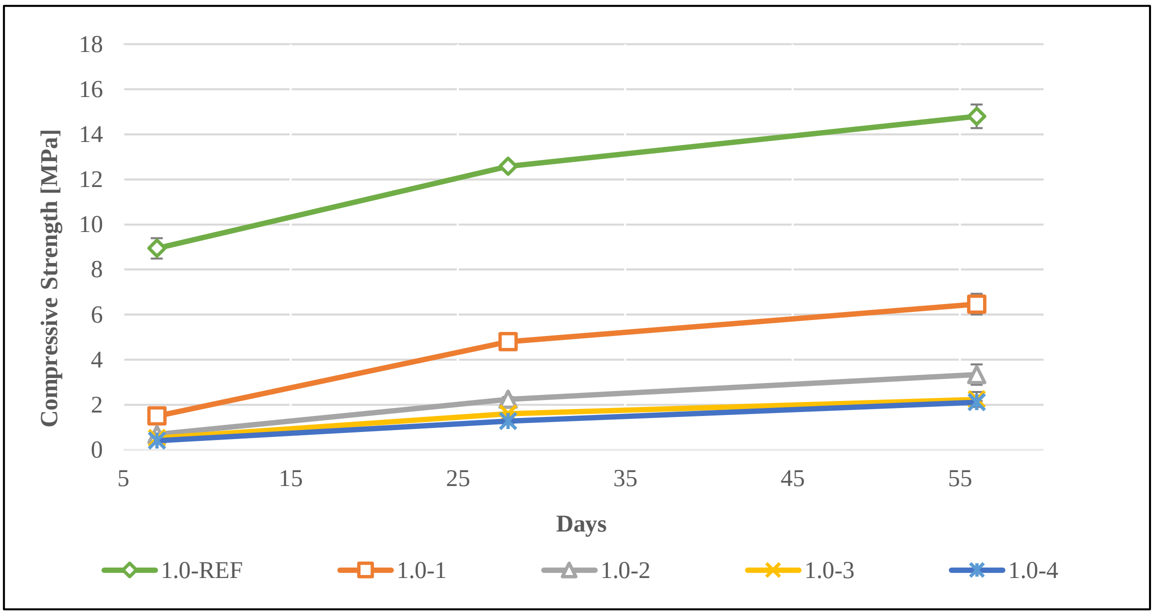

Figure 4.8 Compressive strength line chart W/B 1.0

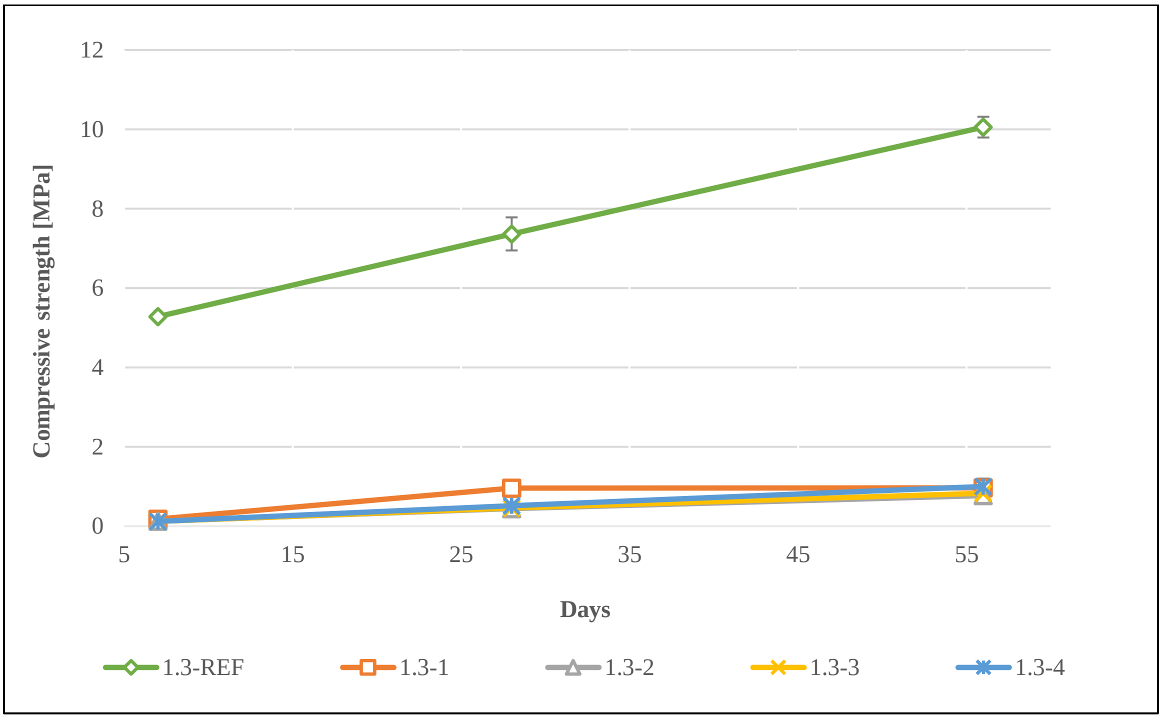

Figure 4.9 Compressive strength line chart W/B 1.3

The displayed charts in Figure 4.8 and Figure 4.9 illustrate in detail how the OPC outperforms the SCM mixtures as the W/B ratio increases. In addition to this the SCM mixture also experienced separation and large flowability, as mentioned. This explain an important factor where it appears to be crucial that if any of the SCM mixtures are to be used, W/B ratio should be decreased. This can be done using the filter press. Since test number 1 appears to have improved water absorption abilities, so the binder composition in test number 1 might perform well in W/B ratios of 0.7-0.9, based on our tests.

4.2.1 The Relationship Between Compressive Strength and SCMs

This chapter displays the relationship between the compressive strength and each SCMs used. The pozzolanic reaction is the primary cause of strength, and this study aims to investigate how different binder compositions affect this process. To focus on the impact of the pozzolanic reaction, this comparison will mainly use 56 days compressive strength tests results. The results are presented in scatter charts to illustrate the relationship between compressive strength and the quantity of each SCM used. As previously described, mixtures with W/B ratio of 0.6 exhibited superior compressive strength compared to the other W/B ratios. To provide a clearer visual representation of the performance of the W/B ratio 1.0 and 1.3, we created a separate scatter plot that excluded values with a W/B ratio of 0.6, these charts can be found in appendix D.

Compressive Strength in relation to Cement Kiln Dust (CKD)

Table 4.4 describes the compressive strength results from the laboratory. Since there were performed two tests for each mixture design, the average of the two has been found to ensure the results and will be used in further comparison.

Table 4.4 Overview of compressive strength vs CKD

ID	**0.6-REF**		**0.6-1**		**0.6-2**		**0.6-3**		**0.6-4**	
Test number	1	2	1	2	1	2	1	2	1	2
Compressive strength [MPa]	44.57	43.83	37.12	37.01	32.02	31.72	21.98	22.46	11.36	11.32
Average [MPa]	44.20		37.07		31.87		22.22		11.34	
CKD [%]	0		40		50		60		50	
ID	**1.0-REF**		**1.0-1**		**1.0-2**		**1.0-3**		**1.0-4**	
Test number	1	2	1	2	1	2	1	2	1	2
Compressive strength [MPa]	14.43	15.17	6.14	6.79	3.66	3.02	2.00	2.47	2.15	2.07
Average [MPa]	14.80		6.47		3.34		2.24		2.11	
CKD [%]	0		40		50		60		50	
ID	**1.3-REF**		**1.3-1**		**1.3-2**		**1.3-3**		**1.3-4**	
Test number	1	2	1	2	1	2	1	2	1	2
Compressive strength [MPa]	9.87	10.24	1.13	0.80	0.79	0.75	0.71	0.95	1.06	0.94
Average [MPa]	10.06		0.97		0.77		0.83		1.00	
CKD [%]	0		40		50		60		50	

Figure 4.10 displays a graphical representation of the relationship between the compressive strength and the content of CKD. From the graph, we can observe a general trend where the compressive strength decreases as the CKD content increases. Nonetheless, there appears to be an exception to this trend as evidenced by test 4, which stands out as a consistent under-performer in comparison.

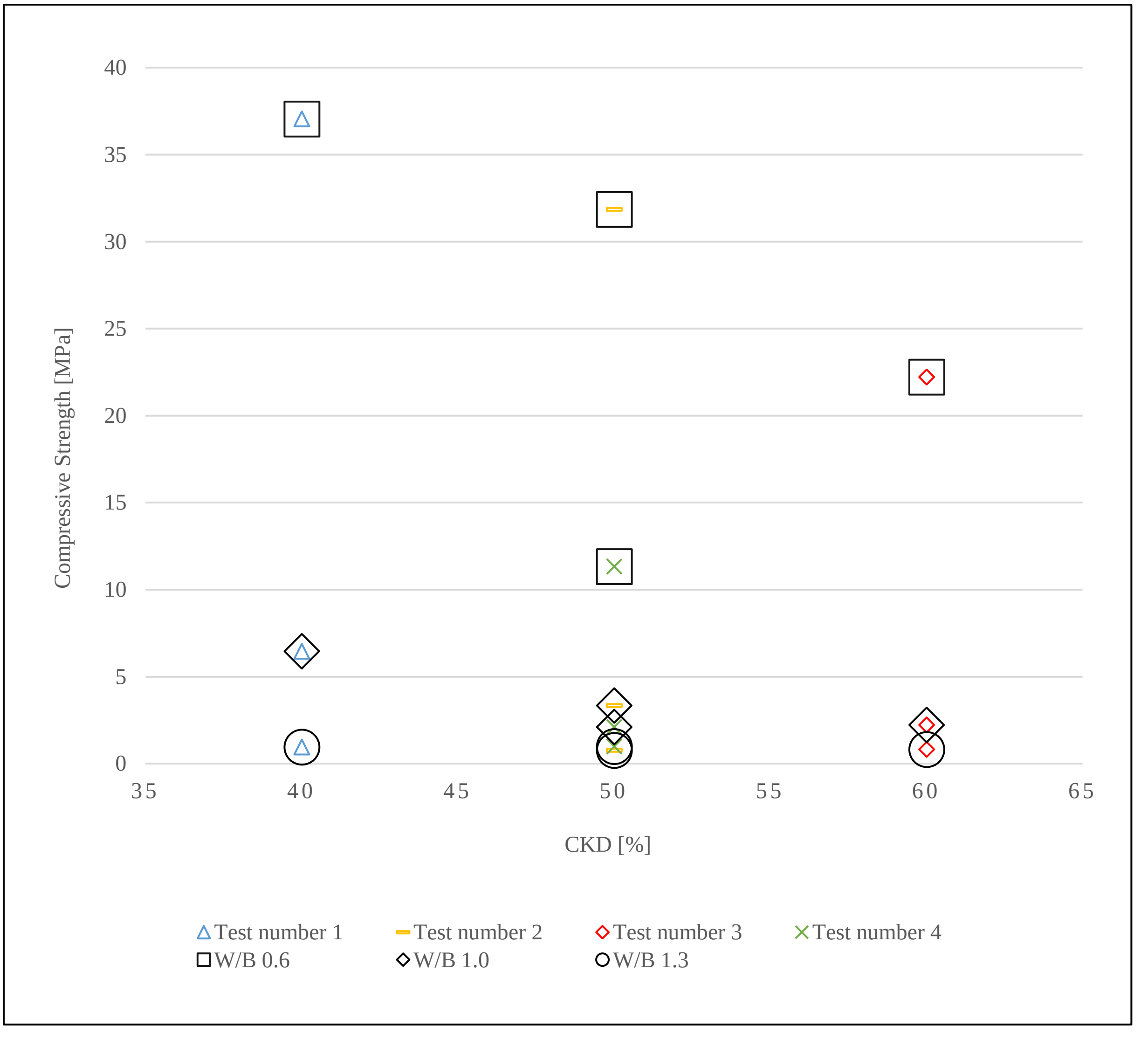

Figure 4.10 Scatter Chart compressive strength vs CKD [%]

There are several explanations why increased amounts of CKD can lead to a decrease in strength. It could be that the addition of a more CKD leads to a reduction in more effective alternatives. As more CKD is added to the mix, the proportion of other binder components, such as Microfil and mortar waste, is reduced. These other components may possess larger strength-contributing properties compared to CKD.

The decrease in compressive strength of mortar with increased CKD content can also be attributed to its potentially lower pozzolanic reactivity compared to other binder components. Pozzolanic reactivity means the materials ability to react with calcium hydroxide, which is generated during the hydration of cement, to form additional cementitious compounds, as explained in Chapter 2.5.4 The reactivity of CKD with calcium hydroxide may be less dominant compared to other Microfil or mortar waste. As the proportion of CKD increases, the number of strong bonds formed decreases, which could result in a structurally weaker mortar exhibiting diminished strength.

Lastly, the decreased compressive strength may also be explained due to a variation in the mortar's microstructure caused by the increased CKD content. CKD can often obtain variations in particle sizes, as illustrated in Figure 3.3. These variations in size and form may create localized areas with weaker bonding or inconsistencies in the cementitious matrix, which can create small voids between larger CKD particles, similar to the effect described by Ali S Al-Harthy et al. (42) in their research completed on the influence of CKD. The experienced higher porosity can negatively impact the overall performance and strength of the mortar by creating easy pathways for cracks and collapse of the structure.

Compressive Strength in relation to Microfil 750 DOS

Table 4.5 provides data on how compressive strength compared to amounts of Microfil, which amounts ranged from 10% - 40% as described.

Table 4.5 Overview of compressive strength vs Microfil

Category	0.6-REF		0.6-1		0.6-2		0.6-3		0.6-4	
ID	1	2	1	2	1	2	1	2	1	2
Compressive strength [MPa]	44.57	43.83	37.12	37.01	32.02	31.72	21.98	22.46	11.36	11.32
Average [MPa]	44.20		37.07		31.87		22.22		11.34	
Microfil [%]	0		40		30		20		10	
Category	1.0-REF		1.0-1		1.0-2		1.0-3		1.0-4	
ID	1	2	1	2	1	2	1	2	1	2
Compressive strength [MPa]	14.43	15.17	6.14	6.79	3.66	3.02	2.00	2.47	2.15	2.07
Average [MPa]	14.80		6.47		3.34		2.24		2.11	
Microfil [%]	0		40		30		20		10	
ID	1.3-REF		1.3-1		1.3-2		1.3-3		1.3-4	
Test number	1	2	1	2	1	2	1	2	1	2
Compressive strength [MPa]	9.87	10.24	1.13	0.80	0.79	0.75	0.71	0.95	1.06	0.94
Average [MPa]	10.06		0.97		0.77		0.83		1.00	
Microfil [%]	0		40		30		20		10	

Figure 4.11 displays a pattern where the compressive strength tends to improve as the quantity of Microfil increases, which stands in contrast to the trend observed with increasing amounts of CKD. The mixture containing the highest amount of Microfil, 0.6-1, exhibits the greatest resistance to applied forces.

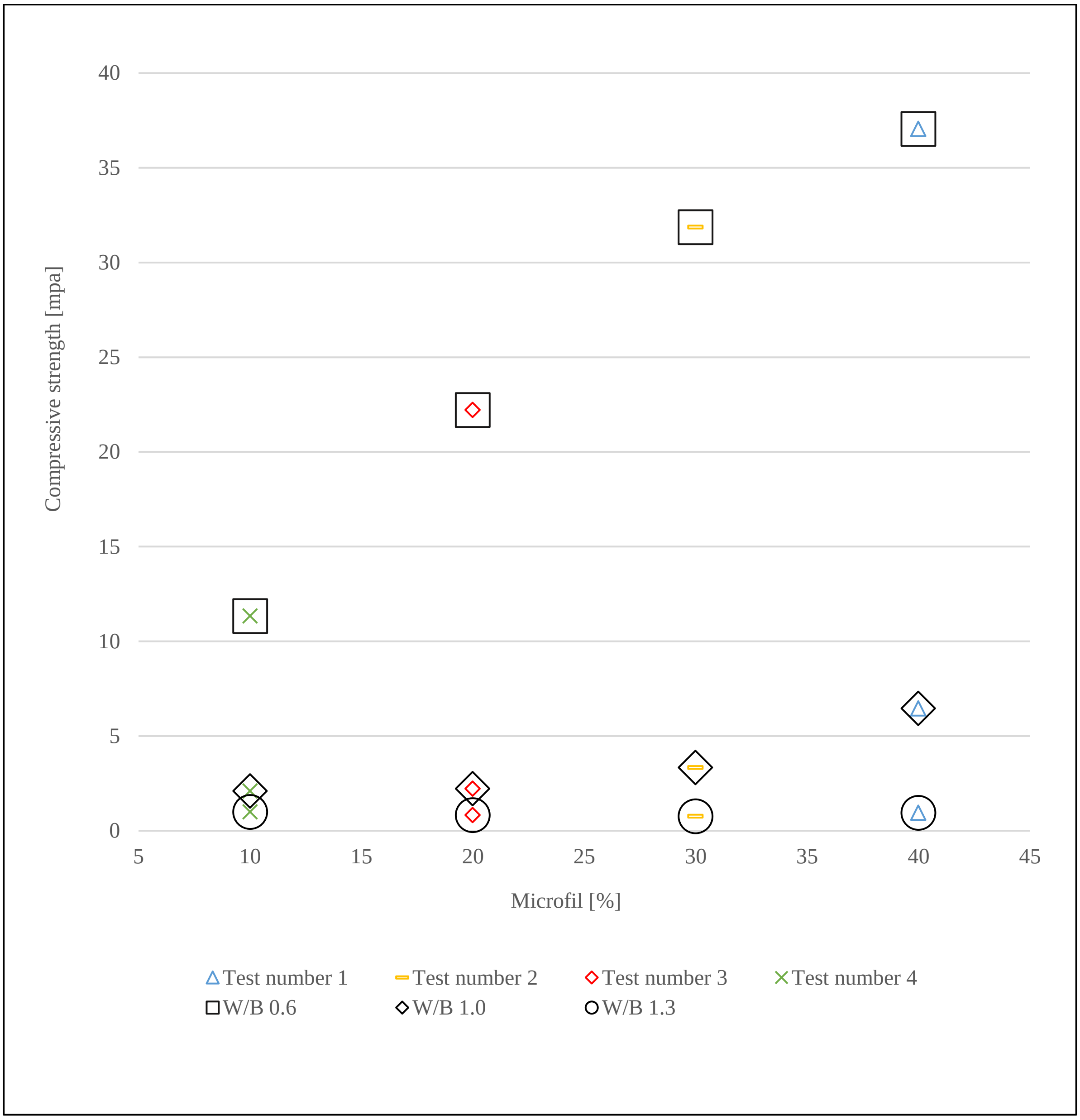

Figure 4.11 Scatter chart compressive strength vs Microfil [%]

The observed increase in compressive strength of mortar including higher amounts of Microfil can be explained by the filler effect of Microfil, where the fine particles fill the small voids created within the mixture. As discussed in Chapter 2.5.3, where studies written by and Sharma et al. (44) have also reported this phenomenon, highlighting the ability of Microfil to occupy small pores with its small particles. This causes the Microfil to reduce the mortars porosity and can therefore increase its compressive strength.

Another aspect discussed in Chapter 2.5.3 is particle packing, discussed by Sharma et al. (44). The fine particle size of Microfil makes it a good particle packing material in the cementitious mixes, which improves the overall strength of the mortar. The presence of Microfil results in a more homogeneous and compact microstructure as a result, this could be an explanation to why 40% Microfil results in the largest compressive strength.

Microfil has a high surface area because of its small particle size, which provides a greater area of contact between the Microfil and the cementitious particles. The large surface area allows it to interact with the calcium hydroxide produced during the hydration process, forming additional cementitious compounds, as explained in chapter 2.5.3. This reaction takes place due to the unique properties of Microfil and its ability to interact with the cementitious components and can be one of the reasons why increased amounts of Microfil appears to increase compressive strength.

Compressive Strength in Relation to Mortar Waste

Table 4.6 provides data on how compressive strength compared to amounts of mortar waste in the mixture. Test samples 1, 2, and 3 have 20% of mortar waste, and test number 4 has 40%.

Table 4.6 Overview of compressive strength vs mortar waste

ID	**0.6-REF**		**0.6-1**		**0.6-2**		**0.6-3**		**0.6-4**	
Test number	1	2	1	2	1	2	1	2	1	2
Compressive strength [MPa]	44.57	43.83	37.12	37.01	32.02	31.72	21.98	22.46	11.36	11.32
Average [MPa]	44.20		37.07		31.87		22.22		11.34	
Mortar waste [%]	0		20		20		20		40	
ID	**1.0-REF**		**1.0-1**		**1.0-2**		**1.0-3**		**1.0-4**	
Test number	1	2	1	2	1	2	1	2	1	2
Compressive strength [MPa]	14.43	15.17	6.14	6.79	3.66	3.02	2.00	2.47	2.15	2.07
Average [MPa]	14.80		6.47		3.34		2.24		2.11	
Mortar waste [%]	0		20		20		20		40	
ID	**1.3-REF**		**1.3-1**		**1.3-2**		**1.3-3**		**1.3-4**	
Test number	1	2	1	2	1	2	1	2	1	2
Compressive strength [MPa]	9.87	10.24	1.13	0.80	0.79	0.75	0.71	0.95	1.06	0.94
Average [MPa]	10.06		0.97		0.77		0.83		1.00	
Mortar waste [%]	0		20		20		20		40	

Figure 4.12 provides a scatter chart illustrating how the performed test compares to the amounts of mortar waste graphicly. The provided figure illustrates a trend were test number 4, consisting of 40% mortar waste as its binder, is consistently exhibiting less compressive strength compared to the other mixtures containing 20% mortar waste.

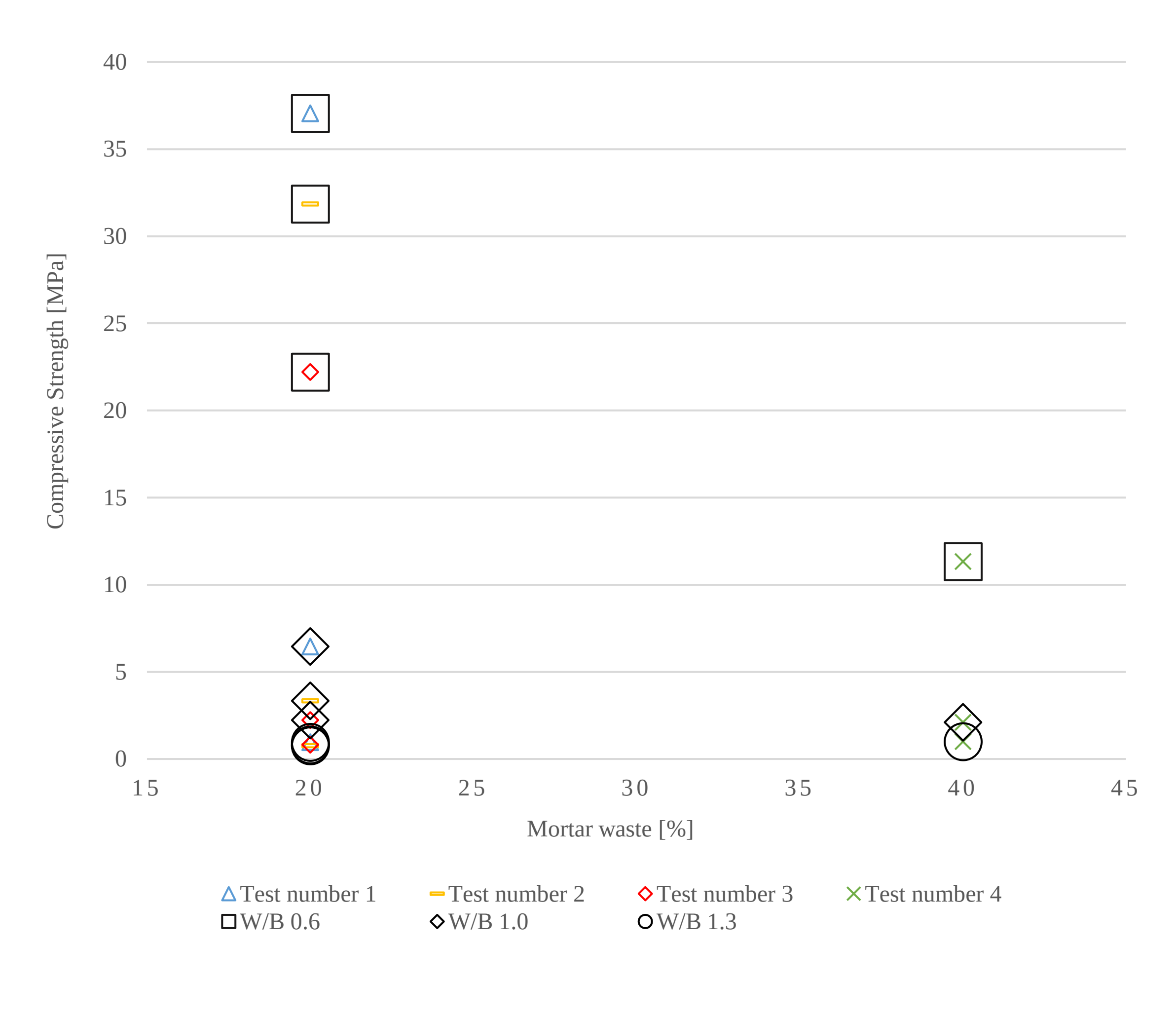

Figure 4.12 Scatter Chart compressive strength vs mortar waste [%]

An explanation for the experienced decrease in compressive strength related to the increase of mortar waste amounts could be related to particle packing. A phenomenon described in the comparison between compressive strength and Microfil. In general, a well-balanced mixture allows particles of varying sizes to fill spaces between each other efficiently, contributing to a denser structure and increased strength. When mortar waste, that has a different particle size distribution and shape, is added to the mortar mixture, it still needs to integrate well with CKD and Microfil. This integration might be well balanced in a mortar waste content at 20%, however, when this percentage increases to 40%, the particles might struggle to achieve effective packing.

The amount of completed research on mortar waste as a potential SCM is limited and therefore it is difficult to find exact material properties. Mortar waste is not utilized as a building material today, hopefully this thesis will inspire the building industry thinking more sustainable by incorporating mortar waste in the production of new building materials.

4.3 Development in Density

By comparing the density of each specimen Figure 4.13 was conducted. Results indicate that the reference specimen had a higher density than the other mixture designs, probably because of SCMs particle size. Generally, it seems to be very similar density results in reference to time. Mixture designs containing a W/B ratio of 0.6 seem to obtain a higher density than W/B ratios of 1.0 and 1.3.

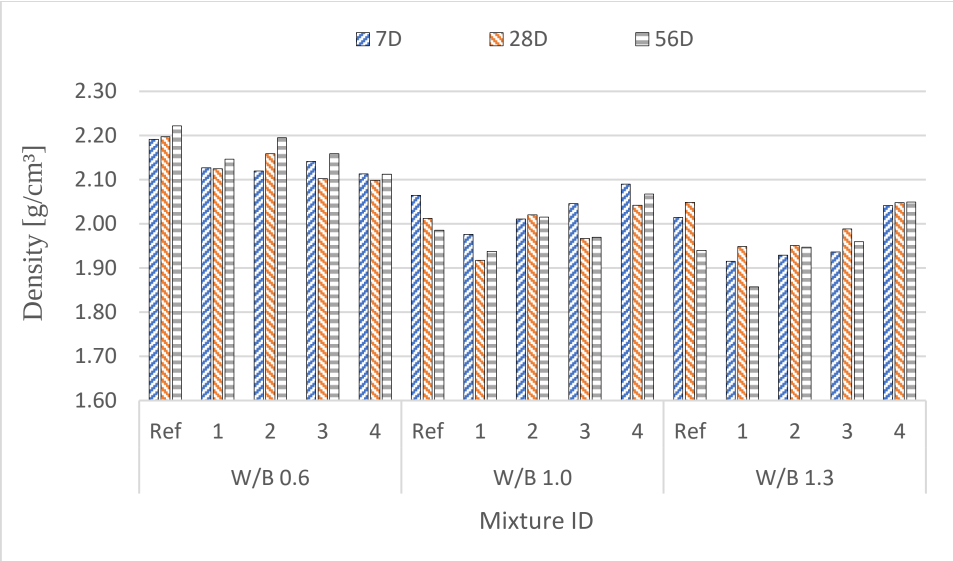

Figure 4.13 Comparison of density of each mixture

The diagram shows small variations between results for every sample. Density results vary with 0,35 g/cm^3, from 1,85 g/cm^3 to just above 2,20 g/cm^3. The results show that test 1 in each of the W/B ratios has lower density than the rest of the specimens. This means that sample 1 in all three W/B ratios has absorbed more water than the other samples and thereafter has a higher weight.

As detailed in Chapter 2.5, explaining how the W/B ratio corresponds to an increase in the volume of pores within the structure. This porosity growth leads to the expectation that mixtures with W/B ratios of 1.0 and 1.3 will exhibit a reduced density, given the opposite relationship between porosity and density. This correlation is graphically displayed in Figure 4.13, which demonstrates a trend of decreasing density with increasing W/B ratio. The highest densities were observed in mixtures possessing a W/B ratio of 0.6.

Test 4, distinguished by its composition of 50% CKD, 10% Microfil, and 40% mortar waste, exhibited the highest density among the tested mixtures. This outcome can be explained by the high proportion of CKD in the mixture. CKD is a by-product of the cement production process and has properties similar to those of cement itself, including its high density.

One weakness in these results worth mentioning is that the samples may not have been thoroughly dried before the compressive tests were conducted. No measurements of the time were made between the time the components were removed from the curing tanks and the time they were weighted and tested. The findings related to density could be impacted by this.

Another weakness, illustrated in Figure 4.14, is that W/B ratio 1.3 (B) had huge workability compared to W/B ratio of 0.6 (A). A result from this is that occasionally the samples did create voids in the mould when finishing. The mixtures were stamped, but some pores were inevitable. This provides the risk of inaccuracy in the density results as not 100% of the mould volume was filled in W/B ratio of 0.6. This inaccuracy also transfers to the compressive strength test because the compressive strength was calculated by assuming a 40 x 40 mm specimen. As Figure 4.14 illustrates, the samples were successfully stamped in order to remove the majority of the voids, but some voids remained.

Figure 4.14 Presentation of laboratory samples

Conclusion

The conclusion for this study is presented below.

- Among the four amounts of CKD tested, the highest compressive strength was observed in a mixture containing 40% CKD. Increasing the CKD content generally resulted in higher flowability and less compressive strength. Several factors can explain these results, including CKD's particle size variations leading to void formations, which may contribute to the observed increase in flowability and reduction in mortar's compressive strength.
- Increasing the quantity of mortar waste resulted in decreased strength and increased flowability.
- By evaluating four different quantities of Microfil (from 10% to 40%), a trend appeared where 40% Microfil exhibited the least flow and the highest compressive strength. Typically, a reduction in Microfil content resulted in lower compressive strength and increased flowability. This can be explained by Microfil's ability to fill smaller voids and therefore create an improved packing of particles compared to other mixtures.
- Tested SCM mixtures appeared to reach their water saturation point earlier than OPC, making them competitive at lower W/B ratios. At a W/B ratio of 1.3 and 1.0, these SCM mixtures exhibited separation and decreased compressive strength.
- Typically, SCM hydration at W/B ratios of 1.0 or 1.3 is a time-consuming process. Achieving compressive strength at these ratios needs a minimum curing period of 7 days for sufficient strength development under ideal conditions (20°C). This will hinder the aggregates that will be formed using RCZ from hardening faster as requires. Admixtures could be selected in the future to ensure a faster hardening process.
- The 0.6-1 mixture, consisting of a W/B ratio of 0.6, 40% CKD, 40% Microfil, and 20% mortar waste, gave impressive results, achieving 84% of the strength of 0.6-REF and exhibiting less flow than OPC at 56D testing. Despite utilizing solely waste materials, this mixture proved competitive with the OPC mixture performance.

These findings further improve the understanding of how to recycle binder-free sludge and makes them possible to incorporate with Re-Con Zero powder to generate smaller aggregates from waste sludge. Furthermore, the option of blending the composition used in test 1 with OPC could influence the mechanical properties of OPC while utilizing waste materials.

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APPENDIX

List of Appendices

Appendix A:

Technical Data Sheets

Description

This appendix contains thoroughly description of each of the materials that has been used in the mortar mixtures. The descriptions are presented as technical data sheets written by the manufacturer of the product.

A.1 Ordinary Portland Cement – CEM 52,5 N

PRODUKTDATABLAD

ANLEGGSEMENT

CEM I 52,5 N

Sist revidert desember 2018

Sementen tilfredsstiller kravene i NS-EN 197-1:2011 til Portlandsement CEM I 52,5 N.

Egenskap		Deklarerte data	Krav ifølge NS-EN 197-1:2011
Finhet (Blaine m^2/kg)		415	
Spesifikk vekt (kg/dm^3)		3,14	
Volumbestandighet (mm)		1	10
Begynnende størkning (min)		120	45
Trykkfasthet (MPa)	1 døgn	21	
	2 døgn	33	20
	7 døgn	49	
	28 døgn	63	52,5
Sulfat (% SO_3)		4,0	4,0
Klorid (% Cl^-)		0,07	0,10
Vannløselig krom (ppm Cr^{6+})		2	2[1]
Alkalier (% Na_2O_{ekv})		0,6	
Klinker (%)		96	95-100
Sekundære bestanddeler (%)		4	0-5

1. I henhold til EU forordning REACH Vedlegg XVII punkt 47 krom VI-forbindelser.

NORCEM
HEIDELBERGCEMENT Group

Norcem AS, Postboks 142, Lilleaker, 0216 Oslo
Tlf. 22 87 84 00 firmapost@norcem.no www.norcem.no

A.2 Cement kiln flue dust, CKD

PRODUKTDATABLAD

BYPASSTØV

SIST REVIDERT JANUAR 2023

Bypasstøv (bypass dust, tidligere kalt CKD, Cement Kiln Dust) selges alene eller blandes med sement til Multicem. Multicem brukes til stabilisering av leire og andre ustabile jordmasser. Andelen bypasstøv i Multicem er 25, 50 og 75 %. Bypasstøv er fint støv fra klinkerovnen, og består hovedsakelig av brent kalk og andre kalsinerte mineraler, og vil naturlig variere. Det tas forbehold om at det kan forekomme en større variasjon enn det som sees i tabellen.

	Normalt variasjonsområde	Gjennomsnittsverdi av Bypasstøv fra Brevik, Kjøpsvik, Slite*
Alkalier (% Na_2O ekv.)	2 - 15	6
Fri kalk (% CaO)	14 - 40	30
Kalsiumoksid (% CaO tot.)	30 - 60	53
Klorid (% Cl^-)	0 - 15	5
Magnesiumoksid (% MgO)	1 - 3	2
Silisiumoksid (% SiO_2)	4 - 20	13
Sulfat (% SO_3)	2 - 20	9
<24 um (%)	20 - 80	49
<30 um (%)	30 - 90	58
>64 um (%)	0 - 40	14
>90 um (%)	0 - 25	7
Spesifikk vekt (kg/dm^3)	2 - 3	3
Volumvekt (kg/dm^3)	0,6 - 0,9	0,7

*Fra perioden 2018-2022

Klinker- og råmelstøvet i Bypasstøvet er tilnærmet fullstendig kalsinert, nesten all CO_2 som støvet opprinnelig inneholdt er drevet av. Dette utslippet tilegnes klinkeren og sementen som produseres, siden alle kvotepliktige klimagassutslipp fra fabrikken tilegnes disse. Bypasstøv skal derfor kun belastes med CO_2-utslipp fra transport og ikke produksjon, siden dette er et restmateriale. Dette prinsippet benyttes for industrielle restmaterialer der CO_2-utslippet fra hhv energi- og stålproduksjon er knyttet til produktene og ikke restmaterialet.

Mer om Bypasstøv samt Sikkerhetsdatablad finnes på norcem.no./spesialsementer

Heidelberg Materials

Heidelberg Materials Sement Norge AS
Postboks 143, Lilleaker, NO-0216 Oslo
Tlf. +47 22 87 84 00 firmapost@norcem.no

A.3 Viscostar 6K

MAPEI

Viscostar 6K

Efficient viscosity modifying admixture used in the production of self-compacting concrete

PRODUCT DESCRIPTION

Viscostar 6K is a liquid admixture, specially formulated for use in the production of ready-mixed and precast concrete which requires high fluidity with no segregation. Control of the viscosity achieved using **Viscostar 6K** allows for the production of selfcompacting concrete with little or no fillers.

AREA OF USE

Thanks to its special, innovative formulation, **Viscostar 6K** represents a real breakthrough in the construction industry, in that, by modifying the dosages applied, it is possible to reach performance levels which solve three specific problems and/or requirements: • improvement of pumping action of concrete;

• integration of fine and very fine parti cles in the production of concrete with crushed aggregates or with low doses of cement;

• production of self-compacting concrete which conforms to current norms and standards regarding fluidity, slump and resistance to segregation without adding minerals (fillers).

TECHNICAL CHARACTERISTICS

Viscostar 6K is an active polymer-based admixture in an aqueous solution, which allows tight control of the cohesion of the cementitious paste, and the production of self-compacting, cementitious mixtures with reduced content of ultrafine particles. Thanks to the product's high efficiency, **Viscostar 6K** avoids segregation and bleeding of the concrete, and helps maintain the fluidity and passing ability of the concrete.

COMPATIBILITY WITH OTHER PRODUCTS

Viscostar 6K is compatible with other admixtures used in the manufacture of high-quality concrete, and especially with:

• admixtures from the **Dynamon**-range, to make mixtures with a low water/ cement ratio, long workability times and/or quick development of the concrete's mechanical properties after short curing times.

• **Mapefast** setting and hardening accelerator admixtures to reach high mechanical strength after short curing times, even in cold weather

• **Mapefast**, retarders to control the setting of concrete

• **Mapeform** form release compounds, used for stripping concrete from moulds.

HOW TO USE

Add **Viscostar 6K** in the cement mixer after all the other ingredients (cement, aggregates, water and acrylic super-plasticising admixture). Mix until a homogenous mix is obtained.

CONSUMPTION

Dosage in volume:

Viscostar 6K

From 0.5 to 1 l per m^3 of concrete when used as a pumping aid.

From 1 to 3 l per m^3 of concrete when used as a mix improver for poor quality sand.

From 1.5 to 4 l per m^3 of concrete when used instead of mineral additives in selfcompacting concrete.

PACKAGING

Viscostar 6K is available in 25 l cans, 200 l drums and in 1000 l IBC containers.

STORAGE

Viscostar 6K may be stored for 6 months in sealed containers. Protect from frost. The product must be stirred before use.

SAFETY INSTRUCTIONS FOR PREPARATION AND INSTALLATION

Instructions for the safe use of our products can be found on the latest version of the SDS available from our website www.mapei.no PRODUCT FOR PROFESSIONAL USE.

WARNING

Although the technical details and recommendations contained in this product data sheet correspond to the best of our knowledge and experience, all the above - information must, in every case, be taken as merely indicative and subject to confirmation after long-term practical application: for this reason, anyone who intends to use the product must ensure beforehand that it is suitable for the envisaged application: in every case, the user alone is fully responsible for any consequences deriving from the use of the product.

Please refer to the current version of the technical data sheet, available from our web site www.mapei.no

LEGAL NOTICE

The contents of this Technical Data Sheet ("TDS") may be copied into another project-related document, but the resulting document shall not supplement or replace requirements per the TDS in force at the time of the MAPEI product installation.

The most up-to-date TDS can be downloaded from our website www.mapei.no ANY ALTERATION TO THE WORDING OR REQUIREMENTS CONTAINED OR DERIVED FROM THIS TDS EXCLUDES THE RESPONSIBILITY OF MAPEI.

All relevant references for the product are available upon request and from www.mapei.no

Viscostar 6K

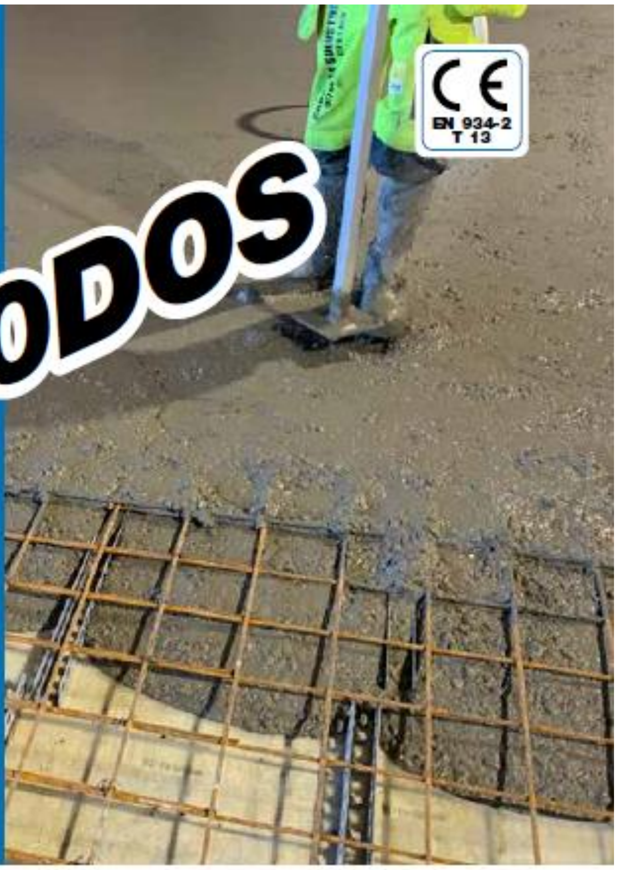
TECHNICAL DATA (typical values)

PRODUCT IDENTITY	
Appearance:	liquid
Colour:	green
Viscosity:	easy flowing; < 30 mPa·s
Solids content, %:	6 ± 0,6
Density, g/cm^3:	1.02 ± 0.02
pH:	11 ± 1
Chloride content, %:	< 0.3
Alkali content (Na_2O-equivalents) %:	< 1.0

A.4 Microfill 750 DOS by Mapei

MAPEI

Microfil 750DOS



Mineralsk tilsetningsstoff til støpeforbedring av betong

BESKRIVELSE

Microfil 750DOS er et mineralsk tilsetningsstoff basert på mikropartikler av amorf silika i pulverform. Produktet tilsettes betong for å forbedre flytegenskaper, støpelighet og konsistens. Kan med fordel benyttes ved utfordrende tilslag som mangler finstoff.

BRUKSOMRÅDE

Microfil 750DOS kan benyttes i alle typer betong. Fordelene blir størst i betong der det stilles høye krav til støpelighet, pumpbarhet og konsistens. Passer spesielt godt for selvkompakterende betong (SKB) og gulvbetong. Typisk dosering vil være opp mot 5 % av sementvekt, avhengig av tilslag og betongsammensetning. **Microfil 750DOS** må kombineres med superplastiserende tilsetningsstoff, for eksempel **Dynamon SX23**, for optimal virkning og effekt.

NB! Selv om **Microfil 750DOS** er basert på amorf silika, er produktet ikke å anse som en godkjent microsilica for betong og det er ikke tillatt å gi **Microfil 750DOS** noen virkningsfaktor ved beregning av masseforhold. Det finnes ikke regler for bruk av **Microfil 750DOS** som bindemiddel i NS-EN 206:2013. **Microfil 750DOS** inneholder allikevel store mengder amorf silika og vil i praksis gi samme effekt som microsilica i betong.

EGENSKAPER

Microfil 750DOS gjør betong:

- Smidigere og seigere (ved høyere dosering).
- Motvirker vannseparasjon pga. sin høye spesifikke overflate.
- Forbedrer kohesivitet og pumpeegenskaper.
- Bidrar til tettere betong (pozzolaneffekt) og økt trykkfasthet.

EMBALLASJE

Microfil 750DOS selges kun i bulk, fra produksjonsstedet, hos ekstern produsent.

LAGRING

Microfil 750DOS bevarer sine egenskaper 12 måneder hvis den oppbevares tørt.

SIKKERHETSINSTRUKSJONER FOR KLARGJØRING OG BRUK

For instruksjon vedrørende sikker håndtering av våre produkter, vennligst se siste utgave av sikkerhetsdatablad som fås på forespørsel.

PRODUKT FOR PROFESJONELL BRUK.

MERK

De tekniske anbefalinger og detaljer som fremkommer i denne produktbeskrivelse representerer vår nåværende kunnskap og erfaring om produktene.

Microfil 750DOS

TEKNISKE DATA (typiske verdier)	
PRODUKTBESKRIVELSE	
Form:	pulver
Farge:	lys grå
Tørrstoffinnhold, %:	100
pH:	7 ± 1
Bulkdensitet, g/cm³:	600 ± 100
Materialdensitet, g/cm³:	2250 ± 100
Spesifikk overflate, m²/h:	15-30

All overstående informasjon må likevel betraktes som retningsgivende og gjenstand for vurdering. Enhver som benytter produktet må på forhånd forsikre seg om at produktet er egnet for tilsiktet anvendelse. Brukeren står selv ansvarlig dersom produktet blir benyttet til andre formål enn anbefalt eller ved feilaktig utførelse.

Vennligst referer til siste oppdaterte versjon av teknisk datablad som finnes tilgjengelig på forespørsel

JURIDISK MERKNAD

Innholdet i dette tekniske databladet kan kopieres til andre prosjektrelaterte dokumenter, men det endelige dokumentet må ikke suppleres eller erstatte betingelsene i det tekniske datablad, som er gjeldende, når MAPEI-produktet benyttes. Det seneste oppdaterte datablad er tilgjengelig på forespørsel. ENHVER ENDRING AV ORDLYDEN ELLER BETINGELSER, SOM ER GITT ELLER AVLEDET FRA DETTE TEKNISKE DATABLADET, MEDFØRER AT MAPEI SITT ANSVAR OPPHØRER.

Alle relevante referanser for produktet er tilgjengelige på forespørsel

07-2019 (NO)

MAPEI
BUILDING THE FUTURE

Appendix B:

Extended Pictures of Results

Description

This appendix presents extended results from the laboratory work performed at Mapei.

Mortar mixture 0.6-REF

Figure 1 0.6-1 flow test

Mortar mixture 1.0-REF

Figure 2 Flowability test for mixture 1.0-REF

Mortar mixture 1.0-1

Figure 3 Flowability test for mixture 1.0-1

Mortar mixture 1.0-2

Figure 4 Flowability test for mixture 1.0-2

Mortar mixture 1.0-3

Figure 5 Flowability test for mixture 1.0-3

Mortar mixture 1.0-4

Figure 6 Flowability test for mixture 1.0-4

Mortar mixture 1.3-REF

Figure 7 Flowability test for mixture 1.3-REF

Mortar mixture 1.3-1

Figure 8 Flowability test for mixture 1.3-1

Mortar mixture 1.3-2

Figure 9 Flowability test for mixture 1.3-2

Mortar mixture 1.3-3

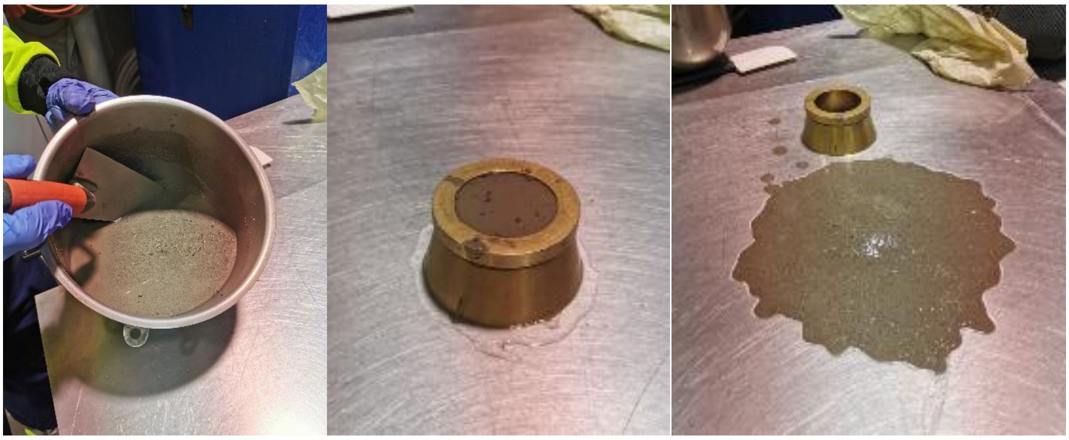


Figure 10 Flowability test for mixture 1.3-3

Mortar mixture 1.3-4

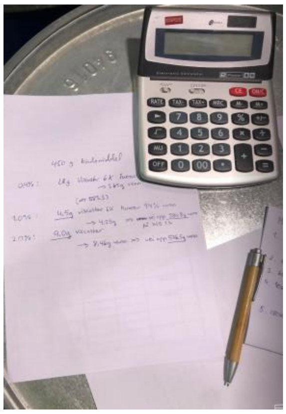
Figure 11 Flowability test for mixture 1.3-4

Appendix C:

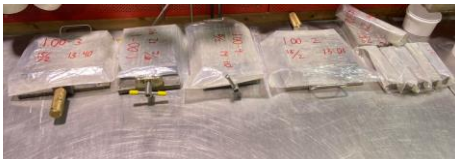
Extended Equipment List

Description

This appendix presents an extended Equipment displaying pictures and additional information about the equipment used in the completed laboratory work.

Name	Description	Picture
Calculation process when using Viscostar	Calculation water amounts to ensure correct W/B ratio when using Viscostar	
Compressive Strength test	Used to check compressive strength. Provides testing results in MPa and total KN applied.	
Curing	Test samples curing in curing tank	

Flat trowel for mortar	Used to ensure simular testsamples.	
Mixer	Has the ability to change the height of the mixture for an easy accessibility to the mortar.	
Mixing beater	Placed inside the mixer.	
Mixture of binders	450g of various binders. After adding the different binder compositions, the plastic bag was shaken in order to create a mixture of the different binders before being added.	
Mould oil	Oil used for reduced stickiness in mortar moulds.	

Presentation of a mixture		
Presentation of mixture	Illustration showing how mortar moulds were used in initial curing.	
Sample mould	Used to create test samples. 3 samples pr mixture. Each mould was oiled before pouring mortar in it. For easy removal of samples.	
Sandbag	1350g of sand mixture. Each bag had the same amount in it, one bag pr mixture.	
Spatula	Used to remove mixture from mixingbowl.	

Stopwatch	Used to control mixing process.	
Test sample removal	Picture illustrating the process of removing the samples from the moulds.	
Viscostar 6K	Viscostar 6K produced by Mapei. Does not have official stickers, as this was made for usage in their own laboratory.	
Water plastic cups	Water was collected from a barrel that was stored in the lab to obtain 20 °C.	

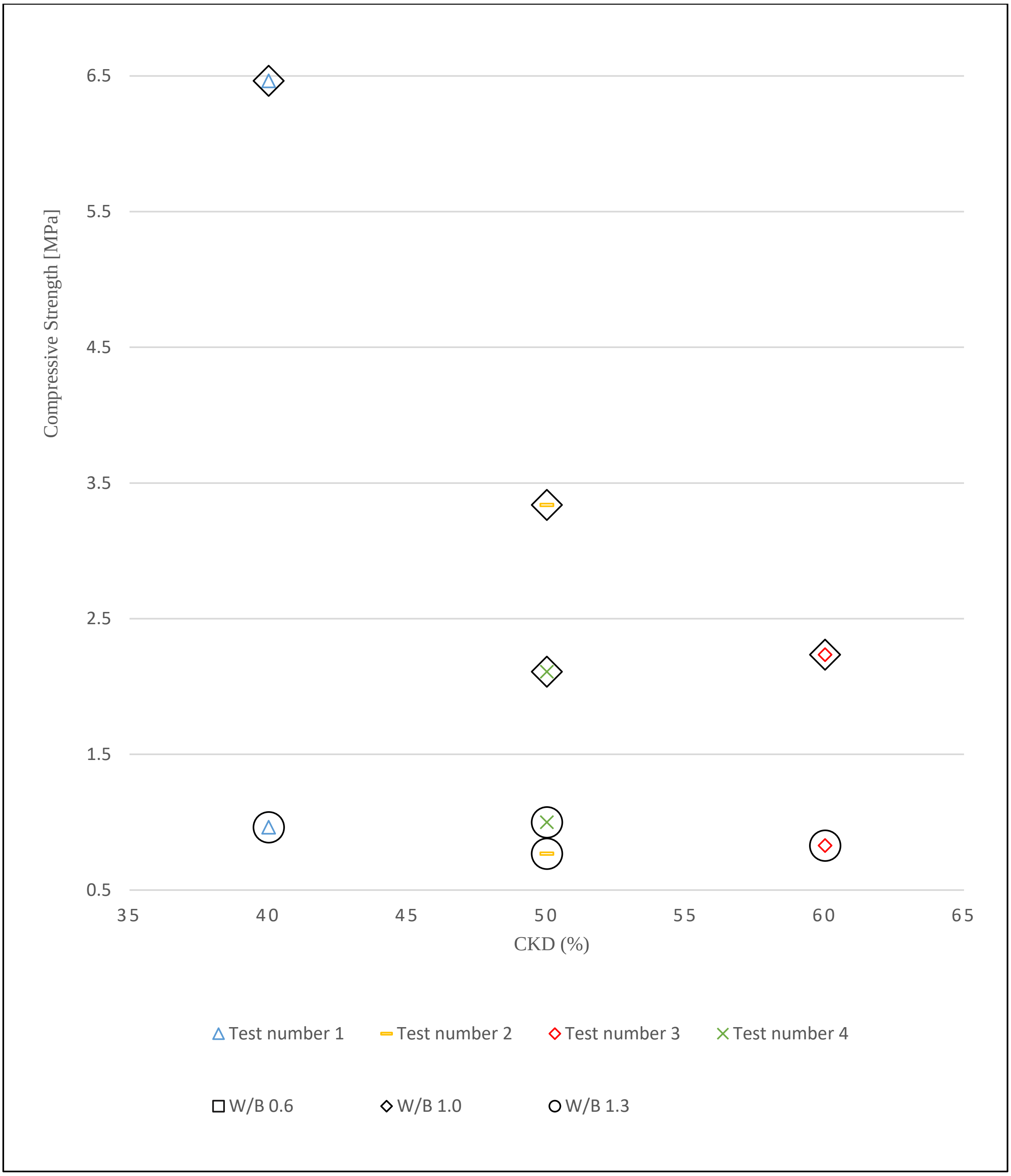
Weight	Weight used to mesure each component; weight provides two decimals.	

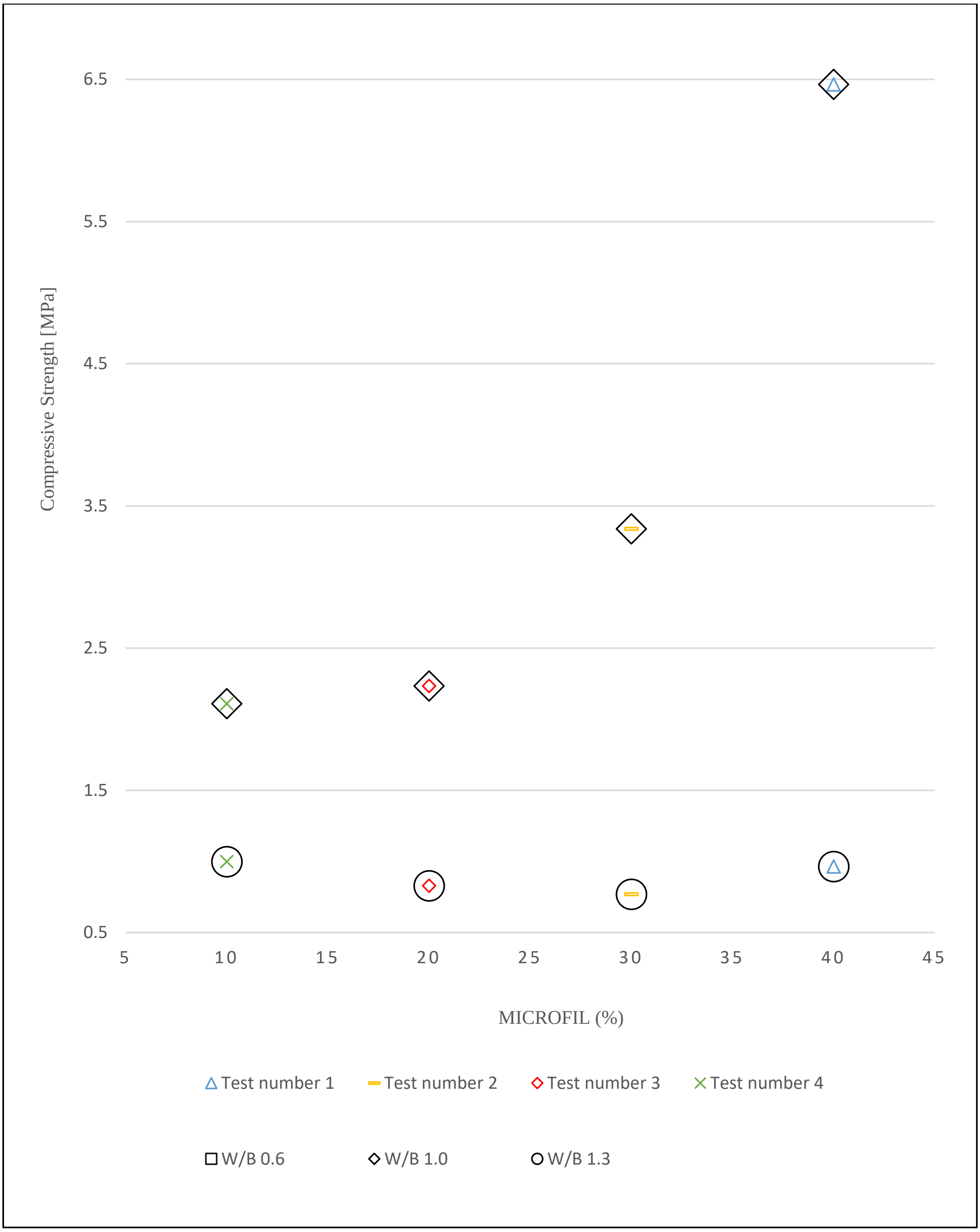
Appendix D:

Scatter charts with excluded W/B ratio of 0.6

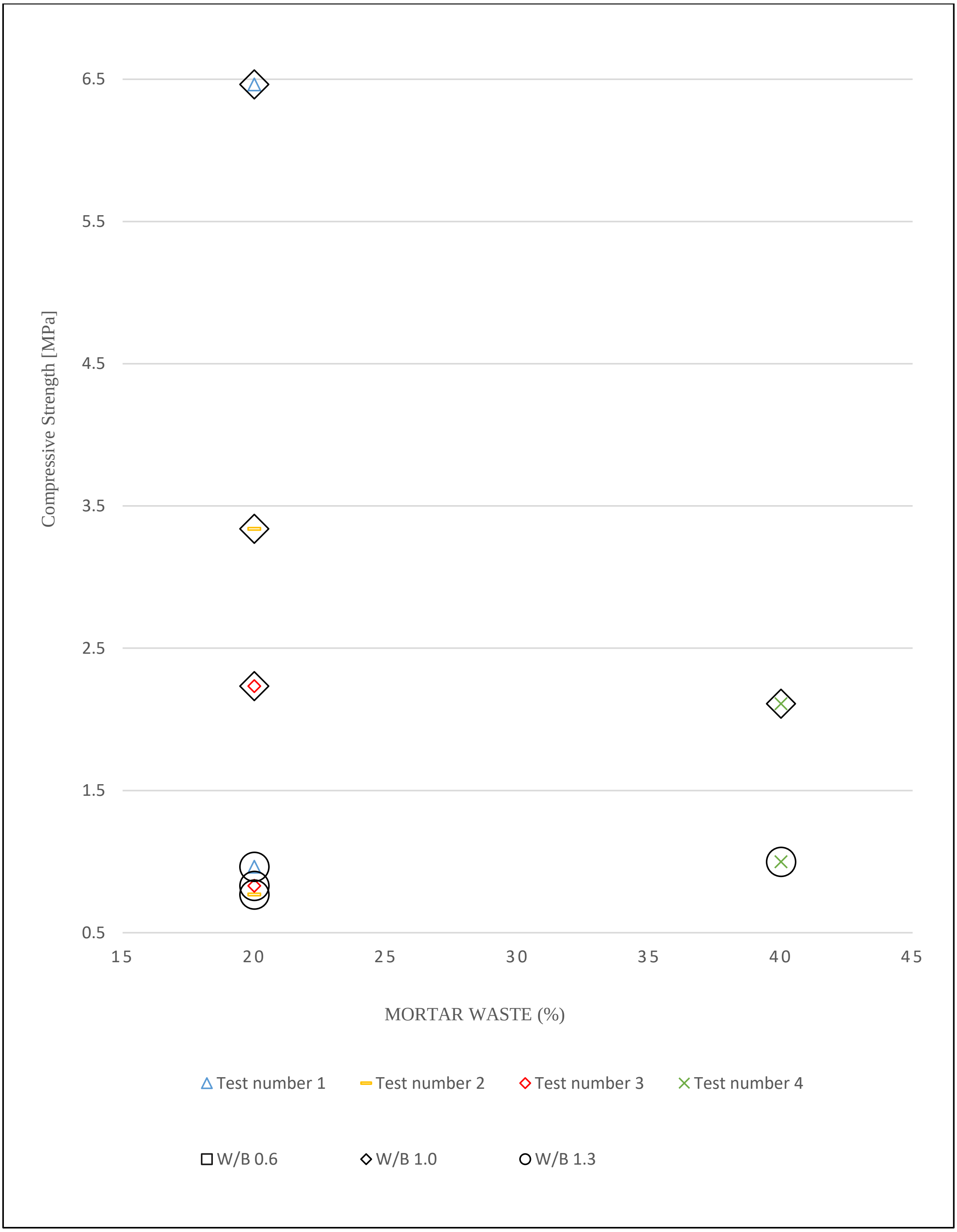
Description

The displayed charts illustrate how mixtures with W/B ratio of 1.0 and 1.3 performed by comparing their compressive strength up against the quantities of each SCM separately.


Compressive Strength [MPa]
6.5
5.5
4.5
3.5
2.5
1.5
0.5
35
40
45
50
55
60
65
CKD (%)
Test number 1
Test number 2
Test number 3
Test number 4
W/B 0.6
W/B 1.0
W/B 1.3



Compressive Strength [MPa]
6.5
5.5
4.5
3.5
2.5
1.5
0.5
5
10
15
20
25
30
35
40
45
MICROFIL (%)
Test number 1
Test number 2
Test number 3
Test number 4
W/B 0.6
W/B 1.0
W/B 1.3


Compressive Strength [MPa]
6.5
5.5
4.5
3.5
2.5
1.5
0.5
15
20
25
30
35
40
45
MORTAR WASTE (%)
Test number 1
Test number 2
Test number 3
Test number 4
W/B 0.6
W/B 1.0
W/B 1.3