From Eruption to Construction - Part B

Investigating the Feasibility of Volcanic Material as Partial Replacement for Cement in Concrete

ACEX-11-VT24-22 Bachelor Thesis

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Cover: Pantheon in Rome, Italy. The world's largest non-reinforced concrete dome, made with lime and volcanic materials.

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Abstract

This study investigates to what extent supplementary cementitious materials, (SCMs) of volcanic material (VM) together with limestone (LS) can replace ordinary Portland cement, (OPC) in concrete through an experimental study. The study is done in collaboration with a partner group named Part A. They are conducting a similar study in which part SCM is replaced only with VM. The project is thus divided into two parts, with this study being part B.
Nine mortar mixtures were tested for compressive strength, with an accompanying X-ray diffraction (XRD) analysis of pastes, to assess chemical properties over time. Out of the nine mixtures, one contains 100% OPC and is referred to as the reference mix (REF). Additionally, there are four mixtures with varying proportions of VM and LS, and four filler mixtures with corresponding amounts of filler to the VM-LS mixtures. Furthermore, a thorough explanation of key materials and concepts is done to provide enough information for sufficient understanding. A detailed description of methods is provided and specific information on each material used, such as Icelandic hyaloclastite from Grindavik and limestone from Cementa, Sweden.

Compressive strength tests were performed to evaluate the strength properties of each mixture relative to a reference mix (REF). Through these results, the optimal ratio of VM and LS to OPC can be concluded. This study showed that the mixture substituted with 40% SCM composed of 30% VM and 10% LS provided the highest strength properties and was comparable to the reference mixture of 100 percent OPC. Therefore, this study concluded that hyaloclastite and limestone can replace 40% of OPC in concrete.

Keywords: Volcanic materials, Cement, Concrete, SCM, Pozzolans, Environment, Hyaloclastite, OPC, Iceland, Grindavik, Roman concrete

List of Acronyms

Below is the list of acronyms that have been used throughout this thesis listed in alphabetical order:

OPC Limestone	Ordinary Portland Cement LS
SCM	Supplementary Cementitious Materials
VA	Volcanic Ash
VM	Volcanic Materials
XRD	X-ray Diffraction
AFt	Aluminate Ferrite trisubstituted (a group of hydration phases
AFm	Alumina, Ferrix oxide, monosubstituted (a group of hydration phases)
CC	Calcite, $CaCO_3$
CH	Calcium Hydroxide
CSH	Calcium Silicate Hydrates
CASH	Calcium Aluminium Silicates Hydrates

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Introduction

Concrete is one of the most important building materials worldwide, with 14 billion m^3 produced in 2020 globally [17]. A similar development can the same year be seen in Sweden, with approximately 15 million tons of concrete produced, translating to over 270 kilograms per person that year [26]. Its demand has been ever-increasing and will likely continue to do so. Ordinary Portland Cement (OPC), which is the most commonly used cement in modern concrete, produces around 700-900 kg of carbon dioxide (CO_2) per ton of concrete [32]. The high environmental impact of cement is due to the production method in which limestone is burnt at high temperatures releasing its embedded carbon in the form of CO_2 [39]. The total impact of cement production amounts to 8% of the world's anthropogenic CO_2 emissions. Considering the billions of tons of concrete produced every year, the concrete-producing industry becomes a significant CO_2-emitting sector. The extensive demand for cement in combination with its substantial climate impact creates a dilemma, considering global warming and ecological footprint. Therefore, finding a material to partially replace cement and reduce the industry's environmental impact is more important than ever. The solution to this dilemma might have already been discovered.

One of the earliest examples of concrete usage was during the Roman Empire. By mixing lime, aggregates, and pozzolana binders [41], the Romans created strong constructions, some of which still stand today. The pozzolana binders were often created from fine volcanic deposits and reacted with water and lime, enabling the pozzolanic effect [51]. The pozzolanic effect resulted in concrete with outstanding mechanical properties and great durability [47]. Although the pozzolana binders could create durable buildings, this method was not scientifically prepared, it was also costly and labor-intensive. Later, during the 1900s, OPC (Ordinary Portland Cement) was invented [37]. The newer type of cement brought several advantages due to its improved cost efficiency and simplified manufacturing process compared to the ancient Roman materials. By adopting a more scientific approach, production became more reliable and consistent. Additionally, reinforcing cement-based concrete with steel rods resulted in the construction of stronger and longer-lasting structures than previously possible with any other materials. As a result of these benefits, OPC quickly gained popularity as a preferred building material, leading to a decline in the use of volcanic deposits. This shift in materials reflects the current state of construction practices.
This study will investigate how volcanic material (VM) can be used as an SCM. The study is named Part B since it is done in collaboration with another group which is Part A. The main difference between the groups is the approach to mixtures for the

concrete. Part A's concrete will solely incorporate VM, while Part B will combine VM and LS. The research questions are presented below.
conducting a similar study in which part SCM is replaced with only VM. Hence, the project is divided into two parts: part A and part B, with this study being part B. The goal is specifically to understand if VM combined with limestone can be an effective way to reduce the use of cement. For this, two research questions are framed as presented below.

1.1 Aim and research questions

The key questions for the study are:

1. To what extent can VM combined with limestone replace OPC while maintaining adequate late-age compressive strength?
2. Which hydration phases will develop in the different mixtures and how will they vary?

1.2 Scope and Limitations

The project is shaped by the scope and limitations outlined in the following chapter.

1.2.1 Scope

The scope of the project is as follows:

1. **Use of VM from Iceland:** The choice to focus on Icelandic VMs is to check the possibilities of VMs in the Nordic region. In general, VMs have already been proven as effective SCMs [51] (eg. Mediterranean VMs and the Romans), however, the potentials of Icelandic VMs have been less explored. The properties of VMs throughout different regions can vary and in order to know the possibilities with Nordic VMs, we have to study them separately. Using Icelandic volcanic materials as SCMs is crucial to explore to achieve more sustainable concrete in Sweden.
2. **Use of limestone as an additional SCM:** When LS is combined with pozzolanic materials such as VM, LS has both a filler and pozzolanic effect [35]. However, the filler effect is significantly more prominent than the pozzolanic effect. In cases where LS is combined with high alumina SCMs such as VMs, the LS reacts with the alumina, resulting in the formation of strength-promoting hydrates. Therefore, the study explored how the usage of limestone as an additional SCM affects the strength properties.
3. **5 mix designs are studied:** 5 different mix designs are considered in this study, including various replacement ratios of VM and LS and a reference mix of 100% OPC. Previous studies suggest that the replacement of OPC is optimized to 30-40% VM[2]. An increased replacement would reduce the strength and durability of the concrete, hence this study limits the replacement of OPC to 50% VM and LS.

4. **Two experimental analyses:** The study prioritizes two analyses to answer the research questions. Strength will be tested in a compressive strength test, and will give data on the durability of the concrete. Hydration phases will be analyzed through XRD to explain the strength and hydration development.
5. **4 mixes to check filler effect:** When SCMs are added to a concrete mix, it helps with strength development in two main ways:
   - Through its reactivity and ability to produce strength-promoting hydration phases, which contributes to strength [8].
   - Contributing to the filler effect, which fills up pores in the hardened concrete, making it dense and able to resist higher loads [4].

   A comparison is made between the strength and hydration phases of the VM-LS mixes, and LS-filler mixes. LS is known to have filler effect and almost no reactivity on its own [30] [23]. By containing equally substituted LS filler to VM it is possible to determine if the VM exhibits both reactivity and filler effect.

1.2.2 Limitations

The limitations of this project are as follows:

1. Only one kind of VM is examined in the project, although it is known that VMs from different regions can be different in their properties. I could be worth comparing the results with more VMs. However, due to constraints in obtaining VMs that are both processed and ready to use, only one could be used for the study. Future studies can compare more types and look into the differences in their behavior.
2. The study is limited to 4 different SCM mixtures (apart from the reference mix with 100% OPC). The chosen mixes are analyzed to enable a representative overview of the possible replacements with this VM. Additionally, the preparation of more mixtures would have required more time than the current project can allow.
3. The project timeline could enable the analyses of two long-duration tests. However, further tests are needed to fully understand their hydration and durability which future studies can look into.

2

Key materials and concepts

The key materials used in this study will be introduced in this chapter and their utilization will be explained. The chapter will also clarify concepts that are obligatory to understand, e.g. the chemical reactions during concrete curing and the effect of pozzolanic SCMs.

2.1 Concrete

Concrete is a hard, durable and alkaline material consisting of cement and water bonded with aggregates (usually gravel and sand) [11]. Concrete is a building material that requires minimal maintenance while sustaining quality over time[39]. It is resistant to moisture, fire, water, and mold compared to timber which is more vulnerable[27]. Concrete can also be reinforced with steel rods to compensate for the material's low tensile strength [39]. Its high strength and cost-effective constructions make concrete a preferred choice for foundations, bridges, as well as houses and skyscrapers [9]. Unlike many other building materials, concrete can be transported in a liquid state, making it easily accessible at construction sites [39].

Regardless of concrete's many advantages, it is susceptible to multiple forms of deterioration, such as creeping, carbonation, shrinking, frost, and chloride ingress [39]. The creeping of concrete is partially caused by the loss of adsorbed water in the cement paste due to applied stress, which leads to deformation over time. Shrinkage is similarly caused by loss of adsorbed water in the cement but is instead caused by climate factors such as relative humidity.

Another form of deterioration in concrete is chemical attacks [39]. Chemicals from the atmosphere, such as carbon dioxide and sulfur compounds may dissolve in water forming acidic substances. These acids may then react with the alkaline substances in the concrete, reducing alkalinity. This can reduce material strength and durability, and cause oxidation of the steel reinforcements, leading to material failure. However, studies suggest using volcanic pozzolans as SCMs may slow this chemical erosion, see Chapter 2.4.

2.2 Cement

Cement is the main binder in concrete, "gluing" the material together [39]. It is produced when heating limestone and additional minerals to a temperature of approximately 1450 ° C, forming cement clinker which is then ground with gypsum into cement. One of the most important variables regarding cement's mix design is the water/cement ratio. To fulfill expectations regarding mechanical and chemical properties, the w/c ratio has to be decided. The weight ratio between cement and water is typically between 0.4 and 0.6 [40]. An inadequate w/c ratio makes the paste less workable and most importantly, there might not be enough water available for the hydration of the cement. The hydration process makes the cement harden [13], in-depth coverage of hydration phases can be found in Chapter 2.8. However, an excessive w/c ratio can decrease strength since water might fill the pores instead of hydrated cement.

2.3 Supplementary Cementitious Materials

Supplementary cementitious materials (SCMs) are materials that show hydraulic or pozzolanic behavior [51]. SCMs also contribute to the filler effect. The filler effect refers to the cement hydration and speeding up the strength development [4]. Hydraulic means that the material hardens by itself in contact with water [51]. Pozzolans are a group of SCMs, which includes natural materials like clays and volcanic materials. They exhibit less or no reactivity when forming hydrate products. However, when pozzolans are finely ground and in combination with Calcium Hydroxide (CH), pozzolans reveals cementitious properties.

Slag is a pozzolanic SCM, and a by-product of the steel industry. Slag is not particularly reactive on its own but becomes more reactive in the presence of OPC and water [51]. Two other pozzolanic SCMs are certain types of clays and volcanic materials, which exist naturally in large quantities [53]. Another SCM commonly used is fly ash from the energy industry and is a by-product of coal power plants. Fly ash usually acts as a pozzolan, however, if containing high calcium it shows both pozzolanic and hydraulic behavior. Both slag and fly ash are effective as SCMs. However, they are not available in sufficient amounts to replace the demand of OPC [55]. In contrast, the reserves of natural pozzolans like volcanic material and clays are sufficiently vast, to fulfill the demand for SCMs in today's industry.

2.4 Volcanic materials as SCM

Volcanic materials are a pozzloans, or pozzolanic SCMs. [51]. VMs have a significantly lower environmental impact than OPC, producing less CO_2, and require no energy to produce since it is naturally available [31]. VMs only need energy when processed to be utilized as an SCM.

Pozzolanic VMs are generally comprised of silicates, alumina, manganese, and iron compounds[51]. However, not all volcanic pozzolans are suitable to use as SCMs. The combined content of silica oxides, alumina oxides, and iron oxides should make up at least 70 percent of the weight of the VM to reach a necessary level of reactivity. Another important factor is the particle size of the VM. Smaller particles contribute to higher reactivity, due to surface area [31]. The degree of reactivity is an indicator of the materials' suitability as an SCM.

In previous studies, VM combined with OPC in ratios from 0-40% VM, obtained a 28-day compressive strength varying from 42.9 MPa to 25.2MPa [49]. When replacing 5% of OPC with VM, the compressive strength increased by 1.5 MPa compared to a mixture with 100% OPC. When replacing 10-20% of OPC with VM, the compressive strength was comparable to the compressive strength of the 100% OPC mixture. The possible hydration compounds when VM partly replaces OPC is similar to the ones forming in conventional OPC concrete [2]. Although the distribution and amounts will vary, primarily consisting of CASH and $Ca(OH)_2$, the main hydrates formed can be found in section 2.8. Due to the varying compositions of different VMs, it is essential to comprehend the strengths achievable from VMs with different compositions.

2.5 Limestone

Limestone is classified as a sedimentary rock and mostly contains the mineral calcite [20]. LS can reduce shrinkage caused by drying when used in concrete [6]. The combination of cement and LS is considered non-reactive by several researchers and therefore acts as a filler [39] [16]. By mixing OPC and LS, the hydration rates decrease, therefore, the replacement of LS filler should not exceed 7% of the total sample [35].

Some other papers suggest that adding limestone may affect hydration rates [39] and could accelerate hydration in early stages [45]. When limestone is combined with pozzolanic materials such as volcanic material, limestone has both a filler as well as a pozzolanic effect [35], although the filler effect is significantly more prominent than the pozzolanic effect. When limestone reacts with the high alumina content present in SCMs it forms hydrates like AFm [19]. These hydrates can produce higher strength and durability in the concrete.

Extracting LS is done by mining, either from open quarries or underground. The extraction of limestone can damage the environment. In addition to harmful emissions due to heating LS, the environment needs to be considered when mining. When mining in quarries, several layers of soil, minerals, and rocks have to be removed to reach the sedimentary rocks [38]. This can harm the ecosystem and the biodiversity.

2.6 Aggregates and fillers

Aggregates in concrete are inert materials such as sand, gravel, and crushed stones [40]. About 60-75% of the concrete's volume consists of aggregates, meaning the aggregates' properties determine the concrete's properties to a large extent. The choice of aggregates affects the hardened properties and mixture proportions of the concrete, where the most important factors are the fine-to-coarse aggregate ratio as well as the maximum aggregate size.

Fillers are defined as fine particulate materials that are chemically inert when mixed with OPC and SCMs [35]. Fillers do not have a pozzolanic effect and exist mainly to fill the pores in the cement paste and decrease porosity. Another purpose of fillers in cement is to substitute some of the OPC and SCMs, hence using fewer clinkers, and reducing CO_2 emissions.

2.7 Compressive strength and testing

Concrete is well known for its compression strength properties and has varying compressive strength (15-105 MPa) according to EN1992-1-1 [1]. It is therefore a beneficial property to examine considering new binder types. To measure the strength of concrete, a compressive strength test is usually done. It is a mechanical test, where a sample of concrete (often in the shape of a cube or cylinder) gradually is exposed to a compressive load until failure of the sample [12], see figure 2.1. The maximum amount of compressive load of a sample can then be measured. A mix with 100% OPC (CEM1, 52,5R) should have a compressive strength of 52.5 MPa after a 28-day curing period [18] [1]. Concrete's compressive strength increases significantly in the first week until the first month of curing. Then, the strength development slows. It is therefore important to test the strength continuously during the first month, as well as on the 56-day mark to examine late age strength. When cement is partially replaced with SCMs, the strength development might be slow in the early age, and may increase and match the later age strength of reference mix with no SCMs [51].

Figure 2.1: Compressive strength test machine on a mortar

Various types of samples can be utilized for the different tests, including paste which is mixed binder and water, mortar which is paste combined with fine aggregates, and concrete which is mortar with the addition of coarse aggregate [29]. While concrete samples give the most accurate results of realistic performance, they demand a significant amount of materials and effort for swift assessment. In laboratory-scale studies, mortars are typically employed to limit the excessive use of materials. Mortars can provide valuable insights into concrete strength development and are used when testing compressive strength.

2.8 Hydration reactions

Hydration reactions are a sequence of exothermic chemical reactions that occur within cement. Heat is released when the hydrated cement hardens and the water solidifies [50]. Hydration of OPC depends on various factors, such as the mineral composition of the cement, curing conditions, and the w/c ratio [8]. As the hydration continues, the cement proceeds to gain strength. Cement's composition, including its hydration phases and additives, plays a crucial role in controlling its reactivity and performance in concrete.

The cement mainly consists of four different hydration phases, see Table 2.1. The alumina and iron compounds are primarily responsible for early reactivity during hydration at low temperatures, although natural limestone sometimes lacks these compounds. Therefore alumina and iron are often incorporated into the mix by adding secondary materials such as clay minerals [39]. One potential source for alumina and iron is volcanic matter, which tends to be rich in Silicates, alumina, and iron [51]. Gypsum is present to reduce early reactivity caused by C_3A, which can otherwise damage the concrete during hydration [39].

Table 2.1: Cement phases and their chemical formula

Name	Chemical formula	Abbreviation
Tricalcium silicate	$3CaO \cdot SiO_2$	C
Dicalcium silicate	$2CaO \cdot Si_2$	C2S
Tricalcium aluminate	$3CaO \cdot Al_2O_3$	C3A
-	$4CaO \cdot Al_2O_3 \cdot 3Fe_2O_3$	C4AF

Hydration phases refer to the chemical reactions that occur when cement and water are mixed [13]. When mixing the OPC with water, a paste is formed. In the paste, cement grains react with water to form hardening compounds around each grain in an exothermic reaction, creating a cement gel [56]. This hardening of the paste occurs in multiple stages, and different compounds dominate different stages of the hardening process [13]. At the early stages of hydration, a porous cement gel is formed around the unhydrated cement grains. Over time, more cement is hydrated and fills these pores, reducing porosity and increasing strength. After 28 days the concrete will start to reach maximum strength [13]. The distribution and evolution of these hydration phases are investigated through an XRD analysis, which can be seen in Chapter 4.2.

Table 2.2: Pivotal compounds during hydration

Name	Chemical formula	Abbreviation
Calcium hydroxide	$Ca(OH)_2$	CH
Calcium silicate hydrates	$C_3S_2 \cdot 3H_2O$	CSH
Ettringite	C3A3CaSO4 · 32H2O	AFt

The main hydrate phases of OPC paste are: CSH (Calcium Silicate Hydrate), CH or Portlandite (Calcium Hydroxide), and Ettringite. In case the OPC is susbstituted with a high alumina SCM such as in the case of VM, then the C-A-S-H (calcium aluminate silicate hydrate) are formed which are known to reduce capillary porosity and provide durability later [24].

CH, or calcium hydroxide does not contribute to concrete strength but is essential for protecting the concrete and its steel reinforcement from chemical deterioration [13]. It maintains the high pH necessary to keep the steel layer protected from the corrosion. The presence of CH also facilitates other hydration reactions necessary for strength development, particularly when utilizing SCMs, see Chapter 2.4.

As one of the main compounds responsible for strength in the hydrated cement paste, CSH and is formed when C_2S and C_3S react with water (see table 2.2). CSH makes up about 70 percent of the hydrated cement paste. The reaction responsible for creating CSH can be written as follows [13]:

$2C_3S + 6H_2O$ -> $C_3S2 \cdot 3H_2O + 3CH$
A similar reaction occurs when C2S react with water, producing similar compounds but less CH.

Another hydrate compound is ettringite or AFt, which is formed when C_3A reacts with water when gypsum is present, which is the case for OPC. The hydration reaction of C_3A is most active in the early stages of hydration and contributes to strength development. Ettringite is vulnerable to chemical deterioration and may deteriorate in later stages of hydration when sulfates are depleted [28]. C_3A reacting with water can be described with the following equation:

$$C_3A + 3CaSO_4 + 32H_2O- > C_3A3CaSO_4 \cdot 32H_2O$$

(ettringite or AFt, trisulfate) [28]. When sulfate content decreases in later stages of hydration, AFt may deteriorate to AFm (mono sulfate) described with the following reaction:

$$2C_3A + ettringite- > 3C_3ACaSO_4 \cdot 32H_2O$$

When C_4AF hydrates, ettringite is also formed but the aluminum, A, is replaced with iron, F. This ferrous ettringite is more resistant to chemical deterioration compared to aluminum ettringite, it also contributes to strength development. Ferrous ettringite is also formed in the early stages of hydration due to its high reaction rate. The amount of ferrous ettringite produced is determined by the relative amounts of iron compounds in the hydrating paste [28].

Table 2.3: Carboaluminates

Name	Abbreviation
Hemicarboaluminate	HC
Monocarboaluminate	MC

Including LS in the VM and OPC mixes have several advantages regarding strength and hydration [10]. LS can fill the pores in the concrete, decreasing porosity might also increase strength and durability [15]. A reaction between LS and VM enables LS to participate in binder hydration, which creates carbo aluminates, a strong compound for the final concrete. When utilizing SCMs with LS, two different carbo aluminates may form, mainly MC and HC. They form when alumina compounds react with calcium carbonates in the presence of CH. MC and HC are expected to form in later stages of hydration [3].

2.9 XRD analysis

X-ray diffraction (XRD) is used to assess precise information about crystallinity, to determine a sample's chemical composition or other physical properties of the material, see the machine used in figure 2.2) [7]. The technique is based on X-ray interaction with crystalline materials. When the X-ray beam hits the sample at different angles (2 theta angle). The difference in the nanostructure diffracts the beam unevenly creating a unique diffraction pattern. The contrasting patterns can then be processed and counted, where certain spikes determine separate chemical structures [44].

This method is used to identify changes in hydrates forming when introducing new binders to OPC blends. XRD is a powerful technique to uncover the mineralogical composition and hydrate phases, such as VMs and LS. The new hydrates impact the strength properties in the binders, a phenomenon clarified through XRD analysis.

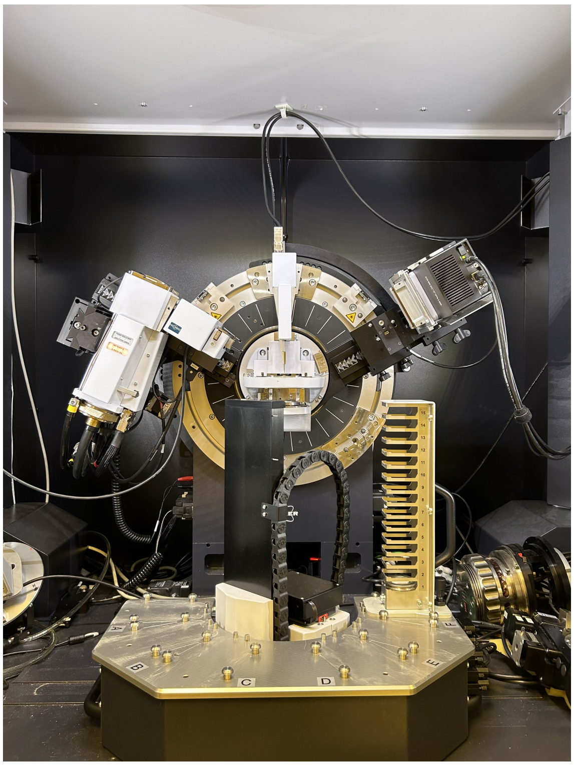

Figure 2.2: XRD machine used for determining hydration phases

3

Materials and Methods

This chapter presents the mixtures and recipes, describing their ingredients and the methods used to examine their mechanical and hydration properties. The materials section will provide a more in-depth explanation of the materials' functions and the specific type of aggregates, cement, etc used in the experiments. The methods section will thoroughly describe the experimental process, from casting and curing to compressive strength test, and XRD analysis.

3.1 Materials

The primary materials in this study are OPC, volcanic material, and limestone. Table 3.1 provides the oxide concentrations and particle sizes of the binder materials. For casting mortars, fine aggregates are also used.

Table 3.1: Material properties: Portland cement, VM from Grindavik, Limus 15

Property	Cement (Portland cement)	VM (Hyaloclastite)	LS (Limus 15)
Na_2O	0.27	2.2	0.1
SiO_2	19.6	44.1	9
Al_20_3	4.5	14.8	0.6
CaO	62.2	12.6	49.5
Fe_2O_3	3	12.6	0.3
MgO	3.5	11.5	-
TiO_2	-	1.5	-
BET	-	2.2	-
D50 (µm)	20	3.1	8

3.1.1 Fine Aggregates

The aggregates utilized were Normsand DIN EN 96-1, Germany, the grain size spans from 0.08 - 2.00 mm [43]. Aggregates are present in the mortar mixtures used during the compressive strength testing. It is shown in figure 3.1.

Figure 3.1: Specified aggregates, Normsand DIN EN 96-1

3.1.2 Ordinary Portland Cement (OPC)

The cement used is Cem I, 52.5 R OPC from Cementa. The numeric designation of 'Cem I' indicates the strength class of the cement, with 'I' being the highest strength category [14]. There are also other types of cement grades, Cem II, III, IV, and V, which all have different properties. The naming '52.5R' means that the cement will attain a compressive strength of 52.5 MPa after 28 days of curing.

A reference mixture (REF in table 3.2) with 100% OPC will be compared with the results obtained from the other mixtures containing VM and LS. While OPC will be present in all of the mixtures, the amount will vary as it is substituted with different quantities of SCM and LS throughout the mixtures.

3.1.3 Limestone as a filler and an SCM

Limestone was used both as a filler and an SCM. The limestone used is Limus 15, also called KÖ100 from Nordkalk, with an approximate grain size of 0.1 mm [42]. The proportion of limestone in the VM-mixes is limited to 20% [10]. Mixtures containing more than 20% LS are less effective in creating sought-after reactions and formations of carbo aluminates, hence decreasing the mixtures' strengths.

Comparing the mixtures with VM-LS to the mixes where fillers replace OPC, it is possible to distinguish the pozzolanic effect from VM. This will be done by comparing the results of a mix with 25% VM-LS with a mixture replaced with 25% LS. By concluding whether the addition of LS is sufficient, it may be possible to aim for higher levels of cement substitution compared to only using VM.

3.1.4 Volcanic material (Hyaloclastite)

The volcanic material used as a pozzolanic SCM is known as hyaloclastite sourced from Grindavík, a region in southern Iceland, as seen in figure 3.2. Hyaloclastites are deposited through explosive fragmentation of basaltic magma which solidifies in varying degrees in contact with water or ice during eruption [34]. The result is a heterogeneous material in a matrix of fine, glassy fragments. Hyaloclastite's chemical composition is summarized in Table 3.1. According to previous studies, hyaloclastite can be more reactive than fly ash which is currently used as an SCM [22].

Figure 3.2: Map of Iceland and the location of Grindavík (red pin) [The image and information shown here are provided by © Universal Images Group].

3.2 Methods

The Methods section is divided into two subsections, mechanical properties and hydration phases. Mechanical properties describes the process to enable examination of mechanical properties i.e strength. It will include casting, strength test and management of outliers. The subsection on hydration properties explains the creation of hydration pastes and the principles of XRD analysis.

3.2.1 Mechanical properties

For this study, the following recipes were used for the mixes, according to Swedish standard EN196 [52] with different percentages of OPC, VM and LS, which were used to calculate the corresponding weights. The recipes are represented with both the percentage ratio of each material and the calculated weight used in the experiment in Table 3.2. The reference mixture with 100% OPC is named REF, the other mixtures are named based on the input amounts of either VM-LS or the amount of filler (F). These names are used when discussing results.

Table 3.2: Mix variations and ratios for casting mortars

	OPC	VM	LS	Sand	Water
REF	100 %	-	-	-	-
Weight (g)	450	-	-	1350	225
VM15-LS5	80%	15%	5%	-	-
Weight (g)	360	67,5	22,5	1350	225
VM20-LS5	75%	20%	5%	-	-
Weight (g)	337,5	90	22,5	1350	225
VM30-LS10	60%	30%	10%	-	-
Weight (g)	270	135	45	1350	225
VM30-LS20	50%	30%	20%	-	-
Weight (g)	225	135	90	1350	225
F20	80%	-	20%	-	-
Weight (g)	360	-	90	1350	225
F25	75%	-	25%	-	-
Weight (g)	337,5	-	112,5	1350	225
F40	60%	-	40%	-	-
Weight (g)	270	-	180	1350	225
F50	50%	-	50%	-	-
Weight (g)	225	-	225	1350	225

Based on the calculations of the mixes, equivalent amounts of each material were measured for each respective mixture (see figure 3.3). The dry materials, besides the sand, were measured in the same container, while the water was measured separately, using a precise weight scale. The dry materials and water content were combined and blended in a mortar mixer. The mixer is an Auto- Mortar Mixer, supplied by Nycander AB, Stockholm. It is programmed according to mortar mixing steps outlined in Standard EN 196 [52]. The mixer operates at two speeds: low (140 rpm) and high (285 rpm) and has an automatic sand dispenser that fills the sand into the mixing bowl for a 30-second period (see Figure 3.4). Then, the machine stopped, and the mixture was manually scraped down from the sides of the container to ensure a homogeneous blend. For some of the mixes, the consistency was too firm, necessitating an addition of superplasticizer resulting in a more fluid mixture without increasing water content [5], thus improving mold filling.

The cubes were cast in molds of 4x4x4 cm, each mix batch generated 12 cubes. This

Figure 3.3: Measure and weighting of the material

Figure 3.4: Incorporating sand into the mixture during the blending process

results in that three cubes were tested for each mixture and on each day when the strength test was conducted, providing a broader and more accurate representation of the mortar strength. The preparation of the molds was accomplished by applying "Pieri decobio" oil (see Figure 3.5). An oil dispenser was used to distribute the oil throughout the mold, ensuring an easy release of the hardened cubes after curing as seen in Figure 3.6. After application, the oil was evenly spread around the mold in a thin layer, using either a finger or a brush.

Two different molds were used, green plastic molds and wooden molds (see Figure 3.6). The wood molds were prepared solely with oil, and the plastic molds had a small hole in the bottom that were secured with parafilm to ensure minimal leakage while vibrating the mixtures. The oiled molds were filled with the mixtures with a clean spade (see Figure 3.7). It was important to properly pack the molds to prevent air in the test cube. Therefore, the molds were also vibrated as seen in Figure 3.8.

It is important to prevent the water from evaporating especially in earlier stages since it could cause plastic shrinkage [21]. This process occurs in the first 24 hours when the mortar has not hardened, as it could happen at a fast rate. This is prevented by by putting plastic wrapping around the samples as seen in figure 3.9.

After 24 hours, it was time to remove the samples from the molds (see Figure 3.10). The wooden molds resulted in a much more difficult demolding process which required the molds to be unscrewed to enable retrieval of the cubes. The other green plastic molds used were easier to extract the cubes from, requiring only air pressure through a hole in the bottom of the mold for removal. The cubes produced from the plastic molds were also more symmetrical compared to those of the wooden molds.

The hardened samples were put into containers filled with deionized water (see Fig-

Figure 3.5: Details on the used oil

Figure 3.6: Distributing the oil in the molds

Figure 3.7: The molds filled with the mixture

Figure 3.8: Vibration of the mixture

ure 3.11) until it was time for the compressive strength tests. Curing is a process where the mortar has continuous access to water, allowing it to hydrate and making the binders react with the water, producing hydrate products such as calcium hydroxide [36]. An inadequate amount of water leads to hydration not proceeding,

Figure 3.9: Plastic wrapped molds

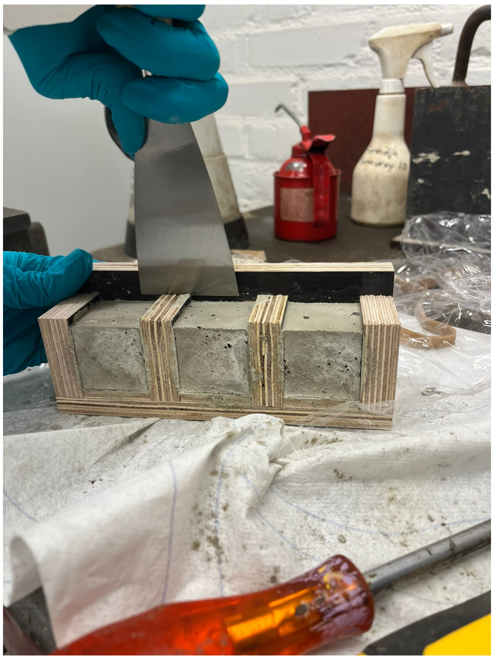

Figure 3.10: Demolding of the cubes

resulting in cracks and shrinkage on the surface. It will also lead to incomplete strength of the mortar, concluding that the water and curing process is important for the final durability of the mortar.

Figure 3.11: Samples stored in water-filled containers

A compressive strength test was performed after 3, 7, 28, and 56 days to provide information about the strength and its development of the different concrete mixtures. Three mortars were tested for each mixture on each day the compressive strength test was conducted. Choosing the specific amount of three mortars provided a broader and more accurate representation of the mortar strength.

The interquartile range (IQR) method was applied to statistically exclude outliers. The IQR tolerance was adjusted to eliminate the same outliers as first determined by general understanding. The tolerance for the compressive strength data was then set at 30 percent. By incorporating the IQR method with the 30 percent tolerance, a representative dataset was established.

3.2.2 Hydration pastes

Hydration pastes were cast to enable XRD analysis. Binder proportions were preserved from the original recipe, but without the addition of sand to avoid interference in the XRD analysis from the sand grains. The ratio of the various binders can be observed in Table 3.3.

Table 3.3: Mix variations and ratios for casting pastes

	Cement	SCM/VM	Limestone	Water
REF	100%	0%	0%	50%
Weight (g)	300	-	-	150
VM15-LS5	80%	15%	5%	50%
Weight (g)	240	45	15	150
VM20-LS5	75%	20%	5%	50%
Weight (g)	225	60	15	150
VM30-LS10	60%	30%	10%	50%
Weight (g)	180	90	30	150
VM30-LS20	50%	30%	20%	50%
Weight (g)	150	90	60	150
F20	80%	0%	20%	50%
Weight (g)	240	-	60	150
F25	75%	0%	25%	50%
Weight (g)	225	-	75	150
F40	60%	0%	40%	50%
Weight (g)	180	-	120	150
F50	50%	0%	50%	50%
Weight (g)	150	-	150	150

The preparation and casting of the hydration pastes were similar to the casting of the strength test mixtures. The dry materials and the water were measured and weighed on a scale. The dry content was put into a container and dry-mixed with a spatula. Then the water was poured in and roughly mixed with the same spatula. Afterward, the blend was mixed with a hand-held Bosch mixer for 2 minutes.

The concrete pastes were poured into labeled tubes, two tubes for each mixture, and then vibrated to ensure minimum bubbles. After being vibrated, the tubes were put into a rotator, which can be seen in figure 3.12. The rotating speed was set to 40rpm, to ensure that the binders did not settle in the bottom of the tubes.

Figure 3.12: Rotator used for rotating the pastes

After 24 hours, the tubes with the pastes were released from the rotator. The tubes were sawed into four roughly equal parts and put into water to cure (see Figure 3.13). The curing process was stopped after 3, 7, 28, and 56 days.

Figure 3.13: Sawed paste samples curing in water

The curing process was stopped to prepare the samples for the XRD analysis. This was done by taking one sample (1/4 of a test tube) and sawing it in half. One-half was then crushed using a hammer to increase the surface area. Both halves were transferred into a labeled test tube which was later filled with the alcohol isopropanol to ensure the stoppage of hydration phases by displacing water. The newly filled tubes were put into a fume hood for seven days. The alcohol was replaced every 24 hours to ensure maximum water diffusion from the samples. During the replacement, the used isopropanol was poured into a waste bin and handled as chemical waste.

A week later the samples were removed from the alcohol and put into labeled baking cups made of aluminum. The cups were placed into an oven set to 30°C for 24 hours. The specimens were then taken out, and crushed into fine powder using a mortar and pestle, see figure 3.14. The crushed sample was then sorted through a sieve, ensuring a particle size $< 75\ \mu$m, and carefully placed into small test tubes, which were put into bags and stored in a vacuum bottle to ensure no reaction with the moisture in the air. The sieve was cleaned using high-pressure air, while the mortar and pestle were cleaned using sandpaper, then washed with isopropanol and blow-dried using high-pressure air. This minimizes the risk of the tools contaminating the next sample. All these steps were repeated for every sample during each hydration stoppage. The specimens were thereafter sent for XRD analysis.

Figure 3.14: Mortel and sieve for crushing samples

The samples were prepared before the XRD test to ensure accurate results (figure 3.15. The XRD was divided into two occasions, the 3-day and 7-day were prepared at the same time, and then the 28-day and 56-day. Small glass trays were cleaned using isopropanol and paper, then the trays were filled with the samples. A cleaned microscope slide was then used to flatten the sample surface to benefit the machine's ability to analyze the specimens. The 18 trays were divided into two sample holders and loaded into the machine, which ran overnight. The next morning the samples were put into their separate plastic bags to store. Lastly, the trays were cleaned and the materials returned to their respective place.

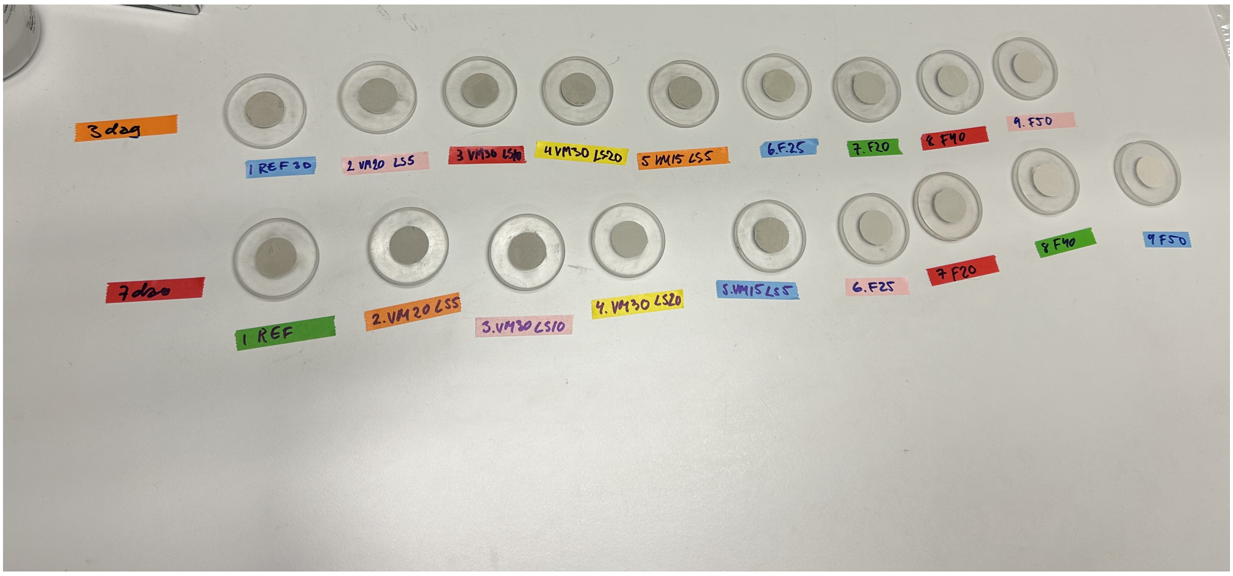

Figure 3.15: Prepared and labeled samples for XRD

X-ray diffraction examined differences in the hydration pastes to determine variations in hydration phases. The XRD analysis was conducted with the same spacing as the compressive strength test, after 3, 7, 28, and 56 days of curing. The results were then compared to one another. A sample's hydration phase can inform how the chemical structure and composition might affect compression strength and strength development.

4

Results

The purpose of the study was to investigate two major questions:

1. To what extent do volcanic materials combined with limestone replace OPC while maintaining adequate late-age compressive strength?
2. Which hydration phases will develop in the different mixtures and how will they vary?

The mixtures are referred to as VM%-LS% or F% to show the percentage in VM and LS or filler. The mixture with 100% OPC is called a reference mix or REF. The VM-LS mixtures are compared with their corresponding filler mix, and to one another.

4.1 Compressive strength test

The compressive strength tests were done for 3, 7, 28, and 56 days of hardening. The results are presented in a bar chart in Figure 4.1 and the strength progression is shown in Figure 4.2. On each strength testing day, three mortars per mixture were tested. The mean values are presented in the figures and error bars illustrate the variability between the mixture. REF is presented in a bright red color. The VM-LS mixtures are in various colors while the filler mixtures are in hues of green.

The 3-day strength test showed the reference mixture as the sample with superior strength. All the mixtures with varying amounts of VM had low strength. The VM20-LS5 (mix 2) compared to F25 showed the filler mix to be higher. The F20 was also higher than its corresponding mix with VM15-LS5 (mix 5). However, VM30-LS10 (mix 3) and VM30-LS20 (mix 4) both had higher strength than their corresponding filler mix (F40 and F50).

During the 7-day test, the reference mix showed the highest strength, and the other samples also showed development. The highest strength from the VM samples was observed in VM30-LS10 and its corresponding filler mixture (F40) was noticeably lower. The VM30-LS20 sample showed lower strengths than the other mixtures, which showed similar strengths. VM30-LS20 had a higher strength than its filler mixture, F50. VM30-LS10 and F25 had identical strengths. F20 had higher strength than its VM correspondent, VM15-LS5.

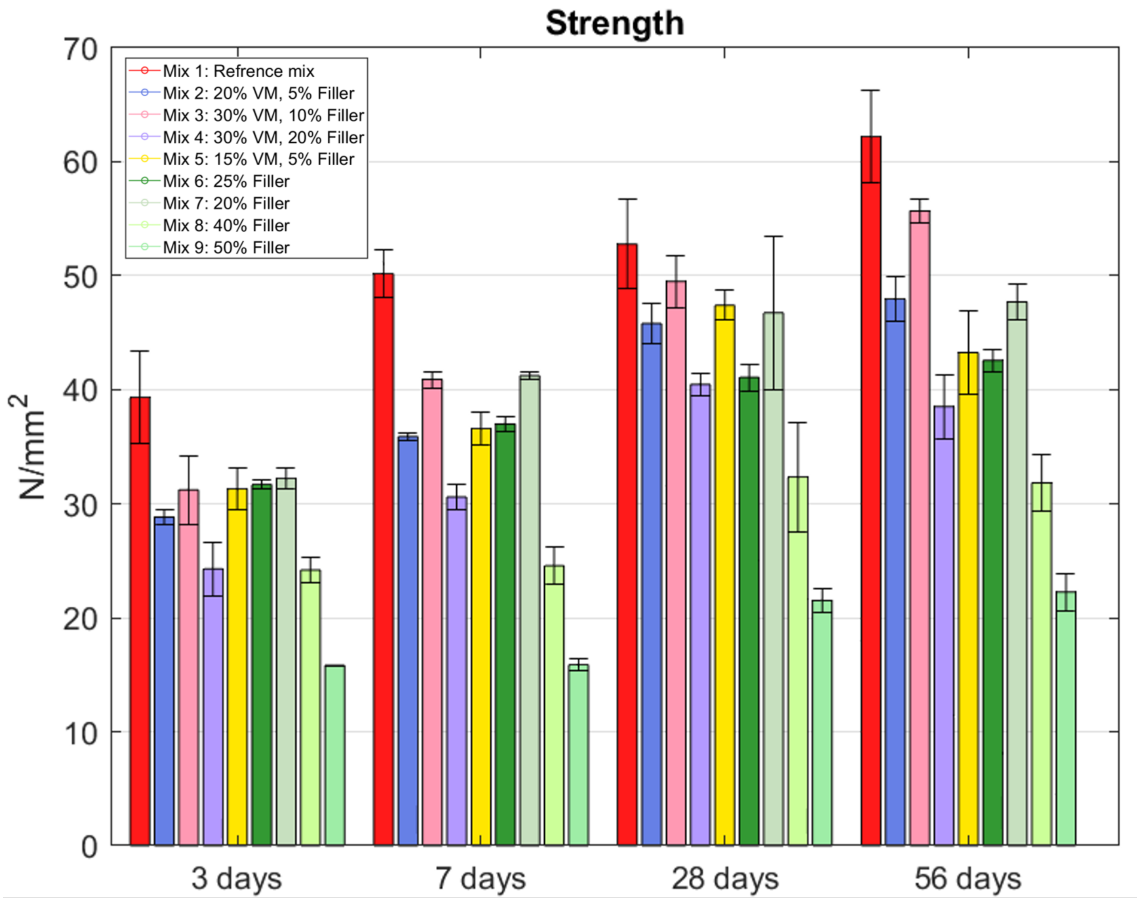

Figure 4.1: Bar chart of compressive strength results for the mortar mixtures

On the 28-day strength test, the mixture with VM30-LS10 and VM15-LS5 was similar to the strength of REF. All VM samples showed higher strength than their corresponding F-mix. VM30-LS20 showed low results compared to the other VM samples.

Results from the 56-day tests showed REF as the highest strength. VM30-LS10 showed the highest result among the VM mixtures, and its comparable F40 was lower. The other VM mixes showed higher results than their corresponding filler mixtures except for VM15-LS5 and F20. The mixtures VM30-LS20 and VM15-LS5 decreased in strength between the 28-day and the 56-day tests. The reduction of strength would not be possible and this result is thus incorrect.

Observing the strength development as a whole showed interesting results. The reference mix developed a strength of approximately 50 MPa at 28 days. The VM samples showed slow growth in the first week but reached the approximate same strength as REF on the 28th day. After that, the development slowed for most of the VM specimens, none grew significantly between 28 and 56 days, though VM30-LS10 continued to advance and grow. Some mixtures showed lower strength on the 56th day than the 28th, for example, VM15-LS5 whose strength was reduced by approximately 5 MPa.

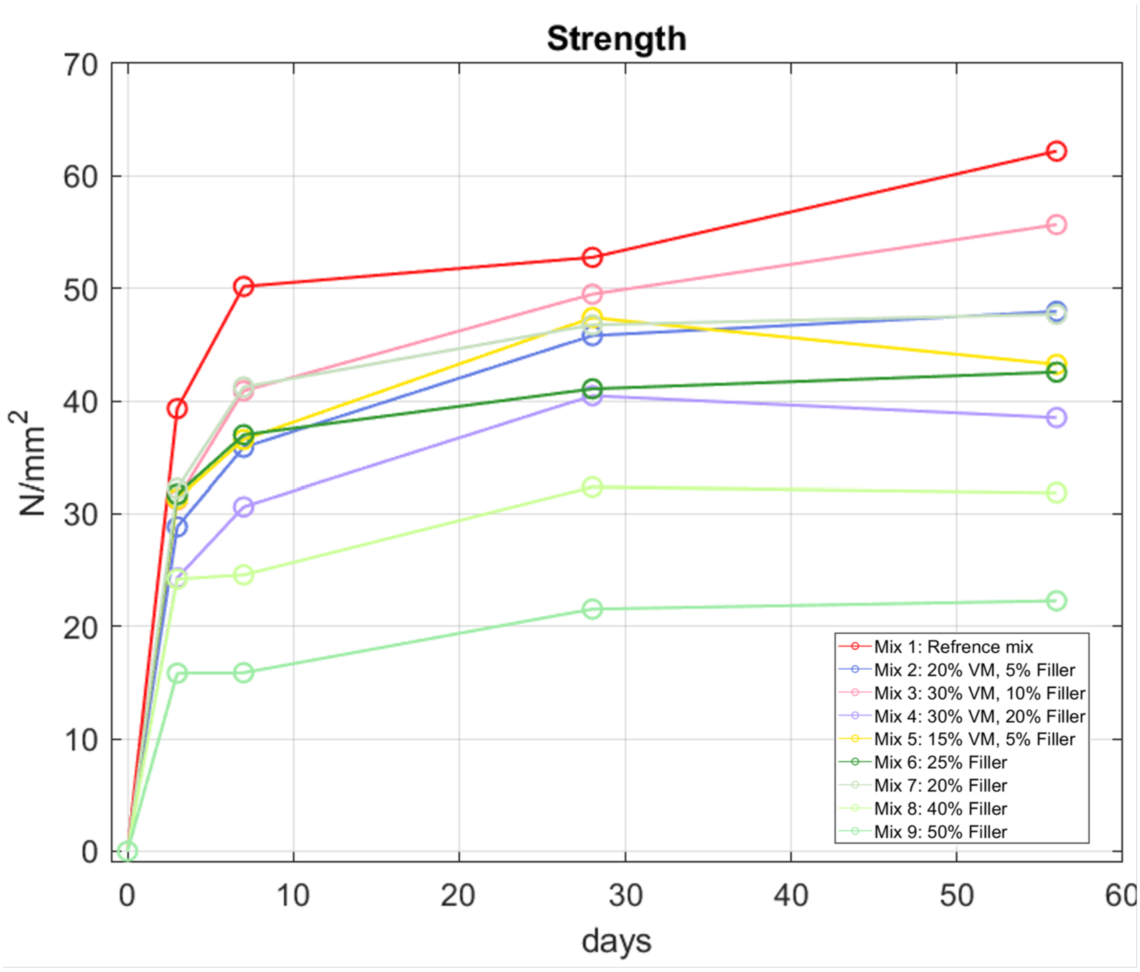

Figure 4.2: Strength developing over time for the mortar mixtures

4.2 XRD

An XRD analysis was performed for 3, 7, 28, and 56 days. 2 theta angle explains the angle at which the beam hit the sample and created the diffraction pattern for certain hydration phases. E.g. CH will show up at 28.7 2 theta. The results is presented for 3 days in Figure 4.3, for 7 days in Figure 4.4, for 28 days in Figure 4.5, and from 56 days in Figure 4.6. Comparison between the VM-LS mixes with the REF mix showed differences regarding the hydrate phases of the samples.

The chemical compositions and abbreviations that can be present in the hydrate samples are presented in the table below 4.1

- **CH**
  At 28.7° 2 theta, there is a peak for CH, where REF shows higher intensity than the VM mixes. A similar trend is seen for the CH peaks.

- **AFt/ettringite**
  At 9.12 and 18.8 ° 2 theta there are peaks for AFt for all mixes, where REF shows higher intensity. The results also show that AFt- phases decrease intensity over time for all mixes.

Name	Abreviation
Calcium Carbonate	CC
Calcium Hydroxide	CH
Ettringite	AFt
Hemicarbonate/ monocarbonate	AFm
Calcium silicate hydrate	CSH
Tricalcium silicate	C3S

Table 4.1: Hydrate phases present in XRD analysis

- **AFm**
  AFm is present at 10.8 ° 2 theta, increasing intensity over time. This is according to theory and is expected. AFm concentration is higher for VM mixes compared to REF and F mixes. This is also seen for 28 and 56 day results, with even more AFm phases present.

- **CSH**
  CSH concentration is slightly lower for VM than ref REF, but significantly lower for filler mixes.

- **CC**
  The VM-LS mixes and the filler mixes show a significant peak around 29.4 theta, which is not as prominent in the REF mix. This is due to calcite (CC) from the limestone. It should be noted that the CC peaks for the VM mixes are significantly higher than what is visible in figures 4.3 and 4.4.

- **C3S** C3s, or alite is present in all mixes in early stages of hydration. After 7 days, it has significantly decreased for the reference mix which is according to theory, although the VM and filler mixes still show a significant peak at about 29.4 degrees 2 theta. This is possibly due to interference of CC from the limestone.

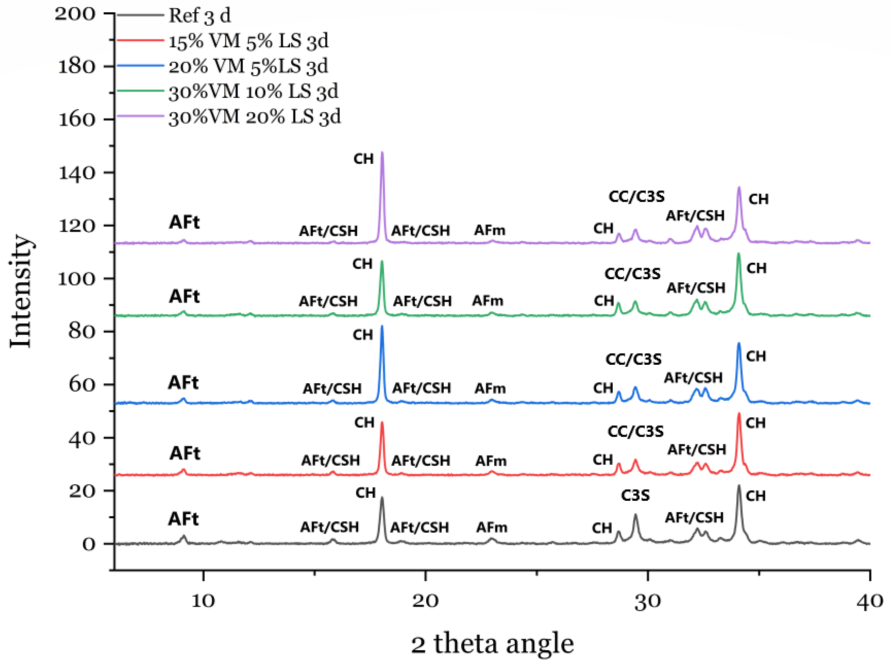

Figure 4.3: XRD results at 3 days

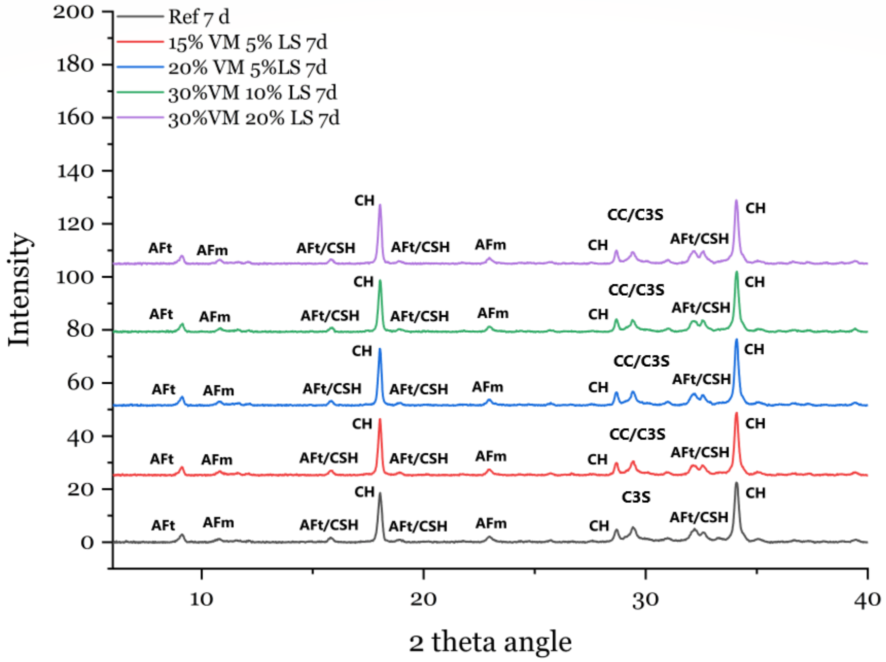

Figure 4.4: XRD results at 7 days

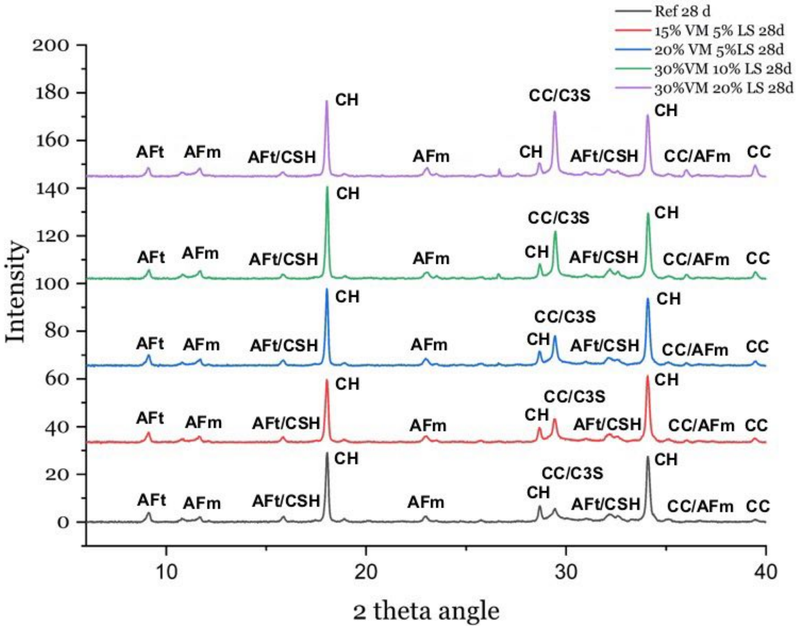

Figure 4.5: XRD results at 28 days

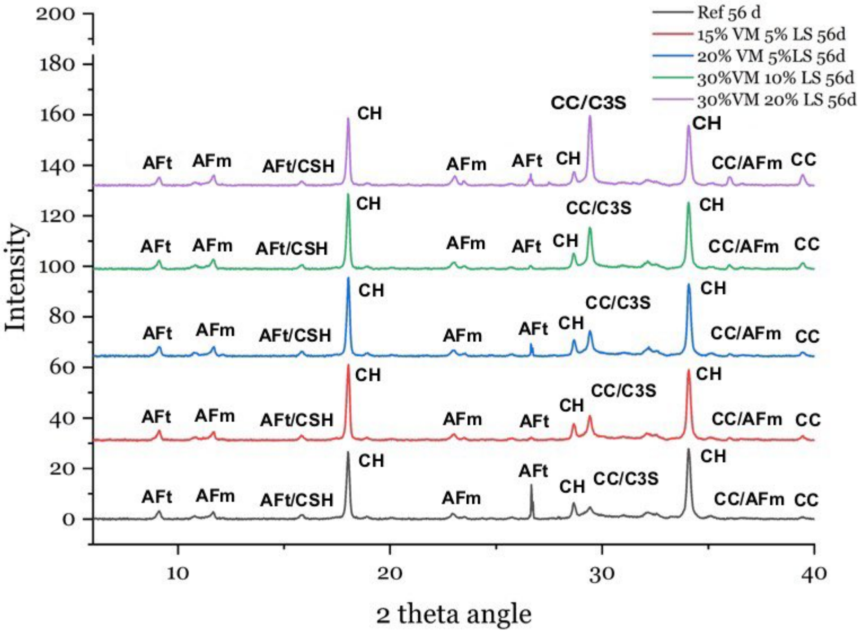

Figure 4.6: XRD results at 56 days

5

Discussion

This chapter discusses the results of the compressive strength tests and will be reinforced by the XRD results. Sources of errors are addressed to analyze the study from a critical perspective, along with a discussion of the project's societal and ethical aspects.

5.1 Strength and hydrate properties

In the early stages of hydration, the results show that the reference mix (REF) with 100 percent OPC performs significantly better during the compressive strength test than the VM-LS and filler mixes. The reason is that the VM mixtures develop strength slowly, and show low early on strength, as was also reported in another literature [48]. The XRD results can explain the low early strength of the VM-LS mixes when compared to the REF mixture. One reason is that a lower concentration of hydration phases that contribute to strength is present in the VM mixes compared to REF at the early stages of hydration. This is the case for AFt and CSH, which both contribute to strength [46]. VM mixes also have lower concentrations of CH which can explain their lower early reactivity. The lower CH amount is because they react with CH to form C-A-S-H [24]. On the other hand, in later stages of hydration, the VM mixtures show significantly higher concentrations of AFm phases compared to REF, which is explains why its strength increase accelerates and approaches REF before 28 days [48].

After 28 days the blends VM30-LS10, VM15-LS5, and VM20-LS5 have reached a similar, but slightly lower strength compared to the reference mix of approximately 50 MPa, see Figure 4.1. REF's strength has continued to increase with a mean of roughly 63 MPa on the 56th day. Figure 4.2 revealed some mixtures with decreasing strength between 28 and 56 days. The phenomenon that strength could decrease over time is incorrect, and its explanation could be due to sources of error explained further in section 5.2.

During the 28-day test, the VM15-LS5 mixture showed promising results, comparable to the top-performing VM mix, VM30-LS10. If VM15-LS5's strength had been accurately developed, it would have altered the study's conclusions regarding optimal ratios. This is only an assumption since VM15-LS5 mixture has more OPC than to VM30-LS10. While reviewing the strength development of the REF mixture, it is increasing a lot between 28 days and 56 days. Therefore it is possible to assume that the VM15-LS5 mixture could have the highest performing strength at the 56-day compressive strength test had it developed optimally.

It is also possible that excluding LS from the mixes entirely and instead using only VM as an SCM could produce better results. VM has a higher pozzolanic effect compared to LS which could lead to higher compressive strength. Therefore an additional project parallell to this study was conducted, focusing solely on mixtures containing VM and OPC. To read about those results, see "From Eruption to Construction - Part A: Investigating the Feasibility of Volcanic Material as Partial Replacement for Cement in Concrete".

5.2 Sources of Error

- **Sensitivity of strength testing machine**
  While performing the strength tests, some results became unrealistic due to excessively low strength. During these instances, the cube broke in a brittle manner and showed force and stress to be unrealistically high. It was particularly during the 3-day and the 7-day testing while testing the F50 mortars. This happened because the compressive strength machine was unable to handle such low strengths. The mortars with 50% filler are the weakest of the samples which explains why they broke during the compressive strength test. This caused some results to be outsourced which resulted in a less representative sample selection. The appendix contains figures illustrating the machine's readings during this case (Figure A.2, as well as the cube's behavior in Figure (A.1)). A solution for another study could be to use a different machine that is better adapted to cubes with low concrete percentages.

- **Outliers:**
  By applying the IQR (Interquartile range) method, outliers like the F50's unrealistic results are ignored to ensure the most representative results. Each test consisted of three cubes which is a small data pool, reducing the data pool may make the results less precise compared to the mixture's "true" compression strength. A larger data pool would create a normal distribution per mixture and is ideal for discovering the most accurate strength. The next study would therefore require more samples to be cast per mixture to consider the risk of outliers.

- **Imprecise molds for the concrete cubes:**
  During the casting of the concrete mixes two different types of molds were used. Preferably, standardized plastic molds were utilized for concrete casting. However, wooden molds had to be employed instead due to a shortage of plastic molds. The wooden molds were produced in the university workshop and demonstrated slightly asymmetrical sizes, differing approximately +-1 mm, which may have interfered with the result of the strength tests. The strength machine is designed for samples with sizes of 40x40 mm which is why asymmetrical mortars can give inaccurate results. This is a potential cause for the spread in strength performance from the different samples. The weight

of each cube produced with the wooden molds also differed by +- 8 grams compared to the plastic molds which usually only differed by a maximum of +- 4 grams. Detailed information on measurements and weights for each cast mortar can be found in appendix A.1. The process of removing the cubes from the wooden molds was challenging, which contributed to the formation of micro-cracks in the mortars and consequently reduced their strength performance. The cubes irregular sizes and micro-cracks could be an explanation as to why some mortars showed a significant spread in compressive strength. It could also be a cause of why VM15-LS5 performed worse in the 56-day strength test compared to the 28-day test.

- **Leaching of hydration phases into water during curing:**
  As the cubes were cured in a water bath there was a risk of calcium hydroxide leaching into the curing water [33, 25]. This could happen due to the size of the mortar cubes and their large surface area compared to their volume and could affect strength development. One solution to reduce leaching could be to cast bigger cubes, the surface area would then be smaller compared to its volume, which could decrease the risk of leaching.

- **Evaporation of water:**
  The water that enabled the hydration development evaporated in some extent from the water bath during the time between experiments. This was specially the case for 28 and 56 days. In these late ages, the cubes were consequently exposed to air on one side and dried. Lack of an uniform water exposure could have interfered with hydration development in that part of the cube and could have resulted in an altogether weaker sample than the optimal strength for that mixture.

5.3 Societal and ethical aspects

It is crucial to review the project's societal and ethical aspects. Modern society depends on OPC, with Swedish demands being up to 2,9 million tons of cement per year [54]. In Sweden, cement is mainly used for building materials, infrastructure, and water pipes. Concrete is irreplaceable, its durability and strength stays unmatched against any known materials which makes it a national societal interest. Due to OPCs huge environmental impact, more sustainable alternatives need to be researched.

This project is also attractive from a global perspective since it could promote environmental goals. The study specifically focuses on Icelandic volcanic materials, which differ from VMs found in other regions. With optimism, the results from this study can be locally applied for other VMs. With the goal of making concrete more sustainable, by using VMs as SCMs in replacement of OPC.

One concern is the environmental impact caused by transportation. OPC used in

Sweden is typically sourced from Gotland and shipped by boat and trucks. VM gathered from Grindavík, Iceland, indicates a longer transportation route by either boat or plane, as well as trucks. Even though Iceland is further from Sweden than Gotland, using Icelandic VMs could still provide a reduced environmental impact from a holistic standpoint, since the CO_2 emissions from OPCs production are much higher than from SCMs. It would be necessary to conduct a more thorough analysis of transportation methods and production emissions to ensure the most sustainable alternative.

The availability of other SCMs such as fly ash and slag is limited (since they are a by-product), and the demand is increasing for SCM materials. Additionally, access to these materials may decline in the future due to the transition to more sustainable energy and steel production. Therefore other SCMs, such as hyaloclastite, should be explored and researched to ensure a decreasing use of OPC. Although, it is worth noting that VM is a finite resource and accessibility to large quantities of hyaloclastite may be limited. If sufficient amounts of hyaloclastite can not be confirmed, the material can not be commercialized in the concrete industry due to the vast mass needed for production.

Another aspect that needs to be addressed is the mining of volcanic materials in Iceland, considering the unique and sensitive flora and fauna and the island's geological placement. Mining can therefore disturb plants, living species, and nearby villages. Additionally, Iceland's highly active volcanism might make it an unpredictable mining zone.

The results show that VM in concrete is advantageous which can result in an increased demand for Icelandic volcanic material. This should require an overall assessment of the ecological footprint, both ecosystems and surrounding environments. Volcanic material in concrete should result in a more environmentally friendly substitution for OPC. Therefore it should be extracted carefully with the surrounding environment in mind.

6

Conclusion

The study aimed to investigate to what extent SCMs could replace OPC, without altering the compressive strength of the concrete. The results show that 40% of OPC in concrete could be substituted with SCMs while maintaining a similar compressive strength to traditional OPC concrete after 28 days. Additionally, the study showed that a ratio of three parts VM and one part LS produced the best results, with the VM30-LS10 performing slightly below the reference mix at 28 days. It can be concluded that VM impacts strength performance positively when comparing the filler mixes. Therefore Icelandic hyaloclastite is suitable as an SCM.

The results show that blends with VM and LS have low strength on the third day. Slow development of strength in VM SCMs was expected according to previous research. On the 7th day, the VM-LS mixtures gained more strength than the filler correspondent, the added strength was likely due to the pozzolanic effect. Therefore VM recipes could be more suitable for prefabricated concrete structures where concrete has a longer time to cure, rather than cast-in-place concrete where early strength is more important.

The XRD- analysis concludes that the REF mix has a higher concentration of CSH, CH, and AFt- phases at the early stages of hydration compared to the VM mixtures. This explains why VM mixes perform worse during strength testing than REF at early stages. On the other hand, more AFm phases are developed for VM mixes over time, which explains their accelerating strength development before 28 days.

The basis for this study was the necessity to decrease the environmental impact of concrete, by finding a material with lower CO2 emission to replace OPC. On those terms, this study shows promising results with a replacement of 40% OPC to SCMs composed of 30% VM and 10% LS. However, a more in-depth investigation of the highest-performing VM-LS mixtures from the 28-day compressive strength test should be done. To not exclude the possibility of another mixture performing even better. To ensure homogenous mortars, future studies should utilize standardized plastic molds for casting the mortar cubes to minimize sources of errors.

Future research also involves examining:

- Scaling up of the use of VMs and LS to concrete in industrial applications
- Long-term durability effects of concrete made with combined VM and LS, against chlorides, carbonation, frost, sulphate attack, etc.
- Effect on the fresh state properties of concrete made with VMs and LS.

- Life cycle assessments of using VMs and LS in concrete

7

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A

Appendix 1

A.1 Results and measurements from compressive strength tests

Table A.1: Results from strength test after 3 days

Mixes	Area [cm^2]	Weight [g]	F_m [kN]	σ [N/mm^2]
Mix 1	-	-	54.11	33.82
	-	-	62.96	39.35
	-	-	71.59	44.75
Mix 2	3.4 x 3.4	141.9	44.58	27.86
	3.4 x 3.4	141.7	46.45	29.03
	4.45 x 3.5	145.6	47.45	29.66
Mix 3	3.4 x 3.45	148.7	56.51	35.32
	3.35 x 3.35	143.3	43.70	27.32
	3.4 x3.4	141.7	49.72	31.08
Mix 4	3.5 x 3.45	150.4	41.37	25.86
	3.5 x 3.5	157.0	32.67	20.42
	3.4 x 3.4	150.0	42.65	26.65
Mix 5	3.4 x 3.5	152.1	50.32	31.45
	3.4 x 3.4	153.8	42.51	26.57
	3.45 x 3.4	151.4	49.93	31.20
Mix 6	-	-	50.67	31.67
	-	-	50.81	31.76
	-	-	48.93	30.58
Mix 7	-	-	51.40	32.12
	-	-	55.27	34.55
	-	-	51.76	32.35
Mix 8	3.3 x 3.45	159.0	41.56	25.98
	3.4 x 3.5	159.9	37.71	23.57
	3.4 x 3.4	152.4	36.91	23.07
Mix 9	3.4 x 3.4	148.5	-	-
	3.4 x 3.35	147.7	25.33	15.83
	3.4 x 3.4	147.6	-	-

Table A.2: Results from strength test after 7 days

Mixes	Area [cm^2]	Weight [g]	F_m [kN]	σ [N/mm^2]
Mix 1	-	-	71.46	44.66
	-	-	80.60	50.37
	-	-	79.94	49.96
Mix 2	3.8 x 3.8	142.9	57.65	36.03
	4.0 x 4.1	144	57.91	36.19
	4.0 x 4.0	144.7	56.58	35.36
Mix 3	4.0 x 4.1	146.6	67.2	42.00
	4.0 x 4.1	149.4	64.14	42.09
	4.0 x 4.0	143.6	64.89	40.55
Mix 4	4.05 x 4.05	148	50.97	31.86
	4.1 x 4.1	152	46.14	28.84
	4.1 x 4.1	153	49.83	31.15
Mix 5	4.1 x 4.1	152	62.3	38.94
	4.05 x 4.1	150	57.14	35.70
	4.2 x 4.1	155	56.00	35.03
Mix 6	-	-	57.53	35.96
	-	-	60.34	37.71
	-	-	59.62	30.26
Mix 7	-	-	65.39	40.87
	-	-	66.63	41.64
	-	-	65.84	41.15
Mix 8	3.9 x 4.1	151	42.25	26.41
	4.1 x 4.2	154	35.43	22.14
	4.1 x 4.2	165	40.30	25.18
Mix 9	4.1 x 4.1	152	-	-
	4.1 x 4.1	147	24.63	15.39
	3.8 x 4.1	150	26.18	16.36

Table A.3: Results from strength test after 28 days

Mixes	Area [cm^2]	Weight [g]	F_m [kN]	σ [N/mm^2]
Mix 1	-	-	84.52	52.83
	-	-	84.28	52.68
	-	-	67.82	42.39
Mix 2	3.8 x 3.8	144.6	73.30	45.80
	3.8 x 3.8	146.0	77.12	48.20
	3.8 x 3.8	142.0	69.43	43.39
Mix 3	3.8 x 3.8	147.7	85.06	53.16
	3.9 x 3.9	149.0	75.13	46.96
	3.8 x 3.8	143.0	77.33	48.33
Mix 4	4.0 x 4.0	150.7	54.11	40.07
	3.8 x 3.9	150.0	67.06	41.91
	3.9 x 3.9	154.0	63.00	39.38
Mix 5	3.8 x 4.0	151.3	76.06	47.54
	4.0 x 3.9	155.4	75.60	81.26
	3.9 x 4.0	156.6	81.26	50.78
Mix 6	-	-	68.45	42.78
	-	-	65.25	40.78
	-	-	63.39	39.62
Mix 7	-	-	74.86	46.79
	-	-	46.07	28.79
	-	-	74.73	46.71
Mix 8	3.9 x 3.9	153.5	39.12	24.45
	3.9 x 4.0	157.6	56.76	35.47
	3.8 x 3.9	150.9	59.49	37.18
Mix 9	3.7 x 3.9	142.0	37.07	23.17
	3.9 x 3.7	144.3	32.66	20.41
	3.8 x 3.9	150.8	33.64	21.02

Table A.4: Results from strength test after 56 days

Mixes	Area [cm^2]	Weight [g]	F_m [kN]	σ [N/mm^2]
Mix 1	3.9 x 3.9	153.3	82.76	51.72
	3.9 x 4.0	150.8	100.22	62.64
	3.9 x 3.95	156.6	98.84	61.77
Mix 2	3.8 x 3.9	142.8	75.53	47.21
	3.8 x 4.1	147.2	73.21	45.75
	3.8 x 3.9	145.8	80.91	50.87
Mix 3	3.8 x 3.8	145.2	86.65	54.15
	3.8 x 4.0	153.4	91.04	56.90
	3.8 x 3.8	144.7	89.54	55.96
Mix 4	3.9 x 3.9	150.8	66.53	41.58
	3.8 x 3.9	149.2	54.48	34.05
	3.8 x 3.9	146.9	63.82	39.89
Mix 5	3.9 x 3.9	156.6	78.92	49.32
	4.1 x 3.9	154.8	65.26	40.79
	3.9 x 3.9	160.3	63.38	39.61
Mix 6	3.8 x 3.85	146.9	68.94	43.08
	4.0 x 3.8	146.5	69.82	43.64
	3.8 x 3.8	142.0	65.49	40.93
Mix 7	3.8 x 3.8	144.5	79.82	49.89
	3.8 x 3.8	146.3	73.05	45.65
	3.8 x 3.8	139.8	76.09	47.55
Mix 8	3.9 x 3.9	156.0	55.55	34.72
	3.9 x 3.9	156.0	45.19	28.24
	3.8 x 3.9	154.9	52.27	32.62
Mix 9	3.9 x 3.9	153.0	38.87	24.29
	3.8 x 3.9	148.9	36.17	22.61
	3.8 x 3.9	147.2	31.88	19.92

A.2 Sensitivity of strength testing machine and failure of F50 mortars

Figure A.1: Broken, F50 mortar

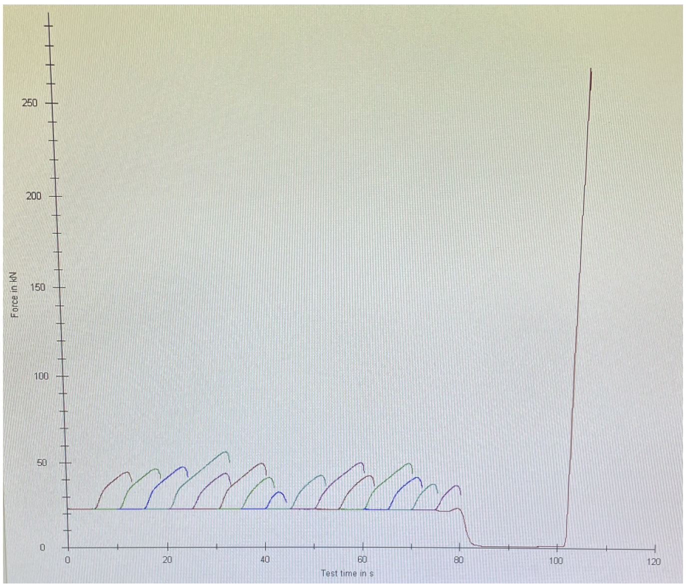

Figure A.2: Graph of strength being unrealistically high for F50 mortar

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