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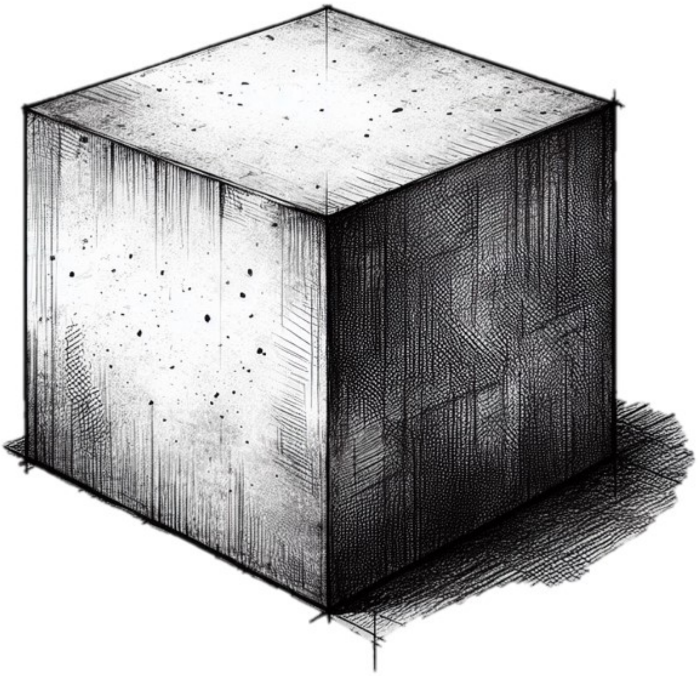

From Eruption to Construction - Part A

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

ACEX11-24-11 Bachelor Thesis

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DEPARTMENT OF ARCHITECTURE AND CIVIL ENGINEERING
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2024
www.chalmers.se

Bachelor Thesis 2024

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Effects of volcanic material from Grindavik, Iceland, on the compressive strength of concrete
Investigative report
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Abstract

Reducing the CO_2 emissions during cement production is of utmost importance when it comes to combating the climate impact of the construction industry. Volcanic material (VM) has garnered a lot of attention due to its capability to function as a supplementary cementitious material (SCM) and its pozzolanic properties. Utilizing VM instead of cement in concrete has shown great potential when it comes to reducing environmental impact. This thesis examines the use of VM from Grindavik, Iceland, as an SCM. The methodology includes testing the reactivity of the VM through an MR^3 test, measuring the compressive strength of the mortar, and examining the crystalline structure of different hydration phases using XRD. The mortar containing VM is compared to a reference sample containing only ordinary Portland cement (OPC), to determine the effects of the VM on the mortar. The results show that the VM has high reactivity in comparison to other natural pozzolans, and mortar containing the VM has high compressive strength. Replacing 40% of cement with VM in mortar gave the highest compressive strength, even surpassing pure OPC. To determine if the VM is suitable as an SCM further research needs to be done. Studying the hydration phases through a scanning electron microscopy (SEM), measuring tensile and flexural strength, as well as durability and workability, would provide further insight into the applicability of VM from Grindavik in concrete. In conclusion, the findings from this study show promising results when it comes to utilizing VM from Grindavik in concrete.

Keywords: Supplementary Cementitious Material, SCM, Volcanic material, VM, Concrete, Compressive strength, Environmental, XRD, Reactivity, MR3

Acknowledgements

First and foremost we would like to thank our supervisor Sahar for her great interest in this thesis, and for answering our every question enthusiastically. Many thanks to our examiner Arezou for your useful insights, and for helping greatly throughout this thesis.

We would also like to thank our co-supervisor Amrita for taking the extra time out of her schedule to help us, although you had a lot on your hands. Thank you Bruno for your assistance in the lab and supportive attitude, and group B for great collaboration.

Furthermore, we extend our gratitude to the following people for their contributions: Thomas Betong for supplying the volcanic material, Nordkalk for providing the limestone, Anders Karlsson for the stregth test instructions, Sebastian Amfeldt for the lab instructions and more, and finally the Chalmers library for giving excellent constructive criticism and helping us structure our thesis.

List of Acronyms

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

LS	Limestone
MR3	Modified R3
OPC	Ordinary Portland Cement
PA	Pozzolanic Activity
R3	Rapid, robust and relevant
SCM	Supplementary Cementitious Materials
VM	Volcanic Material
XRD	X-Ray Diffraction

Contents

List of Figures

List of Tables

1

Introduction

Concrete being the second most used material in existence, topped solely by water, only works thanks to the wonders of cement [1]. When cement was discovered, it was easier to make, cheaper than any other alternative, and more reliable than other binders. This has led to excessive consumption and an overdependence on cement. The extensive use of Portland cement has resulted in negative environmental impacts. The production of cement is highly detrimental to the climate, and is considered a key driver of climate change by being responsible for 5% to 7% of global CO_2 emissions [2]. In turn, two-thirds of the cement production emissions stem from the burning of limestone, and the remaining third from the use of fossil fuels. In Sweden, 90% of the cement used is produced domestically.

In order to reduce the environmental impact of cement, part of the cement can be replaced with a more environmentally friendly material. This type of material is called supplementary cementitious material (SCM). The usage of SCMs in concrete is already established worldwide. Some of the most common SCMs are fly ash and blast-furnace slag, bi-products from electricity- and steel production [3]. The availability of industrial bi-products are limited and are expected to decline even more due to future developments in steel- and electricity production [2]. Consequently, there is a demand for new SCMs .

A category of SCMs that could prove useful are volcanic materials (VM). Volcanic materials have been used instead of cement since ancient times, because of their pozzolanic properties. The Romans are well known for having used volcanic material, with the most famous example being the Pantheon, which is still standing today [2]. There are many benefits to using VMs, such as significantly reducing CO_2 emissions, decreasing cost, and enhancing the durability and mechanical properties of concrete [4]. With regard to transportation emissions, a reasonable source of volcanic material would be from Iceland, wherein Grindavik is the source of the VM for this thesis.

Toward assessing the viability of VM from Grindavik as an SCM, the prime characteristic is its effect on compressive strength over time. This thesis will firstly investigate the reactivity of VM from Grindavik, to assess its potential for strength. Secondly, measure the compressive strength of mortar samples with differing amounts of VM in set time intervals during the curing process. Lastly, analyse the chemical composition of the same VM cement mixes in order to correlate the samples' strength with their corresponding chemical composition. Theses steps, as well as demarcations, will be further explored in the sections below.

1.1 Purpose and Research Questions

The thesis aims to initialize an investigation into how VM from Grindavik, Iceland, functions as an SCM. To accomplish this, three research questions listed below will be addressed:

i. What is the reactivity rate of the volcanic material?
ii. How much cement can be substituted with volcanic materials while maintaining adequate strength?
iii. Which hydration phases are formed at different times and how do they relate to the compressive strength?

1.2 Scope and Demarcations

The scope of this thesis is limited to only investigating volcanic materials sourced from Grindavik, Iceland. This choice stems from the availability of Icelandic VM, which will make it applicable for widespread usage in the industry. The proximity to Sweden, relative to other countries with VM, results in reduced transportation.

Another limitation is that the substitution of cement will be limited to a maximum of 50 %. This restriction has been established based on other studies that indicated the upper limit for incorporating VM in concrete is typically within the range of 30-40% [5]. A test with a 50% replacement ratio will be conducted to investigate this claim.

The reactivity of the VM will be tested with an MR^3 test. The ability of VM as an SCM will be evaluated on macroscale through compressive strength and on microscale through XRD. The compressive strength and the XRD results will be compared against a reference sample containing no substitutions.

2

Background

This chapter aims to give the reader a background to the most central parts of the study's scope and purpose. First, a brief description of cement production and its central chemistry, followed by an introduction to SCM and VM, and lastly, a description of testing methods.

2.1 Cementitious Binder

A cementitious binder is a material that can bind together particles or materials through physical and chemical processes. There are several different kinds of binders, with some of the most common types being OPC, fly ash, and different kinds of clay. The binder is usually mixed with aggregate, sand, and water to create a strong construction material.

2.1.1 Cement

Cement is a binder in concrete. The most common type of cement requires hydration to harden, thus called hydraulic cement, with OPC being the most common example. Many other types of cement exist but will not be discussed in this thesis. Besides a small amount of gypsum ($CaSO_4 \cdot 2H_2O$) added at the very end of production, OPC is predominantly comprised of clinker, which is made by combining clay and limestone at high temperatures. Firstly, the clay and limestone are ground and mixed followed by a process called calcination, which is performed in special cement kilns [6].

The calcination process entails heating the mixture to about 900°C [7]. Under such conditions the limestone releases large amounts of CO_2, forming a substance known as quicklime or burnt lime. This crucial step is the primary source of CO_2 emission from OPC, resulting in about 0.5 kg of carbon dioxide per kg of finished cement, or about 65% of the total amount released from the entire production chain [8][9][6].

Next the temperature is increased further to between 1400-1500°C [7]. Here multiple complicated reactions take place, some of which are yet to be completely understood. The product of this step is called Portland clinker, a gravel-like amalgamation of many chemical compounds, the primary elements of which are silicon and calcium, with some iron and aluminium as well.

The most important chemical compounds are shown in table 2.1 using Cement Chemists Notation (CCN) and chemical formulas:

Table 2.1: The chemical formula of the four main mineral phases of Portland.

Name	**CCN**	**Chemical formula**
Alite	C_3S	$3CaO \cdot SiO_2$
Belite	C_2S	$2CaO \cdot SiO_2$
Tricalcium aluminate	C_3A	$3CaO \cdot Al_2O_3$
Brownmillerite	C_4AF	$4CaO \cdot Al_2O_3 \cdot Fe_2O_3$

Finally, the clinker is cooled and pulverized with about 3% gypsum by weight in order to lower the initial reaction rate [1][6].

2.1.1.1 Hydration

A vital step to the use of hydraulic cement is the mixing, and further reaction, with water. The following reactions are formally referred to as cement hydration, also known as curing.

Hydration is composed of many complex chemical reactions, each affecting one another and further increasing the complexity of the topic. Therefore only the main reactions will be recorded here. Initiating the hydration, commencing the moment water is mixed with cement, the tricalcium aluminate and the gypsum present in the cement react with water to form a compound colloquially known as ettringite as well as some heat. The immediate result is a slight gelification of the cement mixture, somewhat decreasing viscosity. The gypsum acts as a delaying agent preventing the tricalcium aluminate from forming stronger, harder compounds, known as flash setting, which would aggravate the pouring of the concrete. Once all the gypsum has reacted as seen in reaction 2.1 the remaining tricalcium silicate hydrates with the ettringite to form the much harder substance; monosulfate aluminate hydrate, contributing moderately to the early strength of the mixture [6] [10]

$$C_3A + 2CSH_2 + 27H \rightarrow C_6AS_3 \cdot 31H \tag{2.1}$$

Next, over a couple of hours to days, depending on the exact mixture, tricalcium silicate begins its hydration process, contributing greatly to the initial strength of the concrete. Its reaction can be seen in equation 2.2 [11].

$$C_3A + 5.2H \rightarrow 1.2CH + CSH \tag{2.2}$$

Lastly, the dicalcium silicate hydrates, although much slower than tricalcium silicate. Also producing calcium silicate hydrate crystals, the belite hydration contributes greatly to later strength, seen in equation 2.3 [6]:

$$C_2S + 4H \rightarrow C_3S_2H_3 + CH \tag{2.3}$$

2.1.2 Supplementary Cementitious Material - SCM

Supplementary cementitious material (SCM) is a material that has pozzolanic or hydraulic behavior. According to ASTM C618 [12], the definition of a pozzolan is a siliceous, or siliceous and aluminous material, that will have a chemical reaction with calcium hydroxide when in contact with moisture to create a material with cementitious properties.

SCMs can be divided into two different categories; natural and artificial SCMs. Natural SCMs are defined as SCMs that can be used in their naturally occurring form, without any alterations. The only processes they will usually go through are sieving and grinding. Common types of natural SCMs are pyroclastic and sedimentary rocks. Artificial SCMs can be intentionally manufactured or can be acquired as by-products from high-temperature processes, including fly ashes, silica fume, or blast furnace slags. A decrease in production of artificial SCMs is however expected because of developments in electricity and steel production. Furthermore, many of the local sources for natural SCMs have been fully exploited [2].

SCMs are extensively used today in cement. Usage of SCMs can lead to a considerable reduction in CO_2 emissions per ton of cementitious materials [3]. Because of this, utilization of SCMs is an important part of reducing the environmental impact of the construction sector.

2.1.3 Volcanic Material

A large portion of the SCMs used today are of volcanic origin. Historically, VM is one of the oldest cementitious materials and has been used, with a combination of limestone, by the Romans to build the Colosseum and Pantheon [5]. After almost 2000 years, the buildings still stand stable and intact, demonstrating their strength and durability.

Volcanic materials are a type of natural SCM. When it comes to SCMs, VMs are of special interest because they exist in large quantities in many different regions. VMs possess pozzolanic potential, but not all VMs have the same pozzolanic potential. VMs that generate through explosive eruptions have higher pozzolanic activity due to their high glass content and porous nature. Glass is the prime pozzolanically active component in VM. These types of VMs are found in more recently active volcanoes. This is interesting to consider when choosing which volcanic area to harvest VM from [2].

This is far from the first study done on VM as an SCM. Previous studies have demonstrated interesting and partly positive outcomes [4]. Studies have shown that VM can substitute OPC up to 30-40%, but unfortunately, this concrete exhibited lesser qualities in the earlier stages of curing [5]. Another study showed positive qualities that concrete containing VM has good resistance to saltwater and thus is viable for underwater construction. However, since VMs exhibit varying properties depending on their source, it is necessary to examine all potential VMs that one intends to utilize [4]. The specific VM from Grindavik, Iceland, used in this thesis has never been investigated as an SCM.

Volcanic activity has been and continues to be common in Iceland, therefore the availability of VM is abundant. Volcanic eruptions have several negative effects on the environment, both global and local. The primary effects cannot be avoided, but collection of VM can prevent secondary effects. The volcanic ash can easily be spread by the earth's systems, resulting in contaminated water and soil [5]. Since about 9% of the world population is estimated to live within a 100 km radius of an active or historically active volcano it is important to secure the quality of the local resources. Therefore, collection of VM positively affects the local environment. Additionally, if VM is a possible SCM it would be a strong incentive for public and private companies to collect it, which as discussed would improve the local environment. As mentioned in the previous chapter, SCM, replacing cement also positively affects the environment at a global scale.

2.2 Pozzolanic Activity

When considering VM usage as an SCM, pozzolanic activity (PA), needs to be taken into consideration. PA is the reaction during the mortar mixing, hydration, and curing phases where calcium hydroxide ($Ca(OH)_2$) , aluminum oxides (Al_2O_3), and iron oxides (Fe_2O_3), react, in conjunction with water (H_2O), to form calcium-silica-hydrates (CSH), and calcium-alumina-silica-hydrates (CASH) [13]. CSH and CASH are mainly responsible for the mortars compressive strength and are thus of high importance when evaluating different natural pozzolanic materials to be used as SCMs [14].

During the three phases mentioned above, the pozzolanic reaction that occurs can be written as seen in equation (2.4) [15]:

$$xCa(OH)_2+yAl_2O_3\cdot zSiO_2+(n-x)H_2O \rightarrow (CaO)_x\cdot(SiO_2)_x\cdot(Al_2O_3)_y\cdot(H_2O)_{(n-x)} \quad (2.4)$$

Calcium hydroxide, aluminum oxide, and iron oxide react when in contact with water to form the silicates.

These compounds are present in volcanic materials and form a foundation for its usage as an SCM. To increase the pozzolanic activity, the specific surface can be increased through grinding. Grinding also leads to surface defects which has a positive effect on PA [2].

2.3 Testing Methods

2.3.1 Reactivity Test

Reactivity refers to a material's ability to chemically react with other substances. One of the methods for assessing the reactivity of an SCM is by measuring the heat released in [J/g]. For a material to be considered as a conceivable SCM, one of the most crucial characteristics is the reactivity. The exothermic reactivity estimates the rate of reaction of the binders to form cementitious materials, which in turn is an indicator of the mortar strength and durability [16].

The MR^3-test is used to measure the heat generated by a cementitious binder or SCM, and in doing so gives an estimate of the binders rate of reaction in creating cementitious materials [17]. The reactivity can generally be divided into four levels depending on the heat release as seen in table 2.2 [18], but may vary depending on the exact composition and classification of pozzolan. Natural pozzolans have a average heat release between 50-350 [J/g] of SCM when tested as conventional SCMs [19]. Highly reactive pozzolanic materials are a general indicator if a sample, with a partial replacement of a reactive SCM, can achieve similar or increased compressive strength in comparison to a reference sample [19]. This is generally due to higher weight percentages of oxides in the VM, such as SiO_2, Al_2O_3, Fe_2O_3 and CaO. Factors such as particle size, surface area as a partial dependent of particle porosity, also affect the SCMs reactivity.

Table 2.2: Division of general SCM reactivity levels depending on heat released during test duration in [J/g] of SCM.

[J/g] of SCM	Classification
< 100	Non-reactive
100-200	Slowly reactive
200-600	Moderately reactive
> 600	Highly reactive

To ensure a proper testing environment an isothermal calorimetry machine should be used. The machine tightly controls the environmental temperature, even when the samples emits heat, and measures the heat release from each of the samples. To function properly, the total weight of the samples must be known and the sample containers must be clean to prevent external factors influencing the machine. Mimicking the ions naturally available when mixing cement is achieved by adding a weak potassium-hydroxide solution (KOH) to the solid SCM and calcium hydroxide $Ca(OH)_2$ mix. To further reduce variables influencing heat release the samples do not contain any cement to isolate the heat given off by the SCM. This in turn aims to create a reliable test environment for accurate readings of the SCMs pozzolanic activity.

An alternative to the MR^3 is the industry standard R^3-test. In the cement industry the R^3-test is outlined in the ASTM C1897-20 to be reliable, but more labour intensive than the MR^3, making it a viable alternative if reasonable reliability can guarantee valid data from the test [20]. However, the higher temperature and longer duration of the MR^3 make it more suitable for SCMs with slower reactivity, and it also reflects long-term properties more accurately than the R^3 test [16].

2.3.2 Compressive Strength

The compressive strength of concrete is one of its most important attributes and depends on several different variables and factors, such as porosity, hydration strength, and the strength of the aggregate. Compressive strength measures the material's ability to withstand vertical load without crushing or deforming. Additionally, compressive strength correlates with other strength parameters, such as tensile and flexural strength, both of which are essential for construction [21].

The compressive strength occurs during the curing time and it is determined that 99.99 % of the concrete is completely cured after 28 days when cured underwater [22]. Therefore, 28 days is commonly used when specifying compressive strength, although the strength increases over time. However, other studies indicate that reactivity is slower with the addition of SCM, which may lead to delayed development of strength [4]. When testing SCMs, a compressive strength test is usually done at 56 days to ensure that the concrete is completely cured.

The standard SS-EN-196-1 "Methods of testing cement - Part:1 Determination of strength," established by The Swedish Standard Institute [23], includes a chapter outlining the procedure for determining compressive strength. The used machine should provide a rate of load that increases with 2400 ± 200 [N/s] and be equipped with an indicating device that saves the value for when the specimen reaches failure. Moreover, the standard specifies that the test should be conducted on at least three specimens in order to calculate an average value.

2.3.3 X-ray Diffraction - XRD

Different hydration analyses could be used to define all the hydration phases that cement pastes could go through, such as X-ray powder diffraction (XRD), thermogravimetric (TGA), and scanning electron microscopy (SEM). XRD is a powerful technique for identifying and determining the crystal phases and their characteristics that are present in the pastes of hydrationbinder systems. This technique involves the use of an X-ray diffractometer platform, which targets powdered samples with X-rays. As the samples are targeted, the electrons within the samples' atoms then diffract the X-ray energy back, with the resulting pattern being recorded by a detector.

XRD can be used to identify the hydrationphases in cement pastes. As the cement paste reacts with water, a hydration reaction occurs, resulting in the formation of various new hydrationphases, mainly portlandite (CH), tobermorite (CSH), ettringite (AFt), calcite, and hemi-mono-carbonate (AFm). These phases are generally strongly ordered crystalline phases that produce visible diffraction peaks.

3

Materials and Methods

The reactivity and compressive strength were examined through an empirical study to assess the applicability of VM from Grindavik as an SCM. To address the research questions, three analyses were employed, which include MR^3, compressive strength, and X-ray diffraction.

In this chapter, firstly, the specific material data are presented followed by a brief description of the methodology, and lastly a more detailed description of the three testing methods used.

3.1 Specific Material Data

The material used in the mixtures in this study was OPC "CEM I 52.5", limestone "LIMUS-15", sand "Cen-norm sand din EN 196-1" and VM from Grindavik, Iceland. The 52.5 in "CEM I 52.5" refers to the expected compressive strength in [MPa] of the concrete produced with it . In table 3.1 the material data of the VM, OPC and LS used are specified.

Table 3.1: Material data of OPC, VM and LS

Property	**OPC Weight** [%]	**VM Weight** [%]	**LS Weight** [%]
Na_2O	0,27	2,2	0,1
SiO_2	19,6	44,1	9
Al_2O_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	-

Table 3.1 shows that VM in comparison with OPC contains higher percentages of sodium oxide (Na_2O), silica (Si_2O), aluminum oxide (Al_2O_3), ferric oxide (Fe_2O_3), and magnesium oxide (MgO). It also contains titanium-dioxide (TiO_2), which OPC does not. The OPC contains larger amounts of calcium-oxide (CaO), also know as quick- or burntlime.

As stipulated in ASTM C618-03 the percentage of silica, aluminum oxide, and ferric oxide in natural pozzolan should exceed 70% to be used as an SCM. This VM has the percentage of 71.5%, and thus it can be used according to the standard [12].

The surface area of particles and the average size of particles, know as BET and D50 respectively, is specified in table 3.2.

Table 3.2: BET and D50 of OPC, VM and LS

Property	**OPC**	**VM**	**LS**
BET	-	2,2	-
D50 (µm)	20	3,1	8

The volcanic material has been subjected to industrial grinding to attain the particle size mentioned in table 3.2. In addition to grinding, the volcanic material has remained untreated. The average particle size of OPC is larger and this points to the total surface area of the VM being larger than that of OPC.

3.1.1 Limestone as Filler

Limestone is mainly sedimentary rocks that are rich in calcium carbonate ($CaCO_3$) in the form of calcite [24]. Research has shown that ground LS, due to its fine texture and relatively low reactivity, acts as a filler when added to the mortar. However, LS has various properties that make it a valuable addition to mortar mixes, such as enhancing the durability of concrete by reducing the likelihood of cracks and increasing overall strength. Moreover, its fine texture helps fill the pores of the concrete, resulting in a denser microstructure and greater resistance to cracking [25].

Several research papers show that processed LS is mostly inert with a cement binder, but it also has been proved that ground LS can react with the high alumina (Al_2O_3) contents present in SCMs. This can then produce hydration phases such as AFm, which would provide the mix with better durability and strength [25] [26].

3.2 Method

To observe the impact of VM, an equivalent percentage of cement was replaced with a filler material, in this case LS and one reference mix without SCM. This resulted in nine different mix designs, table 3.3.

Table 3.3: Mix designs

Type of mix	Replacement [%]	OPC	VM	Filler	W/b
Reference	0%	100%	x	x	0.5
Filler	15%	85%	x	15%	0.5
	30%	70%	x	30%	0.5
	40%	60%	x	40%	0.5
	50%	50%	x	50%	0.5
VM	15%	85%	15%	x	0.5
	30%	70%	30%	x	0.5
	40%	60%	40%	x	0.5
	50%	50%	50%	x	0.5

These mix designs will be used for the compressive strength test and the XRD.

3.2.1 Reactivity Test - MR^3

The MR^3-test began by adding solid calcium-hydroxide, ($Ca(OH)_2$), and SCM in the form of VM, with a ratio of 3:1, calcium hydroxide to SCM. To ensure proper measurements, a high-precision scale was used since the small sample sizes demand more accurate measurements. After the two solids were added, according to the ratios mentioned above, liquid potassium-hydroxide solution 0.5 [M] was added with a liquid-to-solid ratio of 0.9:1. The samples were thoroughly mixed using a vibrational mixer, model Vib2, for two minutes at maximum frequency. Then promptly set into the calorimeter, Model I-Cal Flex, for 10 days at 50°C since the reaction starting immediately when in contact with liquid. This method was repeated for all the samples as seen in table 3.4.

Table 3.4: Reactivity samples 1, 2, and 3, with components in grams

Mix	$Ca(OH)_2$	VM	KOH 0.5[M]
1	2.985	1.024	3.70
2	2.986	0.993	3.60
3	3.002	0.998	3.62

In total, three samples were prepared to enable an average to be taken and ensure that individual inaccurate results were accounted for. For the duration of the test the heat given off by the samples' were continuously measured to assure that the variations in reaction rate were observed from beginning to end.

3.2.2 Compressive Strength Test

To determine the strength of the sample, the standard SS-EN 196-1:2016 "Methods of testing cement - Part: 1 Determination of strength" was used [23]. According to this standard, the proportions were calculated, presented in table 3.5 - 3.6

Table 3.5: The exact contents of the mix, reference, and filler.

Batch		**OPC**	**SCM**	**Filler**	**Sand**	**w/b**
Ref	%	100%	x	x	1:03	0.5
	g	450	0	0	1350±5	225±1
Filler 15%	%	85%	x	15%	1:03	0.5
	g	382.5	0	67.5	1350±5	225±1
Filler 30%	%	70%	x	30%	1:03	0.5
	g	315	0	135	1350±5	225±1
Filler 40%	%	60%	x	40%	1:03	0.5
	g	270	0	180	1350±5	225±1
Filler 50%	%	50%	x	50%	1:03	0.5
	g	225	0	225	1350±5	225±1

Table 3.6: The exact contents of the mix VM.

Batch		**OPC**	**SCM**	**Filler**	**Sand**	**w/b**
Ref	%	100%	x	x	1:03	0.5
	g	450	0	0	1350±5	225±1
Filler 15%	%	85%	15%	x	1:03	0.5
	g	382.5	67.5	0	1350±5	225±1
Filler 30%	%	70%	30%	x	1:03	0.5
	g	315	135	0	1350±5	225±1
Filler 40%	%	60%	40%	x	1:03	0.5
	g	270	180	0	1350±5	225±1
Filler 50%	%	50%	50%	x	1:03	0.5
	g	225	225	0	1350±5	225±1

The method for casting the samples follows the same standard, SS-EN 196-1:2016 [23]. All materials were weighed and mixed using the standardized mixer "Auto-Mortar Mixer", supplied by Nycander AB. The used molds had the dimensions 40x40x40 [mm] and were prepared with oil to simplify demolding. The filled molds were vibrated to remove any air bubbles, and when necessary, the molds were filled up with additional cement mix to achieve a smooth surface.

To restrict plastic shrinkage, a phenomenon where water evaporates from fresh concrete and negatively affects the hydration process, the mortar is covered in plastic until demolding [27]. After 24 hours the mortar was demolded and put in water to cure until the predetermined time of the compressive strength tests. By allowing the mortar to cure in water it is enabled to hydrate and build up strength [21]. At the predetermined time of the compressive strength test, the samples were weighed and measured to correlate potentially divergent results with respective divergent measures or weights. The samples were placed with the two smoothest surfaces sides facing upwards and downwards in the machine. The machine "Toni Technik" uses constant velocity and stops automatically when the first crack occurs. Since the machine is preset to the sample dimension 40x40 [mm] it automatically recalculated the speed to pressure in [MPa].

The reference batch failed, however, therefore the compressive data from Part B of this thesis was used instead. The obtained results were documented and the unprocessed data is presented in Appendix A.

3.2.3 X-ray Diffraction

XRD was used because it helps identify the intensity of the different hydration phases, and how the intensities change with different amounts of VM and filler added. In this way, it would be possible to identify properties for different hydration phases.

To conduct the XRD test, samples were prepared by mixing paste consisting of cement, water, and either VM or filler. The proportion of the paste was calculated with the water-solid ratio of 0.5, presented in table 3.7 - 3.8

Table 3.7: Reference and filler paste recipe

Batch		OPC	SCM	Filler	w/b
Ref	%	100	x	x	0.5
	g	150	0	0	75
Filler 15%	%	85	x	15	0.5
	g	127.5	0	22.5	75
Filler 30%	%	70	x	30	0.5
	g	105	0	45	75
Filler 40%	%	60	x	40	0.5
	g	90	0	60	75
Filler 50%	%	50%	x	50%	0.5
	g	75	0	75	75

Table 3.8: VM paste recipe

Batch		OPC	SCM	Filler	w/b
Ref	%	100	x	x	0.5
	g	150	0	0	75
Filler 15%	%	85	15	x	0.5
	g	127.5	45	0	75
Filler 30%	%	70	30	x	0.5
	g	105	45	0	75
Filler 40%	%	60	40	x	0.5
	g	90	60	0	75
Filler 50%	%	50	50	x	0.5
	g	75	75	0	75

First, all the material was mixed with Bosch ergo mix 600 [W] for two minutes into a paste. Afterward, the paste was cast in tubes of 30 [mm] in diameter, to then be compacted with a vibrating table. Lastly, the sample was rotated for 24 hours to ensure a homogeneous paste and then stored at 20°C until the testing age.

To connect the XRD with the compressive strength, the cement hydration was stopped at the same ages, 3-,7-,28-, and 56 days. There are several hydration stoppage methods, stopping the hydration means removing the free water in the capillary pores. In this thesis, a method with solved exchange with isopropanol was used [28]. At the right age for the hydration stoppage, a two centimeter thick disc was cut off from the tube and divided into two halves. One of the two was crushed into smaller pieces to facilitate the hydration stoppage, the other piece was saved for further research.

The samples were stored in isopropanol, with greater than 99.5% 2-propanol, for seven days with daily change of isopropanol to ensure accurate exchange between the alcohol and the water. After seven days the sample was dried in a oven for 24 hours at 30 °C to then be stored in a vacuum-sealed desiccator.

The last step before the XRD was to manually grind the samples with a mortar and pestle. The ground samples were strained to obtain a particle size below 75 [nm]. The mortar and pestle were cleaned with sandpaper and isopropanol and the strainer was cleaned with compressed air to minimize contamination between the samples. At the time for the XRD the grounded samples were placed evenly on the specimen holders for the XRD machine. The XRD was conducted on BrukerD8 Discover in the 2theta range 5-60°, with step size of 0.02°, and 0.8 seconds per step.

The results for the diffraction file from the XRD were analyzed with the software DFFRACE.EVA. The hydration phases were identified using the codes in table 3.9

Table 3.9: The hydrationphases that were examined in the XRD tests and their respective COD (Crystallography Open Database)

hydrationPhases	**COD**
CH	1001768
CSH	9002245
Ettringite	9012922
Calcite	9016706
Quarts	1011097
AFm	2105252

4

Results

The following chapter contain the results from the modified R^3-test, the compressive strength test, and the XRD test.

4.1 Reactivity Test

The average result of three samples of the determined VM reactivity shown in [J/g] of VM over the 10-day test duration is compiled in figure 4.1 . The data was acquired using sample composition and amounts as seen in table 3.4.

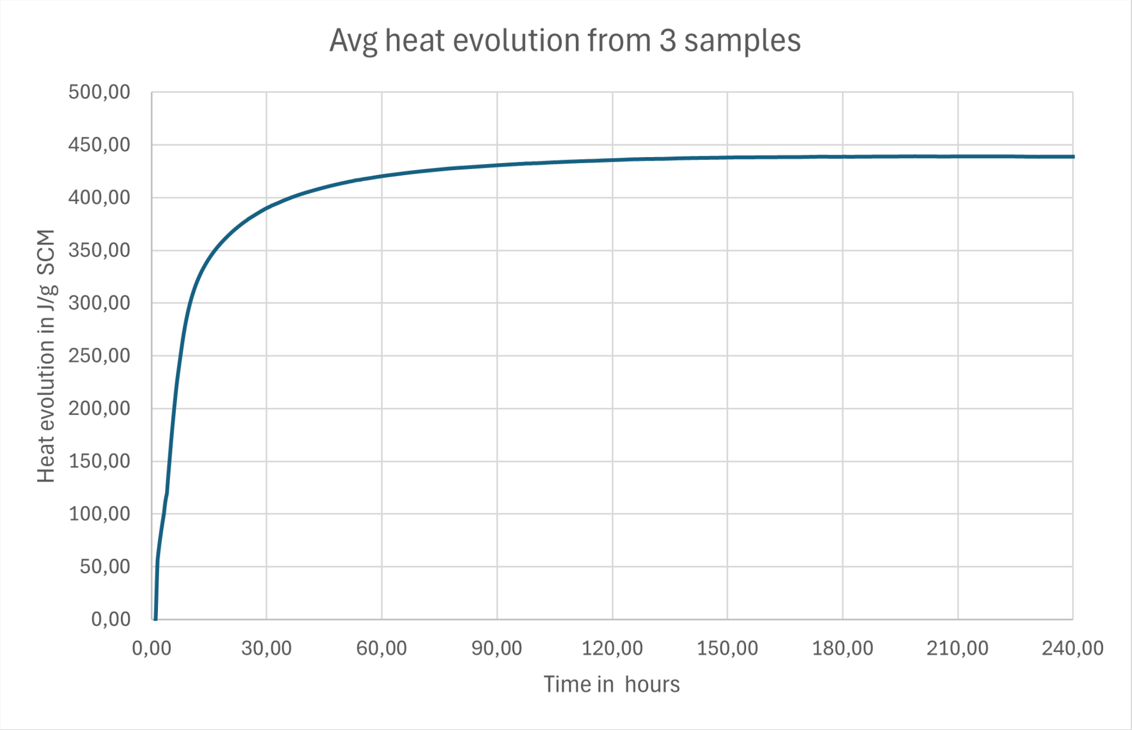


Figure 4.1: Average total heat release of three VM samples in [J/g] of SCM over the 10-day test duration

The test shows a stabilizing of the total heat evolution at approximately 150 hours, with the data indicating a final heat evolution of 439 [J/g] of SCM at the end of the 240-hour test duration, as observed in figure 4.1.

4.2 Compressive Strength

The average results of the compressive strength tests, of three samples per mix, are shown in table 4.1. For the complete experimental data see Appendix A.

Table 4.1: The compressive strength in [MPa] of the samples with different amounts of VM and filler substitutions after 3 to 56 days

Type of mix	**Replacement [%]**	3 days	7 days	28 days	56 days
Reference	0%	39.31	48.33	49.3	58.71
Filler	15%	33.61	42.43	47.46	50.44
	30%	28.94	33.89	33.48	43.72
	40%	24.21	24.58	32.37	31.86
	50%	15.83	15.88	21.53	22.27
VM	15%	35.69	42.43	49.77	48.03
	30%	32.85	44.79	52.38	46.36
	40%	42.07	48.19	62.2	70.38
	50%	37.65	44.54	59.36	61.44

The Data from table 4.1 was compiled to form the figures 4.3, 4.2, and 4.4. The test results in figure 4.2 show that the 40% VM mortar mix has the highest compressive strength, followed by 50%, then 30%, and lastly 15%.

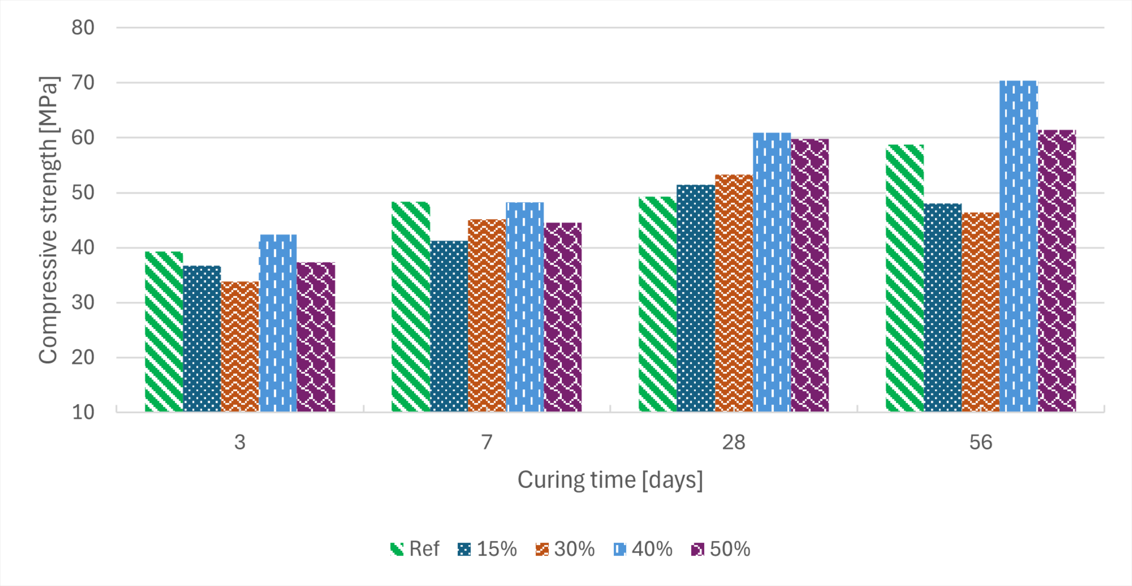


Figure 4.2: The average compressive strength of each VM substitution percentage after 3 to 56 days.

The results in 4.3 show that the compressive strength of filler mixes are at their highest at a low percentage of replacement. The compiled results from the compressive strength test comparing a reference sample of 100% OPC with 15%, 30%, 40%, and 50% filler and VM replacement over the 56-days test duration, shown in figure 4.4.

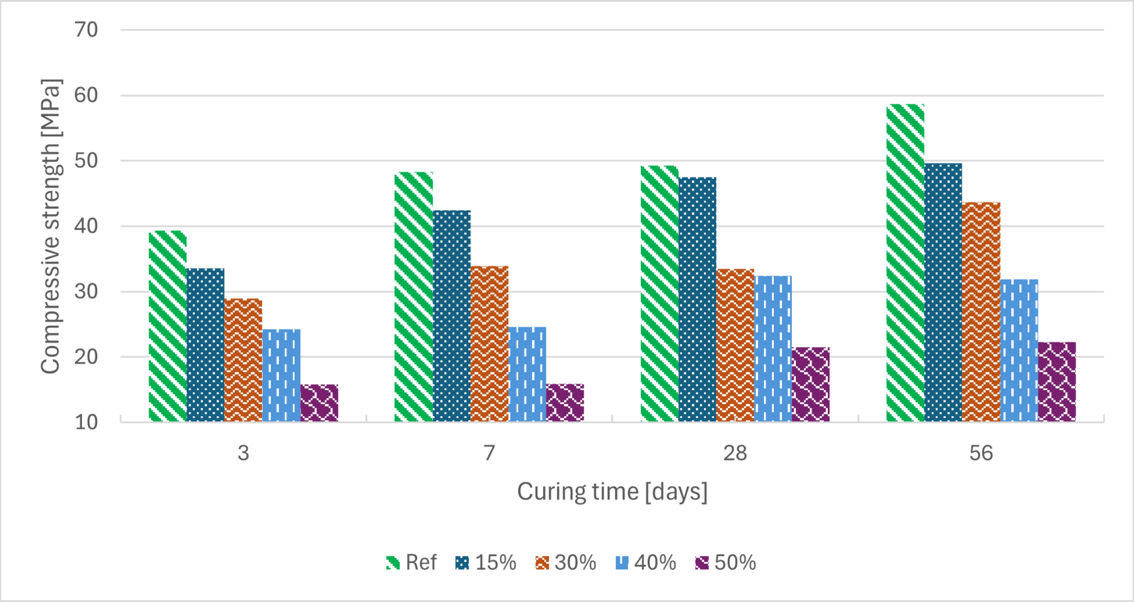
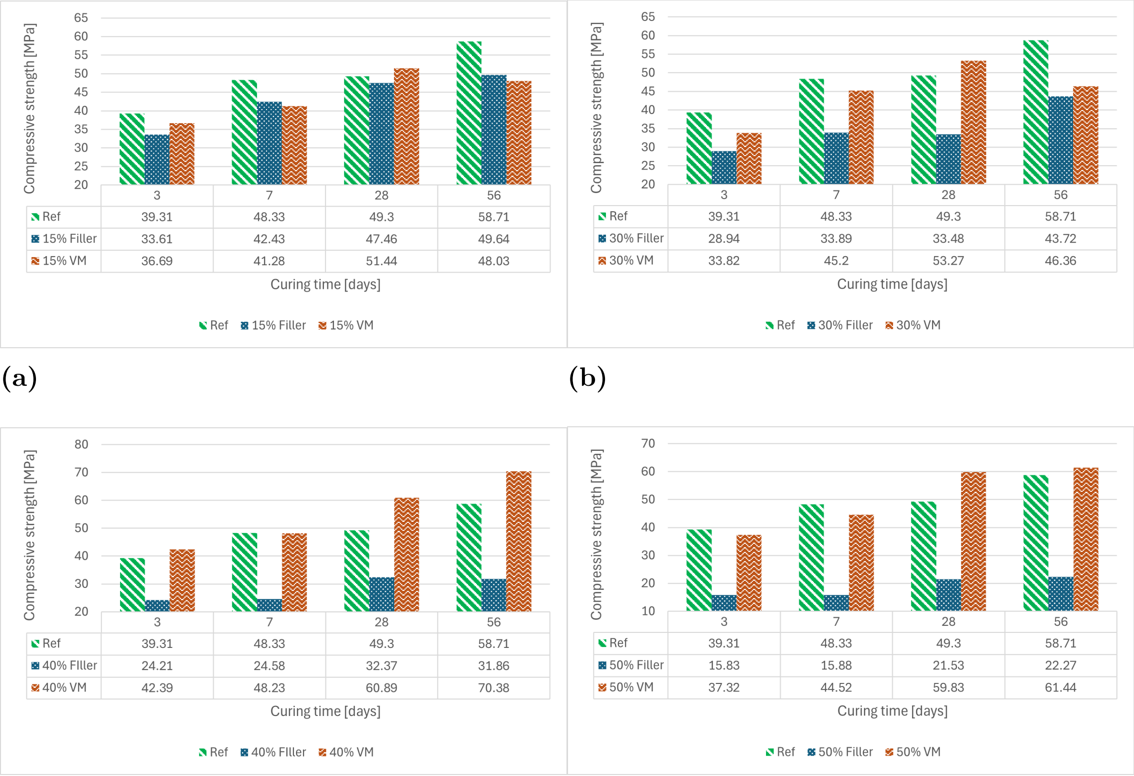


Figure 4.3: The average compressive strength of the reference batch and the different filler substitution percentages after 3 to 56 days.



(a)

	3	7	28	56
Ref	39.31	48.33	49.3	58.71
15% Filler	33.61	42.43	47.46	49.64
15% VM	36.69	41.28	51.44	48.03

(b)

	3	7	28	56
Ref	39.31	48.33	49.3	58.71
30% Filler	28.94	33.89	33.48	43.72
30% VM	33.82	45.2	53.27	46.36

(c)

	3	7	28	56
Ref	39.31	48.33	49.3	58.71
40% FIller	24.21	24.58	32.37	31.86
40% VM	42.39	48.23	60.89	70.38

(d)

	3	7	28	56
Ref	39.31	48.33	49.3	58.71
50% Filler	15.83	15.88	21.53	22.27
50% VM	37.32	44.52	59.83	61.44

Figure 4.4: Comparison of compressive strength: 15% in 4.4a, 30% in 4.4b, 40% in 4.4c, and 50% in 4.4d, over the span of 56 days.

The mortar with 15% and 30% replacement for both VM and filler shows an overall decrease in compressive strength concerning the reference sample over the curing duration. An exception is 30% VM replacement after 28 days, where a higher compressive strength was achieved in comparison to the reference sample, as seen in figure 4.4b. A higher compressive strength was achieved for both 40% and 50% VM replacement after 56 days, with 40% VM replacement showing a 20.7% increase in compressive strength. In comparison, 50% VM replacement shows a 4.6% increase after 56 days in comparison to the reference sample.

4.3 XRD-tests

The mineralogical results from the XRD are presented in figures below. In the figures, the primary hydration phases formed in the pastes after the different days of curing are marked with corresponding chemical notation.

Figure 4.5, 4.6, 4.7, and 4.8 shows the XRD result of the paste with VM at the 3-, 7-, 28-, and 56-days and the reference paste.

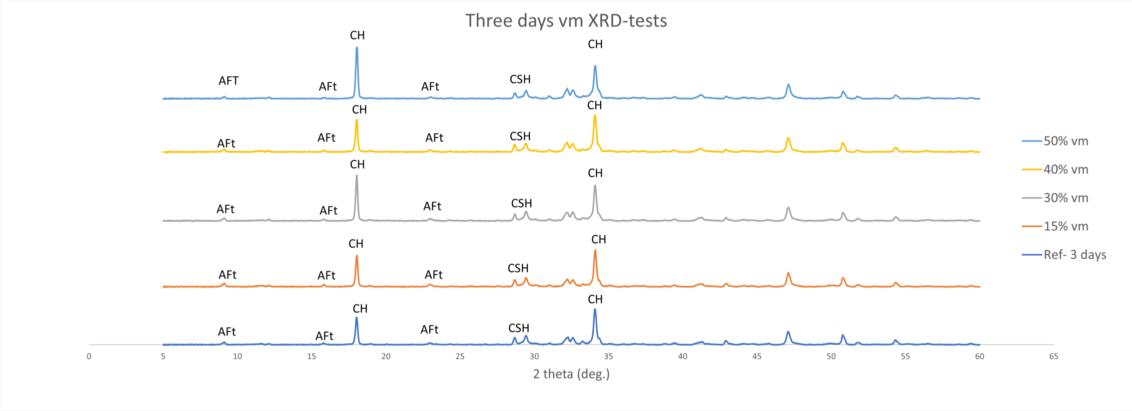


Figure 4.5: Comparison of XRD peaks between the reference paste and the pastes with different amounts of VM at 3 days.

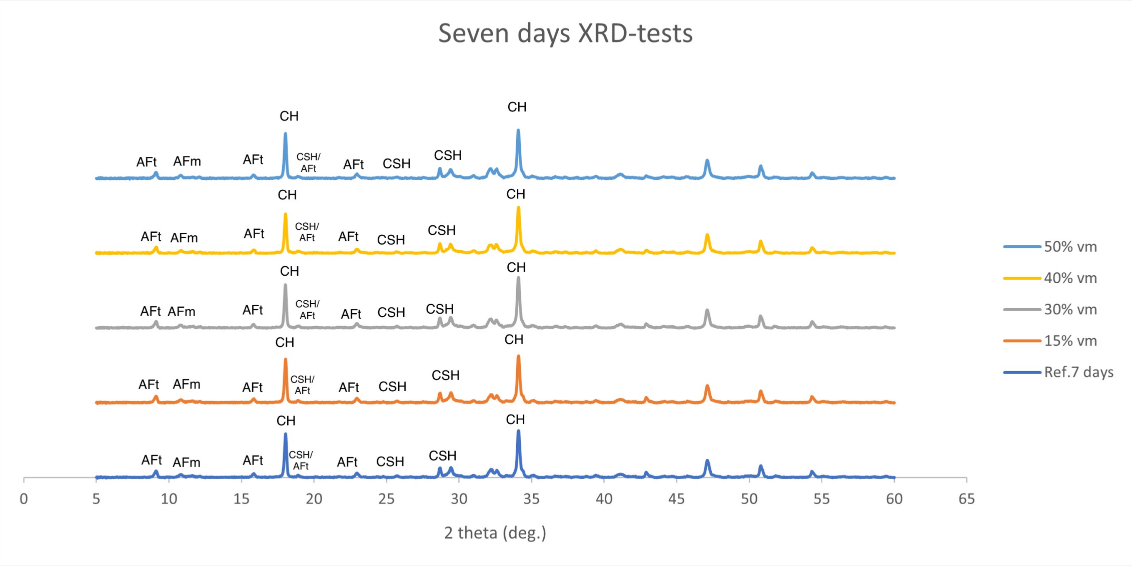


Figure 4.6: Comparison of XRD peaks between the reference paste and the pastes with different amounts of VM at 7 days.

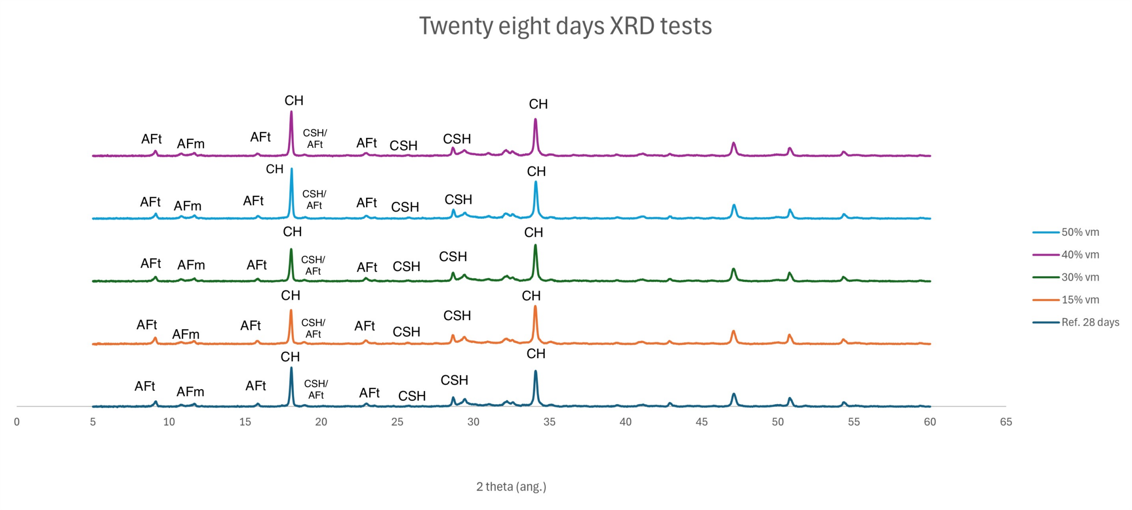


Figure 4.7: Comparison of XRD peaks between the reference paste and the pastes with different amounts of VM at 28 days.

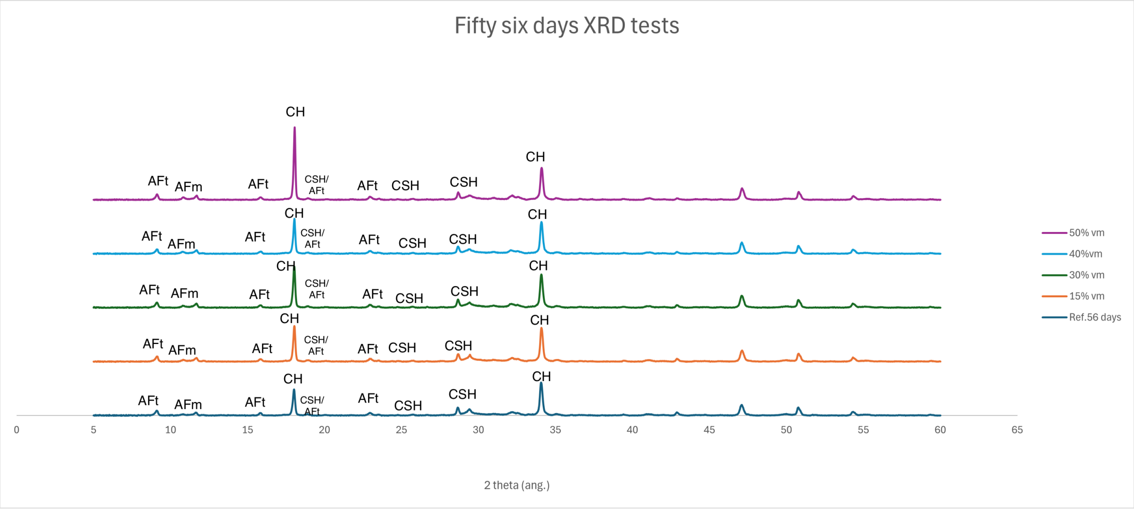


Figure 4.8: Comparison of XRD peaks between the reference paste and the pastes with different amounts of VM at 56 days.

The figures show that the VM and reference paste contain several hydration phases. The XRDs of all samples have peaks that are attributable to ettringite (AFt), calcium hydroxide (CH), calcium silicate hydroxide (CSH), and hemi-mono-carbonate (AFm). However, the intensity of the peaks varies with the amount of replaced cement. After 2θ greater than 40° the previous patterns repeat and are thus not discussed. Figure 4.6 on day seven appears to have more hydration phases than figure 4.5 on day three. The ones that have been formed are AFm by around 12° and CSH by around 26°. On the other hand, Figure 4.7 and 4.8 did not form any new hydration phases that could be detected as peaks in the figures.

The results have shown that, on day 3, the CH increases at the angle of around 18° as more VM is replaced in the paste. While on day 7, the CH at the same angle does not change as more VM is added. However, the CH amount on day 3 is lower than the corresponding amount on day 7 at an angle of 18°. At remaining angles, the amount of CH diminishes with the VM amount increasing in the pastes. Minor events include that the AFt peaks at 7 days are consistently higher than those at 3 days. In contrast, the AFm decreases with time showing higher intensity at 3 days for all peaks. The CSH content decreases with time as well.

Figure 4.9 and 4.10 show the XRD results of different pastes that contain LS at 3 days successively 7 days. When adding LS, calcite is the only new hydration phase that forms. Since there is no LS in the reference, there are no calcite peaks in those graphs.

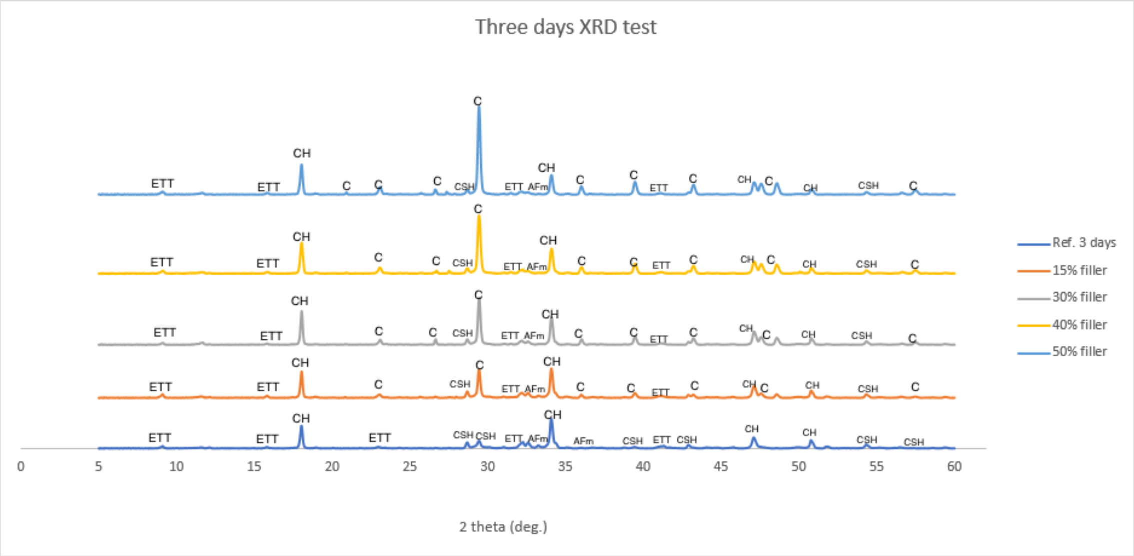


Figure 4.9: Comparison of XRD peaks between the reference paste and the pastes with different amounts of filler at 3 days, C is calcite.

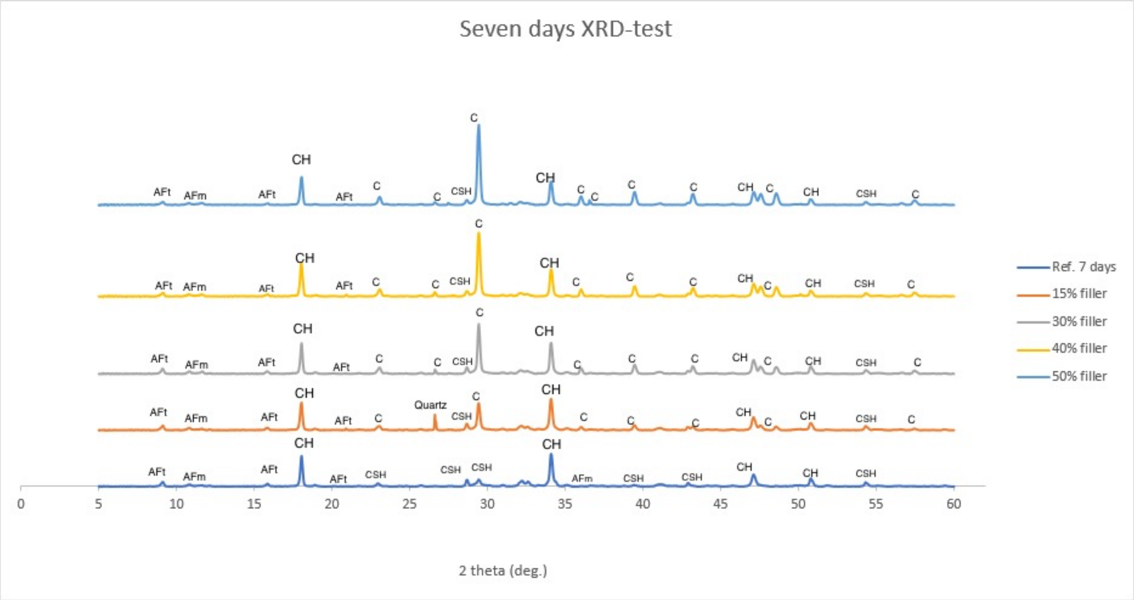


Figure 4.10: Comparison of XRD peaks between the reference paste and the pastes with different amounts of filler at 7 days, C is calcite.

As the percentage of LS increases, the peaks that correspond to calcite (C) increase. The calcite peaks only appear when LS is present, and some peaks only appear when adding a higher amount of LS. In figure 4.10, a peak that corresponds to quarts has appeared in the 15% filler paste, by the 2θ angle 26.44°. Furthermore, some calcite peaks overlap with other hydration phases at certain angles, making it difficult to identify other hydration phases than calcite.

5

Discussion

The testing throughout this study investigates the applicability of VM as an SCM, and the chosen areas of research are defined via the research questions. The findings presented in the results chapter are discussed in this chapter, starting with the reactivity, followed by compressive strength, and finally XRD.

i. *What is the reactivity rate of the volcanic material and how does it relate to compressive strength?*

Results of the MR^3-test show an average heat release of 439 [J/g] of SCM and is in comparison to other natural pozzolans highly reactive. Though the relative composition of CaO, SiO_2, Al_2O_3, and Fe_2O_3 in the VM is similar to others SCMs, the measured heat release is above average in comparison with similar oxide compositions. Thus classifying it as highly reactive when compared to other natural pozzolans, whilst considered moderately reactive in comparison to previously mentioned reactivity levels.

If greater amounts of pozzolanic reactants are present it might equate to a higher rate of reaction due to available material and the VMs ability to convert these into CSH and CASH. Since these products are mainly responsible, and correspond to the mortars' final strength, a correlation between higher reactivity and increased compressive strength can be drawn. As highly reactive SCMs tend to achieve similar or higher compressive strength, the immediate results show promise of its suitability as an SCM.

Further research into additional factors concerning reactivity, such as average particle size, average particle surface area, and porosity, are needed to enforce the VMs reactivity values.

ii. *How much cement can be substituted with volcanic materials while maintaining adequate strength?*

The paramount quality of all concrete is its resistance to compressive force. As such, the foundational answer to whether Icelandic volcanic material could be beneficial as an SCM lies in its effect on the compressive strength of the concrete. By comparing the strengths of the different mixes in this thesis, presented in figures 4.2, 4.3, and 4.4, it is clear that the VM has a distinct influence, since the strength far surpassed the filler at every step.

Curiously, in low amounts, the volcanic material appears to negatively impact the 56-day strength of the mortar. The markedly less reactive limestone, used as filler, has a lesser negative impact in comparison. Yet with higher amounts of VM replacement, the mortar performs distinctly better than the filler mixes across the entire interval, even meeting or surpassing the reference mix in terms of long- and short-term strength. Worth noting is that this is somewhat opposite to the general trend of other SCM where higher amounts lead to overall worse performance. An explanation for our result could be due to the high reactivity of the VM as mentioned earlier.

Moreover, the development of strength is usually slower in mortar using OPC with VM substitutions than comparable undiluted cement, negatively affecting early strength but increasing strength far beyond 28 days. In our case, the result for 40% VM in the mortar mix has a higher compressive strength at all the testing ages except 7 days, where the compressive strength is slightly lower than the reference. An explanation for this phenomenon could be the silica and alumina in the VM reacting with the calcium hydroxide at close to optimal proportions. More VM could lead to this balance becoming skewed, which could explain 50% VM having lower compressive strength than the mortar with 40% VM. However, the compressive strength of the mortar with 50% VM still surpassed the strength of the reference mortar at 28- and 56 days.

A reevaluation should be done regarding the limitation of the VM replacement to a maximum of 50%, as the strength at 50% was comparable to the reference mortar across the entire interval. It would be prudent to investigate higher amounts of VM replacement in further studies.

The first batch of reference mortar tested gave a similar decrease in compressive strength to the 15% and 30% VM mixes at 56 days, and therefore another batch was used. This could point to an error with either the method or the material and is further discussed in the sources of error below.

Particle size likely also plays a part in the compressive strength of the VM samples, considering the lower D50 of the VM than of the OPC. Be that as it may, this topic is outside of the scope of this thesis, though any contingent effects should be investigated in further studies.

iii. *Which hydration phases are formed at different times and how do they relate to the compressive strength?*

The results from the XRD test in figure 4.5 show a general increase of CH with greater amounts of VM replacement at 3 days, with a maximum at 30% VM. This result is not reasonable since all previous studies shows that the amount CH decreases when adding SCMs. This is likely due to error when preparing the sample. In figure **??**, which shows the 7-day test, the intensity of the CH is somewhat similar in all the paste samples including the reference. This result once again points to a possible error.

When comparing the XRD result between 3 and 7 days several observations can be made. The calcium hydroxide (CH) has in general decreased, which is as expected since the CH is consumed by the VM, to form CASH which contributes to strength. The hemi-mono-carbonate (AFm) is present in the 7-day XRD, which is also consistent with our expectations since AFm phases develop in cement blended with SCMs.

The peaks corresponding to calcium silicate hydrate (CSH) have shown increased intensity over time, primarily because of continued hydration leading to increased formation of this hydrate. This correlates to the increasing strength that was found at 7 days, compared to 3 days. Peaks for ettringite (AFt) phases increase in intensity as well, and thus the hydration phase development is overall as expected. One particular observation is that the CH peaks from the VM, especially the ones at 18 ° 2 theta, were higher in intensity than for reference OPC. These peaks were expected to have a lower intensity when comparing with the reference, since it is known that VM consumes CH in blended mixes. The different observations in our study could be a result of an error when preparing the samples or some contamination. Therefore, it could be explored in future studies to repeat this set.

One of the most possible reasons why the CH is not decreasing as more VM is added could be because it may contain CH. In other words, the VM contains CH that might convert to calcium carbonate ($CaCO_3$) as time passes, depending on the relative humidity of the environment and its contact with air. However, as the VM pastes are mixed with the cement the CH in the VM would only convert to $CaCO_3$ if the material is left in the air without drying, but the samples in this study were dried, which is why the CH peaks on the same day increase as more VM is added. As days pass, the CH peaks generally decrease and this has been conducted by comparing the corresponding CH peaks for every day. In general, further analysis and tests need to be done in the future to assure if any CH content is present in the VM.

The raw VM samples that have been taken could have a variation of CH-amount in different positions, which would have resulted in specific peaks in the XRD diagrams such as those by 18 °. These variations might differ next time an XRD-analysis is done on the same VM due to differences in composition as a result from where in Grindavik the VM is collected.

5.1 Sources of Error

There are several potential sources of error. Regarding the compressive strength test, one of the first potential errors could occur during the demolding. For some of the samples, wooden molds were used, and problems occurred when extracting the sample from these molds. Some needed to be vibrated to detach, and others needed to be pried or gently tapped out. The vibration and the other methods may have led to internal cracks that later on affected the compressive strength.

Another source of error concerned the underwater curing process. At some time between the 28- and 56 days of the compressive strength test, some water had evaporated such that approximately one millimeter of the samples was not covered with water. This applies to all the samples, the reference, the VM and the mortar with filler. The lack of water can lead to internal cracks. As mentioned, this applies to all samples between 28- and 56 days. Therefore, if this has affected the compressive strength negatively, it has affected all the samples and not only some of them.

The used machine for the compressive strength test automatically recalculates the force [kN] to pressure in [MPa] by using the pre-setted sample dimension 40x40 [mm]. To prevent varying sample dimensions from affecting the result, the samples' dimensions were measured before testing. Some of the sample has deviating sizes by ±0.3 [mm]. This is a minor deviation that should not impact the result.

When conducting the XRD test there are several potential sources of error. Since the powder was ground to 75 [μm], it is hard to ensure that all the equipment was completely clean between the testing of different samples. The most challenging equipment to clean was the specimen holders for the XRD due to traces of previous samples in the bottom. This became apparent in the result since it showed traces of sand (quartz), which was not included in the sample powder.

5.2 Further Research of VM as SCM

This study represents an initial investigation into the performance of VM from Grindavik as an SCM in mortar. Therefore, further research is needed before VM can be feasibly utilized as an SCM in the construction sector.

Further investigation into the hydration phases formed by the VM would be of interest to explain the increase in compressive strength. This can be done through SEM and TGA. In this study, in terms of strength, only compressive strength was tested. Even though this is one of the most important aspects of strength, several other strength aspects need to be investigated. For instance the tensile and flexural strength.

Additional areas for further research include durability and workability, to mention a few. A possible area of research would be VM coupled with LS, since the Romans used this in their concrete. Part B of this thesis investigates the use of VM and LS in combination. Since the main reason for using VM as an SCM is the environmental impact, a life cycle analysis to determine this would be interesting.

6

Conclusion

This study aims to evaluate VM as a possible SCM based on the reactivity, the compressive strength and mineralogy through XRD. From the result and the discussion in this thesis the following conclusions can be drawn:

1. The VM from Grindavik is highly reactive with a total heat evolution of 439 [J/g] of SCM. The reactivity is most likely related to the small particle size and the chemical composition of the VM.

2. The addition of VM proves to be a viable SCM since the compressive strength was comparable to or greater than the reference with exclusively OPC. The mix with 40% VM shows the greatest results regarding compressive strength, and 50% VM had comparable strength with the reference. Therefore, both 40% and 50% VM are viable mix options for use.

3. The hydration phases found generally supported the strength results, in line with the theory regarding pozzolans. However, the amount of CH in the samples where likely erroneous since the amount in the reference sample where lower than expected.

The results from this thesis illuminate the positive aspects of utilizing VM as an SCM. However, considerably more research is needed before VM from Grindavik can be used as an SCM in the industry.

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A

Appendix A

The raw data for the compressive strength of samples with 15% and 30% filler can be found in tables A.1,A.2,A.3,A.4, as well as all samples with VM substitutions in tables A.5,A.6,A.7,A.8.

Table A.1: The compressive strength of the the ref and filler samples 3 days after casting

Reference	**Fm [KN]**	**N/mm2**
1	54.11	33.82
2	62.96	39.35
3	71.59	44.75
Average:	62.886667	39.306667

85/15	**Fm [KN]**	**N/mm2**
1	53.08	33.17
2	52.7	32.94
3	55.55	34.72
Average:		33.61

70/30	**Fm [KN]**	**N/mm2**
1	45.01	28.13
2	43.89	27.43
3	49.99	31.25
Average:		28.94

60/40	**Fm [KN]**	**N/mm2**
1	41.56	32.12
2	37.71	34.55
3	51.76	32.35
Average:		33.01

50/50	**Fm [KN]**	**N/mm2**
1	25.33	15.83
Average:		15.83

Table A.2: The compressive strength of the ref and filler samples 7 days after casting

Reference	**L**	**W**	**area**	**weight**	**Fm [KN]**	**N/mm2**	**N/mm2 (corr)**
1					71.46	44.66	
2					80.60	50.37	
3					79.94	49.97	
Average:						48.33	

85/15	**L**	**W**	**area**	**weight**	**Fm [KN]**	**N/mm2**	**N/mm2 (corr)**
1	41.00	42.00	1722.00	157.36	68.81	43.01	39.96
2	40.50	39.00	1579.50	145.28	71.95	44.97	45.55
3	40.00	39.00	1560.00	144.59	62.91	39.32	40.33
Average:						42.43	41.95

70/30	**L**	**W**	**area**	**weight**	**Fm [KN]**	**N/mm2**	**N/mm2 (corr)**
1	41.00	40.00	1640.00	148.18	51.32	32.07	31.29
2	39.50	40.50	1599.75	144.28	49.02	30.64	30.64
3	41.50	41.00	1701.50	153.54	62.35	38.97	36.64
Average:						33.89	32.86

60/40	**L**	**W**	**area**	**weight**	**Fm [KN]**	**N/mm2**	**N/mm2 (corr)**
1	39.00	41.00	151.00	151.00	42.25	32.07	279.80
2	41.00	42.00	154.00	154.00	35.43	30.64	230.06
3	41.00	42.00	165.00	165.00	40.30	38.97	244.24
Average:						33.89	251.37
		12th March		8-days			

50/50	**L**	**W**	**area**	**weight**	**Fm [KN]**	**N/mm2**	**N/mm2 (corr)**
1	41.00	41.00	1681.00	152.00			0.00
2	41.00	41.00	1681.00	147.00	24.63	15.39	14.65
3	38.00	41.00	1558.00	150.00	26.18	16.36	16.80
Average:						15.88	10.49

Table A.3: The compressive strength of the ref and filler samples 28 days after casting

Reference	**Fm [KN]**	**N/mm2**
1	95.31	59.57
2	95.68	59.8
3	101.42	63.39
Average:	97.47	60.92

85/15	**Fm [KN]**	**N/mm2**
1	59	36.87
2	82.86	51.79
3	85.96	53.72
Average:	75.94	47.46

70/30	**Fm [KN]**	**N/mm2**
1	47.83	29.89
2	63.38	39.61
3	49.52	30.95
Average:	53.58	33.48

60/40	**Fm [KN]**	**N/mm2**
1	39.12	24.45
2	56.76	35.47
3	59.49	37.18
Average:	51.79	32.37

50/50	**Fm [KN]**	**N/mm2**
1	37.07	23.17
2	32.66	20.41
3	33.64	21.02
Average:	34.46	21.53

Table A.4: The compressive strength of the ref and filler samples 56 days after casting

Reference	**L**	**W**	**area**	**weight**	**Fm [KN]**	**N/mm2**	**N/mm2 (corr)**
1	39	39	1521.00	153.30	82.76	51.72	54.41
2	39	40	1560.00	150.80	100.22	62.64	64.24
3	39	39.5	1540.50	156.60	98.84	61.77	64.16
Average:					93.94	58.71	60.94

85/15	**L**	**W**	**area**	**weight**	**Fm [KN]**	**N/mm2**	**N/mm2 (corr)**
1	41	40	1640.00	145.80	65.91	41.20	40.19
2	41	40	1640.00	147.70	93.37	58.36	56.93
3	41	39	1599.00	146.30	82.81	51.75	51.79
Average:					80.70	50.44	49.64

70/30	**L**	**W**	**area**	**weight**	**Fm [KN]**	**N/mm2**	**N/mm2 (corr)**
1	40.5	40	1620	144.91	68.48	42.89	42.27
2	41	41	1681	154.68	73.52	45.95	43.74
3	41	40	1640	149.4	74.04	46.28	45.15
Average:					72.01	45.04	43.72

60/40	**L**	**W**	**area**	**weight**	**Fm [KN]**	**N/mm2**	**N/mm2 (corr)**
1	39	39	1521	156	55.55	34.72	36.52
2	39	39	1521	156	45.19	28.24	29.71
3	38	39	1482	154.9	52.27	31.62	35.27
Average:					51.00	31.53	33.83

50/50	**L**	**W**	**area**	**weight**	**Fm [KN]**	**N/mm2**	**N/mm2 (corr)**
1	39	39	1521	153	38.87	24.29	25.56
2	38	39	1482	148.9	36.17	22.61	24.41
3	38	39	1482	147.2	31.88	19.92	21.51
Average:					35.64	22.27	23.82

Table A.5: The compressive strength of the 15%, 30%, 40%, and 50% VM samples 3 days after casting

85/15	**L**	**W**	**area**	**weight**	**Fm [N]**	**N/mm2**	**N/mm2 (corr)**
1	40.1	40	1604	147.77	63040	39.4	39.30
2	41	41.4	1697.4	152.93	52430	32.77	30.89
3	41	40.1	1644.1	149.67	60640	37.9	36.88
Average:						36.69	35.69

70/30	**L**	**W**	**area**	**weight**	**Fm [N]**	**N/mm2**	**N/mm2 (corr)**
1	40.3	41	1652.3	145.44	58290	36.43	35.28
2	41	40	1640	145.06	49350	30.84	30.09
3	41.1	40.1	1648.11	146.4	54700	34.19	33.19
Average:						33.82	32.85

60/40	**L**	**W**	**area**	**weight**	**Fm [N]**	**N/mm2**	**N/mm2 (corr)**
1	40	40	1600	142.04	66880	41.8	41.80
2	40.2	40.3	1620.06	143.41	69930	43.71	43.17
3	40.3	40.1	1616.03	142.84	66650	41.66	41.24
Average:						42.39	42.07

50/50	**L**	**W**	**area**	**weight**	**Fm [N]**	**N/mm2**	**N/mm2 (corr)**
1	40.1	40.3	1616.03	144.87	60490	37.81	37.43
2	39.7	40.3	1599.91	142.85	61830	38.65	38.65
3	40	38.5	1540	137.02	56800	35.5	36.88
Average:						37.32	37.65

Table A.6: The compressive strength of the 15%, 30%, 40%, and 50% VM samples 7 days after casting

85/15	**L**	**W**	**area**	**weight**	**Fm [N]**	**N/mm2**	**N/mm2 (corr)**
1	40	39	1560	144.2	67250	42.03	43.11
2	40	39.8	1592	147.4	67250	41.08	42.24
3	40	40.1	1604	149.2	67250	40.74	41.93
Average:						41.28	42.43

70/30	**L**	**W**	**area**	**weight**	**Fm [N]**	**N/mm2**	**N/mm2 (corr)**
1	40.05	40.05	1604.00	147,1	73100	45.69	45.57
2	41	40	1640	147.3	70200	43.87	42.80
3	40.05	40	1602	144.9	73660	46.04	45.98
Average:						45.2	44.79

60/40	**L**	**W**	**area**	**weight**	**Fm [N]**	**N/mm2**	**N/mm2(corr)**
1	39.3	40.2	1579.86	142.3	78510	49	49.69
2	40.1	41.1	1648.11	139.8	76650	47.91	46.51
3	40	39.5	1580	140.5	76440	47.78	48.38
Average:						48.23	48.19

50/50	**L**	**W**	**area**	**weight**	**Fm [N]**	**N/mm2**	**N/mm2 (corr)**
1	40.05	39.95	1600.00	143.3	73120	45.7	45.70
2	40.05	39	1561.95	141	70650	44.16	45.23
3	39.95	41	1637.95	140.5	69920	43.7	42.69
Average:						44.52	44.54

Table A.7: The compressive strength of the 15%, 30%, 40%, and 50% VM samples 28 days after casting

85/15	**L**	**W**	**area**	**weight**	**Fm [KN]**	**N/mm2**	**N/mm2 (corr)**
1	41.00	40.50	1660.50	151.90	84.43	52.77	50.85
2	42.00	40.00	1680.00	150.40	77.08	48.17	45.88
3	40.60	40.00	1624.00	146.20	85.40	53.37	52.59
Average:						51.44	49.77

70/30	**L**	**W**	**area**	**weight**	**Fm [KN]**	**N/mm2**	**N/mm2 (corr)**
1	41.00	40.00	1640.00	150.30	88.35	55.22	53.87
2	40.50	39.50	1599.75	146.00	79.91	49.95	49.95
3	40.00	41.00	1640.00	147.00	87.43	54.64	53.31
Average:						53.27	52.38

60/40	**L**	**W**	**area**	**weight**	**Fm [KN]**	**N/mm2**	**N/mm2 (corr)**
1	40.00	39.50	1580.00	143.70	93.57	58.48	59.22
2	40.00	39.00	1560.00	146.20	103.04	64.40	66.05
3	40.00	39.00	1560.00	139.10	95.66	59.79	61.32
Average:						60.89	62.20

50/50	**L**	**W**	**area**	**weight**	**Fm [KN]**	**N/mm2**	**N/mm2 (corr)**
1	40.00	40.00	1600.00	144.60	94.72	59.20	59.20
2	40.00	40.00	1600.00	146.70	99.03	61.90	61.89
3	40.00	41.00	1640.00	147.40	93.44	58.40	56.98
Average:						59.83	59.36

Table A.8: The compressive strength of the 15%, 30%, 40%, and 50% VM samples 56 days after casting

85/15	**L**	**W**	**area**	**weight**	**Fm [N]**	**N/mm2**	**N/mm2 (corr)**
1	40.00	40.00	1600.00	148.20	75.68	47.30	47.30
2	40.20	40.00	1608.00	154.00	70.32	43.95	43.73
3	41.00	41.00	1681.00	152.20	89.21	55.75	53.07
Average:						49.00	48.03

70/30	**L**	**W**	**area**	**weight**	**Fm [N]**	**N/mm2**	**N/mm2 (corr)**
1	41.00	40.00	1640.00	149.30	79.20	49.50	48.29
2	40.10	40.00	1604.00	147.30	70.95	44.34	44.23
3	40.00	41.00	1640.00	147.40	76.36	47.72	46.56
Average:						47.19	46.36

60/40	**L**	**W**	**area**	**weight**	**Fm [N]**	**N/mm2**	**N/mm2 (corr)**
1	40.00	40.00	1600.00	148.20	120.73	75.46	75.46
2	40.00	38.00	1520.00	137.90	99.75	62.34	65.63
3	40.00	38.00	1520.00	141.70	106.49	66.56	70.06
Average:						68.12	70.38

50/50	**L**	**W**	**area**	**weight**	**Fm [N]**	**N/mm2**	**N/mm2 (corr)**
1	40.00	40.00	1600.00	143.20	94.80	59.25	59.25
2	40.10	40.00	1604.00	146.40	94.13	58.83	58.68
3	40.00	40.00	1600.00	146.90	106.22	66.39	66.39
Average:						61.49	61.44

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