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Effect Of Micro Silica On Alkali Activated Repair Mortar

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This study is wholeheartedly dedicated to my beloved mom and dad, who have been my source of inspiration and gave me strength when I thought of giving up, who continually provided their moral, spiritual, emotional, and financial support.

Contents

Abstract ix

Acknowledgement xi

Abriviations xiii

1 Introduction 1
- 1.1 What is mortar . . . 1
- 1.2 Types of mortar . . . 2
- 1.3 Alkali activated mortar . . . 2
- 1.4 Objectives . . . 3
- 1.5 Thesis Structure . . . 3

2 Literature review 5
- 2.1 Introduction to literature review . . . 5
- 2.2 Active alkaline binders . . . 5
- 2.3 Setting mechanism and activation process . . . 7
- 2.4 Effective parameters on alkali-activated binder characteristic . . . 9
  - 2.4.1 Types of slag . . . 9
  - 2.4.2 Effect of alkali activator . . . 11
  - 2.4.3 Curing process . . . 12
- 2.5 Durability in concrete structures . . . 13
  - 2.5.1 Sulfate attack . . . 13
  - 2.5.2 Acidic attack . . . 17
  - 2.5.3 Permeability . . . 20
- 2.6 Conclusion . . . 22

3 Methods 25
- 3.1 Introduction to program method . . . 25
- 3.2 Material . . . 25
  - 3.2.1 Fine aggregate . . . 25
  - 3.2.2 Ground Granulated Furnace Slag (GGBFS) . . . 26
  - 3.2.3 Cement . . . 26
  - 3.2.4 Water . . . 27

3.2.5 Micro silica 28
3.2.6 Alkali activators 28
3.3 Experiments and equipment 31
3.3.1 The mini-slump test 31
3.3.2 The vicat test 31
3.3.3 Compression Test 33
3.3.4 Slant shear test 34

4 Experiment procedure **37**
4.1 Introduction to experimental procedures 37
4.2 Slant shear specimen preparation 37
4.2.1 Mixing the material 38
4.2.2 Casting into the molds 38
4.2.3 unmolding, curing, cutting 38
4.3 Mix design 40
4.3.1 Reference mix designs 40
4.3.2 Alkali activated mix designs with micro silica 41
4.4 How to mix material 41
4.4.1 Cement base mix design 41
4.4.2 Slag base mix designs 41
4.5 Casting mortars and immediately-after tests 42
4.5.1 Casting cement-based mortar 42
4.5.2 Casting slag-based mortars 42
4.6 Breaking the specimens and saving results 43
4.6.1 Cubic specimens 43
4.6.2 Slant shear specimens 44

5 Results and discussion **45**
5.1 Introduction 45
5.2 Results from experiments on the fresh mortar 45
5.2.1 The mini-slump Results 45
5.2.2 The vicat results 46
5.3 Results from the experiments on the hardened mortar 48
5.3.1 Compressive strength 48
5.3.2 Bond strength 49

6 Conclusion and future works **51**
6.1 Introduction 51
6.2 Conclusions 51
6.3 Future works 52

Bibliography **59**

A Cement and slag **67**

B Micro Silica **71**

C Sodium silicate **73**

Abstract

In this era, concrete acts as a primary role in construction technology. Therefore, it is essential to pay widespread attention to the side effects of concrete products for the environment. On the other hand, the vulnerability of concrete against invasive environmental factors such as acids, sulfates, seawater, and freeze/thaw cycle can affect the concrete lifetime. Hence, it is smart to make significant investments to represent innovative methods to repair and extend the existing concrete structures against destructive factors mentioned above and utilize new material instead of cement to cover the weak points. Alkali activated material could be considered as a brilliant alternative to avoid the use of ordinary types of cement. This material can also be utilized in the shape of mortar to repair and improve the functionality of existing concrete structures. This thesis focused on using a wastage of metal production process as the base material to provide a binder with widespread potentials for using in repair mortars. Alkali-activated slag is going to substitute the ordinary portland cement to produce alkali-activated repair mortar. It is also tried to optimize the physical properties as well as compression and bond strength of this mortar for using in practice by finding the optimum percentage of micro silica powder. For this purpose, we do the vicat and mini-slump tests immediately after casting the mortar to measure the setting time and workability. Moreover, The slant shear test is done as well as the cubic compression test for different percentages of micro silica from 0 to 20. The slant shear test helps us to compare the bond strength of mortar in the desired bond interface. Besides, all experiments above will be compared with a reference mix design with ordinary Portland cement to make a better comparison with alkali-activated binders. As a result, 15% of micro silica shows an acceptable compressive and bond strength with allowable workability. Moreover, slag-based mortar shows a significantly shorter setting time compared to OPC mortar, which makes the alkali-activated mortar a considerable substitution for OPC mortars in repairing structures.

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List of Abbreviations

AAM	**A**lkali **A**ctivated **M**ortar
BFS	**B**lasted **F**urnace **S**lag
C-S-H	Hydrated calsium silicate
C-A-S-H	Hydrated calsium silicate with aluminium
cm	**c**enti **m**eter
DEF	**D**elayed **E**ttringite **F**ormation
ESA	**E**xternal **S**ulfate **A**ttack
GGBFS	**G**round **G**ranulated **B**lasted **F**urnace **S**lag
gr	**gr**am
HM	**H**ydration **M**odulous
ISA	**I**nternal **S**ulfate **A**ttack
Kg	**K**ilo **g**ram
KN	**K**ilo **N**ewton
m^3	cubic meter
Mpa	**M**ega **pa**scal
N	**N**ewton
OPC	**O**rdinary **P**ortland **C**ement
Pa	**Pa**scal
SSD	**S**aturated **S**urface **D**ry
°**C**	Celsius
σ_n	Normal stress
τ_n	Shear stress

Chapter 1

Introduction

1.1 What is mortar

Repair and reconstructing the buildings and structures considers as one of the most extensive parts of construction projects. This fact results in growing expenses for life-extending projects for structures and infrastructures. For instance, it costs about 215 million dollars a year just for maintenance of 84000 bridges in the European Union [1]. Moreover, the United States pays 15 to 22 billion dollars each year for repair, maintenance, and strengthening of the infrastructures [2]. Thus, it is logically worthful to invest in the research and development of our knowledge in the field of repair materials to make a considerable reduction in expenses due to repair and reconstructing projects.

The first invented repair mortars were cement-based material in which short setting time, low bond, and compressive strength made an obstacle in the usage of this material in practice. A new generation of repair materials are also made of Portland cement or other types of blended binders like Resins, Polymers, and Epoxies which are used to increase the initial compressive and bond strength [3]. In addition, it is possible to add different types of fibers in order to increase the bond strength [4].

This thesis studies a particular type of repair mortar that can have a massive demand in Norway with a high level of humidity and active in the offshore industry where there is a high potential for sulfate attack in wet environments for concrete structures. There are different regulations about criteria and parameters due to the usage of repair mortars. However, in this study, compressive and bond strength, hardening speed, and workability are considered as some highlight principles to evaluate the quality of the mortar.

1.2 Types of mortar

Different types of repair mortar are used in the industry. However, the most common types are consist of cementitious mortars with and without admixtures such as micro-silica and fibers, modified-cementitious mortar with polymers, alkali-activated mortars and polymer resins. Choosing the most proper type of mortar depends on the size and shape of the repair area, reinforcement, temperature, moisture, and the existence of impact loads. It is possible to name Magnesium phosphate cement as another well-known type of repair mortar which could be used even in the cold temperatures till -10 in case of using proper admixtures. This mortar is commonly used in repair procedures of airport runways or highways [5].

Particular types of bacteria can be used in the construction repair industry. Nutrients for these bacteria change into carbonates during their metabolism procedure, which can be used for filling the cracks in concrete structures [6].

1.3 Alkali activated mortar

Concrete is one of the most common and cheap materials with appropriate ductility and mechanical properties, which is made of cement, water, sand, and gravel as aggregate and admixtures. In ordinary concretes, Portland cement is used as the main type of binder. The production process of Portland cement needs to misspend great sources of money and energy. This industry is known as one of the most energy-consuming industries after steel and aluminum. Production of cement also has lots of adverse side effects on the environment. There are lots of investigations showing that the demand for concrete production will face a noticeable increase in the future, which results in a significant increment of natural resources consumption and a high release of carbon dioxide in the atmosphere. It is also estimated that 5 to 7 percent of greenhouse gas emission in the world is caused by the concrete production process [7],[8].

According to harmful environmental side effects mentioned above and weakness that concrete shows against sulfate and acid attack and also carbonation, scientists are about to find alternatives to use instead of cement as the binder component of concrete. This material should have less harmful environmental effects and be made from existing wastage of other industries and improve concrete properties.

Alkali activated mortar consists of Aluminosilicate-base and cement-like material, which can be provided from byproducts and wastage of factories. The alkali part is called Alkali Activator. The most common source of aluminosilicate material is Ground Granulated Blasted-Furnace Slag (GGBFS) [9].

Nowadays, people and companies have a widespread orientation to repair instead of reconstructing the whole structure, which results in high demand for repair mortars that are made from factory wastages like slag, fly ash and metakaolin. These materials that are known as alkali-activated can be used as a new generation of binders, which is going to substitute the cement in the concrete because of their positive contribution to improved durability and other mechanical properties [10]. Moreover, they have a preference in comparison to the cement according to economic aspects, compressive strength, bending strength, durability in a corrosive environment, fast initial and final setting, and less permeability [11].

1.4 Objectives

According to what mentioned above from the advantages of alkali-activated material, demands for repair weaknesses in the concrete and cement-based materials made a significant motivation in scientists and companies. They try to make investigations and investments to invent new materials to utilize in cheap, durable, and high efficient repair and strengthening of damaged structures. The function of repair mortars in the environments with the existence of Chlorine ion and acids, compatibility and adhesion with damaged layers of concrete or substrate are the main characteristics to illustrate the adequacy and competence of these materials. Thus, it is essential to choose proper material with consideration of loading and environmental situations regarding that quality of repair materials can act as a noticeable factor for the stability of the overall structure.

The main reason for this investigation on alkali-activated repair mortar is to produce mortar with a different type of binder but with proper workability and high-early strength. Moreover, the effect of micro silica powder in mechanical properties such as compressive strength, bond strength, Slump, and setting time will be evaluated.

It is expect to use this kind of mortar in practice instead of regular cementitious mortars to achieve better mechanical properties and shorter setting time. Moreover, it can be a huge step forward in decreasing the emitted amount of greenhouse gas during the process of cement production.

1.5 Thesis Structure

This thesis is organized as follows in five chapters. The first chapter is an introduction about the essence of mortar, repair mortar, side effects of using cementitious binders, and the reasons and demands for substituting them with something more environmentally friendly. The second chapter gives a brief overview of the most relevant studies which are done before about differences of cementitious and alkali-activated binders and the effects of substituting them on general characteristics of concrete or mortar.

In the third chapter, an overview of the investigation method is presented. Experiments, standards, and equipment that are used during laboratory works will be also explained in this chapter. This chapter can be considered as a necessary requisite for following chapters four and five.

A new methodology is described in the fourth chapter, which explains all experimental procedures done in the laboratory by details and according to whatever is explained in chapter three. Detailed analyses on the main results with the help of charts and graphs are given in chapter five. The last chapter includes a conclusion of all experiments done in this study and some worthy topics that are worthful to be considered in the future works.

Chapter 2

Literature review

2.1 Introduction to literature review

There are lots of byproducts or wastages in the industry which could be used as a binder in the concrete or mortar instead of ordinary Portland cement (OPC). If a binder has pozzolanic and cementitious properties, then it has the potential to be used instead of OPC in the industry. Using an alkali activator in combination with slag in the material such as concrete and mortar is considered as a way to produce environmentally friendly material, which can lead to a considerable decrement in the environmental side effects due to cement production process. Another advantage of using alkali-activated slag instead of OPC is to get higher mechanical strength, resistance against chemical attacks and penetration of chlorine ion, and resistance against freeze/thaw cycle. These properties could lead to considerable demand for these materials in countries such as Norway, with lots of offshore concrete structures and a lower average of temperature [12].

2.2 Active alkaline binders

There is a wide range of active alkaline substances that consist of a binder system and are produced as a result of the reaction between an aluminosilicate resource and an alkali activator in both liquid or solid phases [13].

Kuhl made an investigation in 1908 about the reaction of aluminosilicate and an alkaline matter in the production of solid material with similar characteristics as OPC. He showed that amorphous slag, in combination with sulfate or any kind of alkaline carbonate, can result in a new material with similar and even better characteristics in comparison with Portland cement [14].

In 1940 Purdon researched in the field of active alkaline binders, and he proved that activating blasted furnace slag (BFS) in an alkaline environment in the existence of lime can result in the production of an adhesive material which can reach a high strength very fast. It also has a high bending and tension strength with low solubility and heat of hydration. He also suggested mix-designs for producing concrete using these materials as a binder. He also combined dry slag and sodium hydroxide with extra water to produce a new type of mortar [15].

After the first research and investigation in the field of active alkaline binders in western Europe, a scientist in the Soviet Union in 1967 explained a theory to use silicate soils to generate active alkaline binders. As appose to Purdon, who considered alkaline as a catalyzer, Glukhovsky, explained that as the main element in the production of binder [16].

Davidovits in 1978 believed that it is possible to produce a binder in the reaction of an alkaline solution with a byproduct like fly ash or silicon and aluminum, which exists in a substance with a natural origin. As this reaction is a kind of polymerization, Davidovits named the produced adhesive material Geopolymer [17]. Geopolymers considers as a subset for alkali-activated material [18]. Nevertheless, it is possible use the expressions geopolymer and active alkaline material as synonyms for each other [9]. Figure 2.1 shows a better view of this category of material.

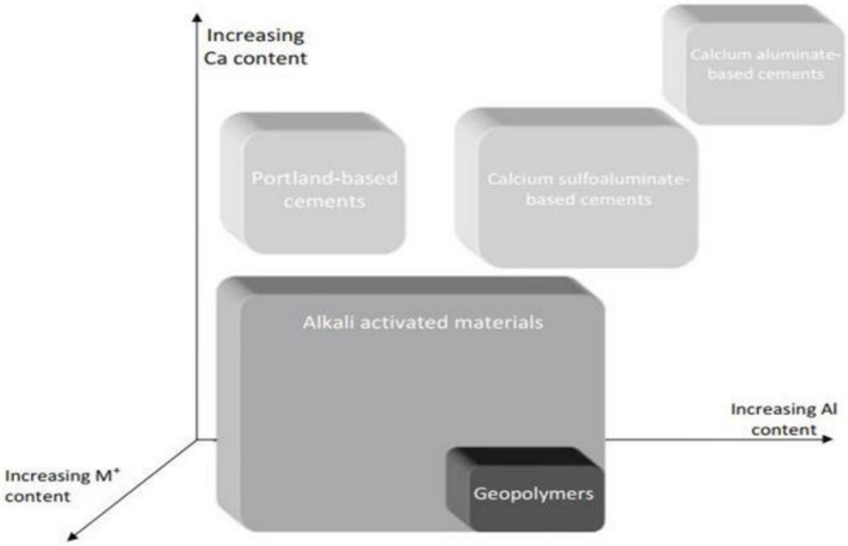


FIGURE 2.1: Classification of alkali-activated material in comparison with geopolymers and other types of cement [9].

As an instance, it is possible to produce common two-part geopolymers due to an alkaline chemical reaction. For this purpose, there should be a high concentration alkaline hydroxide solution, silicate, carbonate, or sulfate to make a chemical reaction with a solid phase of aluminosilicate in the existence of water [19].

Since active alkaline solutions are so viscose and corrosive, it is difficult to produce them in large scales. Thus, one-part geopolymers are developed and can be used in combination with water, similar to OPC in practice [20]. In one-part combinations, it is necessary to have just one dry component in addition to water. Figure 2.2 illustrates a view of the production procedure of one-part geopolymers. In this process, the dry combination of solid alkali activator and raw material like solid aluminosilicate can be used with or without calcination [9].

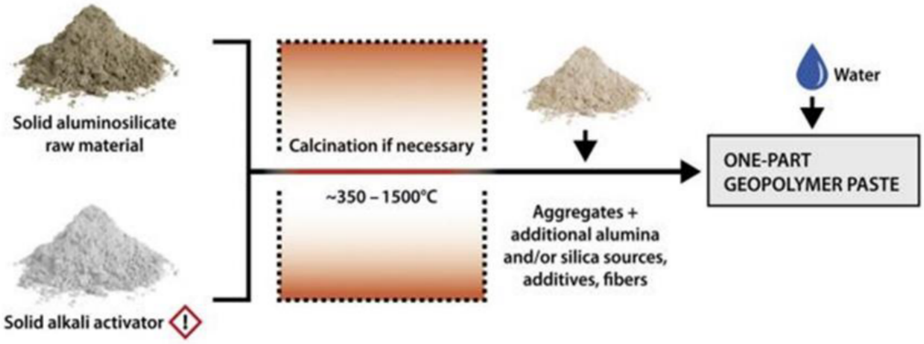


FIGURE 2.2: The general production process of one part geopolymers [9].

Heitzmann and his team in 1980 patented a dry combination of metakaolin, blasted furnace slag, amorphous silica, hydroxide potassium, and silicate in addition to OPC [19]. Duxon and Provis have introduced new conditions for one-part geopolymer combinations. According to their concept, one-part geopolymers are appropriate to be used in cast-in-site projects as oppose to two-part geopolymers that are suitable for precast projects [21],[20].

Alkali activated binders could be categorized into two main groups, including high calcium (slag) and law calcium binders (fly ash type F or metakaolin) [13]. Blasted furnace slag (BFS) is known as a matter with cement-like properties, which is inexpensive and available in most cases. It could be used in the industry as a binder for concrete or mortar when it becomes activated in combination with an alkaline solution with high PH [22]

2.3 Setting mechanism and activation process

Blasted furnace slag (BFS) is regarded as a high calcium binder that is developed and utilized in the recent century. The motivation for research and development in this field in the past decades resulted in new methods for optimizing the activation conditions. Therefore the production of a highly efficient alkali-activated concrete faced a new revolution [21].

A combination of BFS with water in the absence of an alkali activator breaks down the slag particles. However, a useless layer of $Ca_2{}^+$ covers the particles and prevents them from further chemical reactions. If the PH-value is increased enough, this cover breaks down, and the chemical reactions continue. As a result, this is the alkaline's role in increasing the OH^- ion in the solution, which consequently increases the PH-value. In other words, the cover on slag particles is created in the existence of water that results in the restriction of hydration in the further procedure. Thus, it needs an alkaline solution to break down this cover. Glukhovsky and Krivenko built up a model to describe the alkaline material that contains a high amount of silica and lime, such as slag with chemical reactions bellow.

$$= Si - O^- + R^+ == Si - O - R \tag{2.1}$$

$$= Si - O - R + OH^- == Si - O - R - OH^- \tag{2.2}$$

$$= Si - O - R - OH^- + Ca^{2+} == Si - O - Ca - OH + R^+ \tag{2.3}$$

In these chemical equations, alkaline cation R^+ acts as a catalyzer in first levels of hydration in reaction with calcium ion Ca^{2+} [23]. Figure 2.3 is a model that illustrates the mechanism for the chemical reaction in alkali-activated slag.

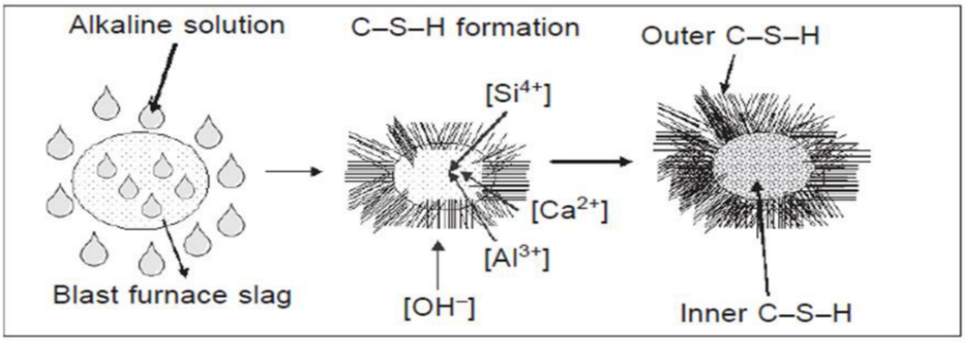


FIGURE 2.3: The mechanism for the chemical reaction in the alkali-activated slag [9]

The main output for the hydration process of Portland cement is a gel with a structure consist of C-S-H in which the proportion of C/S is approximately 2. It affects the mechanical properties of concrete, and the secondary products of this reaction are calcium hydroxide plus calcium monophosphate [16]. The process in alkali-activated binders is similar to Portland cement. However, when it is an alkali-activated procedure, the outputs are hydrated calcium silicate in addition to aluminum (C-A-S-H gel). This gel in the alkali-activated procedure is slightly different from the Portland cement (a smaller proportion of C/S).

One of the secondary outputs of alkali activated slag reaction are AF_m and hydrotalcite which is a natural mineral with a chemical structure consisting of brucite layers ($Mg(OH)_2$) in addition to water and CO_3 ions. These crystals are widespread along with the C-A-S-H gel. The chemical structure and combination of C-A-S-H gel depend on the amount of activator, the chemical structure of slag, and curing conditions. Table 2.1 demonstrates some conventional products of Portland cement reactions in comparison with products as a result of high and low calcium reactions [23].

TABLE 2.1: A comparison between chemical reaction in OPC and systems with high and low proportion of calcium [23].

Binder type	OPC	Alkaline cement	
Primary	$C-S-H$	Na_2O-CaO $-Al_2O_3-SiO_2$ $-H_2O$	$Al_2O_3-SiO_2$ $-H_2O-Na_2O$
Secondary	, AF_m, AF_t $Ca(OH)_2$	$C-A-S-H$ Hydrotalcite, $[Mg_6Al_2CO_3$ $(OH)_{16} \cdot 4H_2O]$, $C_4AC_8Ac_8H_{24}$	$N-A-S$ Zeolites Hydroxysodalite, Chabazite, Zeolite
$C=CaO, S=SiO_2, A=Al_2O_3, N=Na_2O,$ $H=H_2O, C=CO_2$			

2.4 Effective parameters on alkali-activated binder characteristic

The type of used slag, the alkali activator, and the curing procedure directly affect the characteristic of the binder used in concrete or mortar. Each parameter is going to precise separately below.

2.4.1 Types of slag

Slag is a byproduct or wastage in the industry. Melted slag becomes created in the heating furnace during the process of steel production. This byproduct is used in different industries such as asphalt, refractory material, railway, and concrete.

As mentioned, the chemical composition of slag is depended on the furnace type and the metals which are used to produce steel in the production process. Table 2.2 represents typical percentages for constituent oxides of slag [23].

TABLE 2.2: typical percentages for constituent oxides of slag

SiO_2	$27-40$	Cr_2O_3	$0.003-0.007$
CaO	$30-50$	$Na_2O^+K_2O$	$1-3$
Al_2O_3	$5-33$	MnO_2	< 2
MgO	$1-2.1$	P_2O_5	$0.02-0.09$
Fe_2O_3	< 1	TiO_2	< 3
S	< 3	-	-

According to researches, the slag could be appropriately used in alkali-activated concrete or mortar, if the ratio of CaO to SiO_2 is between 0.2 to 0.5 and the ratio of Al_2O_3 to SiO_2 is 0.1 to 0.6. This condition is regardless of the chemical composition of slag [24]. Some scientists define the hydration modulus in order to assure that the hydration can occur completely. For this purpose, hydration modulus (equation 2.4) should be more than 1.4 [25].

$$HM = \frac{CaO + MgO + Al_2O_3}{SiO_2} \tag{2.4}$$

Considering that slag is a byproduct in the industry, its chemical and physical characteristics can differ in different situations. Moreover, it has different crystal structures depending on the cooling process. This characteristic affects the slag's compatibility for use in the concrete industry. The alkali activator can also influence the quality of slags participation in concrete chemical reactions [13].

The main required characteristics of slag for using in the alkali-activated binder are as below:

1. Being ground, granular, and having more than 85-95 percentage of the crystalline phase.

2. Having a lower polymerization degree that results in higher hydraulic activity. The polymerization degree depends on the geometrical structure of SiO_4, Al and Mg components in the crystalline phase.

3. Having alkaline characteristics or the ratio of $CaO + MgO/SiO_2$ more than 1. Because of a high amount of lime in the chemical composition of alkaline slag, it has a high hydraulic potential.

4. Having a specific surface of 400 – 600 m^2/kg. The specific surface of a matter can affect the rate and intensity of activation reaction [13] ,[19].

GGBFS is commonly used in combination with fly ash type F in one-part geopolymer compositions. This type of slag can improve the chemical reactivity in low calcium fly ash [19].

It is also proved that the smaller size of particles in the slag results in higher compressive strength in concrete or mortar [26]. Researches illustrate that the existence of gypsum in the composition of slag can result in a negative influence on its elastic modulus and bond strength [27].

2.4.2 Effect of alkali activator

The function of GGBFS binders is considerably dependent on the nature and type of alkali activator. The alkali activator acts as a solution in the reaction. However, it could be used in the solid phase and in the shape of powder in addition to slag [28]. The alkaline resource (activator) could be a combination of a one-part geopolymer that consists of alkaline cations (such as Na, K, Li) and results in an increment in the PH-value of chemical reaction [16]. The solid alkali activators which are commonly used in one-part geopolymer compositions consist of:

$Na_2 SiO_3$,Na_2CaO_3,$Na_2 SiO_3 \cdot 5\,H_2 O$,$NaAlO_2$,$CaSO_4$, $Na_2 SO_4$,KOH,NaOH

In general, the activators that are used for high calcium binders such as slag could be alkaline hydroxides, alkaline silicates, or a combination of them. Poorly acidic salts such as R_2CO_3, R_2F or RF (which R is alkaline ion) or strong acidic salts such as Na_2SO_4 or $CaSO_4 \cdot 2\,H_2O$ are also able to act as alkali activators in high calcium systems [13]. Alkaline hydroxides (especially NaOH) are considered as more effective activators for GGBFS [23].

Sodium silicate acts as both roles of alkali activator and inducer in the formation of the primary gel. When silicate solution consisting Ca^{2+} reacts with the slag, the hydrated calcium silicate gel forms. The products of this chemical reaction have high strength, and at the same time, considerable shrinkage and short setting time. According to slags essence, the size of particles and curing conditions, the optimum amount of Na_2O is estimated about 4% of slags weight and the ratio of SiO_2 to Na_2O for acidic slags must be 0.75-1.25, for alkaline slags must be 1-1.5 and for neuter slags must be 0.9-1.3 molar [29].

A research in 2018, evaluates the effect of alkaline solution density and sodium silicate on alkali-activated concrete, proved that raising the sodium silicate modulus and density of the alkaline solution, results in an incrimination in Slump, compressive strength and drying shrinkage and reduction in setting time [30].

It is necessary to consider all various aspects of the chemical reaction in order to use alkali activator in the solid phase. As an instance, NaOH is a corrosive matter which absorbs the moist (hygroscopic) and changes into sodium carbonate in adjacent with

CO_2. Nowadays, NaOH is produced as a result of the alkaline chlorotic process which is known as a tough and expensive procedure because Cl_2 (as a requirement for this procedure) has a limited global market [9].

Kim and his team found CaO as a more effective activator in comparison with $Ca(OH)_2$ for GGBFS. However, CaO results in higher hydration heat in practice [31].

Dehydrated solid metasilicate (Na_2SiO_3) which is used as an activator in one-part geopolymer that consists of fly ash and GGBFS, results in better compressive strength and workability that hydrated metasilicate ($Na_2 SiO_3 \cdot nH_2 O$).

In a one-part geopolymer composition with existence of fly ash, increasing slag, results in a longer setting time [32]. Yang's experiments showed that setting process for alkali activated GGBFS is slower when he used solid phase of activator [33].

2.4.3 Curing process

The curing process for alkali-activated mortar or concrete based on the mix design, aluminosilicate sources, and other factors can occur in room temperature (25°C) or high temperatures (40°C to 80°C)

Suwan and Fan proved that the generated heat in the solubilization of solid activators in one-part geopolymers has a considerable effect on the curing process [34].

An experiment on one-part geopolymers done by Peng and his team has shown that 3-day curing in 20°C results in lower compressive strength for a specimen after 28 days in comparison with a curing process in the same condition but in 80°C [35].

Generally, the thermal curing results in higher initial strength in geopolymers [9]. In addition to thermal conditions, moisture can be another effective factor that should be considered during the curing process. In most cases, researchers prefer to wrap up the geopolymer concrete specimen in order to prevent losing water, which can result in tiny cracks on the specimens and reduce the compressive strength [36].

The generated heat in hydration of one-part polymers can cause in losing water, and it increases the necessity to wrap the specimens to prevent in losing more water [9].

According to research done by Talling, increasing the temperature up to 50°C for 7 hours during the curing process leads to a noticeable improvement in the compressive strength of activated slag with sodium silicate [37].

Behfarnia and Shahbaz, in 2018, made an investigation about the effect of high-temperature curing process on the physical characteristics of alkali-activated slag concrete. In this investigation, they studied on alkali-activated slag concrete specimens after 7, 28, and 90 days of curing in 20°C, 200°C, 400°C, 600°C and 800°C. The results showed a considerable increment in bond strength for specimens in higher curing temperatures in comparison with regular concrete [38].

2.5 Durability in concrete structures

Structural durability means the structure's lifetime with efficient serviceability. In the past, engineers and designers considered the compressive strength of concrete as the only factor which is effective in the quality and durability of structures. However, environmental conditions can act as an effective factor in quality and an efficient lifetime of structures. In other words, in a destructive environmental condition, the concrete hurts in a shorter period than regular useful service life. Premature failures in the structures as a result of destructive environmental conditions could be considered as meaningful evidence for the necessity of concrete durability. This issue in infrastructures like dams, tunnels, bridges, or powerplants, which need to have a long service life and with the expensive cost of repair and maintenance, bolds as particular importance. Although, concretes with high compressive strength regularly have higher resistance against physical and chemical attacks in destructive environments, the other factors such as permeability and congestion in concrete can directly affect the durability and quality of concrete [39]. Generally, concrete destructive factors can be categorized in external and internal factors.

External factors such as:

1. Physical factors: Freeze/thaw cycle, temperature changes, humidity percentage
2. Chemical factors: Sulphate attacks, acidic attacks, carbonation
3. Mechanical factors: Abrasion, erosion, spoilage in hydraulic structures

Internal factors such as:

1. Alkaline reactions in aggregates
2. Existence of minerals in concrete components
3. Permeability of concrete [40]

2.5.1 Sulfate attack

The chemical reactions between sulfate ions and cement hydration productions are called sulfate attack, which can directly threaten the durability of concrete in aggressive environments. Sulfate ions could be found in the sea, groundwater, soil, and wastewater [41]. The reactions mentioned above could lead to crack, crush, softening, expanding, and weakness in the strength of concrete [42].

Sulfate attacks are categorized into two main groups:

1. **Internal sulfate attack (ISA):**

Internal sulfate attack occurs when the amount of sulfate in concrete components like cement, aggregate, chemical admixtures, or water significantly increases. The internal sulfate attack leads to:

- Delayed ettringite formation (DEF): the formation of ettringites after the concrete becomes hardened, causes expansion and results in cracking in the concrete.
- Decomposition and deformation of ettringites and as a result unsuitable condition in the curing process
- Increasing the deformation of ettringites results in increasing cracks and making free spaces around aggregates [43].

2. **External sulfate attack (ESA):**

   External sulfate attack is a result of the chemical reaction between cement paste and the sulfates existing in the soil. This chemical reaction could be a consequence of high permeability in the concrete and high level of moisture and sulfates in the soil. Moreover, External sulfate attack leads to cracking, crushing, and weakness in compressive strength. This sulfate attack can be as a result of chemical reactions below:

3. Sulfates in reaction with hydroxide calcium (CH) and cement paste (C-S-H), forms gypsum:

   $\mathrm{CH} + \mathrm{C{-}S{-}H} + \mathrm{SO_4}^{2-} + \mathrm{H_2O} \longrightarrow \mathrm{C}\tilde{S}\mathrm{H_2}$

   Which $\tilde{S}$ means SO_4^{2-} [44].

   As presented in chemical equation below, the existence of sodium sulfate in adjacent of calcium hydroxide in the concrete generates magnesium hydroxide and gypsum:

   $\mathrm{Ca(OH)_2} + \mathrm{MgSO_4} + 2\,\mathrm{H_2O} \longrightarrow \mathrm{CaSO_4} \cdot 2\,\mathrm{H_2O} + \mathrm{Mg(OH)_2}$

In 2002, Sanathnam and his team made an investigation on concrete specimens adjacent to magnesium sulfate. They saw a layer of magnesium hydroxide forms on the specimen's surface immediately after the existence of magnesium sulfate [45].

In the case of the existence of magnesium sulfate ions, the chemical reaction above continues until all calcium hydroxides existing in the concrete changes to calcium sulfates. Reduction in calcium hydroxide results in a reduction in PH-value. Moreover, the durability of the cement gel is depended on the presence of calcium hydroxide. Thus, some parts of the cement gel should be decomposed to produce some calcium hydroxide and increase the PH-value. In conclusion, this procedure leads to decomposing the cement gel and weakness in concrete strength [45].

Among various types of sulfates, such as magnesium sulfate, sodium sulfate, and calcium sulfate, sodium sulfate has the most destructive effects on the concrete.

- Sulfate attacks to calcium aluminate hydrates $C-A-H$ and $C_3A.C\tilde{S}_{12-18}$

  $$\mathrm{C_3\,A \cdot C\tilde{S}_{12-18}C-A-H + SO_4{}^{2-} \cdot 2\,H_2\,O + H_2\,O \longrightarrow C_3A \cdot C\tilde{S}H_{32}}$$

  In this reaction, ettringite is generated, which expands and results in cracking and crushing in the concrete.

- The reaction below illustrates how thymocytes generate as a result of sulfate attack to calcium hydroxide (CH) and cement gel:

  $$\mathrm{CH + C-S-H + SO_4{}^{2-} + CO_3{}^{2-} + H_2O \longrightarrow CS \cdot CS \cdot CCH_{15}}$$

  The existence of thymocytes results in compressive and bond strength and can also lead to the softening of concrete. This reaction occurs in high humidity and low temperature [46].

Research in 2002 on the chemical resistance of alkali-activated slag mortars with various kinds of activators proved that sulfate resistance of these mortars is depended on the nature of activator, which is used in the mix design. Slag mortars that are activated with sodium hydroxide due to their high ratio of Ca to Si in comparison with slag mortars, which are activated with sodium silicate, are more sensitive to sulfate attack [46].

Bakharev and his team in 2002 investigated alkali-activated slag concrete in the condition of sulfate attack with ASTM C1012 standard. These specimens were immersed in 5% sodium sulfate solution and 5% magnesium sulfate solution for 12 months, the same condition was applied on an OPC concrete but for 60 days. Figures 2.4 and 2.5 illustrates that the strength development was the same in both environments. However, after that, weakness in strength was more significant in OPC in comparison with alkali-activated slag concrete. After 12 months in sodium sulfate, the alkali-activated slag concrete had a 17% weakness in strength; however, in OPC, this weakness development was about 25%. In magnesium sulfate after 12 months, the weakness for alkali-activated slag concrete was about 23%, but OPC concrete was about 37% of initial strength.

As mentioned above, OPC concrete in the existence of sodium sulfate generates ettringite. These specimens in the existence of magnesium sulfate generate ettringite in addition to gypsum. Alkali activated slag specimens with adjacent of sodium sulfate, were out of ettringite or gypsum. However, these specimens adjacent to magnesium sulfate produced gypsum. The generated gypsum causes cracks on the edges of specimens. It leads to the softening of concrete in the existence of magnesium sulfate [47].

Rodriguez and his team in 2008 made an investigation on sulfate resistance of alkali-activated slag concrete and OPC concrete. Their results proved that after 90 days, the

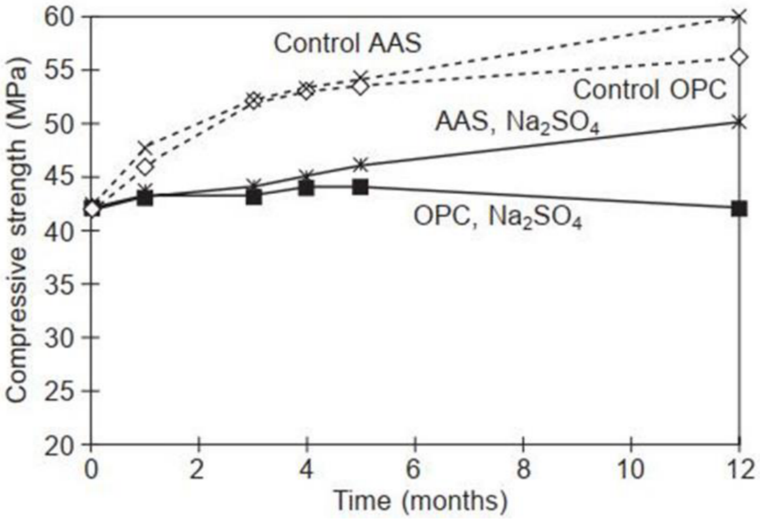


FIGURE 2.4: compressive strength in the OPC and AAS specimens exposed to the sodium sulfate solution [47]

compressive strength of alkali-activated slag concrete, which was in adjacent to 5% sodium sulfate solution, remains constant as oppose to OPC concrete in which the compressive strength drops for about 43% in same conditions [48].

Komljenovic and his team in 2013 studied on alkali-activated slag concrete in comparison with binders that are made of slag and cement. They showed that alkali-activated slag concrete has more resistance against 5% sodium sulfate solution [49].

Heikal and his team in 2014 found out that alkali-activated slag concrete, which is activated with sodium silicate after 180 days in adjacent to 5% sodium sulfate are more durable in comparison with OPC concretes [50].

Mostofinejad in 2016 made a study on the effect of sulfate environments on concretes, which consist of micro silica, slag, and limestone powder. The results show that when he substituted cement with 10% of micro silica, the resistance of concrete against magnesium sulfate environments reduced [51].

In 2018, Cho and his team investigated alkali-activated geopolymer mortars based on fly ash and slag in two environments, such as sodium sulfate and magnesium sulfate. They used sodium hydroxide and sodium silicate solutions where slag was substituted with fly ash in 0, 30, and 50%. The curing process took 24 hours at 23 and 70. After warm curing, they immersed the specimens at 23 cconstant and 60% of moisture for 28 days

Figures 2.6 and 2.7, show the increment in the mass of specimens depends on the type of sulfate solution where the specimen is immersed. The most increment in the mass of specimen was 1.8% in sodium sulfate solution, which is for the specimen with 100% of fly ash. On the other side, with increasing the proportion of slag, the increment in

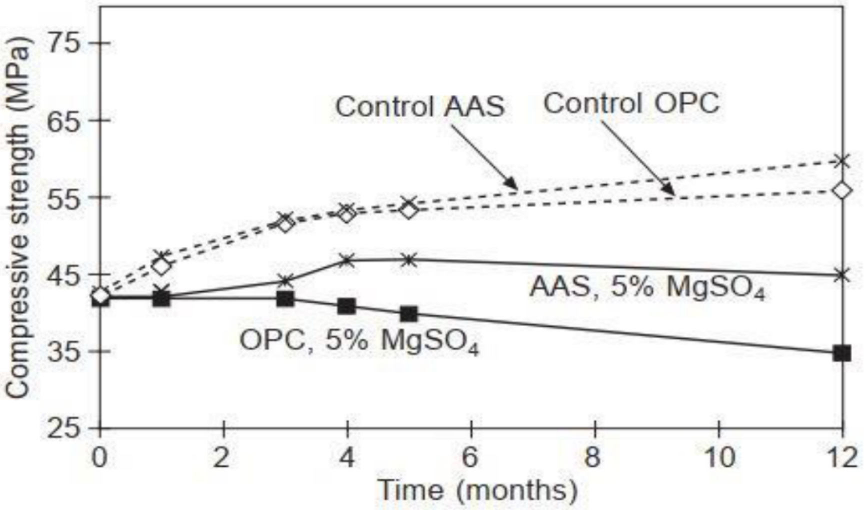


FIGURE 2.5: compressive strength in the OPC and AAS specimens exposed to the sodium magnesium solution [47]

mass decreased, and in magnesium sulfate solution, increasing the proportion of slag results in increasing the mass.

Figures 2.8 and 2.9 show that increasing the proportion of slag in sodium sulfate environment results in increasing compressive strength as oppose to a magnesium sulfate environment, which drops the compressive strength in the specimens. Increasing the mass and decreasing in the compressive strength in magnesium sulfate solution is a result of forming gypsum and brucite in the chemical reactions [52].

2.5.2 Acidic attack

Concrete structures are commonly adjacent to groundwater, industrial wastewater, and acidic rains. Thus, acidic resistance of concrete could be an essential characteristic that affects its performance in practice [53]. OPC concrete cannot perform acceptable behavior in acidic environments [40]. Besides, the aggressive acids which are exposed to the concrete are in a wide range of variety. All acidic solutions have PH-value under seven and they are also categorized in organic (weak acids) and mineral acids. Nitric acid (HNO_3), Hydrochloric acid (HCL) and sulfuric acid (H_2SO_4) are the primary mineral acids that are so dangerous for concrete and can directly affect the durability of concrete [54]. Sulfuric acid is one of the most harmful acids as it can affect the concrete as both acidic and sulfate aspect of its characteristics which can double the problem. Destruction of sewage concrete pipes due to sulfuric acid attack is a global problem [55]. The chemical reactions below illustrate how corrosion happens in concrete in the existence of sulfuric acid:

$Ca(OH)_2 + H_2SO_4 \longrightarrow CaSO_4 \cdot 2\,H_2O,$

$CaSiO_2 \cdot 2\,H_2O + H_2SO_4 \longrightarrow CaSO_4 + Si(OH)_4 + H_2O,$

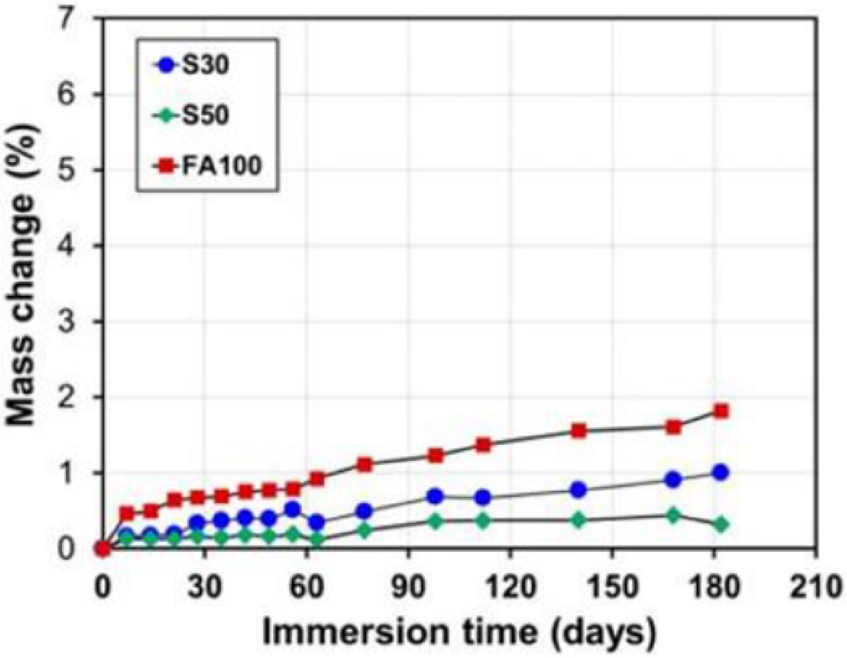


FIGURE 2.6: Specimens exposed to magnesium sulfate solution [52].

$$3\,\mathrm{CaO}\cdot\mathrm{Al_2O_3}\cdot 12\,\mathrm{H_2O} + 3\,(\mathrm{CaSO_4}\cdot 2\,\mathrm{H_2O})$$

$$+\,14\,\mathrm{H_2O} \longrightarrow 3\,\mathrm{CaO}\cdot\mathrm{Al_2O_3}\cdot 3\,\mathrm{CaSO_4}\cdot 32\,\mathrm{H_2O}$$

Gypsum, as the first production of this reaction forms on the surface of concrete it can result in tension stress and cracking in the concrete. This layer of gypsum can cover the surface of concrete and reduce the corrosion speed [56]. On the other hand, this gypsum on the concrete can react with calcium aluminate and generate ettringite, which leads to an increment in volume up to 7 times in gypsum. It can lead to forming micro and macro cracks in the concrete [57].

In 2003, Bakharev and his team studied on corrosive effects of acetic acid solution (PH=4) on alkali-activated slag concrete, and OPC concretes. The results showed a weakness in the compressive strength of about 47% in OPC specimens and 33% in alkali-activated slag specimens after immersion in an acidic solution for 12 months in comparison with immersed specimens in the water. It proves that alkali-activated slag concrete restrains better against acidic attacks in comparison with OPC concrete. This result is because of a smaller ratio of Ca to Si in slag paste [58].

A study in 2005 on the resistance of binders with fly ash and activated slag against acidic corrosion has been done. In this study, after 28 days of curing, the pastes were immersed in sulfuric acid with different PH. The alkali-activated slag and fly ash in the acidic environment with PH=1, formed a crushed and hardened corroded layer. In the environment with PH=2, this corroded layer was stiffer with tiny cracks. In

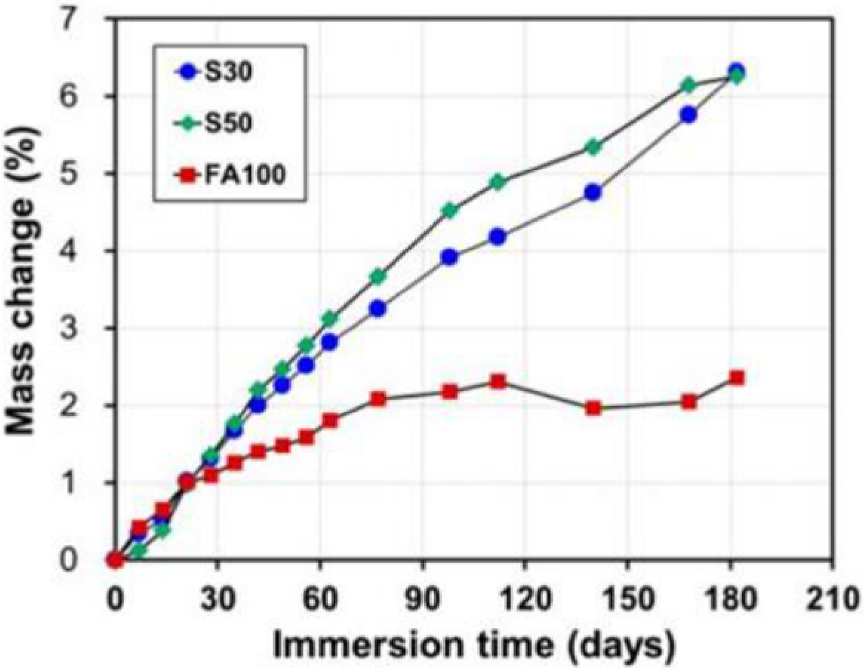


FIGURE 2.7: Specimens exposed to sodium sulfate solution [52].

the environment with PH=3, a soft layer formed, which can be removed easily. Researchers checked the specimen after curing in the environment with PH=2 under the microscope, and they saw gypsum crystals in the corroded layer [59],[60]. The researchers concluded that the deposited gypsum in the corroded layer leads to covering the concrete and disturb the destruction process with acidic solution [23].

In 2012, Bernal and his team made another investigation on the resistance of alkali-activated slag mortars and OPC mortars against acidic attack. They made specimens and immersed them in hydrochloric acids, nitric acids, and sulfuric acid solution with PH=2. They found an insignificant change in the strength of alkali-activated slag mortars in the existence of mineral acids. They even showed a noticeable increase in compressive strength in adjacent of nitric and sulfuric acids (figures 2.10 and 2.11) [61].

Granero and his team in 2016 did some experiments on the durability of alkali-activated material against sulfuric acid. The alkali-activated material was GGBFS and type F fly ash. They also used OPC as a reference mix design. In OPC specimens, they saw a reduction in both mass and size; however, in alkali-activated slag specimens, they saw an increment in both mass and size. They also saw the formation of gypsum as a corrosion production in both OPC and alkali-activated slag. Besides, there was nothing changed noticeably in the mass and size of alkali-activated fly ash specimens [62].

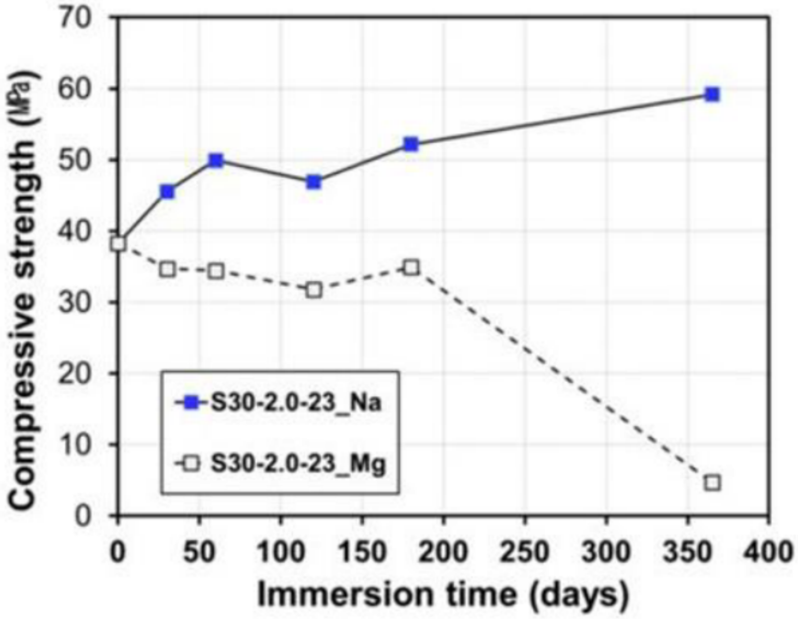


FIGURE 2.8: compressive strength with 50% of slag [52].

Rao and Madhuri, in 2018, used a composition of sodium silicate and sodium hydroxide for activating slag in alkali-activated slag concrete and studied on their resistance against sulfuric acid in comparison with OPC concrete. As a result, mass reduction and permeability were significantly lower than OPC specimens. On the other hand, alkali-activated slag specimens showed less weakness in compressive strength in comparison with OPC concrete.

2.5.3 Permeability

The resistance that a concrete show against external destruction factors such as water, air, chemicals with high and low PH-value, external gases such as corrosive or non-corrosive, is called the impermeability of concrete. As these factors are external, but they need to penetrate the concrete to act as an effective attack. Thus, permeability is considered a noticeable factor in the durability of concrete.

Concrete is known as a permeable and porous material. On the other side, water as the most crucial solution which exists in most chemical reactions is considered as a significant destructive factor for permeable materials. Tiny pores and internal cavities are called the porosity of a material, which is commonly calculated as a percentage of the total volume of the concrete [38].

The porosity of concrete and the carbonation around the rebars can make the reinforcement sensitive to corrosion with the existence of chloric ion [63].

The carbonation process is a result of CO_2 penetration as a negative factor for concrete. A tiny layer of oxide covers the external surface of the concrete, which prevents

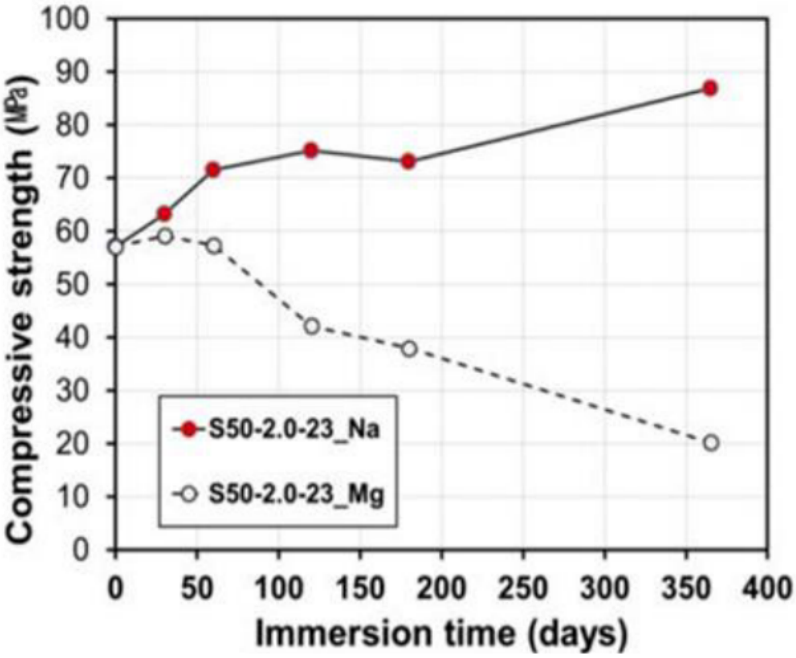


FIGURE 2.9: compressive strength with 30% of slag [52].

corrosion. This layer remains even in high alkaline environments (PH=13). However, during carbonation, this PH-value reduces to less than nine and simplifies the corrosion process of reinforcement [64].

The carbonation is a result of the chemical reaction between Co_2 and water. This reaction produces carbonic acid. Then, this weak acid reacts with productions from hydration and reduces the alkaline of concrete [65]. This chemical reaction is demonstrated below:

$CO_2 + H_2O \longrightarrow H_2CO_3$

$Ca(OH)_2 + H_2CO_3 \longrightarrow CaCO_3 + 2\,H_2O$

$C-S-H + H_2CO_3 \longrightarrow CaCO_3 + SiO_2 \cdot nH_2O$

The most effective factor in rustiness and corrosion in concrete is the chloride ions. These ions can exist in aggregates or admixtures or external mater like seawater. For activating the corrosion process in rebar, the concentration of chloride ion must exceed the allowable amount. The required concentration of chloride ion for activating the corrosion process depends on the PH-value in the cement paste. The corrosion can even begin without the existence of chloride ion in the PH-value of less than 11.5. However, for PH-value of higher than 11.5, the existence of chloride ion is necessary. When the amount of chloride ion exceeds the allowable concentration, the protective layer on the rebar disappears. In the next step, the iron ions react with chloride ions and produce $FeCl_2$. This product reacts with water and changes to unstable hydrochloric acid. The unstable acid leads to decreasing PH-value and decomposes to

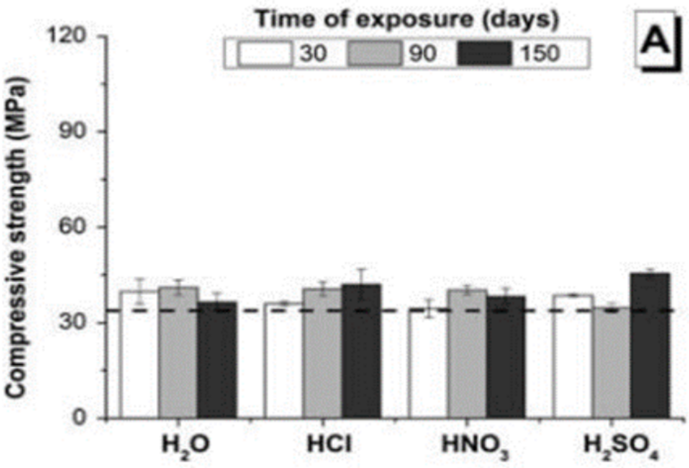


FIGURE 2.10: compressive strength of OPC mortars [61].

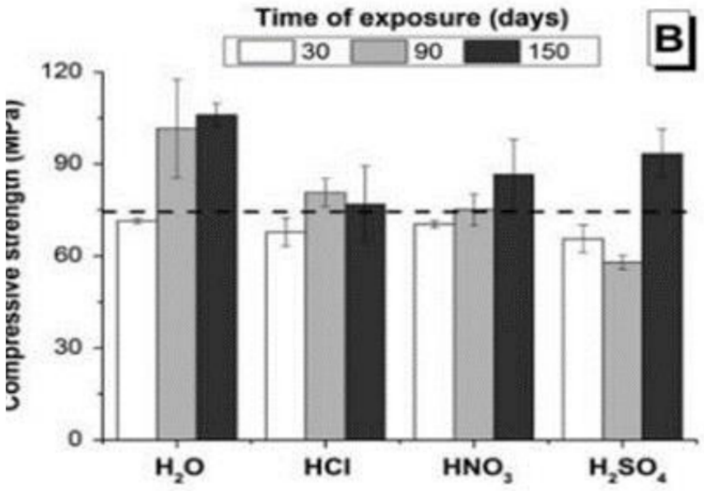


FIGURE 2.11: compressive strength of AAM mortars [61].

chloride ions. Furthermore, the produced chloride ions repeat this procedure to making a loop, which leads to the corrosion of rebars [66].

An investigation by Pu and his team proves that the characteristics and structure of alkali-activated concrete depend on the characteristics of the alkali activator [67].

2.6 Conclusion

In this chapter, we made an overview through the studies and experiments from the past, which are relevant to the alkali-activated binders, alkali-activated slag concrete, and valid parameter in the durability of concrete in different situations. It is also explained that the solid sodium metasilicate is the most frequent ingredient in the production of one-part alkali-activated binders. Besides, alkali-activated binders' durability properties are directly dependent on the sulfate solution, which is used. Moreover, using micro silica and polypropylene improves concrete durability.

In chapter 3, the experiment process, materials, equipment, mix designs, and the standards used during the investigations are going to discuss.

Chapter 3

Methods

3.1 Introduction to program method

In this chapter, the materials and their properties, mix designs, types of specimens, curing process, equipment in the laboratory, and standards are going to discus. Evaluating the physical and mechanical properties of the material is considered as a rational way to evaluate the characteristics of the produced mortar or concrete. Fine aggregates, slag (GGBFS), cement, water, potassium hydroxide, sodium silicate, and micro silica powder are the primary use material in this investigation.

In order to evaluate the functionality of two-part alkali-activated slag mortar, it is intnded to figure out the optimal percentage of silica powder concerning a fixed portion of other components such as activators. Thus, it is necessary to compare the workability, setting time, bond and compressive strength in different mix designs with different amounts of silica powder and also in comparison with a reference mix design with OPC as the regular type of binder.

3.2 Material

In this section, all material and components in the mortar will be explained precisely. The sources, types, and standards, which are the essential information for recognizing the material, are also going be discussed.

3.2.1 Fine aggregate

Stone material or aggregate comprises 70 to 80 percent of the total weight in the concrete or mortar. Mortar includes just fine aggregate in which the particles become hardened in interaction with binder and acts as a primary role in mortar strength.

Although using more and more aggregate can be advantageous in the economic aspects, the mix design must satisfy the expectations from the mechanical characteristics, workability, or other concrete properties.

According to standard ASTM C33, the aggregate which passes from sieve no. 4 (4.75 mm) and remains on the sieve no. 200 (0.075) is called sand. The sand, which is used in any mortar and concrete, should be free of any mud or pollution. The sand acts as a filler between gravel, which is known as aggregate with more significant dimensions. However, in the mortar, sand is the main and only aggregate, and there is no gravel as it is necessary to have a proper workability and ability to penetrate the cracks for mortars.

Table 3.1 illustrates the physical properties of the sand, which is used in this experiment, and were available at the University of Stavanger.

TABLE 3.1: Physical properties of the sand in use

Material	Fineness modulus	SSD (%)	Density (gr/cm^3)
Sand	3	0.95	2.64
Standard	ASTM C136	ASTM C128	ASTM C 128

3.2.2 Ground Granulated Furnace Slag (GGBFS)

Slag is a material that acts as the main component in an alkali-activated binder. Slag is a combination of silicates and metal oxides that is produced in the furnaces during the iron and steel production process. This byproduct can be used in various industries such as the slag cement industry, production of refractory materials, roads and highway infrastructures. The slag powder, which is used in this experiment, is Morex Merit 5000, with general properties that are illustrated in the table 3.2.

TABLE 3.2: General properties of the slag in use

Specific weight (kg/m^3)	Bulk density (kg/m^3)	Blain (cm^2/g)	Mleting (°C)
2920	600-1400	4600-5400	1350

3.2.3 Cement

In this experiment, there is a specimen as a reference that has the typical type of binder (OPC). It helps us make a better comparison between the characteristics of alkali-activated binder and the ordinary Portland cement. The cement in use in this experiment is Norcem Industrisement CEM I 52.5 R. The chemical and physical characteristics for this cement are illustrated in tables 3.3 and 3.4.

TABLE 3.3: Chemical components of the Cement in use

Chemical Components	Data	NS-EN 197-1:2011
SO_3 %	≤ 4.0	≤ 4.0
Cl^- %	≤ 0.085	≤ 0.10
Cr^{6+} ppm	≤ 2	≤ 2
Na_2O %	1.3	
Clinker	96	95-100

TABLE 3.4: Physical properties of the cement in use

Specific weight (kg/dm^3)	3.13	
Blain (m^2/kg)	550	
Compress. strength (MPa)	3 days	41
	7 days	50
	28 days	59
Setting time (min)	Initial	110
	final	?

3.2.4 Water

The water is used in the concrete industry for three main reasons:

1. Acting the main concrete component and necessary for the hydration process
2. Washing the aggregates, removing muds and pollutions
3. Curing the specimens and accomplish the hydration process

The quality of water is depended in the impurity which can affect the setting process directly. On the other hand, quality of the water which is used in the concrete is in direct contact with the rebars. Thus, impurities or minerals in the water can leads to corrosion in the reinforcements. The water we use for drinking which is without any taste or smell can be suitable for using in the concrete industry. However, non-drinking water in which the PH-value is between 5 to 8.5, in the concrete leads to 90 percent of compressive strength in the specimen with distilled water [68]. The consumed water in this experiment for all material washing, mix and curing process is the regular drinking plumbing water in the city of Stavanger.

3.2.5 Micro silica

Micro silica is a byproduct of furnaces from the silicon production process. This powder is mostly used for the concrete industry. The grains of this powder is 100 times smaller than cement, and it results in a more specific area. Micro silica is known as a perfect pozzolan because of the high amount of silica and high specific area. This mater also has a noticeable effect on the durability and strength of concrete structures.

The micro silica which is used in this experiment is from Elkem company, which has the physical and chemical characteristics illustrated in the table 3.5.

TABLE 3.5: Chemical and physical properties of the micro silica in use

Properties	Unit	Specification
SiO_2	%	>90
Retention on 45 sieve	%	<1.5
H_2O	%	<1.0
Bulk Density (U)	Kg/m^3	200-350
Bulk Density (D)	Kg/m^3	500-700

FIGURE 3.1: The micro silica in use.

3.2.6 Alkali activators

In this study, the furnace slag needs to become alkali-activated in order to accomplish the chemical process in the binder. The alkali activation is usually possible with a one-part or two-part activator, which is precisely described in previous chapters. Two-part alkali activator is used in this experiment, which consists of potassium hydroxide with the existence of sodium silicate.

It is also possible to use other kinds of alkaline such as sodium hydroxide instead of potassium hydroxide as it is just acting as a component that adjusts the PH-value in a chemical reaction with the second part of activator.

Potassium hydroxide (KOH):
Potassium hydroxide is a substance usually in the phase of solid with a density of 2.12 g/cm^3. The Potassium hydroxide can chemically react with the moist, which makes transportation very risky. Thus, it needs an isolated cover to prevent chemical reactions. Potassium hydroxide in react with water decomposes to its initial ions (K^+, OH^-). Table 3.6 elaborates the general properties of this mater.

TABLE 3.6: General properties of potassium hydroxied

chemical name:	Potassium Hydroxide	Appearance:	Solid,white
Other names:	Lye , Caustic potash	Density:	2.13 $gr/(cm^3)$
Chemical formula:	KOH	Melting point:	1088°C
Molar mass	65.11 gr/mol	Boiling point	1388 °C

FIGURE 3.2: The potassium hydroxide in solid phase.

In order to generate one litter of 8 molar sodium hydroxide solution, the equation 3.1 is used:

$$8mol/lit \times 56gr/mol = 448gr/lit \tag{3.1}$$

Thus, 448gr of potassium hydroxide is needed for one liter of solution. Then the potassium hydroxide and water are added gradually while shaking. It should be continued until all the sodium hydroxide becomes disappeared in the water. Next, the extra water is added to reach the volume of one liter for the solution. Adding a hydroxide to the water results in a chemical reaction that generates heat. In the end, the solution has to be left for about 24 hours and let it become the temperature of the room.

Sodium silicate (Na_2SiO_3):

This is a solvable alkali silicate which is also known as Water glass in the industry. Sodium silicate is usually available in the solid phase. However, it can be used in form of liquid solution in the industry during production process of detergents, cement, and casting. It is also used for peroxide stabilization process to prevent corrosion in the metal pipes and facilities. Tables 3.7 and show general properties and characteristics of the sodium silicate that is used in this experiment.

In the concrete industry, sodium silicate is used to shorten the setting time and improve the initial strength of specimens. One of the most critical properties of sodium silicate, which is used in the industry, is the molar ratio which means the ratio of SiO_2/Na_2O.

TABLE 3.7: General properties of sodium silicate.

chemical name:	Sodium silicate	Density:	1.54 gr/cm^3
Other names:	Glass Water	Molar ratio (SiO_2/Na_2O):	2.6
Chemical formula:	Na_2SiO_3	Melting point:	1088°C
Molar mass:	122.06 gr/mol	Boiling point:	1388 °C
Appearance:	powder or liquid	Percentage of H_2O:	46

FIGURE 3.3: Sodium silicate in liquid phase in use.

3.3 Experiments and equipment

Alkali activated repair mortar has many aspects that are worthful to be elaborated. However, this study is just focused on the consequences of using a various amount of micro silica on compressive and bond strength, workability, and the setting time. In order to evaluate any strength in the mortar, It is necessary to mold them for 24 hours, and after unmolding the specimens, the curing process will start for particular periods. On the other side, it is necessary to do the Vicat and the mini Slump tests immediately after casting to evaluate initial and final setting time and the workability. It is expected for the geopolymer binders to be fast hardener. In the following, all the experiments and the curing condition are going to be elaborated.

3.3.1 The mini-slump test

In concrete technology, the workability of concrete is measured by the experiment named slump Test. However, for mortars, one of the flow table or the mini-slump tests is used. According to ASTM C143, the procedure for the mini-slump test is as below:

First, place the Heidelberg measurement board or the base plate on a flat and horizontal surface free from external vibrational shocks. Check the top surface for the horizontality using a spirit level. Place the cone (Figure 3.4 shows the standard cone dimensions) centrally within the circle on the table. Then, fill the cone with fresh mortar immediately after mixing in a single operation without any mechanical compaction. Allow the cone to stand not more than thirty seconds and, during this time, remove any spilled concrete from the baseplate. Lift the cone vertically in a single movement. In the end, without disturbing the mortar or the table, measure the diameter of the flow in two perpendicular dimensions and calculate the average.

$$Flowdiameter = \frac{(D_1 + D_2)}{2} \tag{3.2}$$

3.3.2 The vicat test

This section elaborates on the method to evaluate the initial and final setting time in the mortar. The method is the vicat test in which, according to ASTM C191, it is possible to measure the standard consistency of mortar as well as setting time. The essential equipment for The vicat test is named below:

1. The standard Vicat apparatus which is a simple penetrometer with a variable sliding weight that can be attached to a needle

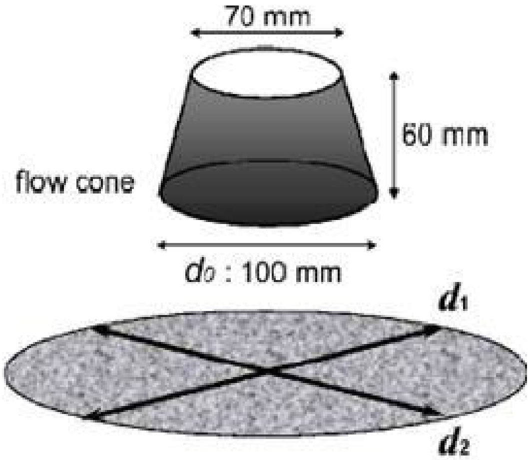


FIGURE 3.4: Mini slump test cone and diameters

2. Standard Vicat needles such as initial set needle, which is a blunt-ended cylinder needle of diameter 1.13 mm, a final set needle which is a cylindrical blunt-ended shape with a hollowed metal collar with a diameter of 5 mm. Figure 3.6 shows all types of standard vicat needles.
3. The cone that acts as the mortar container and should be located in the apparatus with the proper needle attached.
4. 4. The glass plate is located under the mold to provide a smooth surface under the cement paste (mortar).

FIGURE 3.5: Vicat test apparatus and its attachments

As mentioned in ASTM C191, the initial setting time is called to the duration from when the water becomes adjacent to the cement (binder) in the mixer until the time when the Vicat initial set needle penetrates 5 ± 1 mm to the mortar. To measure this time, turn the timer on while adding the water during the mixing process. When the mortar is thoroughly mixed, pour it into the Vicat mold and locate it under the needle fitted on the apparatus. Next, calibrate the needle to gently touch the top surface of the mortar in the mold. Then release the needle and measure the penetration depth. Pull up the needle, recalibrate to the surface over the top surface, and repeat the procedure to reach the desired penetration mentioned above and read the time from a timer.

The final setting time is called to the duration from when the water becomes adjacent to the cement (binder) in the mixer up until the time when the tip of the final set needle just marks the top surface of mortar but does not penetrate it. In order to measure this time, repeat the procedure above but with the proper needle (final set needle) and read the time at desired penetration again.

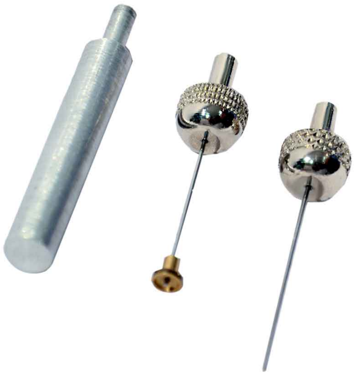


FIGURE 3.6: Vicat test needles

3.3.3 Compression Test

For the sake of evaluating the compressive strength of the mortar, $5 \times 5 \times 5cm^3$ cubic specimens are going to be used. Cubic specimens are going for compressive strength examination in the ages of 3, 7, and 28 days. According to ASTM C109-16a, the load must be applied by a $2000kN$ hydraulic compression jack with $0.5N/mm^2.sec$ of loading speed. Figure 3.7 shows the 5cm mold that is used in this experiment.

FIGURE 3.7: Cubic triple mold

3.3.4 Slant shear test

There are various kinds of tests to evaluate the bond strength of the mortars, and many investigations are done about it to compare them. However, to measure and compare the bond strength of each mix design in this thesis, the slant shear test is done in which a combination of both compression and shear stress applies to the interface between the mortar and concrete.

According to ASTM C882-13a, the specimens for slant shear test are in the shape of $10 \times 20cm^3$ cylinders consist of two layers, a bottom substrate layer which is made of ordinary equivalent concrete and the same for all specimens, and a layer of mortar made of the mentioned mix designs. The interface between these two layers makes an angle of 60 with the horizon. Figure 3.8 shows the shape and dimensions of slant shear test specimens.

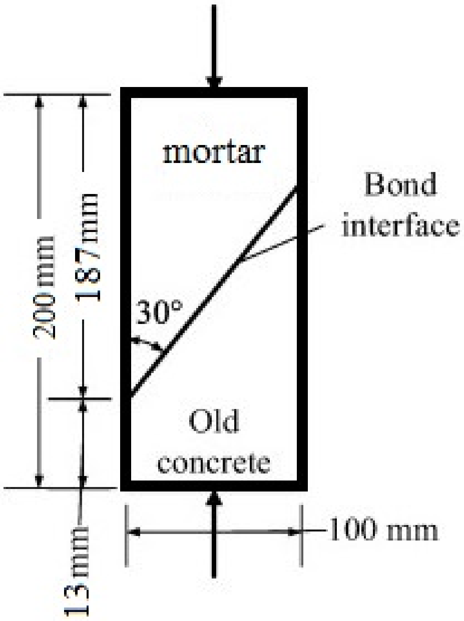
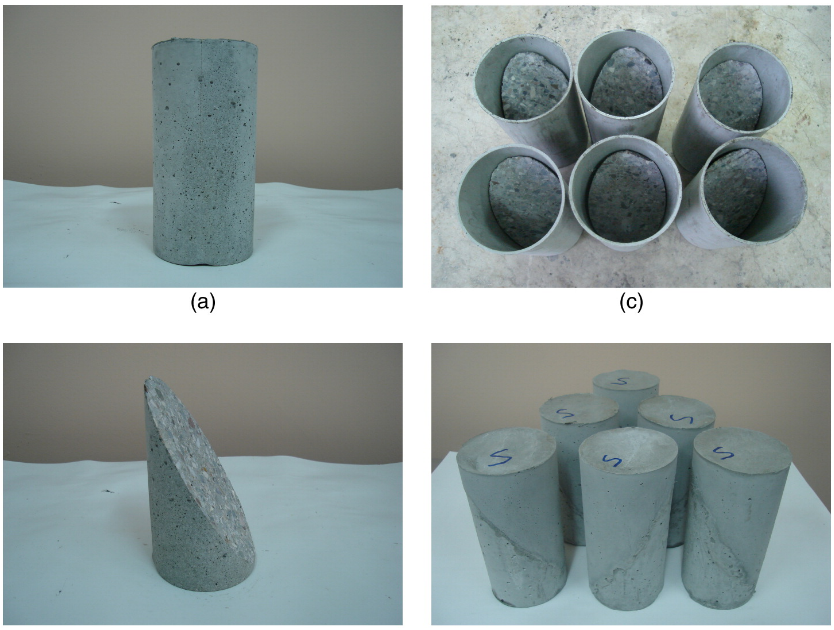


FIGURE 3.8: Slant Shear specimen dimensions

For making a smooth diagonal bond interface on the substrate layer with the desired angle, The whole cylinder mold is filled with OPC concrete. Thus, after unmolding, a full cylinder specimen made of concrete is obtained (figure 3.9 a). Now, the cutting machine is used to divide the cylinder from the diagonal interface. In this way, each concrete cylinder changes to two substrate layers with a smooth diagonal bond surface for the slant shear test (figure 3.9 b). After seven days of curing the substrates in the proper environment (the same environment where use for curing mortars), they have to be replaced in the mold again, which makes them ready to fill the free space of cylinder with mortars (figure 3.9 c and d).



(a) (c)

(b) (d)

FIGURE 3.9: a) Full cylinder concrete, b) concrete cylinder after cutting from the bond interface, c) putting the substrates in the mold again to fill them with mortars, d) unmolded specimens with two layers of substrate and mortar.

In this thesis, there are six mix designs, and it is necessary to break the slant shear specimens for 7 and 28 days of age. Thus, a total of 12 substrates is needed. It is necessary to mention that each substrate layer must be at the age of 7 days while casting each mortar mix design. After breaking the slant shear specimens, the compression machine shows a number as the applied force or the compressive load applied on the specimen. Thus, the Mohr-Coulomb relations are used to derive the shear and normal stress applied to the specimen. Figure 3.10 illustrates the Mohr-Coulomb circle adjusted to a slant shear specimen.

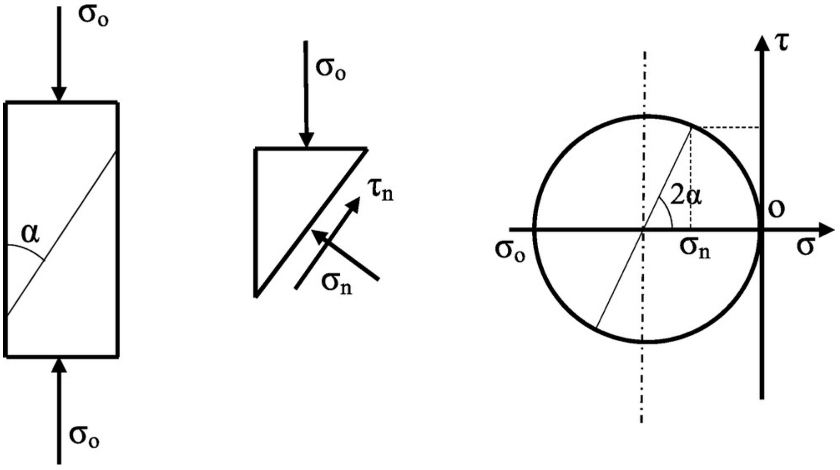


FIGURE 3.10: Mohr-coulomb circle adjusted to a slant shear specimen.

Equations 3.3-3.5 shows how to derive shear stress on the bond surface. In these equations, A is the cross-sectional area of the cylinder, F is vertical failure force, σ_n and τ_n are the normal and shear stress applied to the interface.

$$\sigma_0 = F/A \tag{3.3}$$

$$\sigma_n = \sigma_0 sin^2(\alpha) \tag{3.4}$$

$$\tau_n = 0.5\sigma_0 sin(2\alpha) \tag{3.5}$$

Chapter 4

Experiment procedure

4.1 Introduction to experimental procedures

In the previous chapter, the generality of the experiments required in this thesis is discussed, including material, specimens, equipment, and standards. In chapter 4, more details will be given, and the lab works will be precisely explained step by step.

For the sake of simplification, the experimental work procedure is categorize into three main steps:

1. Slant shear specimen preparation
2. Casting mortar and immediately-after tests
3. Breaking the specimens and saving the results

In order to get the accurate and trustable results in this study, it is necessary to accomplish all the main steps mentioned above in the concrete laboratory, writing down the results, and analyze them.

4.2 Slant shear specimen preparation

As discussed in chapter 3, the bond strength of mortar is evaluated with the slant shear test, in which the specimen consists of a substrate layer in the bottom and the mortar that covers the top. The first step to start the laboratory activity is to cast the substrate level in cylindrical molds and leave them in an appropriate environment for one week of curing. This level is made of a regular OPC concrete with a mix design that mentioned in chapter 3.

For six mix designs, 12 substrates (half of the cylinder) is needed. Thus, six cylindrical OPC concrete specimens with the same mix design are needed. The casting procedure which will be given in below has to be done in 6 consecutive days.

4.2.1 Mixing the material

In this step, the weight of coarse and fine aggregate, cement, and water for two litter of concrete will be measured. A Hobart mixer is used for blending material with the capacity for making five litter of concrete. Then, the fine and coarse aggregate is poured inside the blender for 2 minutes of mixing. After all the aggregates mixed up, the cement is added to the mixer for mixing all dry components for two minutes more. In the end, the water should be added to the mixer gradually while it is still blending.

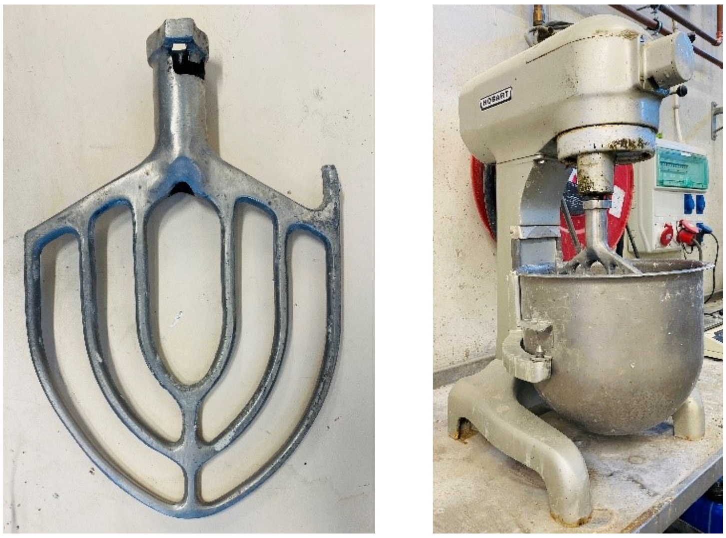


FIGURE 4.1: Habort mixer with blade

4.2.2 Casting into the molds

After mixing the concrete in the blender for 4 minutes, the mixer container has to dislocate near the mold. Next, the concrete is poured in four layers in the mold to become vibrated with the bar. This vibration helps to release the entrapped air bubbles in the concrete. In the end, the head of the mold is fixed, and then it is ready for curing for at least 20 hours at $20 \pm 5°C$ (room temperature).

It is necessary to mention here that each cylindric specimen of OPC concrete that are made are going to divide into two half-cylinders with a smooth interface. Each half-cylinder is going to use as a substrate for two slant shear specimens of a specific mortar.

4.2.3 unmolding, curing, cutting

20 to 24 hours later, the molds are removed, and the cylinder specimens are located in the water with appropriate properties for curing. Each specimen should be kept

in the water for one week to accomplish the curing process before cutting them and being used as a substrate.

FIGURE 4.2: Cutting machine ATM Brilliant 285

All the steps mentioned above have to repeat for six consecutive days. On day seven after casting the first specimen, the sixth specimen is unmolded, and then all six cylinders are ready for the cut. The cutting machine (ATM) is used to divide the cylinders into two substrate levels with the desired smooth interface. Figure 4.2 illustrates the cutting machine and how the cylindrical specimens are fixed to get the desire surface orientation.

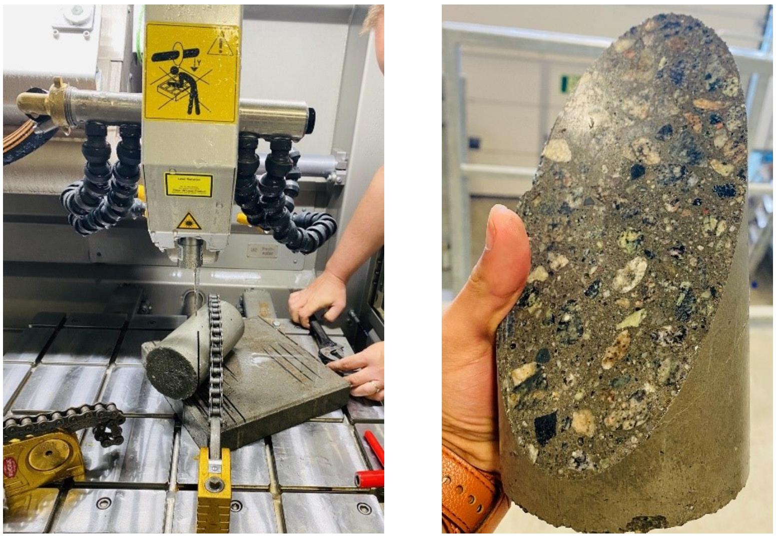


FIGURE 4.3: Cutting process and the cut specimen

4.3 Mix design

In this thesis, the goal is to figure out the optimum percentage of micro silica powder in alkali-activated repair mortars. It is explained that the two-part alkali activator is going to be used in order to activate the furnace slag (GGBFS), which is considered as the binder instead of ordinary Portland cement. For this purpose, two specimens are made as reference mix designs in which one specimen is with OPC as the binder without any kind of admixture or silica powder. The other one consists of slag and alkali activators (geopolymer mortar) but without any admixture or micro silica powder. Moreover, four slag-based mix designs help us to reach the proper insight in comparing characteristics of the mortar such as workability, initial and final setting time, and the strength for different percentages of silica powder. In these mix designs, the silica powder is going to vary substitutional from 5 to 20 percent of the base material (GGBFS). In the following, table 4.1 shows the reference mix designs in comparison with four geopolymer mix designs with different percentages of micro silica.

TABLE 4.1: All mix designs

Material	REF1	REF2	VAR1	VAR2	VAR3	VAR4
Cement(kg/m^3)	500	0	0	0	0	0
GGBFS(kg/m^3)	0	500	475	450	425	400
Micro Silica%	0	0	5	10	15	20
Micro Silica(kg/m^3)	0	0	25	50	75	100
Water(kg/m^3)	171	120	120	120	120	120
Fine agg.(kg/m^3)	1412	1412	1412	1412	1412	1412
KOH(kg/m^3)	0	40	40	40	40	40
KOH Conc.(M)	-	8	8	8	8	8
Sodium Sili.(kg/m^3)	0	100	100	100	100	100

4.3.1 Reference mix designs

The cement mix design (REF1) is just for the sake of comparison between geopolymer mortars and the ordinary mortar, which is used regularly and without any expectations for strength and characteristics. On the other hand, the second reference mix design (REF2) is a mix with the existence of alkali-activated slag as the binder but without any admixture or micro silica powder.

Moreover, the design in REF1 must be equivalent to the geopolymer mix design used in REF2. Two equivalent mix designs are the mix designs in which the water to binder ratio is equal. Thus, the w/c ratio in REF1 is equal to water/binder ratio in REF2. Equations 4.1 and 4.2 represents how to calculate the water/binder ratio in REF1 and REF2. Note that the binder weight in REF2 consists of the accumulative weight of

GGBFS, micro silica, and the solid part of activators. The liquid portion of activator solutions is specified in section 3.2.6.

$$REF1 : w/c = 171/500 = 0.34 \tag{4.1}$$

$$REF2 : w/binder = (120 + 28 + 46)/(500 + 12 + 54) = 0.34 \tag{4.2}$$

4.3.2 Alkali activated mix designs with micro silica

As it is represented in the table 4.1 there are four mix designs (VAR1-VAR4) with variable amounts of silica powder. It has to be emphasized that the sum of micro silica and the slag must be equal in all five designs with the alkali-activated binder.

4.4 How to mix material

The procedure will differ in REF1 with OPC binder in comparison with other mix designs with slag base binder. Thus, they will be explained in two separate sections to make it clear.

4.4.1 Cement base mix design

The mixing process in REF1 mix design will be as below:

1. Pour all the fine aggregate to the mixer and let it blend dry for one minute.
2. Add the other solid part of the mix design, which is cement, and wait for two minutes blending.
3. The water must be gradually added to the mixer and then leave it for seven minutes of blending.
4. The produced mortar is now ready for any immediately-after test or casting in the cylinder and cubic molds.

4.4.2 Slag base mix designs

The mixing process in REF2 and VAR1-VAR4 mix designs will be as below:

1. Pour all the fine aggregate to the mixer and let it blend them dry for one minute.
2. Add the solid part of the binder, which is GGBFS, gradually to the aggregate and let it blend for two minutes.
3. Add the micro silica (for VAR1-VAR4) to the mixer during two minutes blending of GGBFS

4. Add the alkaline solution (KOH) and sodium silicate (that are already mixed) and let it blend for one minute
5. Add the extra water to the mix gradually and leave it for blending in seven minutes
6. The produced mortar is now ready for any immediately-after test or casting in the cylinder and cubic molds.

4.5 Casting mortars and immediately-after tests

After cutting the cylinder on the seventh day after casting the first specimen, it is time to make the mortar and pour them on top of the substrates in the cylindric molds. Thus, the oldest half-cylinders are set in separate molds as substrate and located the others in the water for curing. As it is mentioned before, half-cylinders are going to use as substrates when they get at the age of 7 days.

4.5.1 Casting cement-based mortar

In this step, the weight of the material have to be measured as it is mentioned as the mix design REF1 in the previous chapter. since we are studying on mortars in this thesis, there is no coarse aggregate in the mix designs.

Next, the fine aggregate and cement (solid components of mix design) are poured in the mixer for 2 minutes blending. Then the water is gradually added, and while it continues mixing for 4 minutes more. After blending, the produced mortar is ready for the vicat and mini-slump test.

Finally, the rest of the mortar is poured in two cylindrical molds with a substrate half-cylinder layer in the bottom as well as a triple small cubic mold.

4.5.2 Casting slag-based mortars

This section is going to describe the casting procedure for slag base mortars (REF2, VAR1-4). According to the table 4.1, the variable parameter in these mix designs, is just the amount of micro silica powder. Thus, there is the same procedure for them except for the amount of micro silica. It is necessary to mention here that before starting with the casting procedure, it is necessary to make one liter of 8 molar potassium hydroxide solution as explained in section 3.2.6, and leave it for at least 24 hours to reach the room temperature.

First, the weight for all the material is measured according to the mix design, then the potassium hydroxide and sodium silicate are mixed to make a transparent solution. Then, the solid material like aggregates, slag, and silica powder (for VAR 1-4) is poured in the mixer for two minutes blending. Next, the activator solution is added to the mixer two minutes more blending. At the final step, the water is gradually added to the mixer while it is blending for four minutes. During this time, the blender speed is set at two to ensure that all material, especially the micro silica powder, is blended all over the mortar. After blending, the mortar is ready for Immediately-after tests. It is then necessary to clear the bond interface for each specimen to make it free of dust to improve the adhesiveness of mortar to the concrete.

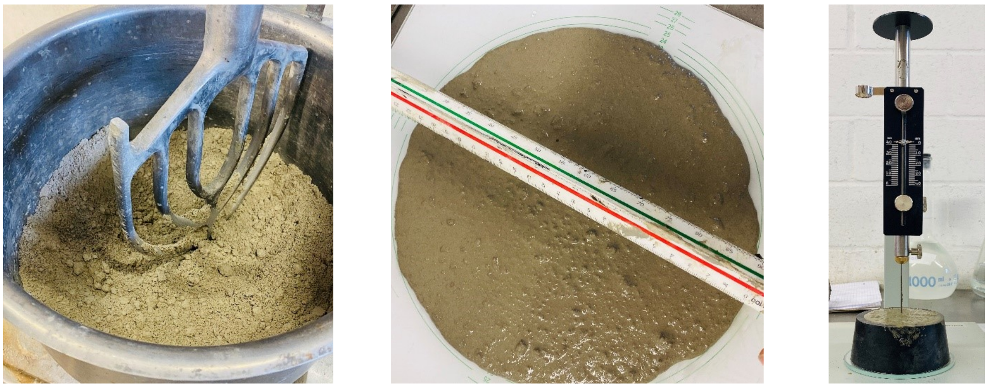


FIGURE 4.4: Blending dry material and immediately after tests

4.6 Breaking the specimens and saving results

In this stage, when the specimens reached the desired age after their curing process (as it is illustrated in table 4.2) the steps below have to be followed according to the type of specimens.

TABLE 4.2: Required curing period for each specimen shape

Spec.shape	3days	7days	28days
Cubic	✓	✓	✓
Cylindrical	×	✓	✓

4.6.1 Cubic specimens

As previously discussed, for each mix design, there are three cubic specimens ($5 \times 5cm$) that are located in an appropriate environment to accomplish the curing process. Next, the surfaces of specimens are made free of water using a drier. The compressive stress is applied to the specimen with the mean of a Toni Technik 1142 jack with a loading capacity of 3000 KN. After preparing the jack and applying the appropriate settings for loading conditions and dimensions, the specimen is placed in the jack and for apply the loading (figure 4.5).

FIGURE 4.5: A cubic specimen collapsed under applied load.

4.6.2 Slant shear specimens

For each mix design, there are two cylindric specimens $(10 \times 20cm)$ located in the same appropriate environment as cubic ones. The same procedure for drying and preparing the jack for loading conditions and dimensions are applied.

FIGURE 4.6: A collapsed slant shear specimen

After the load applied and the specimen collapsed, the crack patterns along the bond interface have to be checked to evaluate the uniformity of mortar and substrate concrete. In the following, the equations 3.3 - 3.5 are used to calculate the normal and shear stress in the bond surface during the collapse.

Chapter 5

Results and discussion

5.1 Introduction

This chapter is focused on analyzing the results obtained from the laboratory experiments and causes and effects. In the end, a conclusion for all activities and studies in this thesis will be given. It is intended to elaborate on the results in two main sections:

1. Results from the experiments on the fresh mortar (which in this thesis are called immediately-after tests) including the vicat and mini-slump test.
2. Results from the experiments on the hardened mortar consist of compressive strength and the slant shear.

These sections evaluate the effects of micro silica on the properties of mortar and compare them with an equivalent cement-based mortar to highlight differences in these types of binders.

5.2 Results from experiments on the fresh mortar

As it is discussed in section 4.5, the immediately-after tests on the fresh mortar are done while doing the casting. Here all tests on fresh mortar are discussed in two separate sections.

5.2.1 The mini-slump Results

In this investigation, the mini-slump test is done according to ASTM C143. It is explained in section 3.3.1, and the results for this experiment are illustrated in table 5.1.

Figure 5.1 compares the workability of all mix designs in this experiment. It is illustrated that all alkali-activated mortars show higher workability in the mini-slump test. It means a slag-based mortar is significantly more workable in comparison with

TABLE 5.1: Mini slump test results

Specimen	diameter (cm)	Specimen	diameter (cm)
REF1	13	VAR2	21.5
REF2	17	VAR3	22
VAR1	19.5	VAR4	23.5

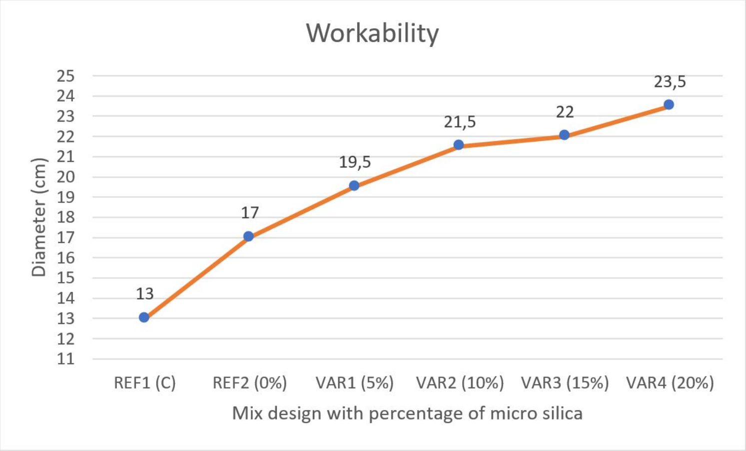


FIGURE 5.1: Comparison of workability in all mix designs

the equivalent mortar with a cement-based binder. Moreover, it illustrates a steady rise in the workability by increasing the percentage of micro silica. This growth can be the effect of increasing silica fume in the binder as a result of increasing micro silica in the mix designs.

5.2.2 The vicat results

For the sake of comparing the initial and the final setting time of the mortars, the vicat test is done while casting each mix design. The test procedure for the vicat test and all the equipment and the apparatus are described in section 3.3.2. The fresh results are also illustrated in table 5.2.

TABLE 5.2: Vicat test results

Specimen	Initial set.(min)	Final set.(min)
REF1	221	278
REF2	27	35
VAR1	29	38
VAR2	30	39
VAR3	33	42
VAR4	34	44

As it is demonstrated in this table, the setting time in the alkali-activated mortars is significantly lower than the cement-based mortar. Figure 5.2 illustrates a graph that demonstrates the initial and final setting time for all mix designs, including cement-based and alkali-activated. In this figure, a sharp fall between setting time in the OPC (REF1) and slag-based mortars (REF2,VAR1-4) have been illustrated.

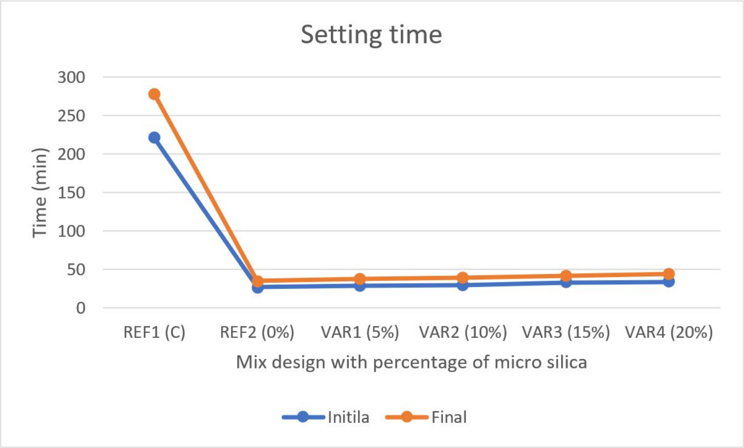


FIGURE 5.2: Comparison of the setting time in all mix designs

As it is hard to see the growth of setting time in the slag-based mortar with increasing the percentage of micro silica, The OPC (REF1) mortar is ignored in the bar chart (figure 5.3) so that it simplifies the comparison between them.

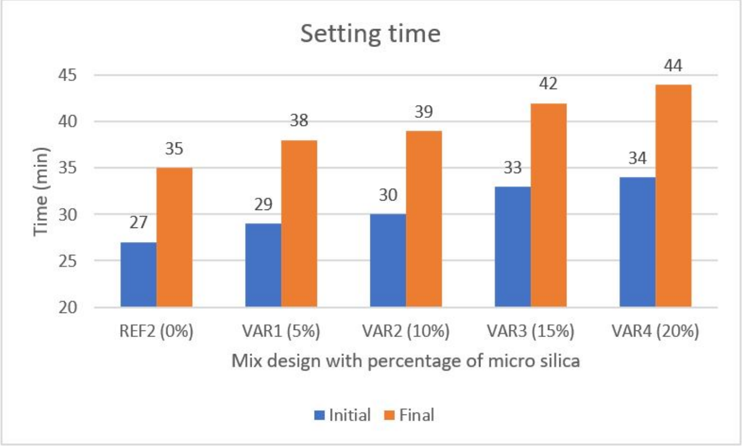


FIGURE 5.3: Comparison of the setting time in alkali-activated mix designs

Besides, short setting time is considered as one of the essential properties of the repair mortars. Thus, regardless of other mortar characteristics, the slag-based binders could be an appropriate substitution for OPC binders for using mortars in repairing concrete structures, regarding their shorter setting time.

5.3 Results from the experiments on the hardened mortar

This section aims to elaborate on the compressive and bond strength of the mortar while comparing them in mix designs to represent the differences between OPC and slag-based mortars as well as the effect of micro silica powder. Bond and compressive strength of mortar are considered as one of the conclusive physical properties that can act as the primary role in the functionality of the mortar in practical use.

5.3.1 Compressive strength

Section 4.6.1 elaborates on the experimental procedures for breaking the specimen as well as the loading conditions and equipment. Table 5.3 illustrates all the raw data mined from the loading machine.

TABLE 5.3: compressive strength for cubic specimens (Mpa)

mix des.	3days	7days	28days
REF1	27.25	32.68	39.99
REF2	26.8	29.35	33.73
VAR1	32.44	36.72	41.06
VAR2	46.13	53.91	63.10
VAR3	41.96	47.58	59.68
VAR4	39.46	44.12	56.19

Figure 5.4 makes the comparison between these data easier in all ages and with all mix designs with a bar chart.

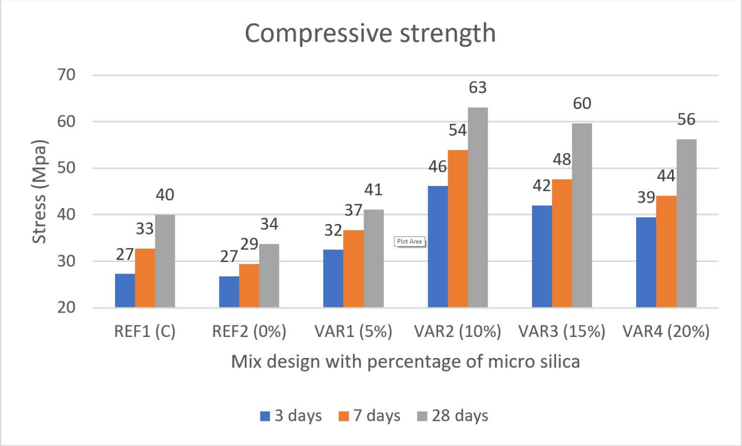


FIGURE 5.4: Comparison of the compressive strength

It is shown the compressive strength in the slag-based reference mix design (REF2) is a bit lower than the cement-based mortar (REF1). Although, the compressive strength in the alkali-activated mortars shows a sharp growth by increasing micro silica percentage from 0% to 10%, increasing the micro silica percentage more than 10%, in this case results in a slight drop in compressive strength. The increment of compressive strength could be a result of the reasons below:

The pozzolanic effect : Alkali-activation chemical reactions of slag with silicate ions (which provides by solving the slag in the activator) leads to producing C-(A)-S-H gel with a low ratio of Ca/Si. The pozzolanic effect of micro silica powder increases the C-S-H gel in the binder, which strengthens the aggregate's interaction with binder [69],[64],[70].

The micro filler effect: the micro silica powder particles are about 100 times smaller than cement particles. This characteristic makes the micro silica fill the fresh mortar's water spaces, which leads to reduce the transaction zone between aggregates [69].

Moreover, the slight fall in the compressive strength could result from exceeding the percentage of micro silica from the optimum amount, which leads to having too many grains of the same size. Moreover, having too much micro silica powder in mortar can make gaps between aggregates, which can decrease the compressive strength.

5.3.2 Bond strength

In this experiment, the bond strength of mortar is examined using the slant shear test, in which the procedure is explained in sections 3.3.4 and 4.6.2. Table 5.4 illustrates the fresh results and the calculated shear capacity of the specimens along with the bond interface (τ_n).

TABLE 5.4: Slant shear test results

	7days			28days		
mix des.	$\sigma_0(Mpa)$	$\sigma_n(Mpa)$	$\tau_n(Mpa)$	$\sigma_0(Mpa)$	$\sigma_n(Mpa)$	$\tau_n(Mpa)$
REF1	9.69	9.50	4.20	10.64	10.39	4.61
REF2	5.24	5.12	2.27	6.04	5.90	2.62
VAR1	7.31	7.14	3.17	8.68	8.47	3.76
VAR2	8.75	8.54	3.79	10.71	10.46	4.64
VAR3	11.28	11.01	4.88	12.06	11.77	5.22
VAR4	11.66	11.38	5.05	14.15	13.81	6.13

Figure 5.5 illustrates the bond strength of the specimens to simplify the comparison between these data.

This bar chart proves that the cement-based mortar shows a better cohesiveness to the substrate layer of concrete than alkali-activated mortars with 0% and 5% of micro silica. However, the bond strength of alkali-activated mortars is growing steadily, with increasing the percentage of micro silica. Moreover, when the percentage of micro

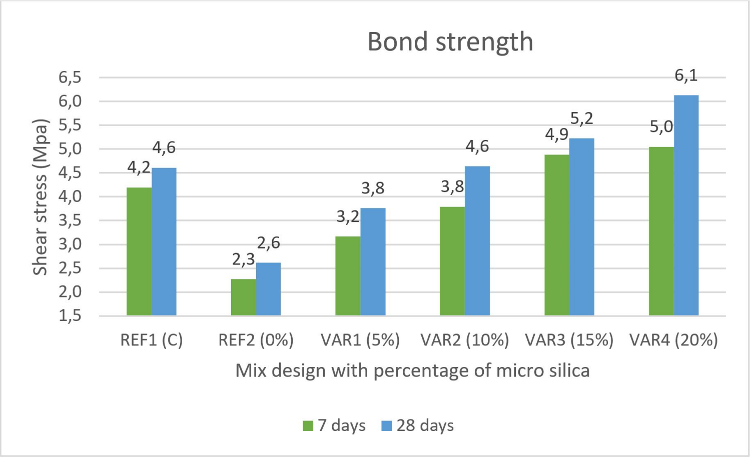


FIGURE 5.5: Comparison of the bond strength

silica exceeds 10%, the bond strength rises even over the cement-based mortar. This growth of bond strength in alkali-activated mortar can be a result of the increment of C-S-H gel by reason of increasing the percentage of micro silica (as discussed in 5.3.1).

It is necessary to mention that the shear stress applied to the interface is a combination of tension and compressive stresses. Therefore, in a tension-weak material like concrete or mortar, the failure is usually occurring because of tensile cracking rather than compression and shear slipping. Thus, it is obvious that the pattern of growing bond strength varies from what it was in compressive strength.

Chapter 6

Conclusion and future works

6.1 Introduction

This experiment's primary goal is to produce an alkali-activated mortar without using cement and with appropriate characteristics for repairing concrete structures. The alkali-activated mortar is expected to have significantly less environmental adverse side effects than cement-based mortar. The functionality of this mortar in repairing the concrete structures can extend the lifetime of existing structures. This thesis tried to improve alkali-activated mortar quality by increasing the substitutional weight percentage of micro silica with slag. Since the proper workability and setting time are considered two essential characteristics of repair mortar, we evaluated micro silica's effect on them by doing the mini-slump and vicat test. After that, compressive strength of mortar at the ages of 3, 7, and 28 days with $5 \times 5 \times 5$ cm cubic specimens are evaluated.

Moreover, the bond strength of mortar was evaluated using the aslant shear test with 10×20 cm cylindrical specimens at 7 and 28 days. This chapter focuses on the conclusion and main results obtained from data analysis in the previous chapter. Then the other aspects of characteristics and experiments on alkali-activated repair mortar will be discussed, which has the potential for more investigation and study.

6.2 Conclusions

1. The maximum percentage of micro silica in practice regarding the workability is 15% since the allowable slump for mortar is 12-22 cm (ASTM C143).

2. The slag-based mortar is noticeably more workable in comparison with equivalent cement-based mortar.

3. The initial and final setting time in alkali-activated repair mortar is considerably shorter than cement-based mortar (less than 1/6 for both initial and final setting time), which can be in most cases beneficial for using this type of mortar in repairing concrete structures.
4. Increasing the substitutional weight percentage of micro silica from 0% to 20% delays the initial setting time to 7 minutes, and the final setting time to 9 minutes.
5. Alkali-activated repair mortar at the age of 3 days reaches about 70%, and at the age of 7 days, it reaches almost 80-85% of compressive strength in 28 days.
6. Substituting a 10% weight of micro silica with the binder in alkali-activated mortar is the optimum amount regarding compressive strength.
7. The cement-based mortar showed a noticeable higher bond strength than a slag-based mortar with less than 10% of micro silica. However, the increasing amount of micro silica steadily raises the bond strength in slag-based mortar.
8. Generally speaking, although the compressive strength of slag-based mortar slightly falls with more than 10% of micro silica, the strength in 15% and 20% is still acceptable for a binder. Therefore, 15% of micro silica could be considered the optimum percentage in all studied mortar (Compressive strength, bond strength, setting time, and workability).

6.3 Future works

Considering the experimental activities in this study on alkali-activated repair mortar, Topics below are suggested for more studies and evaluations.

1. Evaluation of alkali-activated repair mortar in acidic and sulfate environments
2. Using various types of activators with different molarities and their effect on the behavior of mortar in diversified environments.
3. Strengthening growth of slag-based mortars ages of 90 days and one year.
4. Evaluating the bond strength of mortar with different surface preparations for the bond interface in the slant shear test.
5. the possibility of using alkali-activated mortars in 3D printers
6. Using nanopowders and assessing the effectiveness of using them on the physical and mechanical properties of slag-based mortars.
7. Utilizing other pozzolanic powders and the effect of them on the permeability of alkali-activated repair mortars.

List of Figures

2.1 Binder Classification 6
2.2 One-part geopolymer production process 7
2.3 Chemical mechanism of activating slag 8
2.4 Compression in sodium sulfate 16
2.5 Compression in magnesium sulfate 17
2.6 mass change in magnesium sulfate 18
2.7 mass change in sodium sulfate 19
2.8 compressive strength with 50% of slag 20
2.9 compressive strength with 30% of slag 21
2.10 compressive strength OPC mortars 22
2.11 compressive strength alkali-activated mortars 22

3.1 The micro silica 28
3.2 The potassium hydroxide in solid phase 29
3.3 Sodium silicate in liquid phase 30
3.4 Slump diameter 32
3.5 Vicat apparatus 32
3.6 Vicat needles 33
3.7 triple cubic mold 33
3.8 Slant Shear dimensions 34
3.9 Slant Shear procedure 35
3.10 Mohr-coulomb for slant shear 35

4.1 Habort mixer with blade 38
4.2 Cutting machine ATM Brilliant 285 39
4.3 Cutting process and the cut specimen 39
4.4 Blending dry material and immediately after tests 43
4.5 A cubic specimen collapsed under applied load. 44
4.6 Collapsed slant shear 44

5.1 Comparison of workability in all mix designs 46
5.2 Comparison of the setting time in all mix designs 47
5.3 Comparison of the setting time in alkali-activated mix designs 47

5.4 Comparison of the compressive strength 48
5.5 Comparison of the bond strength 50

List of Tables

2.1 A comparison between chemical reaction in OPC and systems with high and low proportion of calcium [23]. 9
2.2 typical percentages for constituent oxides of slag 10

3.1 Physical properties of the sand in use 26
3.2 General properties of the slag in use 26
3.3 Chemical components of the Cement in use 27
3.4 Physical properties of the cement in use 27
3.5 Chemical and physical properties of the micro silica in use 28
3.6 General properties of potassium hydroxied 29
3.7 General properties of sodium silicate. 30

4.1 All mix designs 40
4.2 Required curing period for each specimen shape 43

5.1 Mini slump test results 46
5.2 Vicat test results 46
5.3 compressive strength for cubic specimens (Mpa) 48
5.4 Slant shear test results 49

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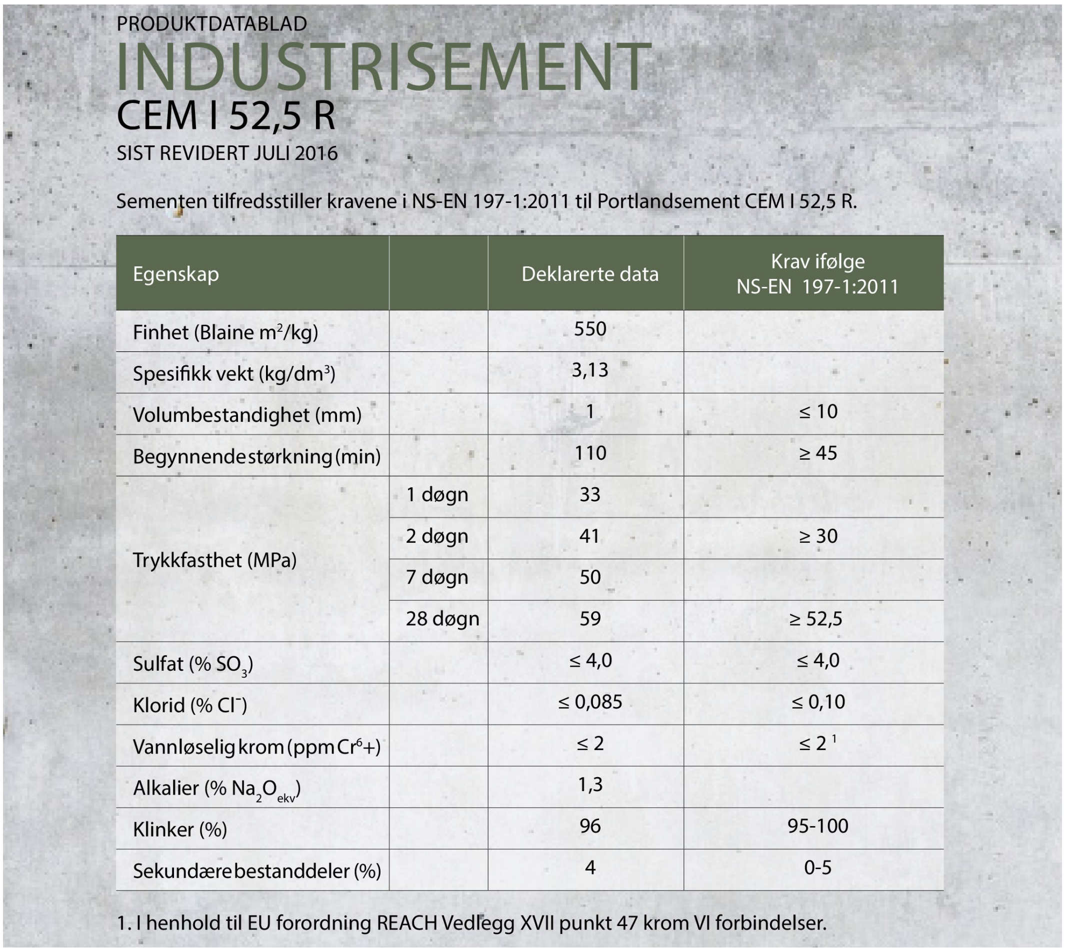
Appendices

Appendix A

Cement and slag



PRODUKTDATABLAD

INDUSTRISEMENT

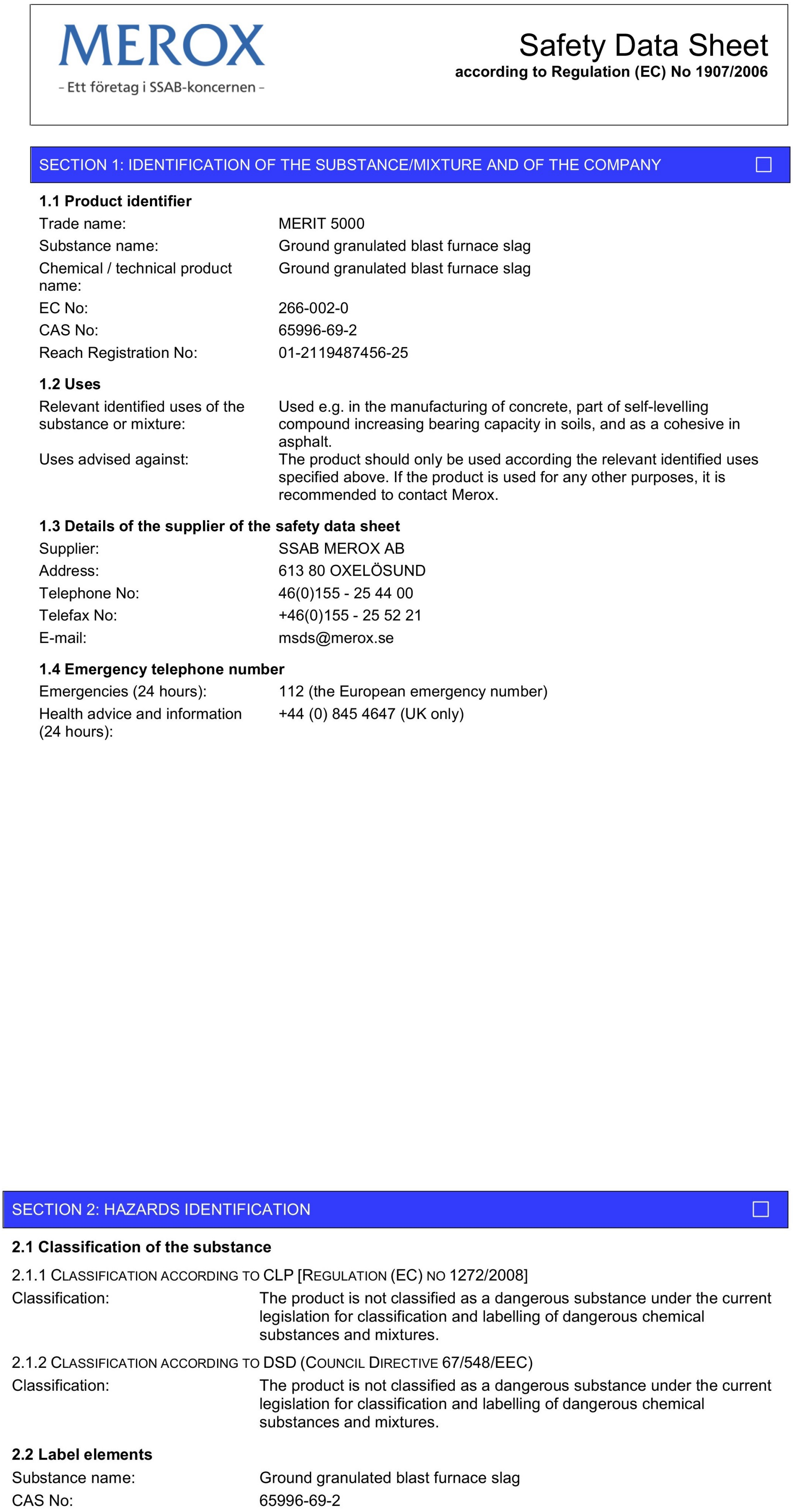
CEM I 52,5 R

SIST REVIDERT JULI 2016

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

Egenskap		Deklarerte data	Krav ifølge NS-EN 197-1:2011
Finhet (Blaine m^2/kg)		550	
Spesifikk vekt (kg/dm^3)		3,13	
Volumbestandighet (mm)		1	≤ 10
Begynnende størkning (min)		110	≥ 45
Trykkfasthet (MPa)	1 døgn	33	
	2 døgn	41	≥ 30
	7 døgn	50	
	28 døgn	59	≥ 52,5
Sulfat (% SO_3)		≤ 4,0	≤ 4,0
Klorid (% Cl^-)		≤ 0,085	≤ 0,10
Vannløselig krom (ppm Cr^{6}+)		≤ 2	≤ 2[1]
Alkalier (% Na_2O_{ekv})		1,3	
Klinker (%)		96	95-100
Sekundære bestanddeler (%)		4	0-5

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



MEROX
– Ett företag i SSAB-koncernen –

Safety Data Sheet

according to Regulation (EC) No 1907/2006

SECTION 1: IDENTIFICATION OF THE SUBSTANCE/MIXTURE AND OF THE COMPANY ☐

1.1 Product identifier

Trade name:	MERIT 5000
Substance name:	Ground granulated blast furnace slag
Chemical / technical product name:	Ground granulated blast furnace slag
EC No:	266-002-0
CAS No:	65996-69-2
Reach Registration No:	01-2119487456-25

1.2 Uses

Relevant identified uses of the substance or mixture:	Used e.g. in the manufacturing of concrete, part of self-levelling compound increasing bearing capacity in soils, and as a cohesive in asphalt.
Uses advised against:	The product should only be used according the relevant identified uses specified above. If the product is used for any other purposes, it is recommended to contact Merox.

1.3 Details of the supplier of the safety data sheet

Supplier:	SSAB MEROX AB
Address:	613 80 OXELÖSUND
Telephone No:	46(0)155 - 25 44 00
Telefax No:	+46(0)155 - 25 52 21
E-mail:	msds@merox.se

1.4 Emergency telephone number

Emergencies (24 hours):	112 (the European emergency number)
Health advice and information (24 hours):	+44 (0) 845 4647 (UK only)

SECTION 2: HAZARDS IDENTIFICATION ☐

2.1 Classification of the substance

2.1.1 CLASSIFICATION ACCORDING TO CLP [REGULATION (EC) NO 1272/2008]

Classification:	The product is not classified as a dangerous substance under the current legislation for classification and labelling of dangerous chemical substances and mixtures.

2.1.2 CLASSIFICATION ACCORDING TO DSD (COUNCIL DIRECTIVE 67/548/EEC)

Classification:	The product is not classified as a dangerous substance under the current legislation for classification and labelling of dangerous chemical substances and mixtures.

2.2 Label elements

Substance name:	Ground granulated blast furnace slag
CAS No:	65996-69-2

Hazard pictogram(s):

THE PRODUCT IS NOT HAZARDOUS ACCORDING TO THE EUROPEAN LEGISLATION.

THE PACKAGING DOES NOT REQUIRE A SYMBOL.

Signal word: No.
Hazard statement(s): None.
Precautionary statement(s): None.
Other labelling: EUH210 – “Safety data sheet available on request”.

2.3 Other hazards

PBT substance: ☐ YES ☐ NO ☒ NOT APPLICABLE
vPvB substance: ☐ YES ☐ NO ☒ NOT APPLICABLE
Physical hazards: No other known hazards.
Health hazards: May cause mechanical eye irritation.
Environmental hazards: No other known hazards.

2.4 Authorisation (substance)

See section 15.1.2 Authorisations and restrictions according to Reach sections VII and VIII.

SECTION 3: COMPOSITION/INFORMATION ON INGREDIENTS ☐

3.1 Chemical identity of the main constituent(s)

Substance name	Index No	CAS No	EC No	Registration No	
Ground granulated blast furnace slag	-	65996-69-2	266-002-0	01-2119487456-25	
	Classification[1]			**Conc (w/w)**	**Other**
	NOT CLASSIFIED[2]			100	-

1. For a complete explanation of the symbol letters and risk phrases go to section 16 Other information.
2. NOT CLASSFIED. The substance does not fulfill the criteria for being classified as a hazardous substance according to CLP.

3.1.1 Description of the main constituent(s)

Allmän beskrivning av produkten: Merit 5000 EN is the name of ground granulated blast furnace slag. Blast furnace slag is a by-product of the production of iron ore in blast furnaces. Raw materials produced from blast furnaces are iron ore, coke/coal and slag formations (limestone). The slag consists mainly of natural remelted rock types.

SECTION 4: FIRST AID MEASURES ☐

4.1 Description of first aid measures

General description of the product: Bring this safety data sheet, safety instructions leaflet or label with you to the doctor treating you. First-aiders do normally not need protective equipment.

Inhalation: If the substance is inhaled, and symptoms like shortness of breath or other symptoms of illness occur, fresh air and rest is recommended. If simple first aid does not produce a quick recovery, call the emergency number.

Skin contact: Wash with soap and water. In contact with chemical substances exposed clothes and shoes should normally be removed. The product does normally not possess any hazard to the exposed person or to first-aiders.

Eye contact: To prevent eye irritation, rinse immediately with a tempered, soft or low pressure water jet or eye wash for at least 5 minutes. If symptoms persist (intense stinging, pain, light sensitivity, poor vision) continue rinsing and seek medical assistance.

Ingestion: Drink a couple of glasses of water. If more than a small quantity has been ingested seek medical advice.

Notes for the doctor: Exposure does generally not possess any hazard to the health.

4.2 Most important symptoms and effects, both acute and delayed

Symptoms: None.
Acute effects: None.
Delayed effects: None.

4.3 Indication of immediate medical attention and special treatment needed

Specific/immediate treatment at the workplace: No.

SECTION 5: FIREFIGHTING MEASURES ☐

5.1 Extinguishing media

Suitable extinguishing media:	The product is not flammable. Extinguishing media should be chosen according to fire and surroundings.
Unsuitable extinguishing media:	Water jets are not a suitable extinguishing media when extinguishing fire from chemical products.

5.2 Special hazards arising from the substance or mixture

Specific hazards:	None.

5.3 Advice for fire-fighters

General safety measures:	Apply general fire safety precautions. Avoid inhalation of smoke fumes.
Safety measures during firefighting:	Adequate protective equipment should be worn for all fire fighting. Protective equipment providing total coverage and an oxygen mask is recommended.

SECTION 6: ACCIDENTAL RELEASE MEASURES ☐

6.1 Personal precautions, protective equipment and emergency procedures

General safety measures:	After accidental release of flammable or volatile substances or substances that generates dust, ventilate the exposed area thoroughly. Use methods to minimize generation of dust.
Personal protective equipment:	Avoid inhalation of dust and exposure to eyes and skin. Always wear gloves when handling chemical substances.
Protection for emergency responders:	See section 8.2.2 Personal protection.

Appendix B

Micro Silica

Elkem
A Bluestar Company

Elkem ASA
Drammensveien 169
Postboks 334, Skøyen
NO-0213 Oslo
Norway
Tel: +47 22 45 01 00
www.elkem.com

Product Data Sheet

Elkem Microsilica® Grade 940 for fibre cement

Elkem Microsilica® Grade 940 is a dry silica fume available in two main forms: Undensified (U) and Densified (D)

Description

Elkem Microsilica® Grade 940 is a dry silica fume available in two main forms: Undensified (U) and Densified (D). In use, it acts physically as a filler and chemically as a highly reactive pozzolan. A key ingredient in many construction materials, Elkem Microsilica® is used in fibre cement products as a process aid, to improve ingredient dispersion and to improve hardened properties and overall durability.

Packing

The product is available in:

- 25 kg paper bags
- Big bags in various designs & sizes
- Bulk road tanker

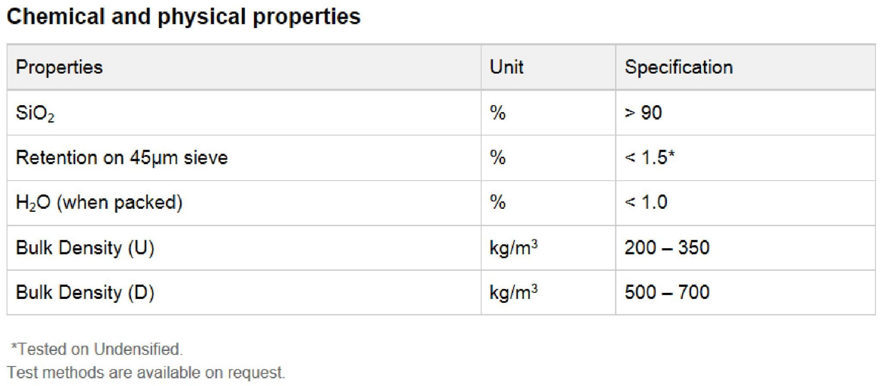
Please contact our representative for more details.

Storage & handling

Elkem Microsilica® Grade 940 should be stored in dry conditions and not exposed to moisture.

Quality assurance & quality control

Elkem Silicon Materials' Management System for development, processing and supply of Elkem Microsilica® is certified to ISO 9001. The chemical and physical properties of Elkem Microsilica® are regularly tested.



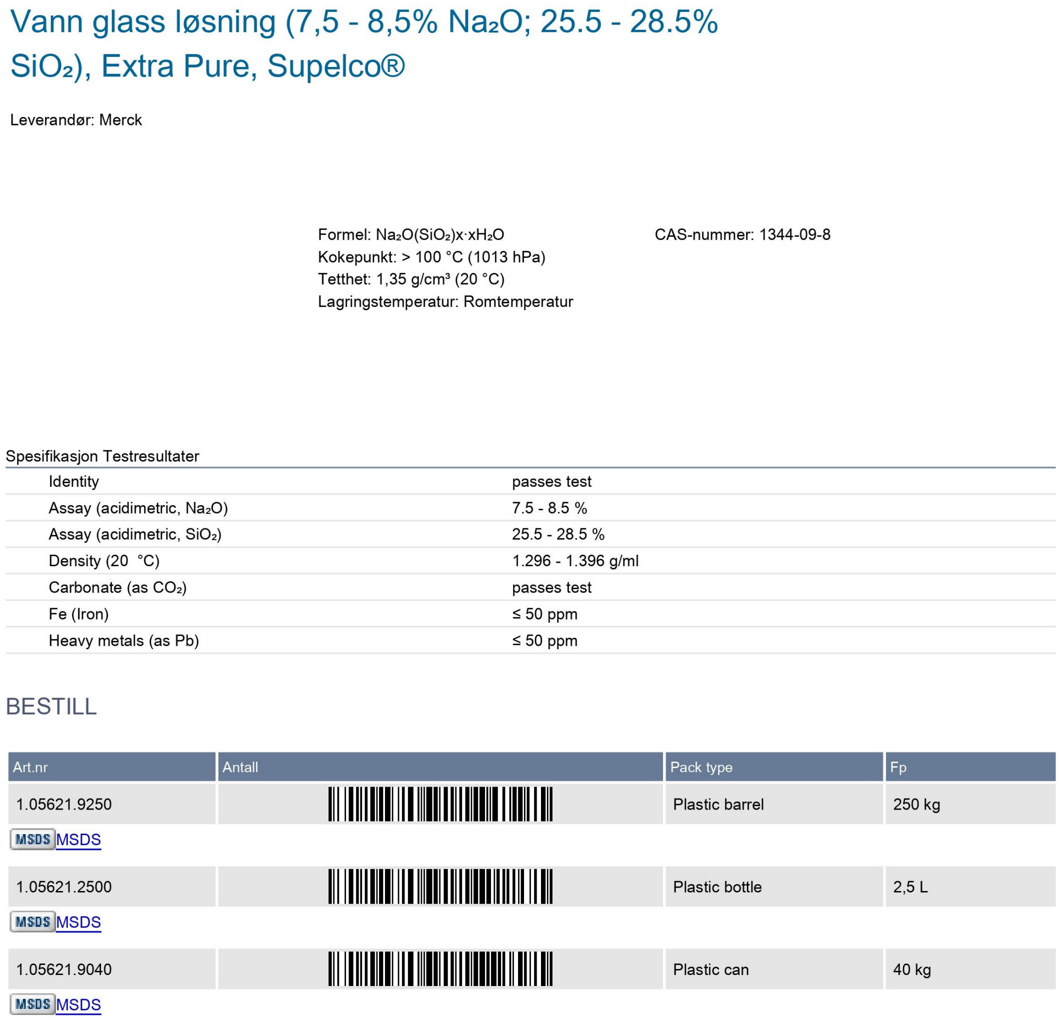
Chemical and physical properties

Properties	Unit	Specification
SiO_2	%	> 90
Retention on 45µm sieve	%	< 1.5*
H_2O (when packed)	%	< 1.0
Bulk Density (U)	kg/m^3	200 – 350
Bulk Density (D)	kg/m^3	500 – 700

*Tested on Undensified.
Test methods are available on request.

Appendix C

Sodium silicate



Vann glass løsning (7,5 - 8,5% Na_2O; 25.5 - 28.5% SiO_2), Extra Pure, Supelco®

Leverandør: Merck

Formel: $Na_2O(SiO_2)x{\cdot}xH_2O$
Kokepunkt: > 100 °C (1013 hPa)
Tetthet: 1,35 g/cm³ (20 °C)
Lagringstemperatur: Romtemperatur

CAS-nummer: 1344-09-8

Spesifikasjon Testresultater	
Identity	passes test
Assay (acidimetric, Na_2O)	7.5 - 8.5 %
Assay (acidimetric, SiO_2)	25.5 - 28.5 %
Density (20 °C)	1.296 - 1.396 g/ml
Carbonate (as CO_2)	passes test
Fe (Iron)	≤ 50 ppm
Heavy metals (as Pb)	≤ 50 ppm

BESTILL

Art.nr	Antall	Pack type	Fp
1.05621.9250 MSDS MSDS		Plastic barrel	250 kg
1.05621.2500 MSDS MSDS		Plastic bottle	2,5 L
1.05621.9040 MSDS MSDS		Plastic can	40 kg