Effect of different silica fume on concrete properties

Comparative testing and analysis

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Summary

Concrete, as the world's most widely used construction material, contributes significantly to climate change due to emissions generated during cement production. The industry has set ambitious goals to achieve carbon-neutral concrete production by 2050. Microsilica is a by-product of the silicon and ferrosilicon alloy industries and processes, and the unique properties of the material may have an influence on the concrete.

The objective of this study is to explore the impact of incorporating 10 different types of microsilica on the properties and characteristics of concrete. Process development and a preliminary study have been conducted as preparative work before investigating the effect of microsilica on concrete properties. The influence of microsilica on fresh mortar properties, strength development and durability has been investigated by execution of flow tests, temperature logging, total heat value calculation, standard mechanical strength tests, pozzolanic activity index, chloride ion migration tests, and microscopic imaging.

As a result of the testing and comparative analysis, several observations about how microsilica influences concrete properties have been obtained. A common denominator in the observations for all tests was that the densification of the microsilica allegedly does not influence the properties of concrete. The BET specific surface area of the microsilica influence both the flowability of the mortar as well as the pozzolanic activity index of the samples after 28 days of curing. Low BET SA (m2/g) gave high flowability and an increase in PAI was observed for mortars containing microsilica with high BET SA (m2/g). The pozzolanic activity index of the mortars also showed an increase as the content of silicon dioxide in the microsilica increased. When assessing how the mortars were influenced by the pH of the microsilica samples, complete setting time was investigated and it was concluded that there was no correlation between pH of microsilica and the complete setting time. However, there was a minor correlation between the complete setting time of the mortars and the alkali content of the microsilica samples, where low alkali content gave an early complete set. No correlation was observed when investigating the influence of moisture in the microsilica samples on the flowability of the mortars.

Contents

List of Figures

List of Tables

1 Introduction

On the 15th of November, 2022 the population of the world reached 8 billion people [1]. The ecological overshoot on earth consequently impacts climate change, extinction of species, ocean acidification, etc and the adverse consequences of climate change are increasingly exerting a direct influence on the lives of individuals [2]. The increasing global population commensurates the growing demand for residential dwellings, thereby accentuating the imperative for sustainable construction materials [3].

Concrete, as the world's most widely used construction material, contributes significantly to climate change due to emissions generated during cement production. The production of Portland clinker involves thermal and chemical combustion processes, accounting for a substantial portion of global CO2 emissions, approximately 8 percent[4]. Efforts within the construction industry have been focused on reducing both direct and indirect CO_2 emissions associated with cement and concrete production [3], [5]. Significant progress has already been made, with a 22% reduction observed since 1990. The industry has set ambitious goals to achieve carbon-neutral concrete production by 2050 [6],[7].

> "We know that the solutions we need now already exist. We know that climate delayism is the new climate denial and that we must reject the self-defeating mentality of 'it's too late'."
>
> Ilari Aho, Chair, WorldGBC Board, 2022-2023.

Continued efforts are crucial in the ongoing development of sustainable building materials, construction techniques, and the mitigation of detrimental effects associated with current practices [7]. Concrete's sustainability advantages, including durability, strength, resilience against harsh environments and extreme weather, and recyclability, make it a favorable choice when compared to other building materials [3].

This report is a contribution to research on the use of sustainable additives in concrete and how microsilica as a pozzolanic additive influences the properties of concrete. The objective of this study is to explore the impact of incorporating microsilica on the properties and characteristics of concrete. As microsilica is a by-product of the silicon and ferrosilicon alloy industries and processes unique properties of the material may have an influence on the concrete [8], [9]. Through a comprehensive investigation, behavioral observations of low-carbon concrete can significantly enhance our understanding of how waste materials can be effectively integrated as standard components in the future of the construction industry [9]. Ultimately, the findings of this study may pave the way for improved

concrete formulations and enable the construction of more durable, sustainable, and high-performance structures.

2 Societal perspective

The climate crisis is a global emergency and all nations, parties, companies, and individuals have to contribute to tackle climate change. This is necessary to handle and reduce the negative impact climate change has on the world we live in [10]. The United Nations Conference on sustainable development was hosted in Rio de Janeiro in 2012, where 17 sustainable development goals were established. The objective of this establishment was to set universal goals so that urgent political, economic, and environmental challenges could be handled locally, and globally [11].

World leaders from 196 parties gathered at the UN climate change conference in Paris in 2015 to discuss which measures had to be made to tackle climate change. The Paris Agreement was signed on this occasion, and the agreement set long-term goals to guide all 196 parties to act towards a more sustainable future [12]. Together, The Paris Agreement and the 17 sustainable development goals provide achievable targets and a set of common standards which can contribute to more sustainable economic, environmental, and social development globally [11].

Figure 2.1: UN sustainable development goal nr. 8, 9, 12 and 13, [13].

UN sustainability goal number 9 specifies how the development of industry, infrastructure, and innovation can contribute to a sustainable future. Target 9.4 says the following: "By 2030, upgrade infrastructure and retrofit industries to make them sustainable, with increased resource-use efficiency and greater adoption of clean and environmentally sound technologies and industrial processes, with all countries taking action in accordance with their respective capabilities" [14]. Sustainable economic growth is incorporated in Goal 8 and Target 8.4 promotes economic growth without causing environmental degradation in addition to improving global resource efficiency in consumption and production [15].

The 12th goal of sustainable development presents targets related to responsible and sustainable consumption and production patterns. Target 12 involves the management of chemicals and all waste in a way that is both sustainable and beneficial for the environment throughout its entire life cycle. It also incorporates the minimization of impacts on the environment and human health by reducing

the pollution of waste and chemicals to air, water, and soil [16].

Concrete technology innovation and research on the use of industrial by-products and waste in concrete can contribute to reaching these three goals. Collecting waste/by-product from industries and using it for other purposes will reduce pollution to air, soil, and water. By researching how waste material influences the properties and characteristics of concrete, one can reduce the use of cement in concrete. Industrial innovation and concrete technology research can also contribute to a circular economy and economic growth. This will be possible because new sources of revenue can be created by recycling waste into materials used for other purposes, in addition to reducing landfill-related costs [9].

Working towards targets 9.4, 8.4, and 12.4 will consequently have a positive effect on climate change by reducing emissions and pollution from industry. It will also reduce emissions from cement production due to a declining demand for cement [9]. Concrete bears the brunt of criticism within the construction sector due to its significant emissions resulting from cement production. In order to make substantial strides toward mitigating the greenhouse gas emissions associated with concrete, it is imperative to undertake rigorous investigations into the realm of sustainable concrete utilization. For more than five decades, the utilization of industrial by-products and waste as additives in concrete has been observed. However, despite this longstanding practice, the adoption of low-carbon concretes has not yet become customary within the construction industry to date. Research regarding the impact of sustainable additives on the properties of concrete and the dissemination of such knowledge plays a pivotal role in facilitating sustainable change within the construction industry [8], [9].

3 Theoretical background

This chapter presents theoretical background information about concrete, cement production, cement hydration, superplasticizer, properties of concrete, microsilica, and the use of microsilica in concrete.

3.1 Concrete

Concrete is a proportioned mixture consisting of water, cement, coarse-, and fine aggregates and the mixture often contains supplementary cementitious materials and chemical admixtures [17]. The composition and quality of ingredients in a concrete mixture have a considerable effect on certain properties and characteristics such as workability, strength, durability, permeability, etc [18]. Cement is one of the main ingredients in concrete and, Portland cement is the most commonly used type of hydraulic cement. Hydraulic cement is a type of cement that hardens due to a chemical reaction that occurs when mixing water and cement [19, p. 2], [20]. A chemical reaction occurs when cement comes into contact with water and this reaction leads to the creation of C-S-H in concrete [21, p. 12].

3.1.1 Cement

Portland cement was patented in 1824 by Joseph Aspdin and it is called Portland cement because Aspdin observed that the concrete made with Portland cement had a similar appearance to the high-quality limestone Portland stone, which was commonly used in construction at the time [19, p. 2]. The material consist of the raw materials silica (SiO_2), Calcium oxide commonly known as lime (CaO), alumina (Al_2O_3), and iron oxide (Fe_2O_3). The raw materials can be extracted from several different sources as illustrated in Table 3.1.

These raw materials are heated to high temperature (maximum $1450°C$) and grounded to create a material called cement [19, p. 4], [22]. Production of cement can be separated into four different processes as illustrated in 3.1 and requires up to 80 separate operations that are continuous. These processes require equipment and heavy machinery which consumes large amounts of electrical energy and fuel.

Table 3.1: Sources of raw materials used to manufacture Portland cement, crediting: American concrete institute [19].

Lime (CaO)	Iron (Fe_2O_3)	Silica (SiO_2)	Alumina (Al_2O)	Calcium sulfate ($CaSO_4$)
Alkali waste	Blast-furnace flue dust	Calcium silicate	Aluminum ore refuse	Anhydrite ($CaSO_4$)
Calcite	Clay	Cement rock	Bauxite	Hemihydrate ($CaSO_4 1/2H_2O$)
Cement rock	Iron ore	Clay	Cement rock	Gypsum ($CaSO_4 * 2H_2O$)
Chalk	Mill scale	Fly ash	Clay	
Clay	Ore washings	Fuller's earth	Copper slag	
Dolomite	Pyrite cinders	Limestone	Fly ash	
Limestone	Shale	Loess	Fuller's earth	
Marble	Fly ash	Marl	Granodiorite	
Marl		Ore washings	Limestone	
Seachells		Quartzite	Loess	
Shale		Rice husk ash	Ore washings	
Slag		Sand	Shale	
		Sandstone	Slag	
		Shale	Staurolite	
		Slag		
		Trap rock		
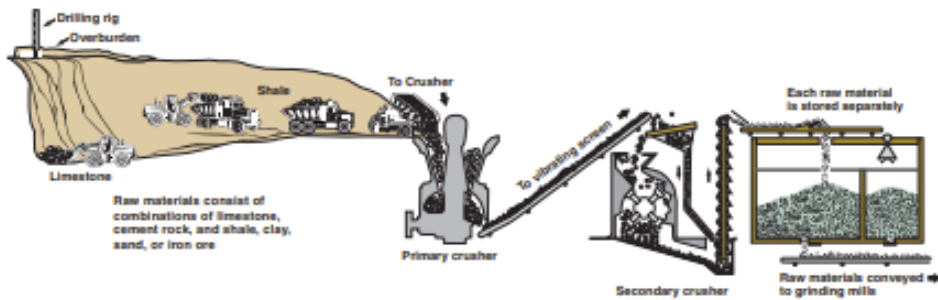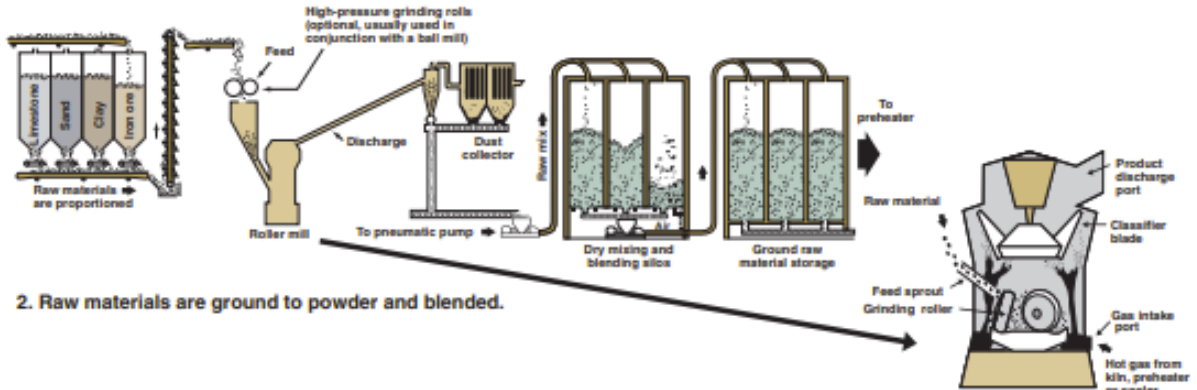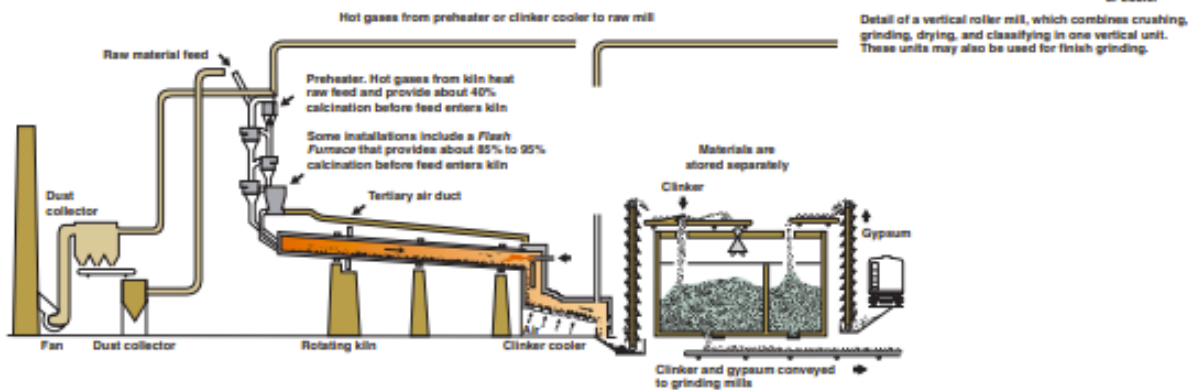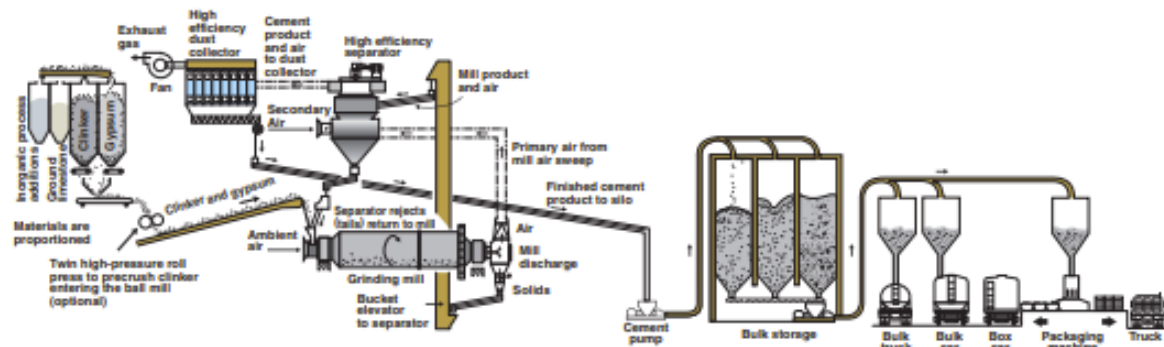
Figure 3.1: Illustration of how cement is produced separated into 4 stages of production, crediting: Kosmatka & Wilson [23, p. 30]

When the raw materials are exposed to high temperatures, it causes chemical reactions between the materials which result in the formation of cementitious minerals the cement [19]. Figure 3.2 illustrates the phase diagram of the formation of phases that occur in a rotary kiln in Portland cement production.
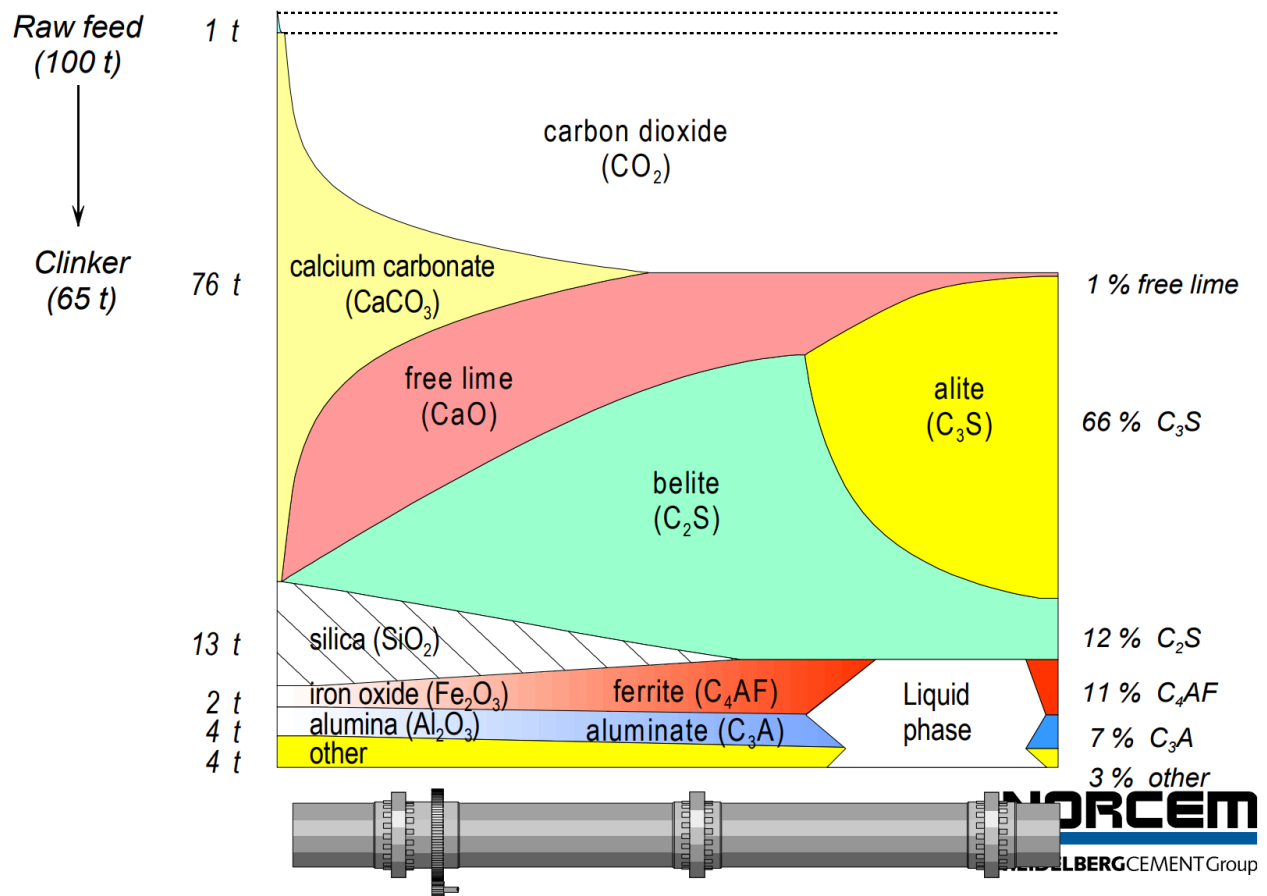
Figure 3.2: Phase diagram of reactions present in the rotary kiln, crediting: Knut Kjellsen, Norcem

The chemical reactions that occur when cement is produced in a rotary kiln can be divided into 3 stages where the chemical reactions are present within different temperature ranges [22].

The first stage occurs when the temperature is below $1300°C$ in the rotary kiln. Several chemical reactions happen at this stage and the most important reactions that occur are the following [22]:

1. Decomposition of minor constituents

2. Calcining, which is the decomposition of calcite; $CaCO_3 => CaO + CO_2$

3. Reaction of lime with quartz and minor mineral decomposition products which result in aluminate, ferrite, and dicalcium silicate (Ca_2SiO_4) also known as belite.

When the temperature of the rotary kiln rises from $1300\,°C$ to $1450\,°C$, the clinker production has entered the second stage which is referred to as clinkering. The following reactions are present in this stage[22]:

1. A melt of mainly aluminate and ferrite is formed. Approximately 20–30% of the melt is liquid when it reaches a temperature of $1450\,°C$ and the reactions

of belite and lime present in the melt give tricalcium silicate (Ca_3SiO_5) also known as alite.

2. Clincker is formed in a semi–solid state and the clinker is completely solidified when subsequently cooled.

The last stage of reactions in clinker production is initiated when the clinker is being cooled. The following reactions are present during cooling [22]:

1. Crystallization of the liquid melt results in aluminate and ferrite.

2. Alite and belite undergo polymorphic transitions.

The clinker is then stored in clinker silos and later grounded to create cement. Calcium sulfate ($CaSo_4$) or gypsum ($CaSO_4 \cdot 2H_2O$) is commonly mixed with the grounded clinker to prevent rapid stiffening [19], [22]. Cement also contains alkali oxides (Na_2O and K_2O) which are secondary components in cement and usually constitute less than 1,2% of the cement. The alkali content occurs both as easily soluble alkalisulphates and in the clinker minerals [24].

3.1.2 Hydration of cement

The chemical reaction between water and cement minerals is referred to as the hydration process which is the cause of the setting and hardening of concrete and mortar [24],[25]. Chemical compositions and fineness of the cement determine the properties of the binder. The use of pozzolanic additives in concrete such as microsilica and fly ash also affects the property development of the concrete. Fillers influence the binder properties to some extent due to the effects filler has on the rate of hydration in concrete as well as the spatial distribution of the reaction products [24].
Portland cement consists of four major phases; Alite, Belite, Aluminate, and Ferrite. These phases are reactive to water and the reactions are exothermic which means that heat is generated. The main product of the reaction is C–S–H (calcium silicate hydrate) and is the cause of impermeability and high mechanical strength of hardened concrete [17], [24].
The clinker phases have different characteristics which are described in Table 3.2.

Table 3.2: Characteristics of the 4 major phases in Portland clinker, [24]

Phase	Cement chemical notation	Characteristics
Alite	$3CaO \cdot SiO_2$	- Contains the most lime (CaO) out of the four phases. - Reacts rapidly with water. - Largely responsible for initial setting, - Largely responsible for early age strength. - Contribute to a high strength at later stages of curing. - Total amount of heat released at complete hydration is approx. 500 kJ/kg. - Constitutes 50–70% of the content in clinker. - High resistance against sulfate solutions.
Belite	$2CaO \cdot SiO_2$	- Contains less lime (CaO) than alite. - Relatively low reactivity. - Little contribution to early-stage strength. - Forms the most C–H–S per unit reacted material. - Contributes to long term mechanical strength. - Slower heat development compared to alite. - Total amount of heat released at complete hydration is approx. 260 kJ/kg. - Constitutes 15–30% of the content in clinker. - High resistance against sulfate solutions.
Aluminate	$3CaO \cdot Al_2O_3$	- Reacts rapidly with water under the formation of calcium aluminate hydrates. - Causes flash setting. - Ettringite (Calcium sulfoaluminate hydrates) are formed. - High rate of heat development. - Total amount of heat released at complete hydration is approx. 900 kJ/kg. - Constitutes less than 5% of the content in clinker.
Ferrite	$4CaO \cdot Al_2O_3 \cdot Fe_2O_3$	- Similar reaction products as aluminate - Relatively low reactivity. - Total amount of heat released at complete hydration in approx. 300 kJ/kg. - Constitutes 5–15% of the content in clincker. - Causes the dark grey color of Portland cement.

Table 3.3: Idealized reaction between water and cement phases, [24]

Phase	Cement chemical notation	Idealized reaction with water
Alite	$3CaO \cdot SiO_2$	$2(3CaO \cdot SiO_2) + 6H_2O \rightarrow 3CaO \cdot 2SiO_2 \cdot 3H_2O + 3Ca(OH)_2$ Tricalciumsilicate + water → C-S-H + calcium hydroxide
Belite	$2CaO \cdot SiO_2$	$2(2CaO \cdot SiO_2 + 4H_2O \rightarrow 3CaO \cdot 2SiO_2 \cdot 3H_2O + Ca(OH)_2$ Dicalcium silicate + water → C-S-H + calcium hydroxide
Pozzolan	$2SiO_2$	$2SiO_2 + 3Ca(OH)_2 \rightarrow 3CaO \cdot 2SiO_2 \cdot 3H_2O$ Silica + calcium hydroxide → C-S-H

The idealized chemical reactions of water and cement compounds that occur during the hydration process are presented in Table 3.3. The chemical reactions occurring in the hydration process can be divided into 6 key reactions [17], [25], [24]:

1. Dissolution of cement compounds

   When water and cement come in contact, the water reacts with compounds in the cement, primarily with alite (C3S) and belite (C2S). A high concentration of hydroxide ions (OH^-) and calcium ions (Ca^{2+}) are released as a result of the dissolution of alite and belite in water.

2. Nucleation and precipitation

   Nucleation and precipitation can be described as the formation of calcium hydroxide ($Ca(OH)_2$) crystals that occur when calcium and hydroxide ions come in contact with each other. These crystals contribute to the early strength development of the cement paste.

3. Alite (C_3S) hydration

   As described in Tabel 3.2, alite is the main cement compound responsible for initial strength development. When alite reacts with water, calcium silicate hydrate (C–S–H) gel is formed which is the primary binder in hydrated cement paste, see Table 3.3. A large amount of heat is released due to this reaction and results in early strength gain of the concrete.

4. Belite (C_2S) hydration

   As belite has a lower reaction rate than alite, it forms C–S–H gel at a slower rate and contributes to the long–term strength of hardened cement paste. The formation of C–S–H gel continues over an extended period which results in the development of strength in later stages of the hydration process, see Table 3.3.

5. Calcium aluminate hydration

   Cement also contains the compounds aluminate (C_3A) and ferrite (C_4AF) and these compounds form calcium aluminate hydrate (C–A–H) and other

hydrates phases when they come in contact with water. As mentioned in Table 3.2, aluminate can cause flash setting and heat generation in cement.

6. Pozzolanic reactions

Supplementary cementitious materials (SCMs) such as silica fume, slag, and fly ash are often incorporated in the cement and these materials react with the calcium hydroxide ($Ca(OH)_2$ and other compounds to form additional C–S–H gel as described in Table 3.3. The C–S–H gel is formed as a result of pozzolanic reactions in the cement paste and gives long–term strength and durability among other properties of cement paste.

Figure 3.3 illustrates the formation of the reaction products C–S–H and Portlandite ($Ca(OH)_2$ mineral), that occur during the hydration of Portland cement.
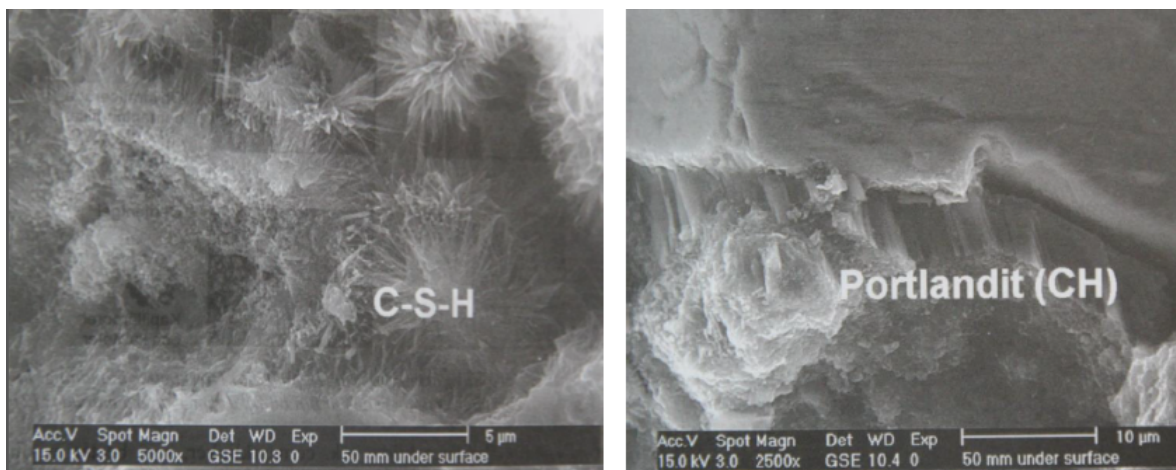
Figure 3.3: SEM Microscopic images of reaction products from cement hydration, crediting: Per Fidjestøl, Elkem ASA.

The alkali content of cement has a significant influence on the strength development of concrete and contributes to early strength development. It also has a negative influence in the sense that alkali content reduces the long-term strength of the concrete [24]. Hydration of cement continues over an extended period and is a gradual process. The degree of hydration is highly affected by the amount of water available for hydration during the hydration process [24]. It is known that the pore size distribution and the pore structure of hydrating concrete are highly affected by water where a decrease in w/b ratio leads to a decrease in the pore size of the hydrating cement paste. As cement hydrates, a large amount of water is not available for the hydration of the cement because the water is bound by absorption in gel pores. Full hydration of concretes with a w/b ratio lower than 0,4 is therefore unlikely because the water content is too low. This also leads to a reduction in the total amount of heat per kg in cement[25],[24].

3.1.3 Heat of hydration

A considerable amount of heat is released during the hydration process which can lead to an increase in temperature during the first days of casting. Temperature development in concrete might give both benefits and disadvantages because the rate of hydration is highly temperature dependent. High temperatures cause fast hydration and high strength, whereas low temperatures cause slow hydration and slower strength development. The consequences of not controlling the temperature development in the concrete and the temperature changes in the surrounding environment can be damage to the structure and reduced material quality [24]. The total amount of heat liberated and the heat release rate of the individual cement compounds can be used as indicators of their reactivity. The heat of hydration data can therefore be used to characterize the setting and hardening behavior as well as the prediction of temperature development in concrete [25].

There are several methods for measuring heat development in concrete, cement paste, and mortar such as ultrasonic pulse velocity (UPV) method and calorimetric methods. Calorimetric measurements can be conducted in both adiabatic and semi-adiabatic conditions, but calibrations of semi-adiabatic measurements are necessary to ensure data corrections of heat loss from the insulated box to the surrounding environment [26]. The UPV test method can be used to measure the time it takes for pulses of longitudinal ultrasonic waves to pass through concrete or mortar. UPV apparatus include the following [25], [17]:

- Transducers that are in contact with the concrete.

- Pulse generator (10-150 Hz)

- Amplifier

- time measuring circuit

- Digital display showing the time it takes for a pulse to travel from one transducer to the other.

The rate of heat liberation (cal/g/h) can be investigated by conducting calorimetric testing which illustrates the evolution of heat from cement pastes during the early stages of the hydration process. Figure 3.4 is an example of a typical plot of data from conducting an isothermal calorimetry test.
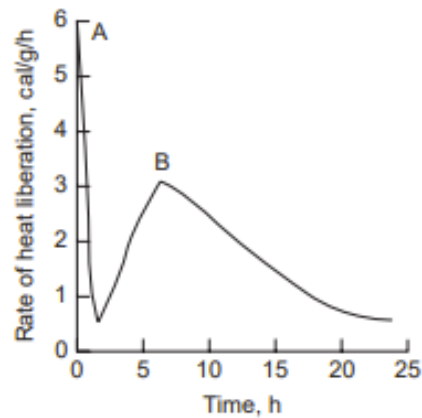
Figure 3.4: Heat liberation rate of Portland cement paste during the first 25 hours of setting, [25, p. 210]

As illustrated in figure 3.4, a rapid heat evolution lasting a few minutes will occur momentarily after the cement and water have been mixed. This heat evolution is most likely caused by alite hydration and heat caused by the dissolution of sulfates and aluminates. The heat liberation rate then decreases as the presence of sulfates in the solution depresses the solubility of aluminate. Peak B represents the second heat evolution cycle caused by the formation of ettringite which occurs after about 4 to 8 hours of hydration[25]. Some of the heat during the heat evolution period is caused by alite and the formation of C–S–H. Before the heat cycle reaches the apex at B, the properly retarded cement paste will lose some of its plasticity and will begin to solidify as it begins to set. When water and cement react and start to form the reaction product calcium hydroxide, the pozzolanic reaction will take place and the hydration rate decreases. The decrease in heat release will consequently result in a slower strength development[25]. Observations and findings related to heat liberation from the hydration of cement are usually produced in controlled adiabatic conditions. This is done to investigate the potential of the material in a controlled environment [26].

3.1.4 Properties of fresh concrete

The properties of fresh concrete have a big impact on the final product when mixing concrete and mortar [27],[28]. Consistency in concrete can be described as the degree of wetness and can be defined as the fresh concretes or mortars' ability to flow. It is important to differentiate between the workability and the consistency of fresh concrete because concretes with the same consistency may have different degrees of workability [17].

Workability is a physical property of concrete and describes the flowability, mobility, consistency, and compatibility of fresh concrete [17],[18]. When considering workability in fresh concrete it is necessary to take into account both the internal friction and the surface friction, where internal friction is friction between individual particles in the mixture, and surface friction occurs between the fresh concrete and the surface of the reinforcement or the mold. Internal friction is

14

an intrinsic property of fresh concrete and therefore workability can be defined as the amount of necessary internal work to produce full compaction [17]. The desired workability depends on the intended use of concrete such as type of structure, cross-section, transportation method, method for compaction, etc and the workability of the fresh concrete can be used to determine the ideal water/cement ratio for the specific mix design [18],[28]. The following three properties have an impact on the quality of the fresh concrete [27],[29]:

- Compressibility in mortar describes the packing ability of the mortar.

- Flowability can be described as the mortar's ability to fill the mold/formwork and its ability to settle around the rebar.

- Stability is the ability of the mortar to maintain a homogeneous state as well as satisfactory flowability.

There is no direct method to measure the workability due to its definition, but there are several tests that provide physical measurements which prevail useful information and indications about the workability of fresh concrete [17]. The most used method for measuring the consistency of fresh concrete is by performing a slump test [17],[18],[28]. Flow test is another method which provides information about the consistency, workability, flowability, mobility, and cohesiveness of fresh concrete, but this method is mainly used for concrete laboratory tests [18],[28]. There are several factors affecting the workability of fresh mortars and concretes, and the most prominent factor is water content [18],[17]. The water content has a large impact on the flowability of mortar, which means an increase in water content results in a higher flowability [27],[20]. It is common to use water-reducing chemical compounds to reduce the amount of water in the concrete and maintain flowability. These chemical compounds are usually referred to as superplasticizers and plasticizers [20].

3.1.5 Superplasticizer

Superplasticizer is a water-reducing admixture made from mainly polymer, defoamer, and water which is commonly used to adjust the consistency of concrete and mortar [20],[27],[17]. It can be described as an improved version of a plasticizer, hence the name superplasticizer. There are regulations for maximum dosages of plasticizer in concrete structures introduced in Handbok R762: Prosesskode 2, section 84.4 [30, p. 181]. There are no regulations for a maximum dosage of superplasticizer, but manufacturers of superplasticizer present recommended dosages for the specific types of SP and claim that excessive use of superplasticizer can cause retardation of cement hydration [31]. When superplasticizer was developed, the main focus was to enhance the positive and desired effect plasticizer had on concrete as well as reduce or eliminate the unwanted effects. Effects such as retardation of cement hydration are therefore still present when using superplasticizer, but to a significantly lower extent when compared

to the retardation caused by plasticizer.

The chemical compound consists of high-molecular-weight, long-chain anionic surfactants. When superplasticizer is mixed with cement, the polymer molecules are absorbed to the surface of cement particles and impart a strong negative charge which lowers the surface tension of the water in the fresh concrete. This leads to an enhanced fluidity of the concrete mixture which enables a reduction in water in the mixture [25],[27],[17].

Plasticizers and superplasticizers can be divided into four subgroups:

- Lignosulphonate

- Naphthalene

- Melamine

- Polycarboxylate

The three first subgroups are sulphonated polymers are by-products from the paper, coal, and plastic industries. Polycarboxylate on the other hand is tailor-made for cement and concrete. Sulphonated polymers have an electrostatic mechanism which means that the polymer molecules have negatively charged sulphonic groups that have a repulsive effect on the cement particles. This mechanism causes the dispersion of cement particles in a concrete mixture. Polycarboxylate, on the other hand, has a steric mechanism that causes dispersion of the cement particles caused by a steric hindrance effect due to side chains or neutral graft on the surface of the polymer molecules [32, pp. 203–207]. The application of polycarboxylate has therefore a significantly larger effect on the dispersion of cement particles than the other subgroups of plasticizer and superplasticizer [33].

When superplasticizer is used to increase the workability in mortars with 0,5 W/C ratio or more, the normal dosage of superplasticizer is between 1 and 3 liters per cubic meter of concrete, which constitutes approximately 0,1-0,3% of the binder. For mortars with a lower w/c ratio, the dosage of superplasticizer must be significantly higher: 5 to 20 liters per cubic meter which constitute 0,5–2% of the binder [17].

Figure 3.5 bellow illustrates how superplasticizer affects cement particles in a concrete mixture.
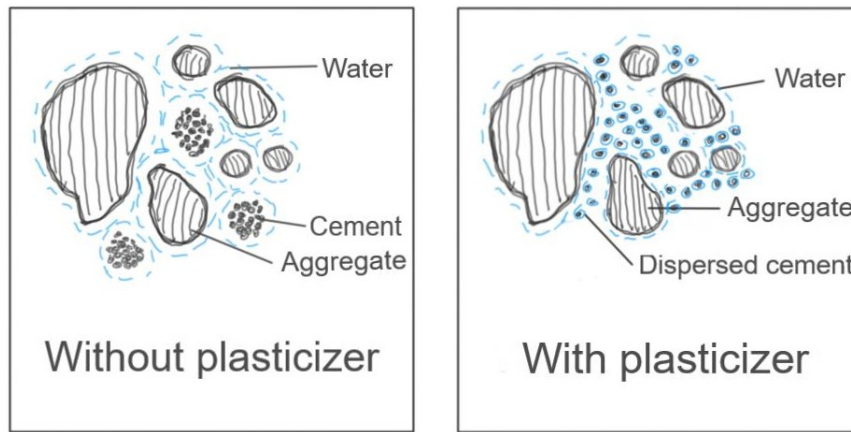
Figure 3.5: Illustration of the effects of plasticizer in a concrete mixture, after [27].

3.1.6 Porosity of concrete

The porosity of a material describes the internal volume that can be filled with water. Volumetric change can be associated with the chemical reaction of water and cement during hydration because the reaction product is smaller in volume than the volume of the reactants (water and cement) [34]. The porosity of hardened cement paste consists of capillary pores and gel pores. Gel pores occur due to the growth of the C-S-H phase from the cement particles. The capillary pores are voids between cement particles that have not been filled with C-S-H as the cement particles react with the water which earlier filled these voids [34]. Capillary pores in the pore structure impose weak zones that reduce important properties of concrete such as impermeability, strength, and durability [34]. The growth of C-S-H and the occurrence of pores during the hydration process is illustrated in Figure 3.6.
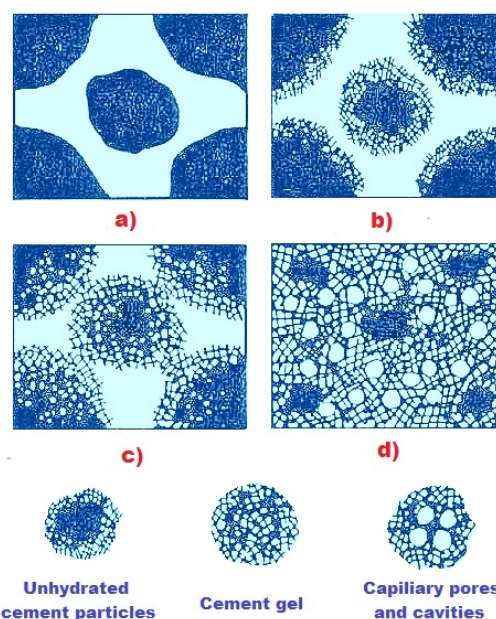
Figure 3.6: Illustration of the growth of C-S-H and occurrence of pores during the hydration of cement paste, [35].

Compaction and strength potential is closely related because the effectiveness of the compaction will determine to which extent the strength potential of the concrete can be exploited. The degree of compaction influences the strength potential because entrapped air pockets in concrete, which are compaction voids create weak zones in the hardened concrete paste. By measuring the density of the hardened concrete sample, the degree of compaction can be obtained. Large variations in air void content and density within the concrete structure indicate uneven compaction of the concrete. Compaction voids have a course and irregular shape and tend to accumulate on the vertical surface of the concrete. These voids can cause large potential negative consequences for durability and strength [28].

3.1.7 Strength of concrete

The strength of a material can be defined as the ability of the material to resist stress without failure where failure can be observed as cracks. Due to the properties and characteristics of concrete, the strength of concrete has to be further specified and defined as the maximum stress a concrete sample can withstand [25]. This specification in the definition is necessary because external and internal cracking can occur before the maximum load is applied, and nonvisible internal cracks can occur when the concrete is being exposed to maximum stress [25].

The occurrence of strength in concrete can be described as the strength of hardening cement which is a result of the hydration process where bonds of cement gel particles, aggregate particles, and other bodies of the concrete occur [17],[25]. Strength is one of the most sought-after properties of concrete and is typically used as an index for several technical properties of importance for the quality of the concrete [18],[36],[25]. It is important to have in mind that strength is an elusive property of concrete which can be affected by many variables related to production, testing, curing conditions, etc, and should therefore only be used for cooperative purposes [17]. The strength measurements can also be used as measures of uniformity and quality but should not be regarded as reliable results to the same extent as measurements of length and mass [17].

Reducing the water/cement ratio commensurate with an increase in mechanical properties in concrete such as compressive strength and flexural tensile strength [17],[25],[18],[20]. A well-dispersed concrete containing superplasticizers will achieve a higher rate of cement hydration, and show higher compressive strengths in the first week of curing compared to the reference concrete containing the same amount of water [17]. Factors such as the maximum size of the aggregate, grading, shape, surface texture, stiffness and strength of the aggregate particles, and cement/aggregate ratio can also affect the strength of concrete [17].

The compressive strength of a material is given in the unit megapascal and can

be calculated by dividing the maximum break load in Newton by the area of the surface in millimeters where the load has been applied [36]. Compressive strength tests are usually conducted after the specimens have cured for 28 days in a water tank with the temperature of $20°C$ [20]. The compressive strength of concrete is commonly used as the most important quality criterion because when dealing with structures it is the most significant property [36]. Specimens are specifically produced to measure compressive strength and these specimens have to fulfill requirements given in standards and regulations for testing concrete to ensure that the specimens are always tested under the same conditions. [37].

Porosity is closely related to the compressive strength of concrete because the total porosity and the pore size distribution affect the strength of the cement paste. It has been proven that when the porosity in concrete decreases, the compressive strength increases [37],[25]. When assessing the porosity of concrete and its effect on compressive strength, it is important to look into the pore structure and the size of the pores. Reduced pore size (fine pores) will increase brittle failure strength and reduce maximum stress, whereas coarse porous concrete with the same total porosity and same solid structure will have lower strength than the fine pore concrete [37].

The flexural tensile strength of concrete is the concrete's ability to resist bending and it is significantly lower than the compressive strength of concrete. It is therefore common to assume that the reinforcement in the concrete must take care of the tensile forces acting on the structure [37]. Compressive strength and tensile strength are closely related because an increase in compressive strength will give an increase in tensile strength but the increase in tensile strength has a decreasing rate compared to compressive strength. It has also been proven that the ratio between tensile strength and compressive strength will decrease as the compressive strength increases[25].

3.1.8 Durability of concrete

The durability of concrete refers to the ability of the material to resist deterioration and damage over time when exposed to different conditions and environments [25]. It is one of the most essential characteristics of concrete due to long-term structural performance and the need for maintenance throughout the concrete structure's lifespan [38]. Aspects of durability are resistance against the following degradation factors [38], [25]:

- Chemical attack: sulfates, chlorides, acids, and alkalis.

- Freeze-Thaw cycling

- Abrasion and erosion

- Corrosion of reinforcement

- Alkali-Silica reaction (ASR)

Concrete permeability is of vital importance for the durability of concrete structures. For structures in marine environments, which are designed to protect against water penetration, permeability is of direct importance. Permeability of concrete occurs due to the transportation of masses through the pore system of the concrete. Because of this, the pore structure of concrete is of crucial importance for permeability and resistance against concrete degradation [38].

Methods of measuring the permeability of different masses in concrete are the water penetration method, capillary suction method, water vapour diffusion (The cup method), Chloride diffusion (submerged chloride penetration), and chloride ion migration [38].

3.2   Microsilica

Silica fume also known as microsilica has been used as a pozzolanic additive in concrete since the 1970s and the mineral admixture was introduced to the US concrete technology by two organizations; Elborg Technology and Norcem. Elborg Technology was a joint venture of Aalborg Portland and Elkem Metals, and the company became the organization Elkem Chemicals when Aalborg left the joint venture. Today the organization is known as Elkem Silicon Products. Norcem was a joint venture between John Wolsiefer, Sr., and Scancem which was a Norwegian cement supplier. The organization later became Norchem Concrete Products and became a part of the Ferroglobe group [39].

Microsilica is a by-product from the production of elemental silicon or alloys containing silicon and the material is a very fine non-crystalline silica product. The smelter plants released the silica fume in the form of smoke in the days before silica fume was captured for use in concrete. Silicon oxide gas is released from the electric-arc furnace and as a result of the condensation of this gas, noncrystalline silica dioxide, commonly known as silica fume or microsilica, can be extracted. A process flow diagram of microsilica production is presented in Figure 3.7 and a schematic illustration of a smelter and the production of silica fume is presented in Figure 3.8.
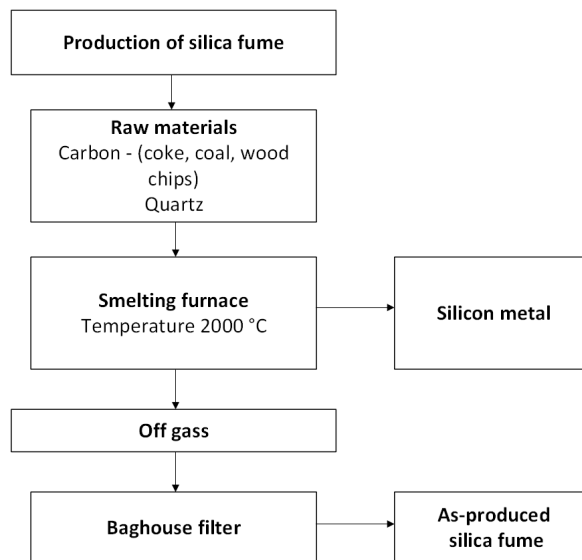
Figure 3.7: Process diagram of microsilica production, after [39, p. 5].
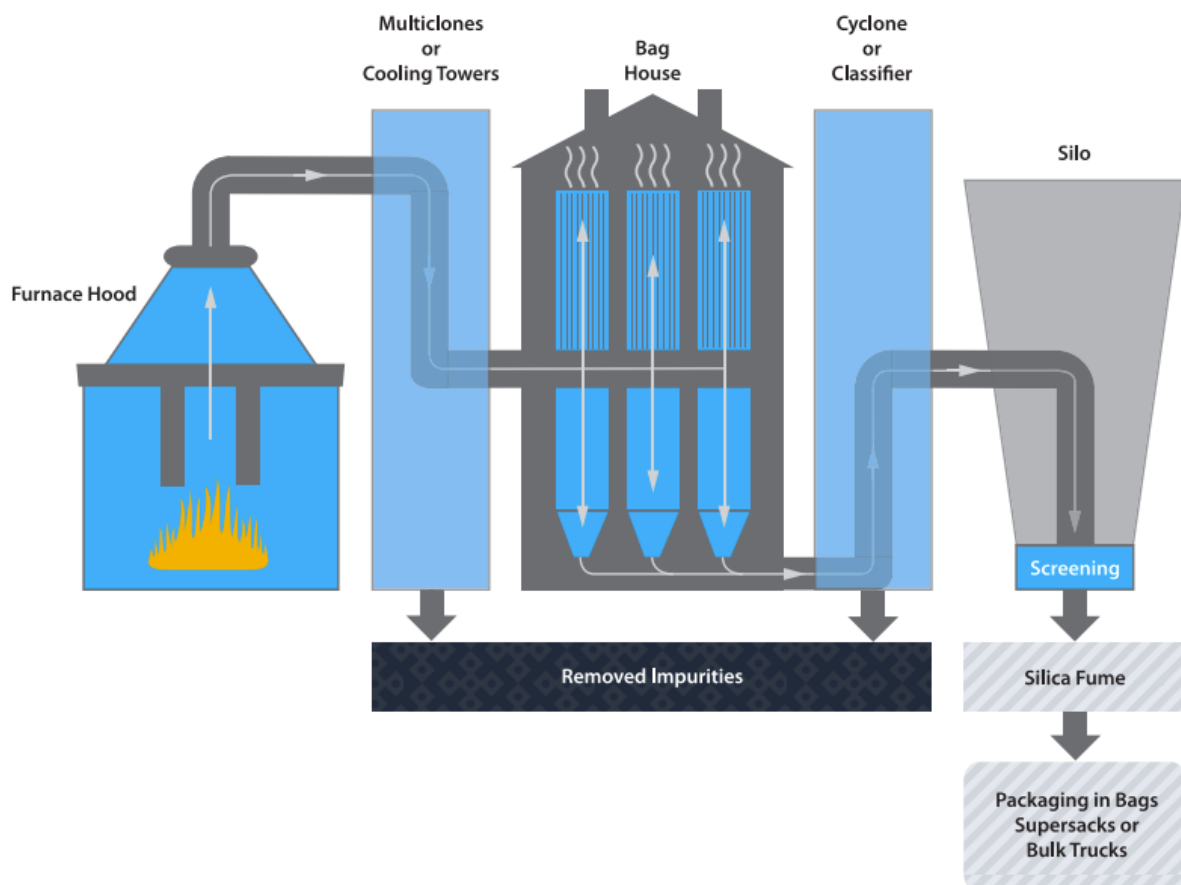
Figure 3.8: Schematic illustration of microsilica processing and cleaning system in a smelter plant, [39, p. 5].

The processing of microsilica can vary since the material can be extracted from several different production plants. The product comes in the form of gray powder and can be categorized as a supplementary cementitious material [39],[19],[17]. Most of the carbon is burnt when microsilica is produced in a furnace with an efficient heat recovery system, which results in a material that is virtually free from

carbon and has a light color. In cases where microsilica is being produced without a full heat recovery system, the material contains small amounts of carbon which give a darker color [17].

The microsilica may contain trace elements also referred to as impurities, which are additional materials that come from the metals. Microsilica typically has a particle size of less than 1 micrometer, which is significantly smaller than the typical particle size of Portland cement (1-100 micrometer) [22], [39]. A comparison of the grain sizes of microsilica and Portland cement can be seen in Figure 3.9.

(a) Cement grains   (b) Microsilica grains
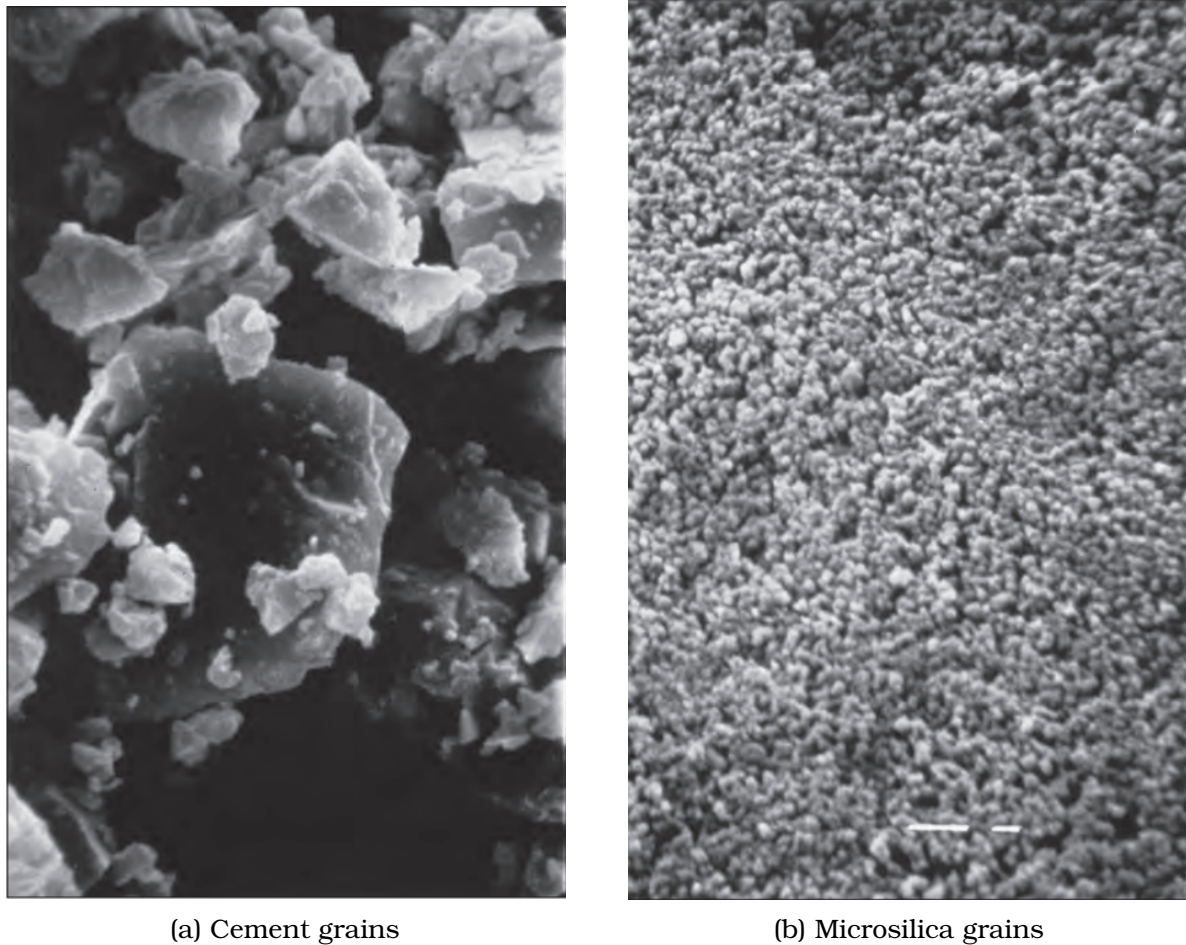
Figure 3.9: Photomicrograph of Portland cement grains and microsilica particles taken at the same magnification,[39, p. 9].

Silica fume can be separated into 3 categories, which are densified microsilica, undensified microsilica, and slurried microsilica. The as-produced microsilica powder, also known as undensified microsilica is distributed in bags and can cause severe dust problems if handled pneumatically [19],[17]. Densified microsilica is the most commonly used type of dry microsilica and has an increased bulk density of 560 to 720 kg/m^3 compared to undensified microsilica which has a bulk density of 128 to 433 kg/m^3 [19]. When using densified microsilica in concrete it is important to ensure that the mixing of the concrete is adequate. This is necessary to break up the particle agglomerations so that the microsilica

particles are dispersed properly in the concrete mixture [39]. Slurried microsilica consists of water, microsilica, and sometimes chemical admixtures. The mixture usually contains equal mass amounts of water and microsilica and when used in concrete, an equal amount of water must be subtracted from the mixture to maintain the intended water/cement ratio [19, p. 24],[17]. Microsilica is a pozzolanic material that is commonly added to concrete to reduce the amount of cement and to increase the performance of strength and characteristics in concrete [20].

3.2.1 Microsilica in concrete

The physical and chemical properties of microsilica influence the microstructure of concrete [39]. The pozzolanic material influences the properties of hardened concrete as illustrated in Figure 3.10.
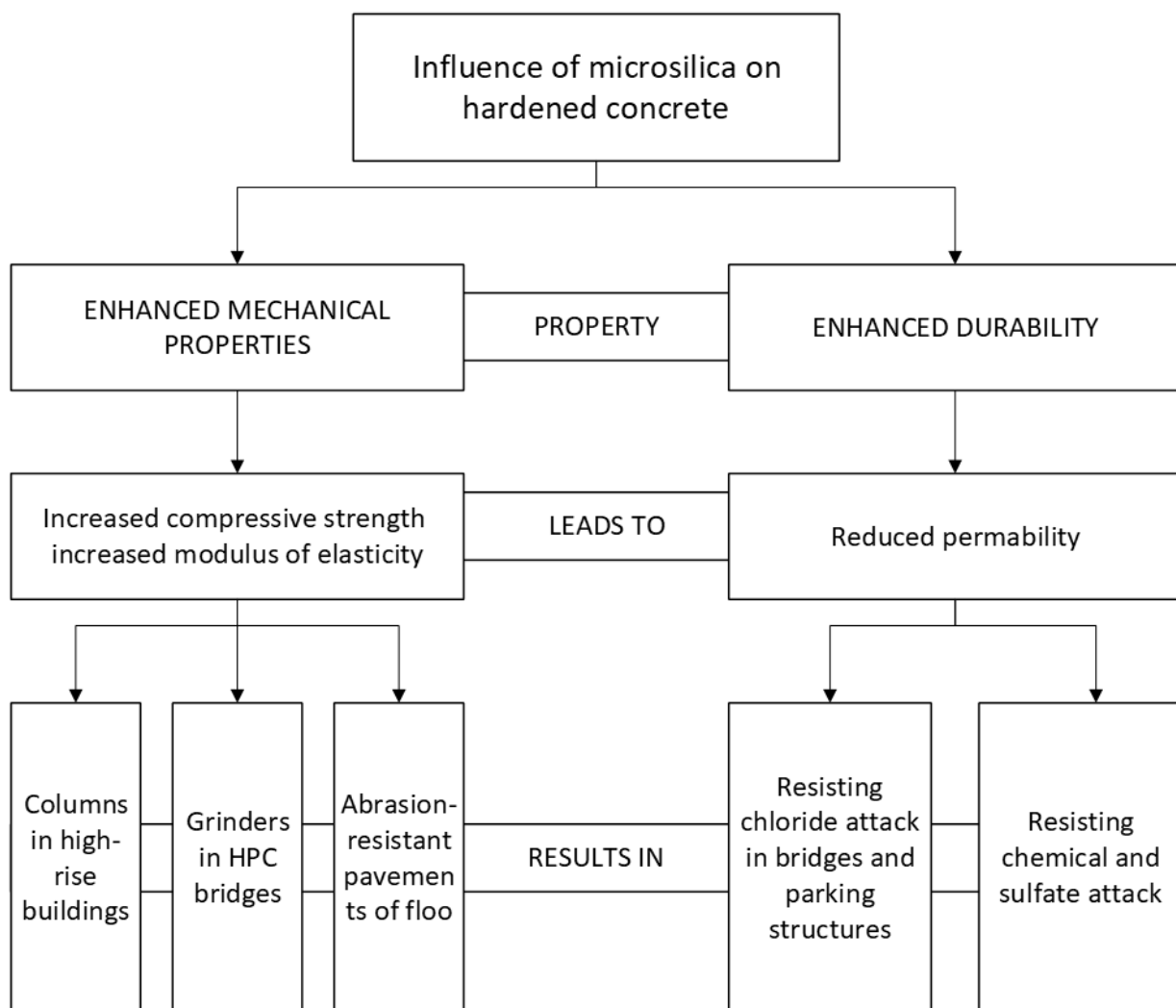
Figure 3.10: Effects microsilica have on hardened concrete, [39, p. 20].

Microsilica is primarily composed of amorphous SiO_2 and which makes it a highly reactive pozzolanic material that reacts with the calcium hydroxide produced by the hydration of cement. This reaction can enhance and improve properties of concrete, such as compressive strength, flexural tensile strength, and durability

[19],[17], [39]. Microsilica also contributes to "packing" of the concrete due to its small and spherical particles which decrease the void spaces in the cement mixture [40],[17],[20]. The pozzolanic material contributes to higher durability by decreasing the permeability of the concrete. It also increases the electrical resistance of the concrete which can prevent macrocell corrosion of reinforcing steel by restricting the current flow [19].

The shape and the size of microsilica particles can cause major changes in the properties of fresh concrete and the changes depend on the mix components as well as the dosage of microsilica [40]. High–range, water–reducing admixtures are often used in concrete mixtures containing microsilica due to an increased water demand caused by the mineral admixture. The water demand increases due to the fineness of microsilica and admixtures are used to control the workability of the concrete mixture while maintaining the desired W/C ratio [19], [20]. The increase in water demand is dependent on the surface area of the mineral admixture which means that microsilica types with high specific surface area will increase the water demand more than microsilica with low surface area [17],[25], [39].

4 Research questions

In this section of the report, the central research question is presented. Limitations of the thesis are also presented.

The research question is:
How does different compositions of microsilica affect the properties and characteristics of concrete?

Three secondary questions have been formulated to further specify the topic of interest investigated in this report. The secondary questions are as follows:

- How does microsilica affect the properties of fresh concrete mortar?

- How does substituting 10% of the binder with microsilica affect the strength development of the mortars?

- Which influence does the microsilica have on the durability of the mortars?

4.1 Limitations

The limitations that have been applied to the research questions are presented below:

- Concrete containing only fine aggregates will be investigated.

- Superplasticizer will be the only form of chemical admixture in the mortars.

- Microsilica will be the only pozzolanic additive in the mortars.

- The concrete will not contain any form of reinforcement.

- All mortars will be made at the laboratory at UiA, Grimstad, Norway.

5 Materials

The materials that have been used to make concrete mortar are specified in this chapter of the report.

5.1 Cement and chemical admixture

In this study, Rapid Aalborg cement CEM I 52,5 N was used in the mortars that were used for process development. The cement contains approximately 95% Portland clinker, 5% gypsum, and lime filler, and the mineral content of PC by weight was: C_3S - 68%; C_2S - 10%; C_3A -8%; Ca_4AF -11%. The specific surface area measured as Blaine-fineness was approx. $430\,\mathrm{m}^2$/kg (+/- $30\,\mathrm{m}^2$/kg). The density and strength of the cement are presented in Table 5.1 and the chemical composition is presented in Table 5.2

Table 5.1: Density and strength of Aalborg rapid cement

Density [kg/m^3]		**Cement strength** [MPa]			
Bulk	Absolute	24 h	48 h	7 days	28 days
1160	3140	23	36	55	67

Table 5.2: Chemical composition of Aalborg rapid cement

Chemical composition (%)						
CaO	SiO_2	Fe_2O_3	Al_2O_3	MgO	Na_2O- equiv.	SO_3
65	21	3	5	1	0,5	3,2

All the information about Allborg Rapid has been provided by Aalborg Portland A/S.

SCHWENK Portland cement CEM I 42,5N was used in mortars made in the preliminary study as well as the research on mortar containing microsilica. Aalborg rapid cement CEM I 52,5 N and SCHWENK Portland cement CEM I 42,5N both comply with the requirements in EN 197-1:2011.

NORMENSAND, CEN-NORMSAND DIN EN 196-1 sand has been used for all mortars. Sika ViscoCrete UHPC-2 superplasticizer has been used as a water-reducing admixture and the superplasticizer contains 40% dry matter. The superplasticizer has a pH of 4 +- 1 and a density of 1,08 +- 0,02 kg/liter.

5.2 Microsilica

All information presented in this section has been provided by Elkem ASA. Microsilica has been used as a pozzolanic additive in this study and ten different compositions of microsilica were provided by Elkem ASA, Fiskå, Norway. These microsilica samples come from ferrosilicon- and silicon manufacturing plants located in different parts of the world. The 10 different microsilica samples are visualized in Figure 5.1.
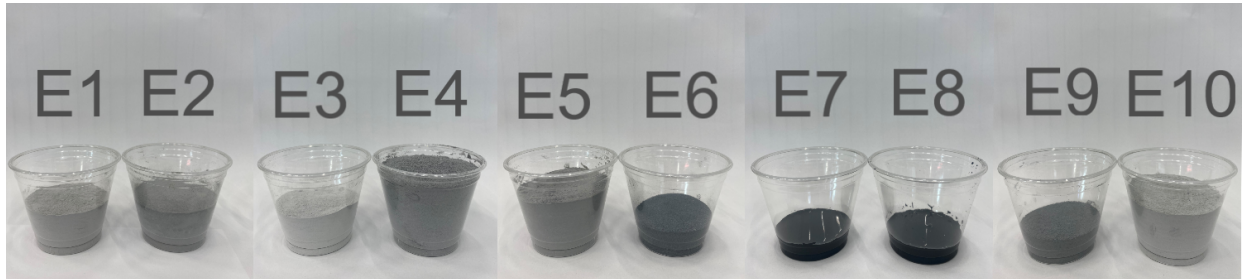
Figure 5.1: 45 grams of each type of microsilica

The chemical compositions of the microsilica samples are presented in Table 5.3.

Table 5.3: Chemical composition of the microsilica

	Chemical composition (%)						
	LOI 950 °C	pH	Free Si	SiO2	Fe2O3	Al2O3	CaO
E1	1,56	8,17	0,01	93,83	2,1	0,359	0,636
E2	0,81	7,49	0,03	96,86	0,08	0,249	0,339
E3	1,57	7,33	0,05	94,38	0,11	0,478	0,22
E4	1,78	7,33	0,03	95,55	0,091	0,231	0,471
E5	0,87	7,14	0,07	95,98	0,082	0,121	0,226
E6	1,62	6,92	0,2	93,16	0,318	0,444	0,295
E7	2,04	5,07	0,1	93,91	0,595	0,392	0,397
E8	2,38	6,06	0,1	93,29	0,698	0,388	0,432
E9	2,61	6,59	0,08	92,46	0,329	0,093	0,296
E10	2,95	2,95	0,02	92,22	0,334	0,089	0,338
	MgO	K2O	Na2O	SO3	Cl	P2O5	Na2O-eq
E1	0,41	0,566	0,381	0,167	0,05	0,02	0,75
E2	0,182	0,21	0,172	0,169	< 0.006	0,03	0,31
E3	0,61	1,976	0,34	0,354	0,0576	0,06	1,64
E4	0,214	0,771	0,129	0,355	< 0.006	0,024	0,6
E5	0,337	1,019	0,246	0,493	0,02	> 0.1	0,92
E6	0,542	1,841	0,305	0,864	0,131	> 0.1	1,52
E7	0,378	0,962	0,234	0,499	0,0588	> 0.1	0,87
E8	0,401	1,052	0,274	0,512	0,0822	> 0.1	0,97
E9	0,812	2,207	0,349	1,209	0,0144	> 0.1	1,8
E10	0,871	2,066	0,278	1,573	< 0.006	> 0.1	1,64

The physical properties of the microsilica samples are presented in Table 5.4.

Table 5.4: Physical properties of E1–E10 microsilica

	Physical properties					
	Bulk Density	Moisture	BET SA	Particle size distribution (µm)		
	(kg/m3)	(%)	(m2/g)	d10	d50	d90
E1	348	0,63	16,9	0,101	0,309	191
E2	330	0,45	27,74	0,0647	0,224	0,812
E3	360	0,88	16,65	0,195	0,448	13
E4	167	0,46	18,16	0,121	0,343	8,8
E5	228	0,65	24,21	0,0459	0,184	0,673
E6	638	0,72	24,62	0,0285	0,131	0,616
E7			24,69	0,0258	0,117	0,623
E8			24,57	0,0283	0,114	0,924
E9	681	0,7	17,15			
E10	252	0,76	18,94			

The microsilica samples come in different forms where samples E1-E5 and E10 are undensified microsilica, microsilica samples E7 and E8 are slurried, and samples E6 and E9 are densified microsilica.

6 Methodology

Several different methods have been used to answer the research question of this report. This chapter presents and describes the methods used to investigate how microsilica affects the mechanical properties and characteristics of fresh, hardening, and hardened mortar. A literature review has been conducted to investigate research on the topic of interest and the results are used for comparison of test methods, measurements, and observations. A description of the process development and preliminary study is presented. The methodology used for testing, measuring, and documenting the influence microsilica has on mortar is also presented in this chapter.

6.1 Report structure and tools

The structure of the research conducted in this report can be roughly separated into three main stages:

1. Process development

2. Preliminary study

3. Research on properties and characteristics of concrete and mortar containing microsilica

Microsoft Projects Professional has been used to create a schedule of progress. This schedule contained information about meetings with supervisors, mixing schedules, and testing schedules.

The online text editing program Overleaf has been used for text editing in this report and Mendeley reference manager was used as a reference library and citation tool. The Mendeley reference manager plugin was activated in Overleaf so that direct importation of references from the reference library was possible.

All data and results produced in laboratory procedures and experiments have been documented in Microsoft Excel spreadsheets. Excel has also been used to create the diagrams presented in this report. Microsoft Teams has been used as a digital meeting platform for meetings with supervisors and meeting reports have been documented in the text editing program Microsoft Word. Microsoft has also been used to create a literature review logbook used in the literature review methodology. Microsoft Visio has been used to create process diagrams. Illustrations have been created using the program Sketchbook. For recreated figures that are not owned by the author, the owner of the work has been referred to in the figure text of the illustration.

Photographs that have been presented in this report which are owned by the

author, have been taken with an iPhone mobile camera. All work that has been presented in this report which does not include a reference, is produced and owned by the author of this report.

6.2   Meetings with supervisors

Meetings with supervisors were arranged more than once a month to discuss project-related topics. These meetings were used to make clarifications on several aspects of the project such as scheduling meetings, planning laboratory experiments, determining testing methods, goals and scope, etc. The meetings took place both digitally on Microsoft Teams and physically at either UiA campus Grimstad or at Elkems facilities at Fiskå. Before the meeting took place, an agenda for the meeting was prepared, so that topics of importance for the report could be discussed. A meeting report was written after every meeting so that important information from the meetings was documented.

6.3   Literature review

A list of literature was provided by Elkem at the beginning of the project and this literature was used as a source of information to write chapter 3 Background. All the articles were read through and assessed to gain knowledge on topics such as concrete, microsilica, cement, test methods, etc. Information presented in the theoretical background chapter has also been collected from books about concrete technology available at the UiA library.

A literature review was conducted to find information about similar projects and research where the characteristics and properties related to the use of microsilica as a pozzolanic additive in concrete and mortar have been investigated. A literature review logbook was established to keep track of the refinements of each literature search and to document the final selection of literature that would be used in this report, see Appendix A - Literature review logbook.

6.3.1   Literature search 1

The first search was conducted at ScienceDirect and the following filters were used to refine the search:

Table 6.1: Filters used in literature search 1

Filters and parameters used in literature review methodology	
Search words	Silica fume & Concrete
Years	2021-2023
Subject area	Material Science
	Engineering
	Environmental Science
Access type	Open access & Open archive

This search gave 5 results and all the abstracts were read through to investigate the relevance of the articles. The articles showed little relevance to the research question in this report and it was therefore necessary to conduct another search.

6.3.2 Literature search 2

The second literature search was conducted using the search engine "ScienceDirect". The search parameters and input is described in B.1 and the search gave the same results as the first literature search.

6.3.3 Literature search 3

The third search was conducted using Scopus and the following filters were used to refine the search:

Table 6.2: Filters used in literature search 2

Filters and parameters used in literature review methodology	
Search words	Compressive strength & Microsilica
Years	2017-2023
Subject area	Material Science Engineering Environmental Science Chemical Engineering
Access type	Open access
Keywords	Compressive strength Microsilica Silica fume Silica Cement Concretes High performance concrete Durability
Language	English & Norwegian

The third literature search resulted in a list of 37 articles and the articles were further investigated by reading the abstracts of all the articles and noting which of the articles contained results related to microsilica's effect on tensile strength, compressive strength, permeability, durability, packing, and microstructure. After the abstracts were read, the list was narrowed down to 16 articles.

These articles were further investigated by opening the articles and using the command "ctrl F" and searching for the expression "Microsilica" and "Silica fume". The sections that contained these words were read through and so was the conclusion to look for findings about increased quality as a result of using microsilica as a pozzolanic additive in concrete or mortar. Articles that contained such findings and results were prioritized and the list of articles was therefore reduced to 11 articles.

The 11 articles were read through to determine the relevance of the articles

compared to the goal and scope of this report. The goal of the literature review methodology was to find articles that contained information about how microsilica affected compressive strength, tensile strength, density, pore structure, chloride ion penetration, thermal characteristics, and the hydration process of concrete or mortar. The characteristics and properties of fresh and hardened concrete presented in each article were noted in a form and used as a parameter for decision-making regarding the exclusion of articles. By creating a table containing the assessed characteristics and properties in the articles it was possible to use a point system to prioritize the articles. This was done by allocating one point per assessed characteristic and property of concrete. The articles that contained the most information about relevant characteristics and properties of concrete were prioritized. The literature review methodology was concluded and resulted in a selection of five articles. A summary of these articles and findings with relevance to this report is presented in chapter 7, section 7.3.1.

6.4 Laboratory work and test regime

This section presents information about the laboratory test regime conducted as a part of this report. Several laboratory procedures were conducted and the results from the experiments have been used to answer the research question. The first laboratory exercise was planned to gain knowledge about the mortar mixture, the use of the equipment, and practicing the procedure for mixing, testing, and casting concrete. A preliminary study was conducted to investigate the effect of reducing the W/C ratio and adding superplasticizer to the mortar mixture. After conducting the preliminary study and manipulating the mortar recipe, the study of characteristics and properties in fresh, hardening, and hardened mortar containing different types of microsilica could be initiated. A rough overview of the laboratory test regime is presented in figure 6.1.
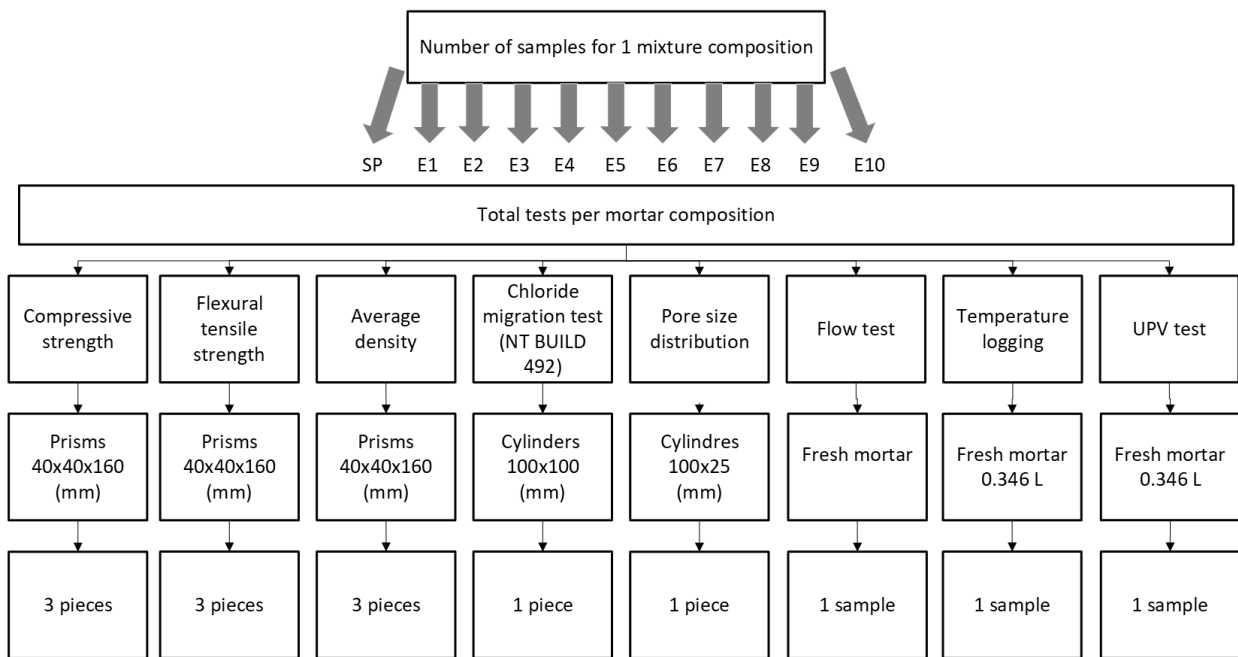
Figure 6.1: Overview of laboratory test regime, after [41].

6.4.1 Mortar batch identification

All samples used in the process development stage have identifications starting with the number 1.

The mortars that were used in the preliminary study are labeled as follows:

SM - Standard mortar.

EXP - Mortar with w/c ratio $\leq 0,4$ and contains superplasticizer.

Mortars that have been used in the research on properties and characteristics of concrete containing microsilica have been labeled using the letters R, E, and C as the first identifier in the identification label. An explanation of the letter system is presented below:

E - Specimen containing microsilica

– E1 - Microsilica type E1

R - Reference sample

– R1 - Associated reference sample for mortars containing microsilica E1

C - Chloride ion migration test specimen

– C.E1 - Chloride ion migration test specimen containing microsilica E1

6.4.2 Mixing procedure and flow test

A procedure description for the execution of EN 13261 pkt 5.3.3, produced by Elkem ASA has been used for the mixing of mortars and casting of mortars as well as the execution of flow test [42]. The standard NS-EN 196-1:2016 has been used as a source of information on equipment used for mixing mortar [43]. As

preparation for the mixing procedure, the instructions, and result forms were printed, laminated, and brought into the laboratory. These documents were also thoroughly read through before conducting the first mixing attempt. An Excel spreadsheet was used to document information about laboratory conditions, weight measurements of mortar components, date of mixing, and time of mixing. A separate spreadsheet was used to document the results from the flow test. The necessary equipment used in the mixing is described in the EN 13261 pkt 5.3.3 procedure description. Additional equipment used for mixing is listed below:

- Laminated lab form

- Whiteboard marker

- Hammer

- Steel brush

- Plastic wrap

- Oil for molds

- Plastic gloves

- Bucket

- Dishwasher brush

Before the mixing was initiated, water and cement were weighed on a scale and the weight was written down in the lab form. The name of the batch, batch ID, date and time of mixing, air temperature, and humidity in the lab was also documented in this form for each batch. This information was later entered into Excel. The mixing of mortar and execution of the flow test was then conducted with modifications of the procedure description of EN 13263-1:2005 pkt 5.3.3. The modifications were as follows:

- The mortar was mixed for additional 30 seconds at high speed after the flow test was conducted. This was done to thoroughly mix the mortar used in the flow test with the remaining mortar in the mixing bowl before the casting process was initiated.

- Plastic wrapping was used to cover the molds as a replacement for a glass plate.

- The samples did not cure under the conditions specified in the procedure description for the first 24 hours. Relative humidity was not controllable because the laboratory at the University of Agder in Grimstad does not have a climatic test chamber. The RH was not 50 %, but the temperature in the lab satisfied the specifications.

Results from the flow test were written on the laminated lab form and later entered into the Excel spreadsheet. After the samples were set to cure, the equipment used for flow test and mixing was cleaned and dried. When the mortar had cured

for 24 hours, the samples were removed from the molds and marked with the date and time of mixing, batch ID, and name. The specimens were then placed in a $20°C$ curing tank for 27 days.

6.4.3 Density calculations

The density of the samples had to be calculated before the compressive strength test and flexural tensile strength test could be conducted. The densities of the specimens were calculated in accordance with "Håndbok R210, 422 densitet" [44, p. 319].

6.4.4 Flexural tensile strength and compressive strength

Compressive strength tests and flexural tensile strength tests were conducted in accordance with NS-EN 196-1:2016 [43]. The test was carried out after 28 days of curing for each batch. The first step of the testing procedure was to collect the samples from the curing tank and place them in a damp towel.

Flexural tensile strength was measured by using Form+test, Prüfsysteme, Compression, and Bending Testing Machine Type MEGA 100. The procedure for testing was done in accordance with NS-EN 196-1:2016 section 9.1 Flexural strength [43, p. 20]. Figure 6.2 presents images from the test regime, where the test apparatus with a test specimen is presented in figure 6.2a and the test specimens after the test had been conducted is presented in figure 6.2b.
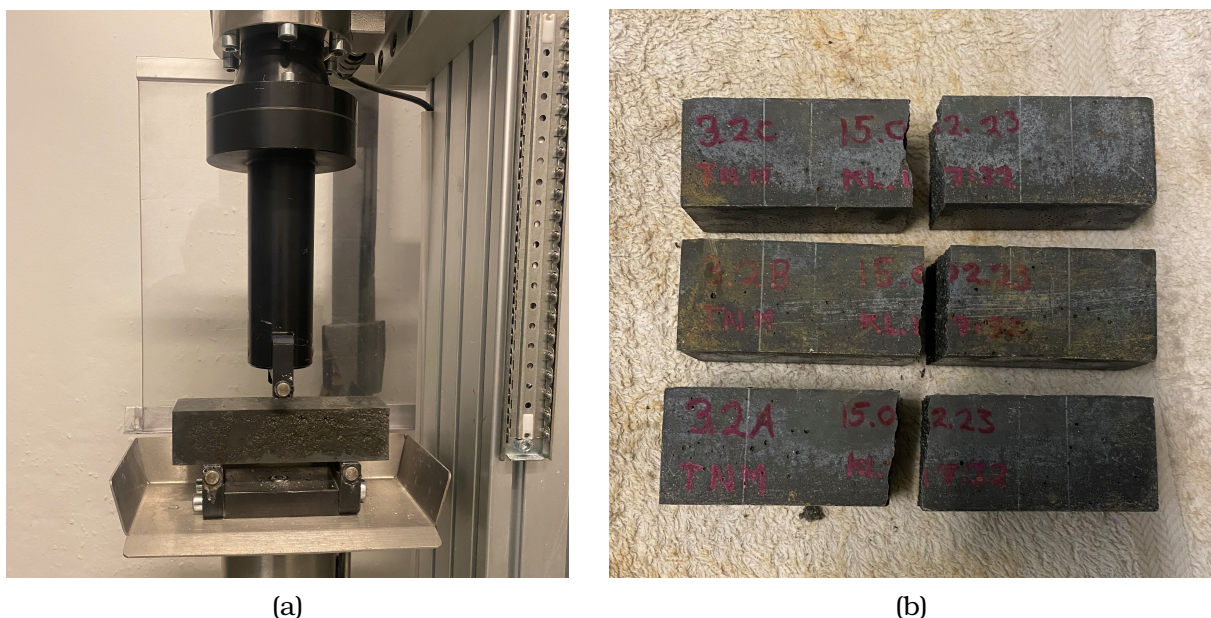
Figure 6.2: Images from flexural tensile strength test

Compressive strength was measured by using Form+test, Prüfsysteme, Compression Testing Machine Type ALPHA 3, and the test was executed in accordance with NS-EN 196-1:2016 section 9.2 Compression strength [43, pp. 20–21]. The compressive strength test apparatus can be seen in figure 6.3a and figure 6.3b shows

the test specimens after they had been tested.

| (a) | (b) |
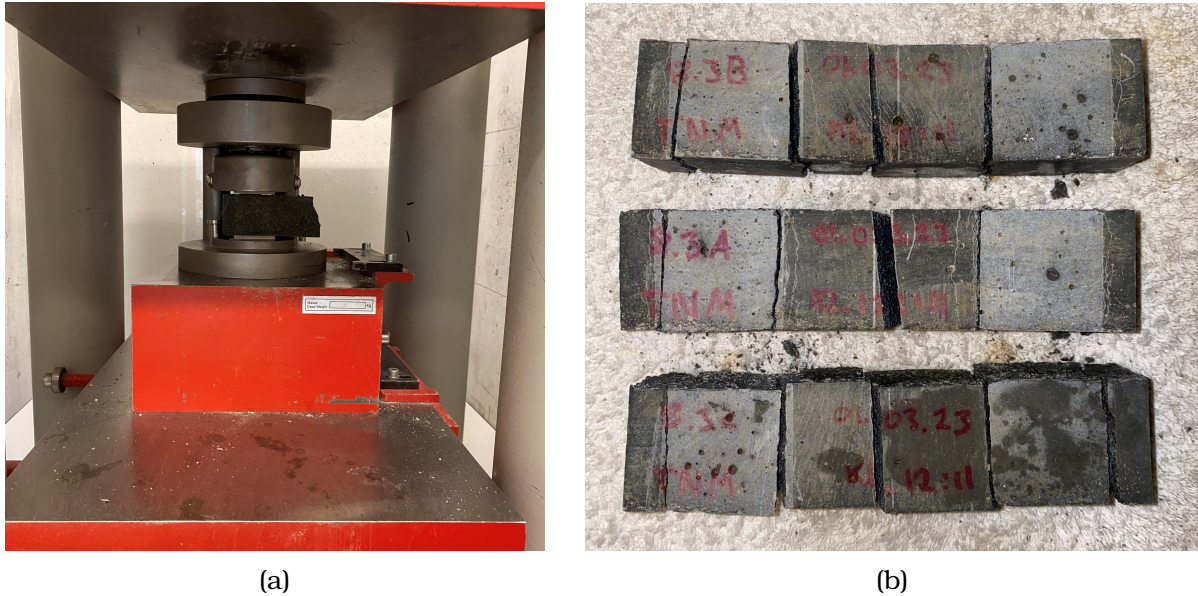
Figure 6.3: Images from compressive strength test

Results from compressive strength tests and flexural tensile strength tests were documented in an Excel spreadsheet where the standard deviation and arithmetic mean was calculated for all samples after NS-EN 196-1:2016, section 10 [43, p. 21].

6.4.5 Pozzolanic activity index (PAI)

The pozzolanic activity index also referred to as the strength activity index was calculated to investigate the pozzolanic activity caused by adding microsilica to the mortar. It was done according to standard NS-EN 13263-1:2005+A1:2009 pkt 5.3.3 and the procedure for PAI calculation is described in the procedure description provided by Elkem ASA [42]. The following equation has been used to calculate the PAS:

$$SAI = \frac{\sigma_{\text{pozzolan mix}}}{\sigma_{\text{reference}}} \cdot 100 \tag{6.1}$$

where:

$\sigma_{pozzolan\ mix}$ = Compressive strength of sample where part of the cement was replaced by a corresponding mass of the pozzolanic additive [MPa];

$\sigma_{reference}$ = Compressive strength of reference sample, [MPa];

The calculations of PAI have been conducted using Excel spreadsheets.

6.4.6 Temperature logging of mortars samples

Temperature logging of mortars was conducted for several mortar samples in this project. The temperature logging was conducted over 45 hours and the temperature was measured every 30 seconds. This was done to investigate the temperature development while the mortar was curing in an insulated curing box. The following equipment was used to execute the temperature-logging exercise:

- Insulated curing box

- Plastic bag

- Grant temperature logger

- Cables/wires

- Computer

- Mortar

- Scale

- Whiteboard marker

- Laminated lab form

- Mixing equipment

Before the temperature logging could be conducted, it was necessary to download software for the Grant temperature logger and create the setup. The temperature logger date and time were set to the same date and time as the computer that was used, and the logging interval was set to measure the temperature every 30 seconds. The mortar was mixed as described in 6.4.2, except for the execution of the flow test. After mixing the mortar was transferred to a plastic bag and the plastic bag was then placed in a curing box. A cable was then inserted into the center of the mortar, the lid was placed on the curing box and logging mode was activated on the temperature logger. After 45 hours the logger was deactivated and the cable was detached from the mortar samples. The temperature logger was plugged into a computer and the data was extracted as an Excel file. To analyze the data, the analysis function in Paintview was used to create graphic illustrations of the temperature changes over time for each mortar composition. This was done to investigate the temperature development inside the mortar as the mortar was curing. The temperature logging results were transferred to an Excel spreadsheet and the sample was disposed of after the temperature logging was completed.

6.4.7 Calculation of total heat value

To investigate the total heat release of the mortars that have been used for temperature logging, the Riemann sum of the temperature logging data was calculated 6.2. This was done to formulate an expression for the total heat of hydration for each mortar. The following formula (6.2) was used to calculate the Riemann sum:

$$S = \sum_{i=1}^{n} f(x_i^*)\Delta x_i \tag{6.2}$$

Where:

$\Delta x_i = x_i - x_{i-1}$

$x_i^*[x_{i-1}, x_i]$ The calculations were executed in Excel and all data points from the temperature logging were used to calculate the total heat release.

6.4.8 Chloride ion migration test

An NT BUILD 942 test was conducted to investigate the chloride ion migration coefficient of the mortar samples [45]. The mortars were made as described in section 6.4.2, with the following exceptions:

- Flow test was not conducted.

- 100 × 200 mm cast cylinders were used instead of molds for prisms.

- The samples were manually compacted instead of using a slip table for compaction.

The necessary equipment and testing procedure are described in NT BUILD 492 [45]. 100 × 200 mm cast cylinders were used and the cylinders were filled half full. The samples were manually compacted by pounding the casts 10 times on a wooden table. Plastic wrap was then placed on top of the mortar surface and the samples were set to cure for 24 hours. The specimens were removed from the cylinder casts, marked with specimen ID, date of mixing, and time of mixing, and set to cure in a curing tank for 27 days.

On the 28th day, the specimens were cut to test specimens and the test was conducted after NT BUILD 492 [45]. Images from the test procedure are illustrated in figure 6.4. After the migration test was finished and the specimens were disassembled from the test equipment and split axially into two pieces as illustrated in figure 6.4a. Silver nitrate was then sprayed onto the surface of the test specimens, see figure 6.4b.

<center>(a)</center>

<center>(b)</center>

<center>Figure 6.4: Images from NT BUILD 492 test</center>

The specimens were set to rest for 15 minutes. When the silver chloride precipitation on the surface of the specimens was visible, measurements of the migration depth could be executed. Figure 6.5 shows the test specimens with visible chloride precipitation before the measurements of chloride ion migration depths were conducted.

<center>Figure 6.5: Test specimens with visible silver chloride precipitation</center>

After the test was finalized and the penetration depth was measured and the non-steady-state migration coefficient [D_{nssm}] was calculated by using the simplified formula 6.3. Figure 6.6 illustrates how the penetration depth was measured.

<center>39</center>
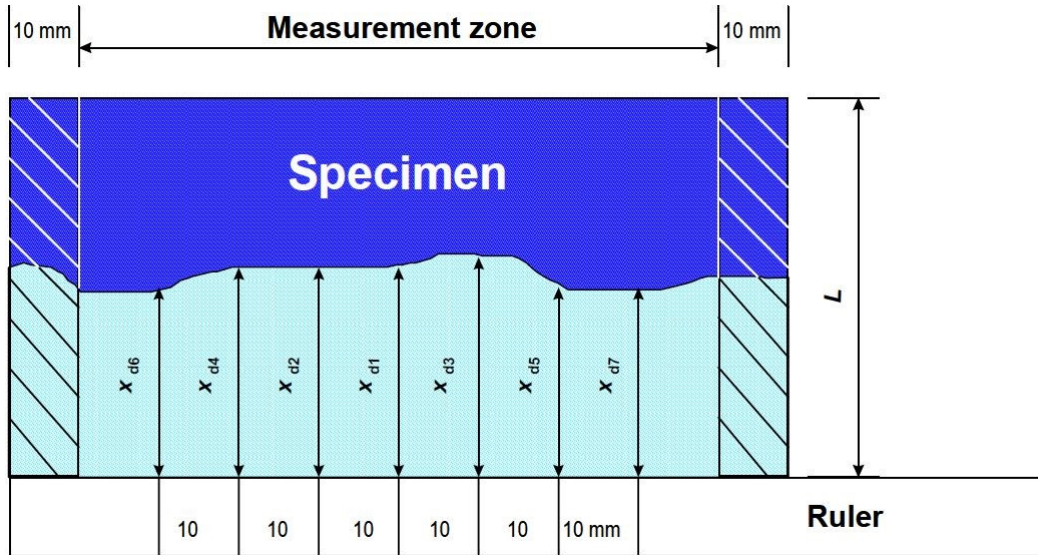
Figure 6.6: Chloride ion penetration depth illustration [45].

$$D_{\text{nssm}} = \frac{0.0239(273 + T)L}{(U - 2)t} \left(x_{\text{d}} - 0.0238\sqrt{\frac{(273 + T)Lx_{\text{d}}}{U - 2}} \right) \tag{6.3}$$

where:

D_{nssm} = non-steady-state migration coefficient [$\cdot$ 10^{-10} m^2/s];

T = average value of the initial and final temperatures in the anolyte solution, [$^\circ$C];

L = thickness of the specimen, [mm];

U = absolute value of the applied voltage, [V];

t = test duration, [h];

x_{d} = average value of penetration depth, [mm];

6.4.9 Microscopic imaging of chloride ion migration test samples

When the chloride ion migration test was conducted, the test specimens were cut into two pieces and only one of the pieces was used for the NT BUILD 492 test. The other half of the cylindrical specimens were used for the investigation of pore structure by microscopic imaging.

A JENOPTIK type:ProgRes speedXT core 3 microscope and ProgRes capturePro 2.7.7 software was used for microscopic imaging of the mortar samples. The samples were placed under the lens, the lens focus was adjusted and a ruler was placed on top of the specimen. A line measuring 1 centimeter was drawn on top of the ruler by using the measuring tool. This was done to create a line that could later be replaced with a linear scale line. The microscopic imaging procedure is illustrated in figure 6.7 and all the images that were taken in the microscopic

lens were later edited in Sketchbook where a linear scale line was inserted.
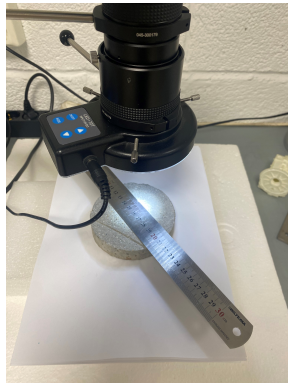
(a) Specimen under lens   (b) creating scale line   (c) Image with scale line
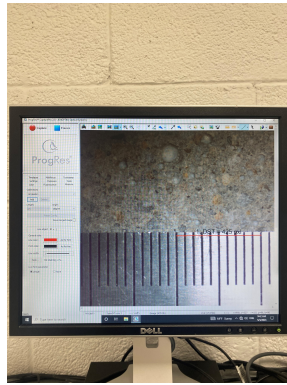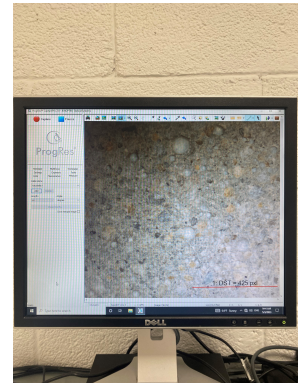
Figure 6.7: Images of microscopic imaging procedure

6.5 Process development

To gain knowledge about how to use the equipment in the laboratory at UiA, it was decided that 2-3 days would be used to learn how to mix, test and mold the mortar to increase the repeatability of the laboratory procedures. The process development exercise was executed to minimize variation in the mixing, casting, and testing procedures. Before the laboratory work could be initiated, it was necessary to retrieve information about the mixing procedure, mortar mixture recipe, and necessary equipment. This information was examined and used to plan the execution of the laboratory experiment.

A total of 5 batches of mortars were made as a part of the process development. Mixing of mortar and execution of flow tests has been done in accordance with section 6.4.2 and Aalborg rapid cement was used in the mortars. Four of the mortars were molded and used for density calculations, compressive strength tests, and flexural tensile strength. The tests were conducted as described in section 6.4.3 Density calculations and section 6.4.4 Flexural tensile strength and compressive strength. Temperature logging was conducted as described in section 6.4.6 and batch 1.5 was used for this purpose. The temperature logging results were produced for further use in the preliminary study.

6.6 Preliminary study: Influence of w/c ratio on concrete

A preliminary study was conducted to investigate the effects of adding superplasticizer and reducing the w/c ratio in the mortar. The objective of the preliminary study was to determine the optimal amount of water and superplasticizer that would be used in mortars where 10% of the binder was substituted with microsilica.

Mortars used in the preliminary study were mixed and tested as described in section 6.4.2. The preliminary study was conducted experimentally so that the

w/c ratio and superplasticizer dosage was adjusted for each mix based on the flow test results of the previous mixture. Figure 6.8 illustrates the procedure cycle used in the preliminary study.
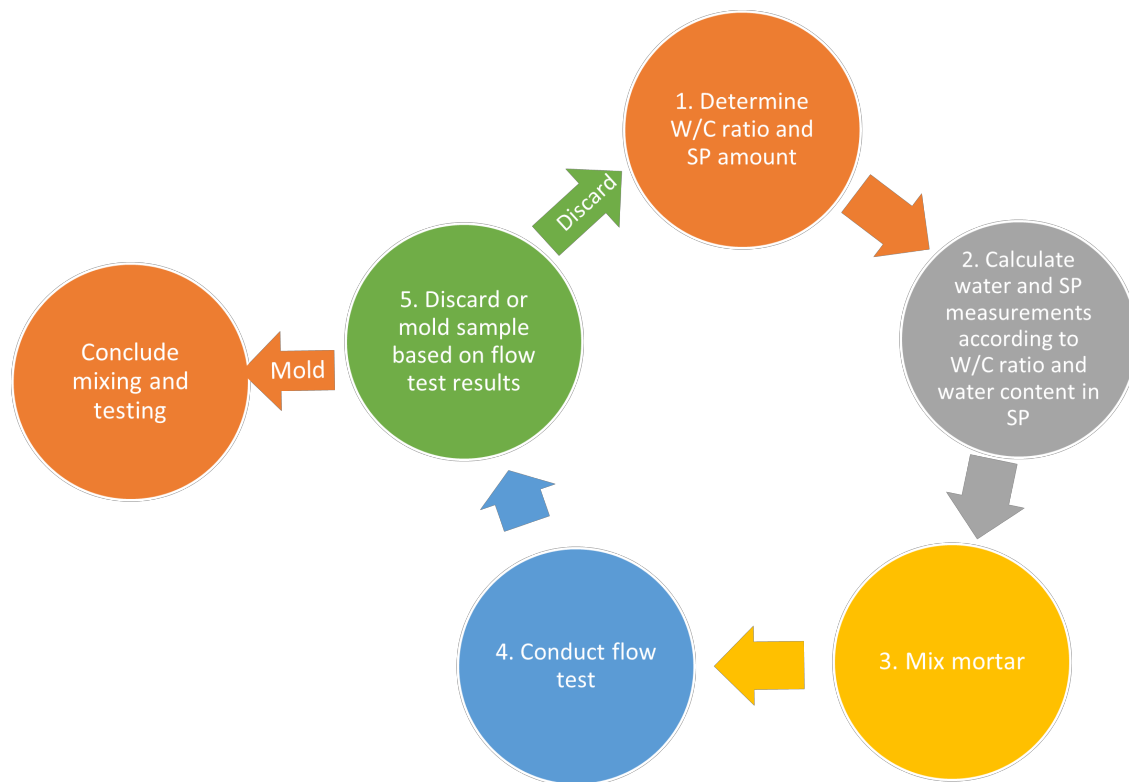
Figure 6.8: Overview of test regime in preliminary study

The dosage of SP used in the mortar was calculated as a percentage of the binder in the mortar. The superplasticizer contained 60% water which had to be considered when calculating the total amount of water in the mortar. This was necessary to ensure that the intended w/c ratio was obtained. The amount of water in the SP solution was then subtracted from the water determined by the W/C ratio. The following formulas were used to calculate the total mass of water that had to be added to each mixture.

$W = (W_c \cdot M_c) - W_{sp}$
$where:$
$W_{sp} = M_{sp} \cdot 0,6$
$M_{sp} = M_c \cdot \frac{S}{100}$

W = Total mass of water added to mortar mixture [g]
W_c = Water/cement ratio
M_c = Mass of cement in mortar mixture [g]
W_{sp} = Water content in superplasticizer [g]
S = Superplasticizer amount [%]
M_{sp} = Mass of superplasticizer [g]

A reference sample of standard mortar (SM) was made as the first step of the mixing procedures conducted every day of mixing. The reference mortar was made as described in section 6.4.2. This was done to ensure that the batches with varying SP dosages and w/c ratios could be compared to a zero-sample. Using superplasticizer and adding it to the water was an additional modification to the mixing standard procedure. Flow tests were conducted and the results were documented in the lab form and later in the Excel data sheet. If the flow test results exceeded the target flow value range (176+-10mm) the sample was discarded. Adjustments to the water and superplasticizer content were done as follows;

- If the flow test results were too high:
  1. Reduce the dosage of superplasticizer.
  2. If the dosage of superplasticizer is reduced to less than 0,5%, reduce the water/cement ratio and determine the new dosage of superplasticizer.

- If the flow test results were too low:
  1. Increase the dosage of superplasticizer.
  2. If the amount of superplasticizer has increased to 5% of the water/cement ratio, increase the water/cement ratio and determine a new dosage of superplasticizer.

The equipment was cleaned and dried between every execution. The preliminary study was concluded when the flow test results were satisfactory. Density, flexural tensile strength, and compressive strength was measured for the samples that cured.

6.7 Mixing, molding, and testing mortar containing microsilica

This section presents the methodology used to mix, test, and mold mortar samples containing different types of microsilica. 10% of the binder in each mortar was substituted with microsilica and 10 different types of microsilica were used in the mortars.

All the mortars containing microsilica were mixed, molded, and tested according to EN 13263-1:2005 pkt 5.3.3 and NS-EN 196-1:2016, with modifications described in section 6.5. The first step of every mixing exercise was to make a reference sample that did not contain microsilica. The mortar composition of the reference sample was determined by the results given by the preliminary study. Reference sample mortar composition:

Cement: 450g

Sand: 1350g

Superplasticizer: 4g

Water: 176,8g

Water/cement ratio: 0,4

Superplasticizer dosage: 0,9% of cement mass.

A sample containing one type of microsilica was then mixed, tested, and molded as described in section 6.5. The mortar compositions for the microsilica mortars are described in appendix A with additional modification in adding superplasticizer.

A flow test was conducted to determine if the flowability of the fresh mortar satisfied the target flow value. The samples were discarded if the flow test gave unsatisfactory results or if the samples were not homogeneous due to insufficient mixing of the mortar. If the flow test results were unsatisfactory, the SP content was adjusted to achieve acceptable flow test results. The samples were set to cure and after 24 hours they were placed in a curing tank for 28 days. After 28 days, the densities of the samples were calculated as described in section 6.4.3. Compressive strength and flexural tensile strength were then tested as described in section 6.4.4.

Temperature logging, chloride ion migration test, and microscopic imaging were executed as described in section 6.4.6 Temperature logging, section 6.4.8 Chloride ion migration test and section 6.4.9.

6.7.1 Criterion for exclusion of test results

Several tests were conducted as a part of the report and the results were processed by using different methods. The systematic processing of results was necessary to detect and eliminate statistical deviations from the database so that the results that were presented were reliable and representative.
The target value range for flow test results was determined by calculating the arithmetic mean of the flow test results of batch SM.1-SM.3 used in the preliminary study. The batches that measured more than +-10mm from the arithmetic mean were discarded except for reference samples. Exclusion criterion for compressive strength–and flexural tensile strength test results are described in standard NS-EN 196-1:2016 [43]. Compressive strength and flexural tensile strength results were determined by calculating the arithmetic mean of all samples with the same batch ID and results that varied more than 10% from the arithmetic mean were discarded. This was done to eliminate deviations so that a representative mean value of the test results could be calculated. If more than one test result in the same batch was outside the target value range, the entire batch had to be discarded.
Test criterion for the chloride ion migration test was presented in NT BUILD 492, [45] and according to the standard, the temperature of each test apparatus must

be within the range of 20–25 $^\circ C$. If any of the test apparatuses measured temperatures outside of the temperature range, the specimen had to be discarded. For mortars containing microsilica the mortar composition must have a w/c ratio of 0,4 and the substitution of the cement with microsilica must be 10% of the cement weight. The mortar samples must be discarded if these criteria are not satisfied.

7 Results

In this section of the report, the results from the process development phase, and the preliminary study execution are presented. Results from the literature review and tests used for the investigation of the influence of microsilica on concrete are also presented in this chapter.

7.1 Process development results

The first laboratory experiment was conducted to learn about the procedures related to mixing, molding, and testing so that the following labs would be sufficiently accurate. In this section of the report, results from lab 1 are presented, where workability, thermal characteristics, density, and strength have been investigated through different test methods.

7.1.1 Laboratory conditions and mortar composition

Temperature and RH conditions were documented as a part of the laboratory procedure and the results are presented in Table 7.1 along with measurements of the ingredients used in the mortar samples.

Table 7.1: Measurements and laboratory conditions for lab 1

Batch ID	RH (%)	Temperature ($^{\circ}C$)	W/C	Water (g)	Cement (g)	Sand (g)
1.1	35,0	20,0	0,5	225,0	450,0	1355,0
1.2	32,0	19,5	0,5	225,0	450,0	1355,0
1.3	32,0	19,5	0,5	225,0	450,0	1355,0
1.4	32,0	19,5	0,5	225,0	450,0	1355,0
1.5	35,5	19,5	0,5	225,0	450,0	1355,0

7.1.2 Test results

Several tests were conducted as a part of the process development and the test results are presented in Table 7.2.

Table 7.2: Results from tests conducted as a part of the process development

Batch ID	Flowability [mm]	Density [kg/m^3]	Felxural tensile strength [MPa]	Compressive strength [MPa]
1.1	173,1	2300,54	8,27	70,27
1.2	169,0	2286,64	8,13	72,03
1.3	169,9	2299,85	8,13	71,87
1.4	177,1	2301,01	7,97	69,30
1.5	194,5	-	-	-

When mortar 1.5 was mixed, there were technical problems with the equipment which delayed the mixing of the ingredients by 30 seconds.

7.2 Preliminary study: Influence of w/c ratio on concrete

The preliminary study was conducted to gain knowledge about the effects of superplasticizer and water reduction in mortar. Measurements of ingredients used in the preliminary study and conditions in the laboratory during the execution of the lab are presented in this section along with results from temperature logging, flow test results, density calculation, and strength measurements.

7.2.1 Laboratory conditions and measurements of ingredients

The preliminary study was executed over two weeks and the temperature and laboratory conditions for every day of mixing are presented in Table 7.3. All mortars that have a water/cement ratio of 0,5 are reference samples.

Table 7.3: Information about laboratory conditions and ingredients in preliminary study

Batch ID	RF (%)	Temperature ($^\circ C$)	W/B	SP (%)	SP (g)	Cement (g)	Sand (g)	Water (g)
SM.1	29,5	20,0	0,5	0	0,0	450,0	1355,0	225,0
EXP.1	29,5	20,0	0,3	1	4,5	450,0	1355,0	131,4
EXP.2	29,5	20,0	0,3	5	22,5	450,0	1355,0	117,0
EXP.3	29,5	20,0	0,4	1	4,5	450,0	1355,0	176,4
EXP.4	29,5	20,0	0,35	5	22,5	450,0	1355,0	139,5
SM.2	30,0	20,0	0,5	0	0,0	450,0	1355,0	225,0
EXP.5	30,0	20,0	0,37	5	22,5	450,0	1355,0	148,5
EXP.6	30,0	20,0	0,37	3	13,5	450,0	1355,0	155,7
EXP.7	30,0	20,0	0,37	1	4,5	450,0	1355,0	162,9
SM.3	30,0	20,0	0,5	0	0,0	450,0	1355,0	225,0
EXP.8	30,0	20,0	0,36	5	22,5	450,0	1355,0	144,0
EXP.9	30,0	20,0	0,36	3	13,5	450,0	1355,0	151,2
EXP.10	30,0	20,0	0,36	1	4,5	450,0	1355,0	158,4
SM.4	34,0	20,0	0,5	0	0,0	450,0	1355,0	225,0
EXP.11	34,0	20,0	0,4	1	4,5	450,0	1355,0	176,4
EXP.12	34,0	20,0	0,4	1,5	6,8	450,0	1355,0	174,6
EXP.13	34,0	20,0	0,4	1	4,5	450,0	1355,0	176,4
EXP.14	34,0	20,0	0,4	0,5	2,3	450,0	1355,0	178,2
SM.5	34,0	20,5	0,5	0	0,0	450,0	1355,0	225,0
EXP.15	34,0	20,5	0,4	0,9	3,8	450,0	1355,0	177,0
EXP.16	34,0	20,5	0,4	0,9	4,0	450,0	1355,0	176,8
EXP.17	34,0	20,5	0,4	0,9	4,0	450,0	1355,0	176,8

7.2.2 Test results

Table 7.4: Test results from the preliminary study (SM.1: Standard mortar 1, EXP.1: Experimental mortar 1.

Batch ID	Flowability $[mm]$	Density $[kg/m^3]$	Felxural tensile strength $[MPa]$	Compressive Strength $[MPa]$
SM.1	168,8	2281,69	7,27	53,32
EXP.1	105,1	-	-	-
EXP.2	110,1	-	-	-
EXP.3	167,5	2381,12	7,77	68,58
EXP.4	108,7	-	-	-
SM.2	173,3	2282,19	7,13	56,03
EXP.5	200,0	-	-	-
EXP.6	122,8	-	-	-
EXP.7	114,6	-	-	-
SM.3	189,0	2295,74	6,93	55,60
EXP.8	176,3	-	-	-
EXP.9	111,4	-	-	-
EXP.10	114,9	-	-	-
SM.4	182,5	2285,68	7,20	54,40
EXP.11	110,8	-	-	-
EXP.12	205,2	-	-	-
EXP.13	204,9	-	-	-
EXP.14	124,1	-	-	-
SM.5	169,4	2284,98	7,10	54,00
EXP.15	154,9	2325,62	7,90	66,43
EXP.16	167,1	2356,39	7,90	67,22
EXP.17	151,5	-	-	-

As a result of the preliminary study, several samples were discarded due to unsatisfactory curing and unsatisfactory flow test results. The samples that were discarded are listed in Table 7.5 which is presented below.

Table 7.5: Samples that were discarded in the preliminary study.

Batch ID	Reason for discarding
EXP.1	The fresh mortar was too dry
EXP.2	Did not cure properly
EXP.4	Did not cure properly
EXP.5	Did not cure properly
EXP.6	Did not cure properly
EXP.7	Did not cure properly
EXP.8	Did not cure properly
EXP.9	Did not cure properly
EXP.10	The fresh mortar was too dry, outside of +- 10 mm range in flow test
EXP.11	The fresh mortar was too flowable, outside of +- 10 mm range in flow test
EXP.12	The fresh mortar was too flowable, outside of +- 10 mm range in flow test
EXP.13	The fresh mortar was too dry, outside of +- 10 mm range in flow test
EXP.14	The fresh mortar was too dry, outside of +- 10 mm range in flow test

7.2.3 Temperature logging

Temperature logging was conducted for a standard mortar made as a part of the process development (1.5) and the mortar with a w/c ratio of 0,4 containing 0,9% superplasticizer (EXP.17). The results from the temperature logging are presented in Figure 7.1.
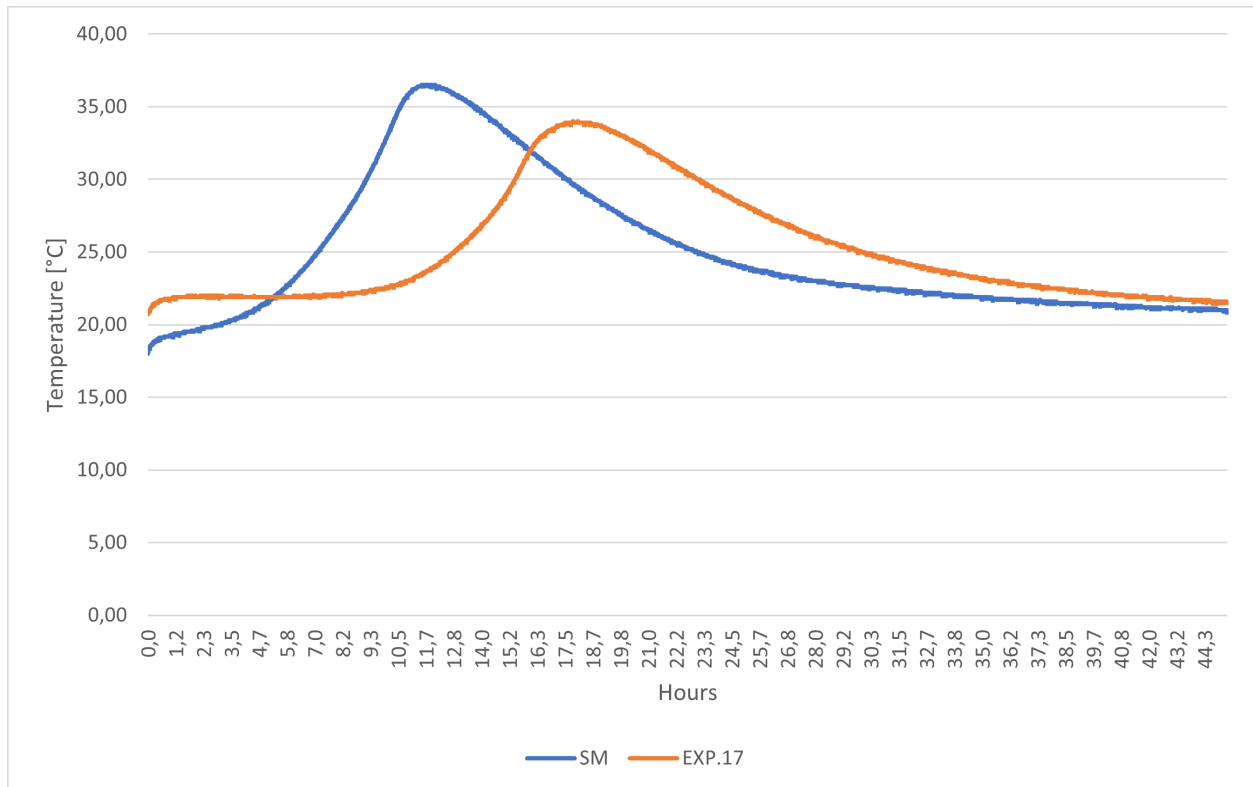
Figure 7.1: Temperature logging results from the preliminary study.

The maximum recorded temperature and the complete setting time of the mortars are presented in 7.6.

Table 7.6: Maximum temperature and complete setting time of standard mortar (1.5) and mortar with w/c ratio of 0,4 containing 0,9% superplasticizer (EXP.17).

Mortar	Maximum temperature $[°C]$	Complete setting time $[h]$	Total heat release $[°C * h]$
SM (1.5)	31	11,47	1169,64
EXP.17	30	18,04	1184,22

As a result of the preliminary study, it was determined that the water/cement ratio for all mortars containing microsilica would be 0,4. It was also concluded that the ideal dosage of superplasticizer was 0,9% of the cement mass of the mortar.

7.3 The effect of using different types of microsilica on the concrete properties

A literature review on the effect of using different types of microsilica on concrete properties has been conducted and the results are presented in this section. As a part of this experimental study, several mixtures of mortar containing densified, unidentified, and slurry micro silica were mixed, tested, and molded.

7.3.1 Literature review

A literature review was conducted as described in chapter 6, section 6.3, and the result of the literature review is presented in this section of the report. A total of five articles have been assessed and summaries of the articles are presented below.

Insulation foam concrete nanomodified with microsilica and reinforced with polypropylene fiber for the improvement of characteristics

In this report, the authors have conducted an experimental study where the purpose of the study was to improve the characteristics of heat-insulating foam concrete by implementing polypropylene fiber reinforcement and nanomodifying microsilica additives to the concrete mixture. The characteristics of foam concrete were determined by using standard methods and the structure of the composite was studied by using optical microscopy methodology. A preliminary study was conducted to identify the optimal percentage range of polypropylene fiber reinforcement content in foam concrete. Experimental studies were then carried out with 22 series of samples containing different values of the percentage of polypropylene fibers and microsilica. Tests were conducted to investigate compressive strength, flexural tensile strength, average density, release humidity, and thermal conductivity.

It was discovered that the optimal dosage of nanomodifying microsilica was reacted by substituting 10% of the binder with the pozzolanic additive. The results showed that the compressive strength and flexural tensile strength of the fiber foam concrete increased by approximately 44% and 73% in foam concrete containing 2% polypropylene fiber and 10% microsilica. The authors also observed that the average density of foam concrete containing 10% microsilica and 1%, 2%, and 3% content of polypropylene fiber was approximately 512 kg/m^3, 510 kg/m^3, 517 kg/m^3. The pore macrostructure of a control specimen and a microsilica fiber-reinforced specimen were analyzed. The results showed that the control specimen had unreasonably thickened interpore partitions compared to the specimen containing fibers and microsilica. This indicates that the control sample has reduced strength characteristics when compared to the microsilica and fiber specimen which has a significant enlargement of the main pores due to the lower microporosity of interpore partitions. Effective compaction of the interpore partitions which eliminates capillary porosity and increases the "packing"

of the particles was achieved by using microsilica as a nanomodifying additive in the foam concrete. This also resulted in denser foam concrete. The authors concluded that a combination of nanomodifying microsilica and polypropylene fiber reinforcement in foam concrete improves both the physical and mechanical properties of the concrete [41].

Influence of recipe factors on the structure and properties of non-autoclaved aerated concrete of increased strength

In this article, the authors studied non–autoclaved aerated concrete with improved characteristics and which influence some prescription factors can have on the structure formation and properties of the concrete. This was done to investigate cellular concrete which is proven to be the most effective building materials regarding energy efficiency in structures and buildings. As a part of the study, the authors conducted a literature review on the influence of applied waste on the characteristics of cellular concrete where several types of waste were assessed as a replacement for binder or aggregates. Ground blast-furnace slag (GBFS) and microsilica (MS) were used as additives in the concrete with a w/c ratio of 0,5 and the influence the additives had on properties and structure was investigated using SEM analysis and standard test methods.

The density and compressive strength were measured for 96 samples. As a result of density calculations, it was discovered that there were no significant changes in density for the samples. From the microstructural analysis performed on the SEM test results, it was concluded that the microsilica additive used as a substitute for cement provided a denser microstructure than the reference samples containing no additives. It was observed that the non–autoclaved aerated concrete showed higher strength characteristics when the MS content was increased from 4% to 16% compared to the aerated concrete containing GBFS and a complex additive, see Figure 7.2.
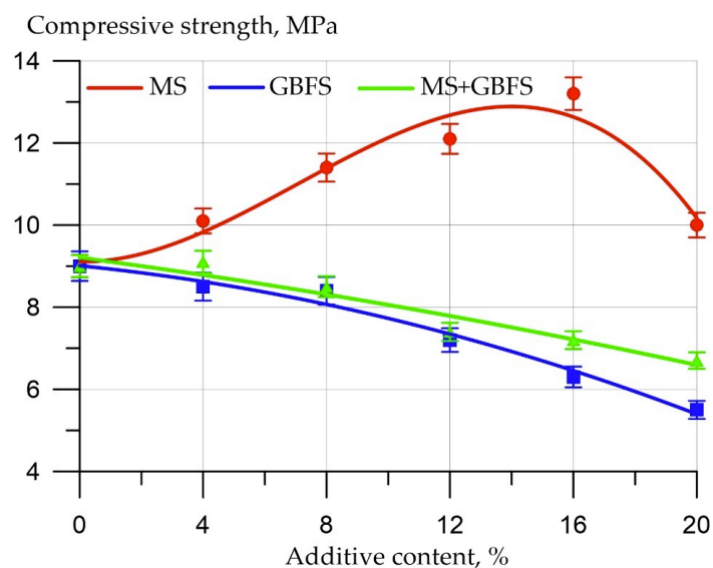
Figure 7.2: Compressive strength of non–autoclaved aerated concrete samples with different percentages of binder replacement, [46].

The authors also disclosed that the highest measured compressive strength value was recorded for the aerated concrete specimen containing 16% microsilica. It was concluded that the addition of microsilica enabled an improvement of the microstructure of aerated concrete when compared to the control composition [46].

Study of the course of cement hydration in the presence of waste metal particles and pozzolanic additives

The need for special heavyweight concrete is increasing as the demand for hydro-technical and energy facilities is growing. Due to this issue, the authors of this report have analyzed the influence of waste–metal particle filler (WMP) on Portland cement paste (PC) and mortars containing pozzolanic additives (microsilica and metakaolin). The objective of the study is to investigate how WMP influences the structure development, hydration process, and mechanical and physical properties of specimens that had been cured for 28 days. The mortar compositions contained 5%, 10%, and 20% microsilica and metakaolin as a substitution for the binder.

Results show that adding pozzolanic additives increased the total heat value by 37% in the WMP paste. The ultrasound propagation velocity (UPV) in WMP-containing mortar with pozzolanic additives increased by 16 % compared to the control sample. Results also showed that the paste containing only WMP had a 4% lower UPV than the WMP—free paste. The water absorption decreased due to the addition of pozzolanic additives, the compressive strength however increased by 22% in the WMP mortar compared to mortar without pozzolanic additives. According to the results, the density of the samples containing WMP and microsilica was calculated to be approximately 4120 kg/m^3 which was significantly higher than the density of the control specimen which was approximately 2200 kg/m^3. Pozzolanic additives in the WMP-containing mortar resulted in an improvement in the contact zone between the WMP and the cement matrix, which facilitated a less porous cement matrix and resulted in a strength of 46,50 MPa after 28 days of curing. This specimen showed an 8,7% increase in strength when compared to the control sample.

The authors concluded that using pozzolanic additives in WMP-containing mortars can contribute to solving problems related to the application of WMP in local heavyweight concrete production. It can also significantly expand the opportunities of using local waste–metal particles in special concrete [47].

Effect of silica fume on high-strength concrete performance

The article "Effect of silica fume on high–strength concrete performance" presents research on silica fume in concrete mixtures and how silica fume affects the mechanical performance in terms of tension, compression, bending, cyclic loading, and interdependencies regarding characteristics. The objective of the study was to determine which effect silica fume had on the performance of high–strength

concrete used in road pavement construction.

Standard methods for testing were used for the three concrete mixtures containing 0%, 7%, and 10% silica fume where all three samples had a water/cement ratio of 0.4. Several strength tests were conducted and the density of the samples was calculated to investigate the difference in microstructure as a result of adding silica fume to the concrete mixture. A total of 63 specimens were made and all tests were conducted after the samples had cured for 28 days. The results show that the density of specimens containing 0%, 7% and 10% microsilica were calculated to be 2,287 kg/m³, 2,392 kg/m³ and 2,411 kg/m³, which illustrates an increase in density by 4,6–5,4% when adding silica fume to the concrete mixture. Strength test results are presented in Figure 7.3 and the results show that an increase of 33,9–37,6% in compressive strength was achieved by adding silica fume to the concrete mixture. The result also indicates that the mixture containing 10% silica fume gave almost the same compressive strength results; however, test results from the flexural strength test and indirect tensile strength test were 5–11% lower that the test results for the concrete mixture containing 7% silica fume.
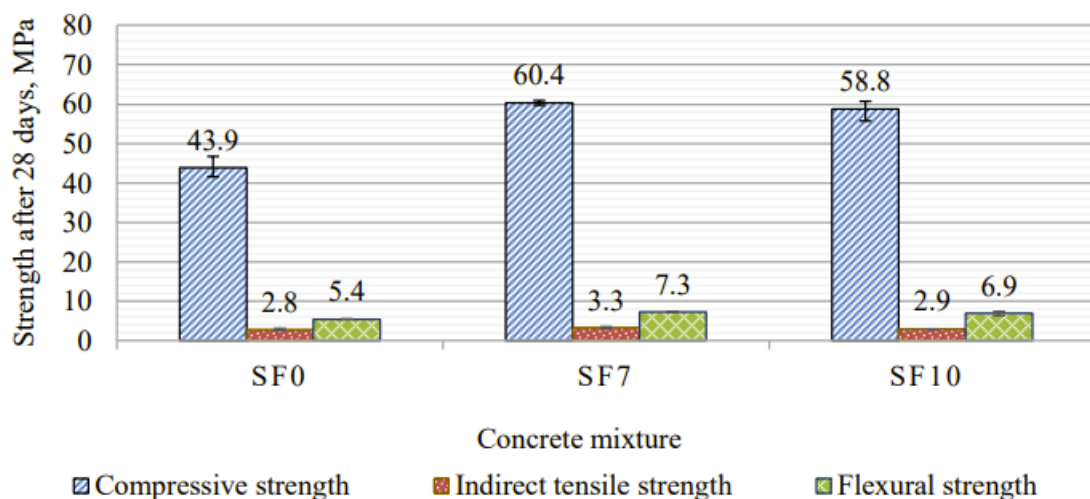
Figure 7.3: Strength test results for concrete mixtures containing different amounts of silica fume after 28 days of curing [48].

The authors concluded that the optimal amount of silica fume was 7% and that performance of the high–strength concrete used for road pavement construction was significantly enhanced due to silica fume in terms of tension, compression, bending, cyclic loading [48].

Effects of reinforced fiber and microsilica on the mechanical and chloride ion penetration properties of latex-modified fiber-reinforced rapid-set cement concrete for pavement repair. The objective of this study was to evaluate the influence of microsilica and fiber reinforcement content on the performance of latex–modified fiber–reinforced roller-compacted rapid–hardening cement concrete used for emergency repair of concrete pavement. 0, 1, 2, 3, and 4% microsilica was used as a substitution for cement, and fiber reinforcement was added.

Water/cement for all concrete mixtures was set to 0,28, 5% of the binder was substituted by latex and fibers were added at a volume ratio of 0,10%. The specimens were tested for compressive strength, flexural and splitting tensile strength, chloride ion penetration resistance, and abrasion resistance.

The results showed that the chloride ion penetration decreased as the substitution ratio of microsilica increased. Test results showed that after 4 hours of curing, the test specimens containing jute fiber reinforcement and up to 2% microsilica achieved target compressive strength and target flexural tensile strength of 21 MPa and 3,5 MPa. By using 3% macrosynthetic fiber in the concrete mixtures, the concrete satisfied the target strength values. The specimens that were tested after 28 days of curing satisfied all strength target values. Chloride ion penetration test results indicate that the chloride ion penetration decreases as the substitution ratio of microsilica increases.

The authors concluded that concrete mixtures that satisfied the target values, had improved abrasion resistance, had up to 3% microsilica substitution ratio or less, and contained macrosynthetic fiber, gave an improved performance of the concrete used for emergency repair of concrete pavements. Results also showed that reinforcing the concrete with macrosynthetic fiber improved the performance of the concrete [49].

7.3.2 Fresh mortar properties of concrete mortar containing microsilica

Flowability

Flow tests were conducted for all mortars containing microsilica and the dosage of the superplasticizer was adjusted if the flow test results were outside the target flow value range. The results from the flow tests are presented in Table 7.7.

Table 7.7: Flow test results for mortars containing microsilica and 0,9% superplasticizer.

Mortar ID	RF [%]	Temp. [°C]	SP [%]	Flow [mm]
E1	23,0	21,5	0,9	203,03
E2	22,0	21,0	0,9	170,41
E3	24,0	21,0	0,9	182,85
E4	33,0	20,5	0,9	199,10
E5	29,0	20,5	0,9	174,77
E6	34,0	20,5	0,9	177,13
E7	24,0	20,0	0,9	177,76
E8	24,0	20,0	0,9	183,03
E9	30,0	20,5	0,9	193,37
E10	30,0	20,5	0,9	191,85

Final mortar compositions

Several of the mortars used in the flow tests gave inadequate flowability and the dosage of the superplasticizer had to be adjusted. The mortar compositions that showed adequate flowability were molded and used for further testing. Compositions of the mortars that were used for strength tests, temperature logging, and chloride ion migration tests are presented in Table 7.8.

Table 7.8: Mortar compositions that gave adequate flowability.

Mortar composition					
Mortar type	Sand [g]	Cement [g]	Water [g]	SP [%]	SP [g]	W/C ratio
Ref	1355	450	176,8	0,9	4,0	0,40
E1	1355	405	177,5	0,7	3,2	0,40
E2	1355	405	176,8	0,9	4,0	0,40
E3	1355	405	176,8	0,9	4,0	0,40
E4	1355	405	177,2	0,8	3,6	0,40
E5	1355	405	176,8	0,9	4,0	0,40
E6	1355	405	176,8	0,9	4,0	0,40
E7	1355	405	131,76	0,9	4,0	0,40
E8	1355	405	131,76	0,9	4,0	0,40
E9	1355	405	177,48	0,7	3,2	0,40
E10	1355	405	177,48	0,7	3,2	0,40

7.3.3 Strength development in mortars containing microsilica

Results from tests used to investigate the strength development of mortars containing 10% microsilica are presented in this section.

Temperature logging

Temperature logging was conducted for the reference mortar and all mortars containing microsilica except mortars containing microsilica E7 and E8. A graphic illustration of all the results from the temperature logging is presented in Figure 7.4. See appendix E.3 for diagrams of temperature logging for each mortar composition.
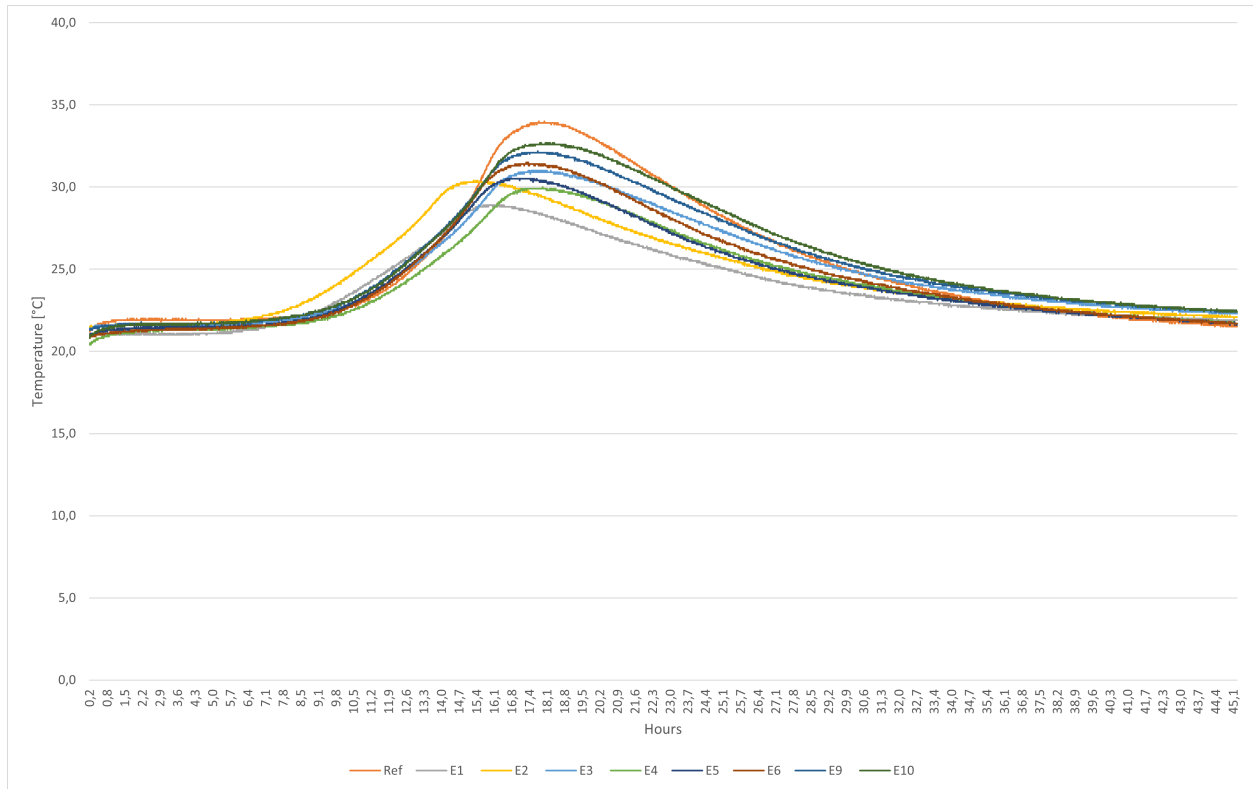
Figure 7.4: Temperature logging of reference mortar and mortars containing 10% microsilica

The complete setting time, maximum temperature, and total heat release are presented in Table 7.9

Table 7.9: Temperatur logging results for reference mortar and mortars containing microsilica.

Mortar	Maximum temperature $[^\circ C]$	Complete setting time $[h]$	Total heat release $[^\circ C * h]$
Ref	34	18,0	1184,2
E1	28,9	15,6	1120,6
E2	30,4	15,3	1154,0
E3	31	17,4	1166,2
E4	30	18,0	1133,8
E5	30,5	16,5	1141,6
E6	31,5	17,3	1153,3
E9	32,2	17,8	1184,6
E10	32,7	17,9	1193,2

The mortars containing microsilica E7 and E8 did not meet the mortar compo-

sition criterion presented in section 6.7.1 and the results from the temperature logging were therefore discarded for a fair comparison.

Density

The density of all batches that cured was calculated as described in chapter 6 Methodology, section 6.4.4 Density calculations. The results from density calculations are presented in 7.5
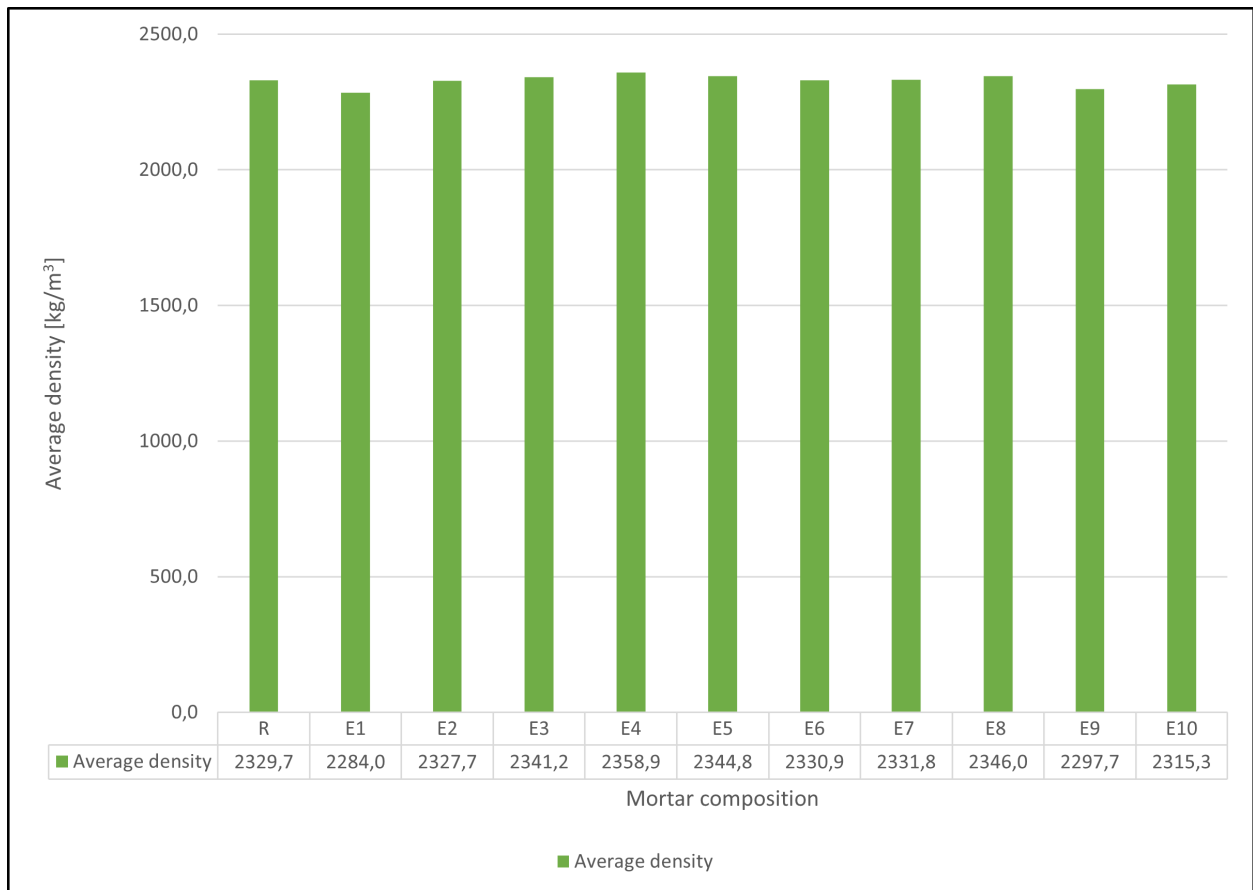
Figure 7.5: Average density of mortar reference mortar and mortars containing microsilica.

The density was also calculated for the specimens used in the chloride ion migration test, and the results are presented in Table 7.10.

Table 7.10: Density calculation results for chloride ion migration test specimens.

Specimen	C.SM	C.R	C.E1	C.E3	C.E4	C.E5	C.E6	C.E9	C.E10
Density $[kg/m^3]$	2242,1	2294,2	2254,0	2287,2	2267,7	2270,6	2279,1	2267,5	2268,1

All density calculation results are presented in Appendix E, Table E.2.

Flexural tensile strength

The flexural tensile strength of all mortars containing microsilica and the reference mortar has been conducted. The results are presented in Figure 7.6.
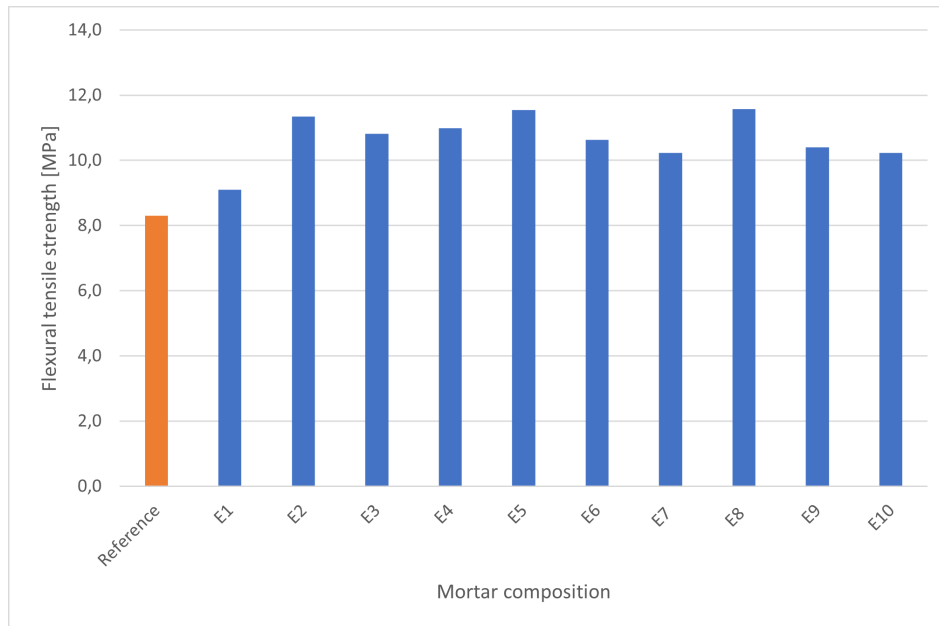
Figure 7.6: Average flexural tensile strength of the reference mortar and all mortars containing microsilica

Compressive strength and PAI

The average compressive strength of each mortar composition that has been used to investigate the effect of microsilica on concrete strength properties is presented in Figure 7.7.
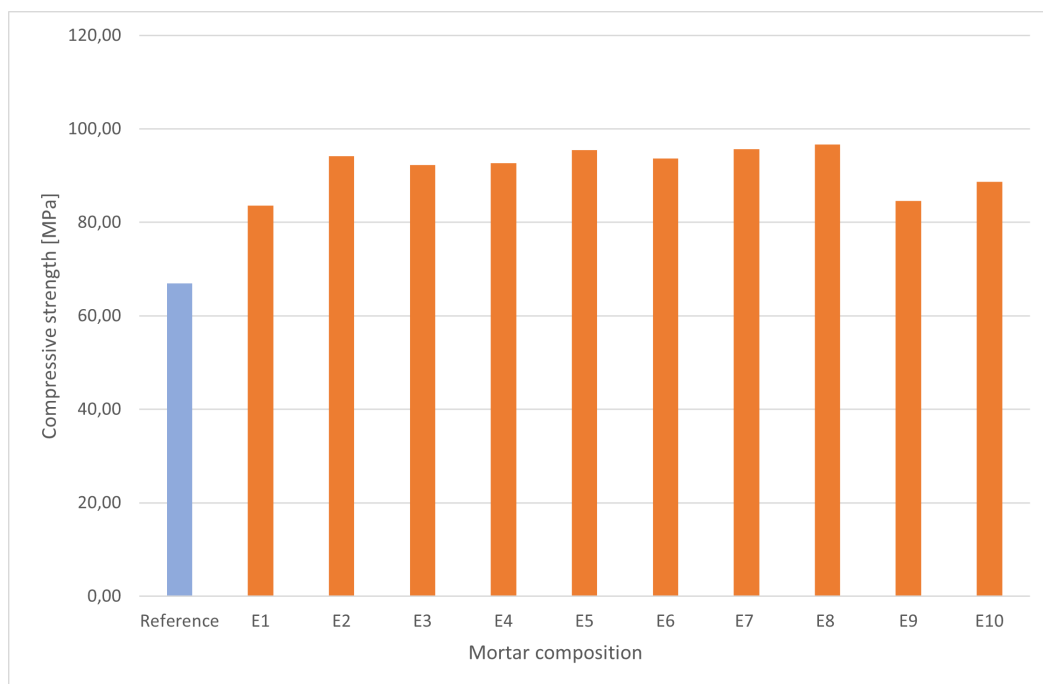
Figure 7.7: Average compressive strength achieved in mortars containing microsilica type E1-E10

A complete Table showing all compressive strength measurements is presented in Appendix E7, Table E.4.

The average pozzolanic activity index has been calculated based on the compressive strength results and is presented in Table 7.11.

Table 7.11: Average PAI for all mortar compositions containing microsilica E1-E10.

Microsilica type	E1	E2	E3	E4	E5	E6	E7	E8	E9	E10
Average PAI [%]	126,4	143,4	139,6	138,8	142,3	138,4	137,8	139,3	128,2	134,4

7.3.4 Properties of hardened mortar: Durability

Chloride ion migration test

An NT BUILD 492 chloride ion migration test was conducted as a part of this project and the results from calculations are presented in Table 7.12 below. To conduct the chloride ion migration test it was necessary to make cylindrical test specimens and the laboratory conditions and mortar compositions for the mortars are described in Table E.6, in appendix E.9.

Table 7.12: Results from chloride migration coefficient calculations

Specimen	C.SM	C.R	C.E1	C.E3	C.E4	C.E5	C.E6	C.E9	C.E10
Dnssm $[*10^{-12}m^2/s]$	3,82	2,47	3,52	4,50	1,96	2,29	0,94	1,67	1,57

Test specimen C.E2 is invalid due to unsatisfactory temperature during the test. The samples that contained microsilica E7 and E8 did not meet the mortar composition criteria, presented in section 6.7.1. Due to this, the samples were discarded and new samples containing E7 and E8 were not tested for chloride ion migration.

Cross section microscopic images of chloride ion migration test specimens

The results from the microscopic imaging procedure are presented in the section for all mortars containing microsilica except the mortars containing microsilica E7 and E8. These samples were discarded because they did not satisfy the mortar criteria presented in section 6.7.1.
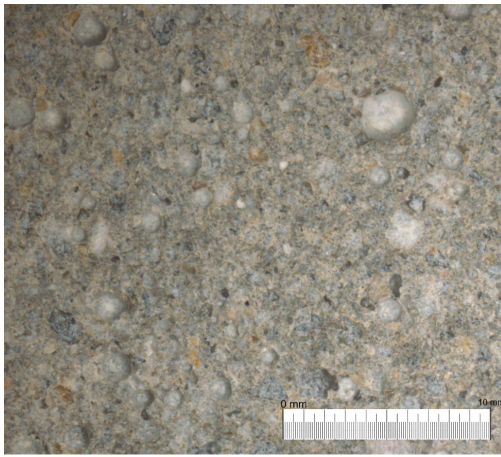
(a) Standard mortar specimen
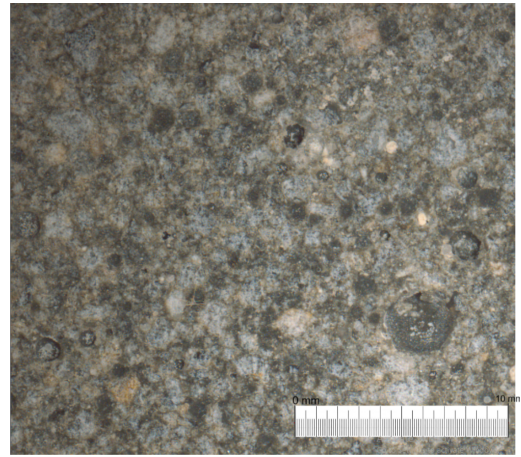
(b) Specimen with 0.4 W/C ratio and 0.9% SP

Figure 7.8: Microscopic images of sample C.SM & C.R
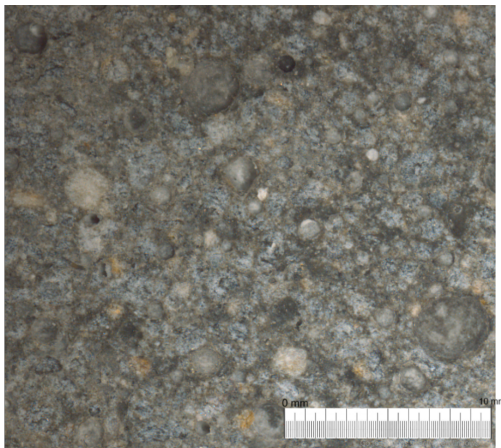
(a) Microsilica E1 specimen
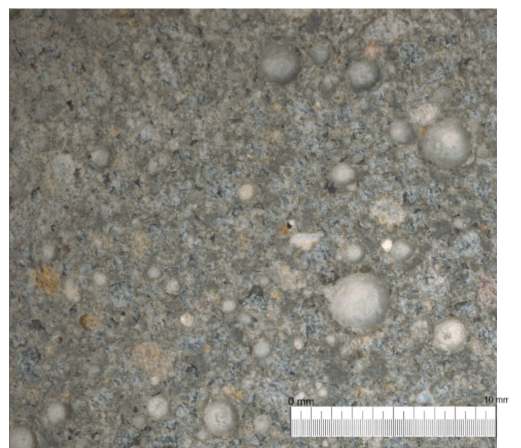
(b) Microsilica E2 specimen

Figure 7.9: Microscopic images of sample C.E1 & C.E2

(a) Microsilica E3 specimen
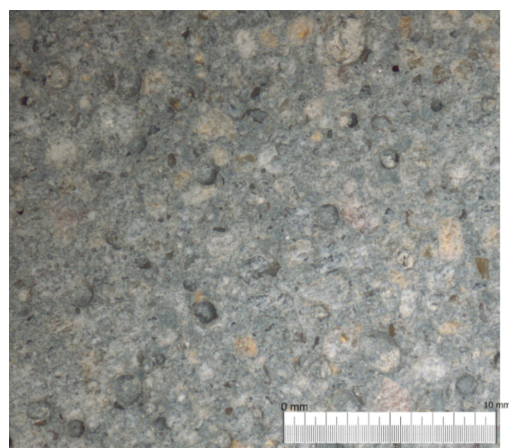
(b) Microsilica E4 specimen

Figure 7.10: Microscopic images of sample C.E3 & C.E4
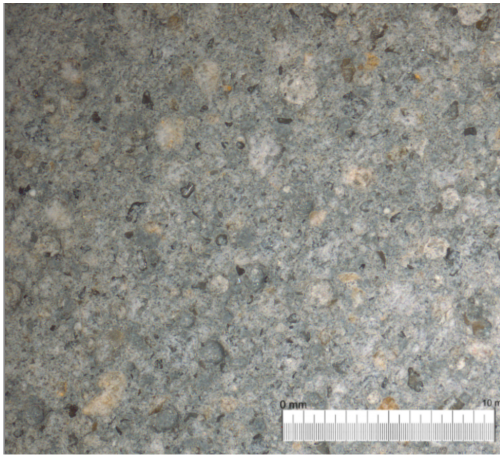
(a) Microsilica E5 specimen
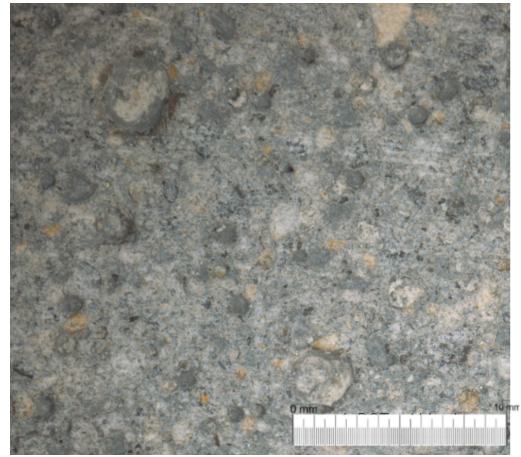
(b) Microsilica E6 specimen

Figure 7.11: Microscopic images of sample C.E5 & C.E6
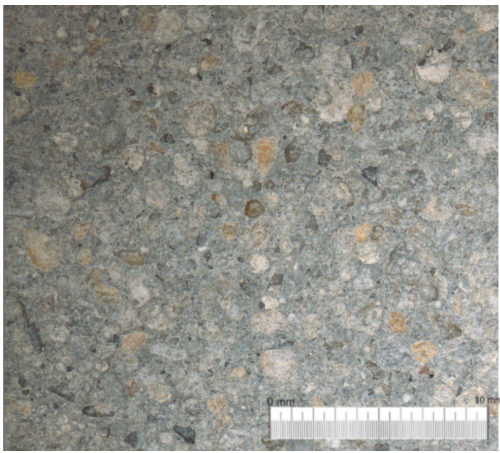
(a) Microsilica E9 specimen
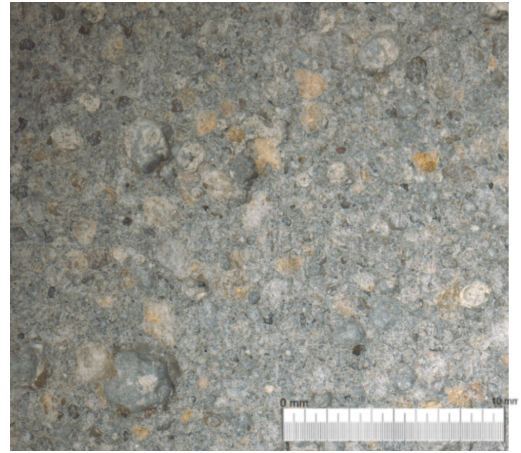
(b) Microsilica E10 specimen

Figure 7.12: Microscopic images of sample C.E9 & C.E10

8 Discussion

This section presents a discussion on the results of the process development, preliminary study, and the effect of using different types of microsilica on concrete properties. The behavior of mortar has been investigated in the process development along with the degree of repeatability of the mixing, molding, and testing procedure.

The preliminary study investigates the effect of reduced water/cement ratio on concrete properties. in the following section, the effect of microsilica on concrete properties is discussed. The observations from the literature review and properties of microsilica and its influence on concrete properties are discussed individually.

8.1 Process development of the experimental methodology used in the research

The first laboratory exercise was conducted to gain knowledge about the mixing, testing, and molding procedure. The purpose of the process development was also to learn about the behavior of mortar. Several tests were executed on fresh and hardened mortar to investigate if the degree of repeatability in the laboratory work procedures was satisfactory. This was done to establish a process routine with an identified degree of variation so that research on how microsilica affects the characteristics and properties of fresh mortar, hardening development, and hardened mortar could be initiated. In the following section, flow test results are used to investigate if the mixing procedure was successful and if the flowability was consistent. The results from the density calculation and strength test were used as indicators to determine if the mortars were homogeneous. The test results are individually compared and discussed and the variations in test results have been identified in the following section.

8.1.1 Flowability

Flow tests were conducted for all five standard mortars (1.1–1.5) and the results are presented in Figure 8.1. The horizontal line in the Figure represents the average flow which is approximately 176,7 mm.
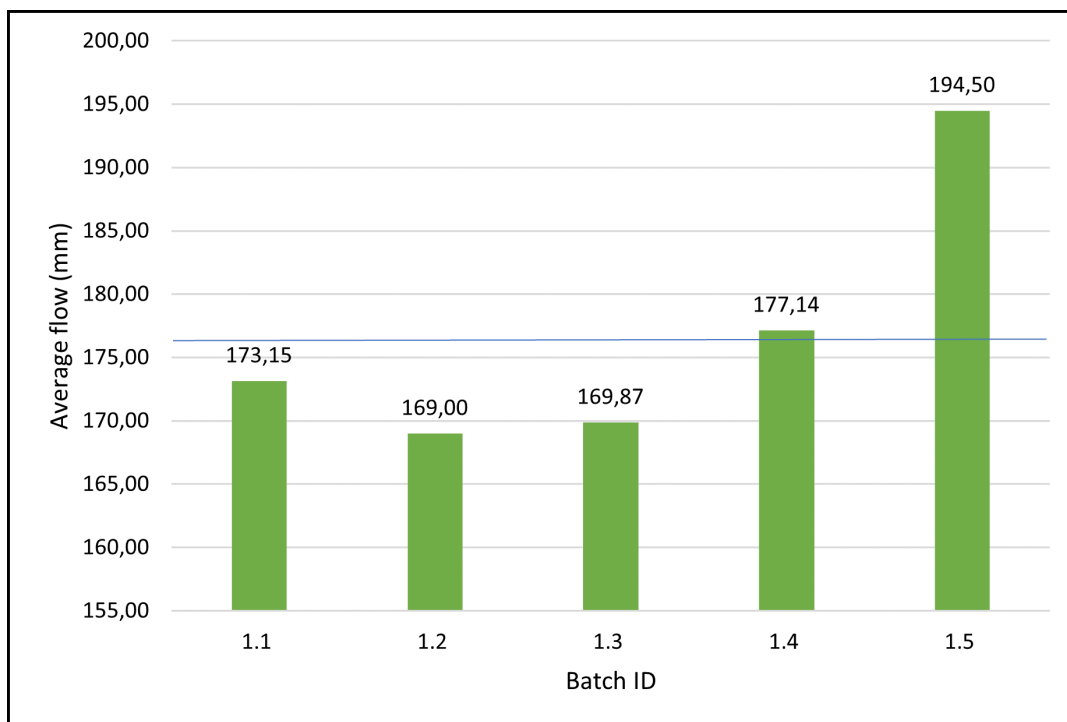
Figure 8.1: Flowability of batch 1.1–1.5

Figure 8.1 shows that batch 1.5 gave significantly higher flow test results than the other batches. As mentioned in section 7.1.2, there were technical problems with the mixer which lead to a 30-second delay in the mixing of the mortar. It was therefore assumed that the delay in mixing, caused increased flowability. Due to this, batch 1.5 was used for temperature logging and not for strength tests like the other samples.

8.1.2 Density and strength

The density was calculated for specimens in batch 1.1–1.4 and the results are presented in Figure 8.2. The average density for all specimens was calculated to be approximately 2297 kg/m^3 and can be seen as a horizontal line in the diagram.
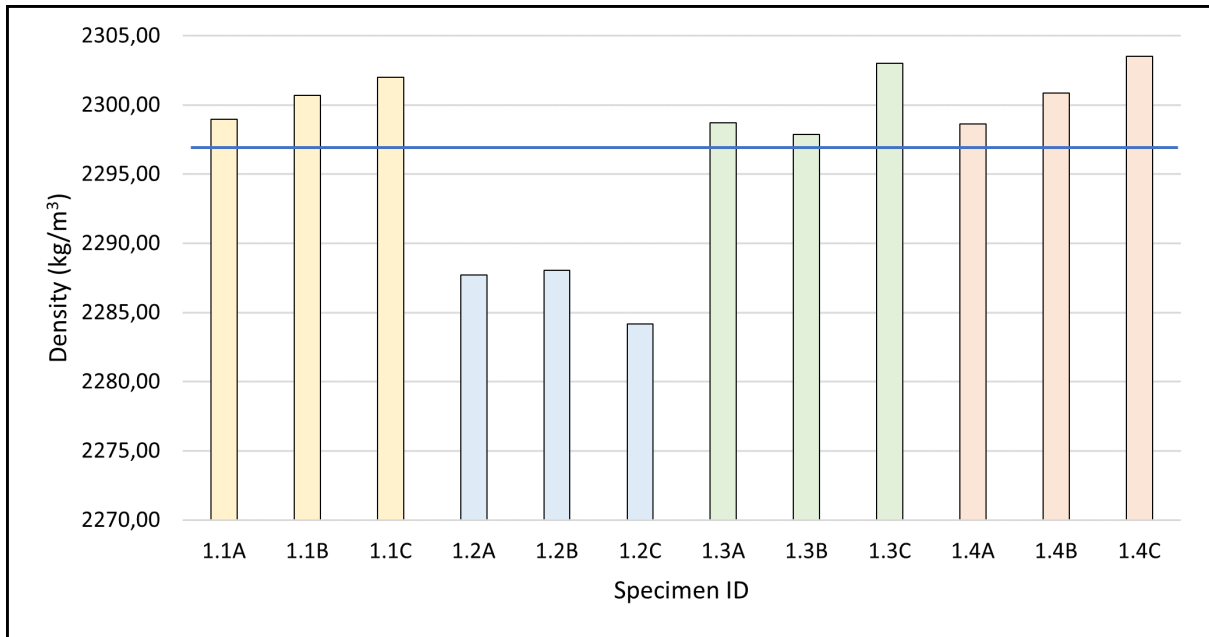
Figure 8.2: Density calculation results for specimen 1.1–1.4

The specimens from batches 1.1, 1.3, and 1.4 showed similar densities whereas all specimens from batch 1.2 had densities that were below average. Calculations showed that the density of specimens 1.2A, 1.2B and 1.2C was 2287,69 kg/m^3, 2288,06 kg/m^3 and 2284,17 kg/m^3, which is 0,41%, 0,39% and 0,56% lower than the average density of all the specimens. As the variation in density was insignificantly low, it can be assumed that some of the variations were caused by variations in the mixing procedure and that all the results are representative. For further density calculation, a variation of approximately 0,56% can therefore be expected. When looking at each batch individually, it was observed that there was little variation in density within the batches. Due to this, it was assumed that the mortar batches are homogeneous.

The flexural tensile strength test results are presented in Figure 8.3 and the average flexural tensile strength was approximately 8,13 MPa.
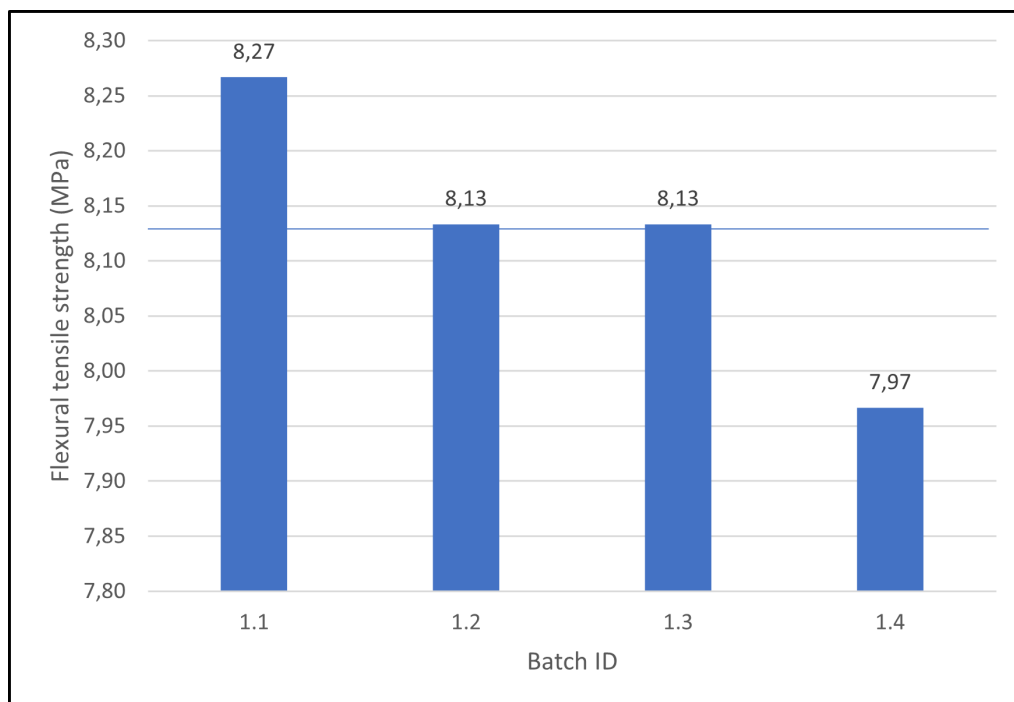
Figure 8.3: Flexural tensile strength results for specimen 1.1–1.4

Flexural tensile strength test results of batches 1.1 and 1.4 were 1,74% higher and 1,95% lower than average flexural tensile strength.

Compressive strength results are compared in Figure 8.4 and the horizontal line in the diagram represents the average compressive strength.
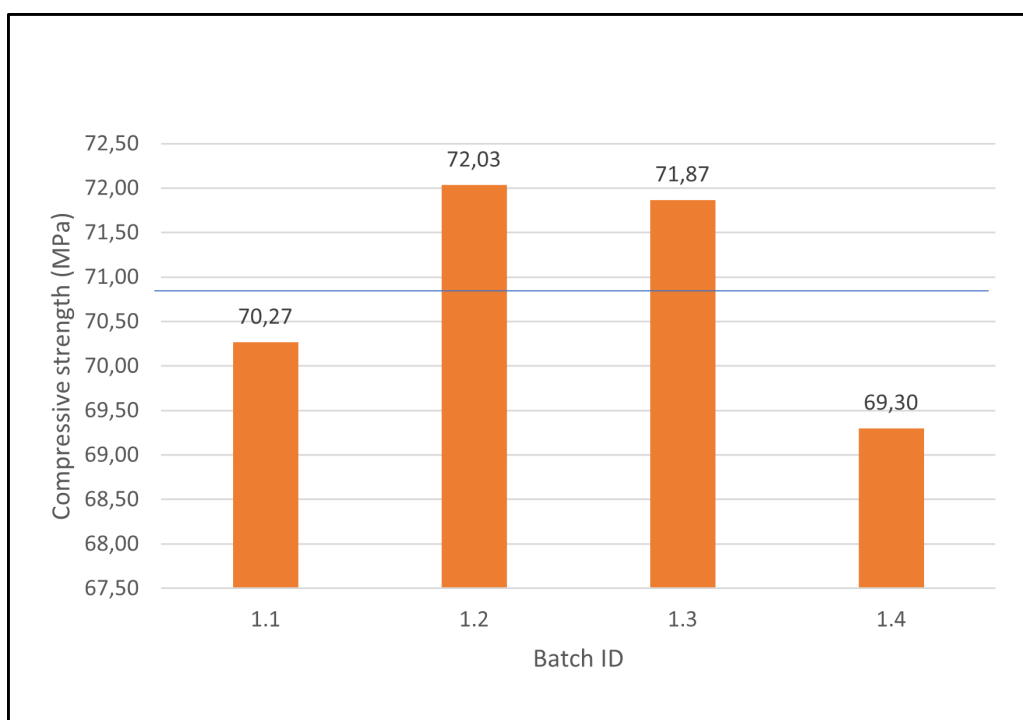
Figure 8.4: Compressive strength results for specimen 1.1–1.4

The average compressive strength was calculated to be approximately 70,8 MPa and batch 1.4 showed the largest variation from the average with a 2,2% lower

compressive strength. Since all the batches showed little variation in results from flexural tensile strength and compressive strength, it was assumed that the mortars were representative and that the degree of repeatability was satisfactory. A variation of approximately 2,2% in compressive strength can therefore be expected as well as approx. 1,95% variation in flexural tensile strength results. Unlike concrete manufacturers and other concrete research laboratories, the laboratory at UiA does not have a climate test chamber for concrete. As presented in Table 7.1, the temperature and relative humidity in the laboratory changed from day to day, and this could have affected the results. It is therefore important to keep in mind that variations in test results could have been caused by changing laboratory climate conditions.

8.2   Preliminary study: Influence of w/c ratio on concrete

The preliminary study was conducted to investigate the effects of reducing the W/C ratio in the mortar. The objective of the study was to compose a mortar mix design that gave high strength and adequate flowability, which would be used for all mortars containing microsilica. Cement hydration, density, and strength were also investigated. Exclusion criteria for flowability measurements were established and used to determine if the composition of SP and water in the mortar gave adequate flowability. This was done to determine which w/c ratio and SP content that would be used for further work with mortars where 10% of the binder was substituted by microsilica.

8.2.1   The effect of reduced water/cement ratio and superplasticizer on fresh mortar properties

The reduction of water content in the mortar was investigated because research shows that reducing the content of water in mortar or concrete can enhance the mechanical properties of hardened cement paste, as mentioned in section 3.1.7. Research also shows that by reducing the water content, the workability will be reduced. To maintain adequate workability, the superplasticizer was added to increase the flowability of the mortars. The study was executed experimentally which in this case meant that the flowability test results for one mortar mix design would determine the adjustment of w/c ratio and SP in the next attempt to find the desired mortar composition. The flow test results for specimens that had a reduced water content and contained superplasticizer are presented in Figure 8.5. The orange horizontal lines illustrate the boundaries of the target flow value range which are 167 mm and 187 mm.
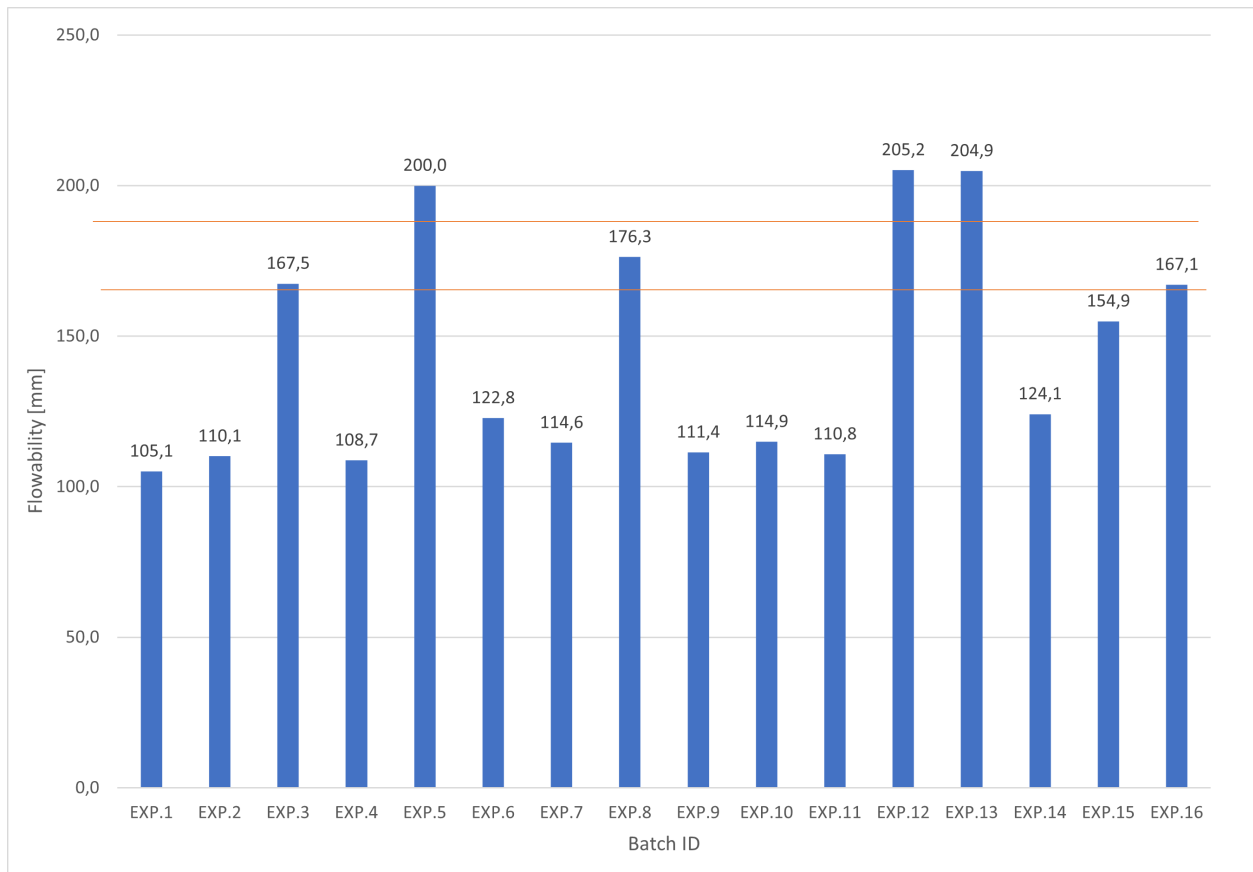
Figure 8.5: Flow test results from preliminary study

As presented in Figure 8.5, the flow test results varied from 105,1 mm to 205,2 mm, and images from three flow tests can be seen in Figure 8.6.

(a) Sample EXP.2   (b) Sample EXP.3   (c) Sample EXP.4

Figure 8.6: Images of 3 flow tests conducted as a part of the preliminary study

According to Table 7.3 samples EXP.2, EXP.3, and EXP.4 had w/c ratio of 0,3, 0,4 and 0,35, and contained 5%, 1%, and 5% SP. The samples presented in Figure 8.6a and 8.6c were very dry and had a very low viscosity. This indicated that the w/c ratio was too low and that the superplasticizer did not have a visible effect on the mortars. Sample 2.3, presented in Figure 8.6b, on the other hand, gave flow test results similar to the flow test results of the standard mortars. This shows that superplasticizer enhances the flowability of mortars because the reduced

w/c ratio should have led to a reduction of flowability, which was not the case for batch EXP.3.

As presented in Table 7.5 in results several of the samples did not cure properly. Almost 50% of the mortars used in the preliminary study had a w/c ratio below 0,39 as presented in 7.3. None of the samples with a w/c ratio lower than 0,39 cured properly after 24 hours according to 7.5. The samples were removed from the molds and the specimens showed signs of unsatisfactory curing. This can be seen in 8.7 where sample EXP.5 crumbled after being removed from the mold and sample EXP.6 broke into two pieces. It was also observed that the molds and the specimens were moist when removed from the molds and the curing was unsuccessful compared to the curing of the reference samples which were dry when they were removed from the molds.

Figure 8.7: Image of sample EXP.5, EXP.6 and EXP.7 after curing in 24 hours

Several of the mortars contained up to 5% superplasticizer and according to section 3.1.5, the recommended dosage of superplasticizer is a maximum of 2%. The information presented in the theoretical background also states that excessive use of superplasticizer can cause retardation of cement hydration. Based on the observations and the theoretical background it can be assumed that the cause of unsatisfactory curing was a combination of retardation and insufficient cement hydration due to excessive dosage of SP and lack of water to properly activate cement hydration.

Halfway into the preliminary study, an evaluation of the flow test results and their relation to water–and SP content was conducted. As a result of the evaluation,

exclusion criteria for flow test results were established. The target flow value was determined by calculating the average flow of the reference samples (SM.1, SM.2 & SM.3) which gave an average flow of 177mm. The target value range was +-10 mm from the target flow value. It was also decided that the content of SP should not exceed 1%. The study was carried out and several samples were discarded after the flow test was conducted, as described in Table 7.5. By implementing the exclusion criterion it was easier to eliminate mortar compositions that did not give the desired flowability.

The specimens that were set to cure in a curing tank were tested 28 days after mixing. The densities of the specimens were calculated the results are presented in Figure 8.8.
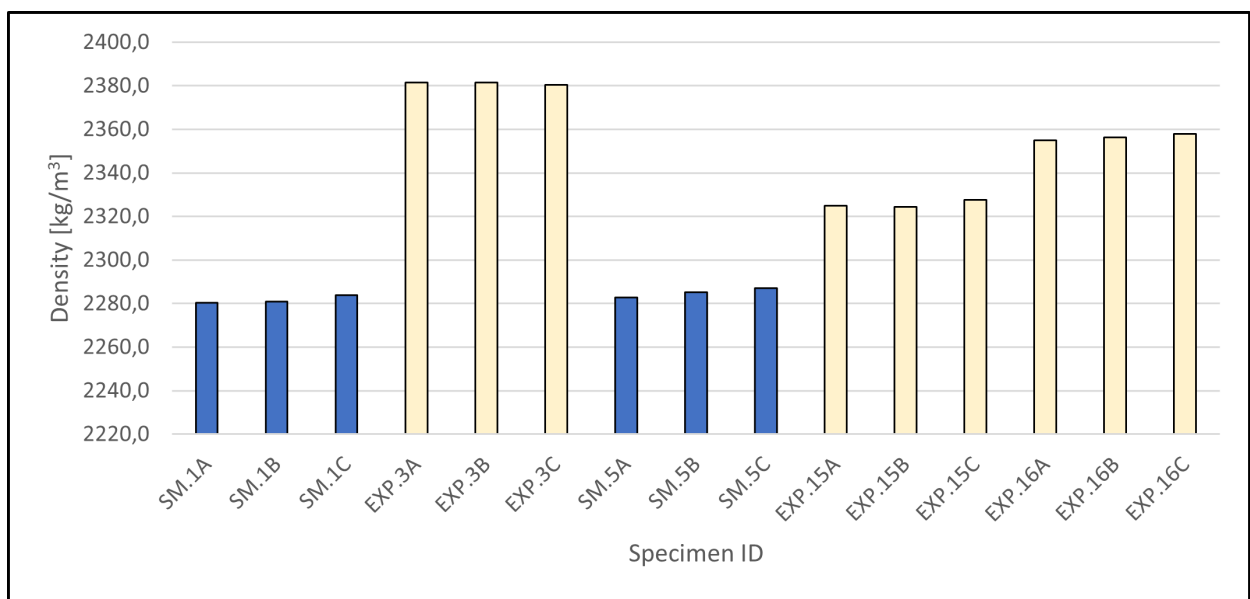
Figure 8.8: Density of sample EXP.3, EXP.15 & EXP.16 and the associated reference samples

According to information presented in chapter 3, section 3.1.2, a reduction of the w/c ratio will cause a pore size reduction, and hence increase the density of the mortar. Observation of increased density caused by reduction of w/c ratio can be seen in Figure 8.8 for the specimens in batch EXP.3, EXP.15, and EXP.16.

8.2.2 The effect of reduced water/cement ratio on strength development

The strength of the specimens was investigated and the results from flexural tensile strength tests and compressive strength tests are presented in Figure 8.9 and 8.10.
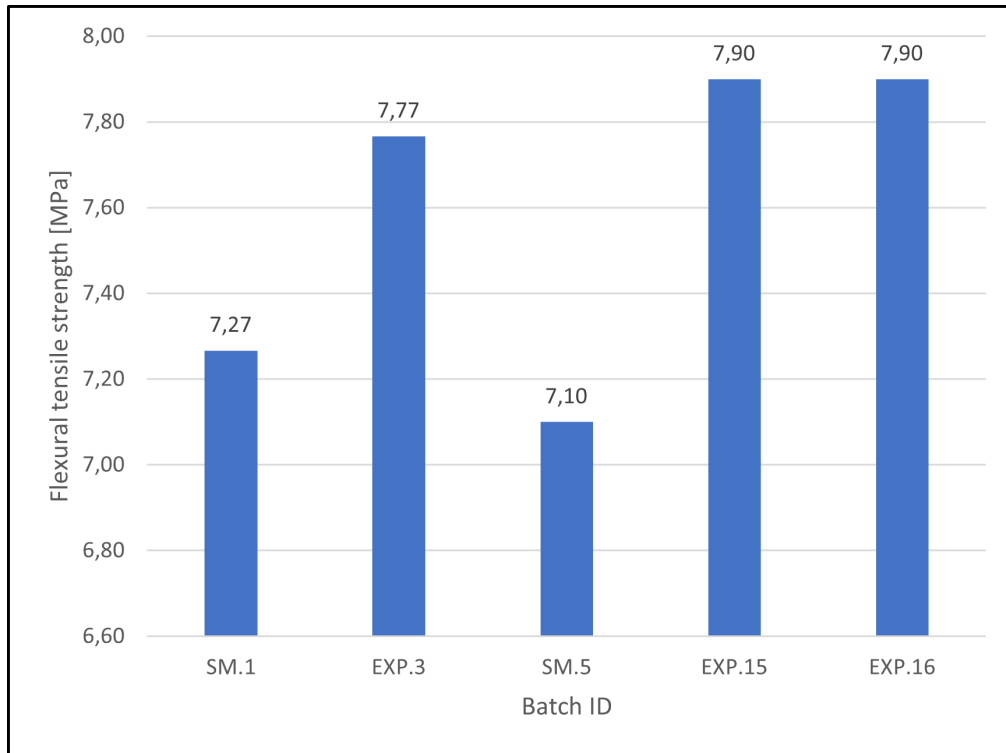
Figure 8.9: Flexural tensile strength of sample EXP.3, EXP.15 & EXP.16 and the associated reference samples
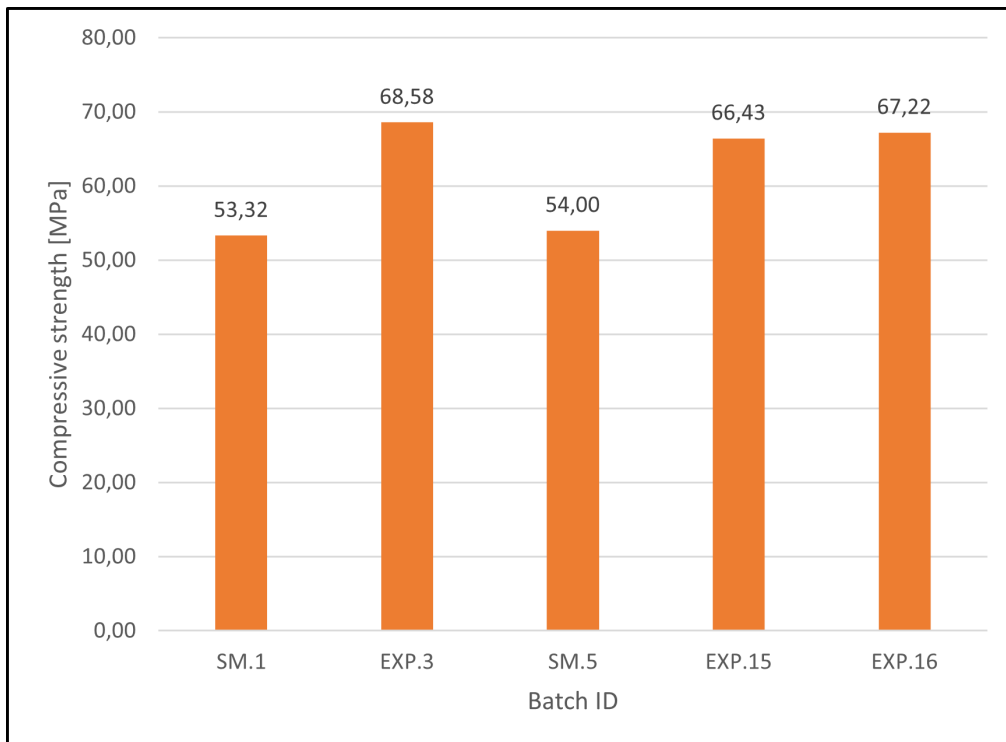
Figure 8.10: Compressive strength of sample EXP.3, EXP.15 & EXP.16 and the associated reference samples (SM.1: Reference sample 1, EXP.3: experimental mortar nr.3)

As illustrated in Figure 8.9, the specimens with reduced w/c ratio gave higher flexural tensile strength than the reference samples. The average compressive strength also increased by approximately 25%. Reduction of the w/c ratio leads

to the enhancement of mechanical properties such as strength, according to the theoretical background. This has been observed for both flexural tensile strength and compressive strength in specimens EXP.3, EXP.15, and EXP.16.

Temperature logging of standard mortar, and mortar with a w/c ratio of 0,4 containing 0,9% superplasticizer was conducted and the results are visualized in Figure 8.11. The Figure shows results from 2,6 hours to 37,7 hours of logging.
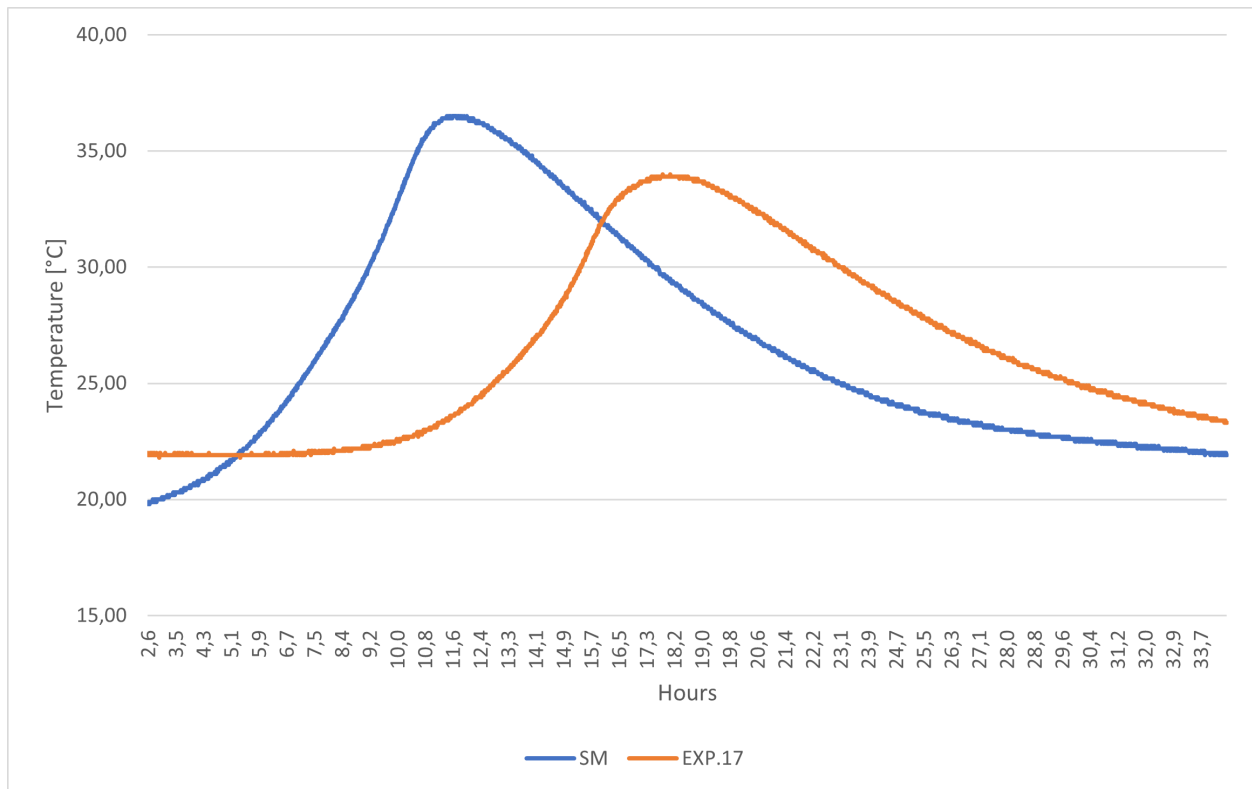
Figure 8.11: Temperature logging diagrams of standard mortar (SM) and mortar with w/c ratio of 0,4 containing 0,9% superplasticizer (EXP.17).

According to Table 7.6, the maximum temperature of the standard mortar (SM) with a w/c ratio of 0,5 was measured at approx. 11,5 hours into the hydration process whereas the maximum temperature of the mortar with a w/c ratio of 0,4 containing superplasticizer was measured after approx. 18 hours of hydration. As the standard mortar (SM) contains 10% more water than the experimental mortar, it can be assumed that SM reached its maximum temperature earlier due to a higher rate of hydration due to a higher water/cement ratio which increased the reaction kinetics. This assumption can be supported by theoretical background information about cement hydration in chapter 3, section 3.1.2.

Based on the observations and the information presented in the theoretical background, one can assume that the cause for the early setting time for the standard mortar was the higher w/c ratio. However, the total heat release integral describes the total heat generated by the chemical reaction of water and cement in the mortars. The total heat release was calculated for the standard mortar with a w/c ratio of 0,5 as illustrated in Figure 8.12a and the mortar with w/c

ratio of 0,4 containing 0,9% superplasticizer as illustrated in Figure 8.12b.

(a) Standard mortar

(b) Final experimental mortar
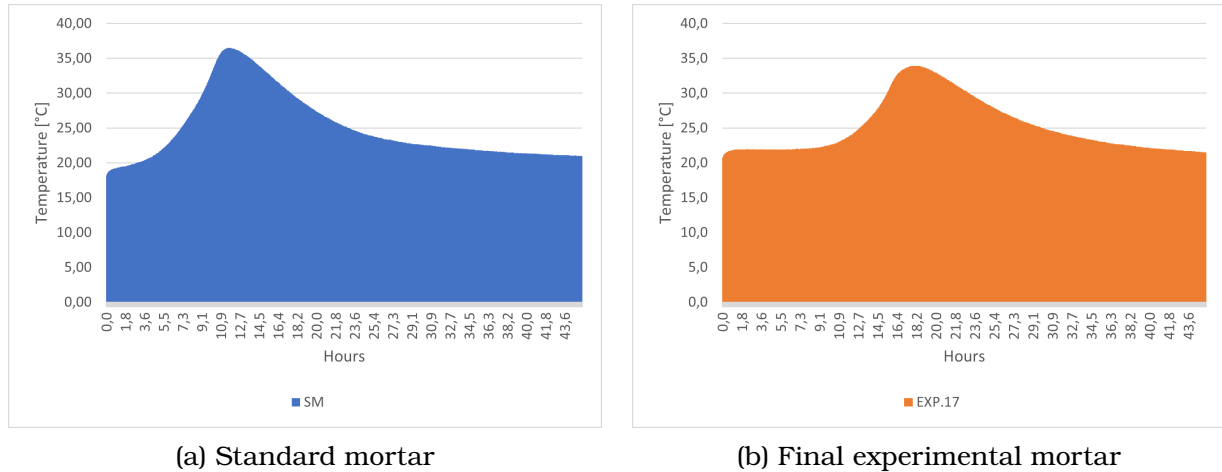
Figure 8.12: Total heat release diagrams of standard mortar and mortar with w/c ratio of 0,4 containing 0,9% superplasticizer

The total heat release was calculated to be 1169,64 for SM and 1184,22 for mortar EXP.17. These values indicate that the reduction of water content in batch EXP.17 did not have a significant influence on the total heat release of the hydration of the mortars.

As a result of the findings in the preliminary study, it can be concluded that a mortar mix design with a w/c ratio of 0,4, containing 0,9% superplasticizer will give adequate flowability, pore structure with fine pores and enhanced strength when compared to a reference sample made of standard mortar. It was also observed that the reduction of water can influence the complete setting time. The preliminary study was concluded and a mortar composition with 0,9% SP and 0,4 w/c ratio was used in further work with mortars containing 10% microsilica as a substitution for cement mass. The high-strength mortar mix design was established to investigate how microsilica could be applied to a high-performance concrete mortar mixture.

8.3 The effect of using different types of microsilica on the concrete properties

A literature review has been conducted to investigate research on the use of microsilica in concrete and how microsilica affects concrete properties. A comparative analysis of the influence of microsilica on concrete properties is discussed in the following section. The physical characteristics and chemical composition of microsilica have been linked to the properties of concrete to investigate if any correlations are present. The fresh mortar properties, strength development the durability of mortars have been discussed separately.

8.3.1 Literature review

As a result of the literature review, five articles were assessed. In the five articles, the authors investigated if microsilica alone or microsilica in combination with other cementitious materials and concrete components could enhance the mechanical properties of the concrete. Different types of concrete used for different purposes, such as foam concrete and heavy-weight concrete were investigated in the articles. This means that the findings and results can not be generalized but can be used for comparison when investigating the enhancement of mechanical properties caused by microsilica as a replacement for parts of the cement. The fact that microsilica has been used in concretes with very varying application areas emphasizes the beneficial characteristics and properties of microcsilica as a pozzolanic additive.

Thermal characteristics of concrete containing microsilica: The articles written by Pundienė I, Pranckevičienė J, Kligys M, et al. investigate the influence microsilica had on mortar containing waste-metal filler. In this article, the authors conducted isothermal calorimetric tests and UPV tests to analyze how microsilica affected the hydration process of the concrete. Results from the calorimetric test show that the addition of pozzolanic additives caused an increase of 37% in the total heat value of the WMP mortar. The increase in total heat value was caused by the pozzolanic reaction which occurs when the pozzolan reacts with the reaction product calcium hydroxide as explained in 3.1.2.

It was also observed in the UPV test that the UPV of WMP-containing mortar with pozzolanic additives increased by 16% compared to the control sample. Results also showed that the paste containing only WMP had a 4% lower UPV than the WMP–free paste.

Strength development: Four articles from the literature review results investigated the density of the test specimens used in their research. From the research conducted in the article written by Meskhi B, Beskopylny A, Stel'makh S, et al. it was revealed that the average density of foam concrete containing 10% microsilica and 1-3% content of polypropylene fiber was 510kg/m^3-517kg/m^3. When the pore macrostructure was analyzed it was observed that the control specimen had

unreasonably thicker interpore partitions compared to the specimens containing fibers and microsilica. These findings indicate that the samples containing fibers and microsilica have significant enlargement of the main pores due to the lower microporosity of interpore partitions which leads to enhanced strength characteristics compared to the control specimen. The authors also claim that effective compaction of the interpore partitions which eliminates capillary porosity and increases the packing of the particles was achieved by using microsilica as a nanomodifying additive in the foam concrete. This also resulted in denser foam concrete.

In the article written by Stel'makh S, Shcherban' E, Beskopylny A, et al. it was also revealed from a microstructural analysis that samples containing microsilica had a denser microstructure than the control specimens. Results from the article "Study of the course of cement hydration in the presence of waste metal particles and pozzolanic additives" show that the density of the sample containing WMP and microsilica was significantly higher than the control specimen and that the microsilica in the mortar improved the contact zone between the WMP and the cement matrix. This led to a less porous matrix and enhanced strength characteristics after 28 days of curing.

The study "Effect of silica fume on high-strength concrete performance" presented results that show an increase in density as the content of microsilica increased. It was observed that the density of specimens containing 0%, 7%, and 10% microsilica was calculated to be 2,287 kg/m3, 2,392 kg/m3, and 2,411 kg/m3. These results illustrate an increase in density by 4,6–5,4% when adding silica fume to the concrete mixture. After assessing the results from the literature review it can be assumed that microsilica has a positive effect on the density and durability of concrete mortar. This assumption correlates with the information about how microsilica influences the density of concrete and mortar presented in section 3.2.1.

Mechanical strength was investigated in five studies where all studies assessed the compressive strength of the research samples. Results from the first study presented in chapter 7.3.1, show that the compressive strength of fiber foam concrete containing 2% polypropylene fiber and 10% microsilica increased by approximately 44%. In the article written by Stel'makh S, Shcherban' E, Beskopylny A, et al, the authors observed that the sample containing 16% MS showed a compressive strength of 13 MPa, which is 146% and 128% higher compressive strength than the samples containing 16% of GBFS and MS+GBFS. An increase in compressive strength was also observed in the article written by Pundienė I, Pranckevičienė J, Kligys M, et al. The specimen containing microsilica achieved a compressive strength of 46,5 MPa which is 8,7% higher than the compressive strength of the reference sample. According to the article written by Gražulytė J, Vaitkus A, Šernas O, et al., an increase in compressive strength by 33,9-37,6% was achieved due to 10% substitution of the cement with silica fume. A com-

pressive strength of 21 MPa was observed after 4 hours of curing for the concrete specimens containing jute fiber reinforcement and up to 2% microsilica in the study written by Kim W, Jeon J, An B, et al. The specimens also achieved all strength target values after 28 days of curing.

As listed above, all the articles from the literature review results claim that microsilica has had a positive effect on the compressive strength of the concrete and mortar samples. Due to this one can assume that adding microsilica up to 16% can lead to an increase in compressive strength when compared to the reference sample. It is necessary to mention that substitution of up to 16% of the cement mass with microsilica does not lead to increased compressive strength for all concretes or mortars. The different concrete types are used for different purposes, hence the compositions of the mortars and concretes will be different for each concrete type and the optimal dosage of microsilica will consequently vary.

The results from the study conducted by show Meskhi B, Beskopylny A, Stel'makh S, et al. show that the flexural tensile strength of fiber foam concrete increased by approximately 73% for foam concrete containing 2% polypropylene fiber and 10% microsilica. As presented in section 7.3.1 an increase in flexural tensile strength was also observed for concrete containing 7% and 10% microsilica, where the sample containing 7% gave the highest improvement in flexural tensile strength. In the study written by Kim W, Jeon J, An B, et al. the authors reveal that the test specimens containing up to 2% microsilica and jute fiber reinforcement achieved a target flexural tensile strength of 3,5 MPa after 4 hours of curing, and when the specimens were tested after 28 days of curing the specimens satisfied all strength target values. These findings indicate that the addition of microsilica to concrete and mortar will give an increase in flexural tensile strength. According to the theoretical background, section 3.1.7, the flexural tensile strength will increase as the compressive strength increases. Some of the increase in flexural tensile strength can assumably have been caused by the addition of microsilica but most of the tensile forces are taken care of by the reinforcement as mentioned in section 3.1.7. The findings from the literature review show an increase in strength characteristics, thus it can be assumed that substituting parts of the cement with microsilica enhances the strength of mortars and concrete.

Properties of hardened concrete: The article "Effects on reinforced fiber and microsilica on the mechanical and chloride ion penetration properties of latex-modified fiber-reinforces rapid-set cement concrete for pavement repair" investigated chloride ion penetration of concrete containing microsilica. The results from the study showed that the chloride ion penetration decreased as the substitution of microsilica increased. This can be explained by the packing effect microsilica has on concrete and mortar which gives lower permeability as described in chapter 3 Theoretical background, section 3.2.1 Microsilica in concrete.

8.3.2 Fresh mortar properties of mortar containing microsilica

The flow test measurements for each batch containing microsilica and 0,9% su-perplasticizer are presented in Figure 8.13.
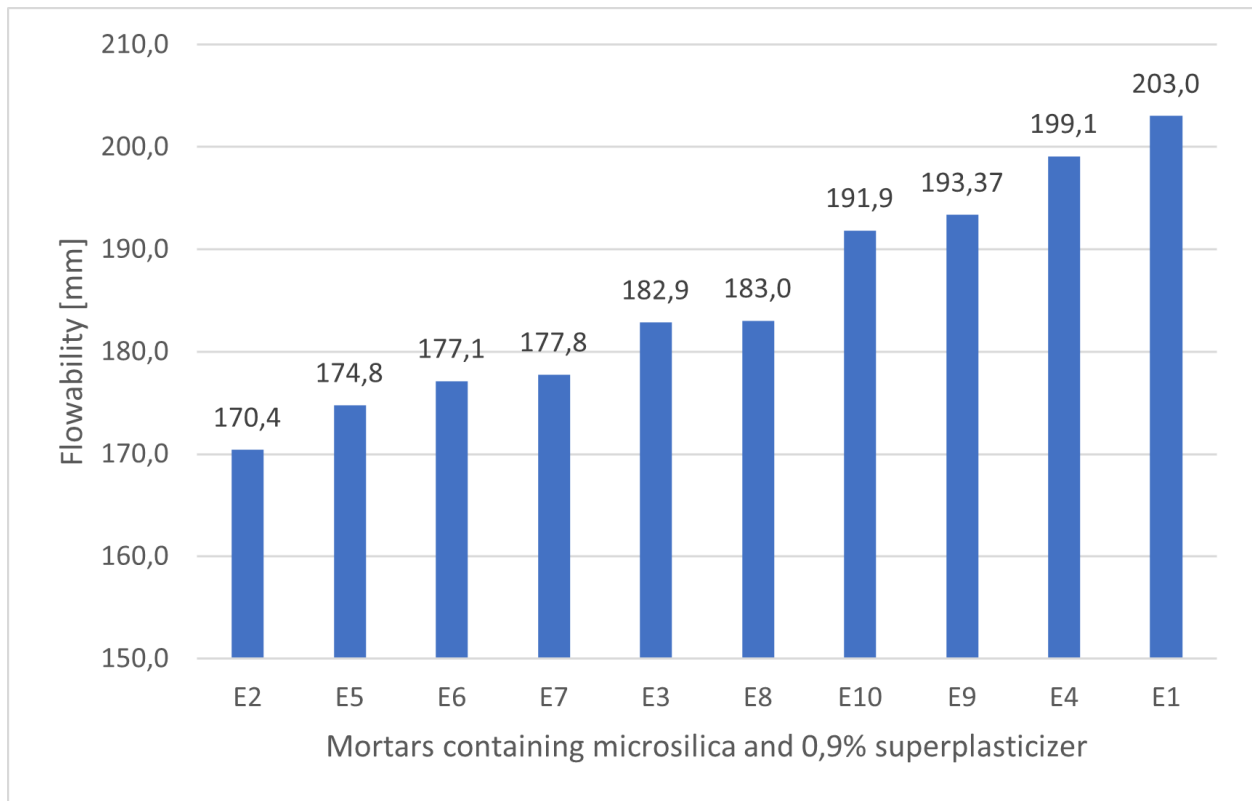
Figure 8.13: Flowability of mortars containing 10% microsilica and 0,9% superplasticizer

It can be observed in Figure 8.13 that the samples containing microsilica E9, E10, E4, and E1 gave flowability that was higher than the upper limit of the target flow value range. Hence, microsilica E9, E10, E4, and E1 have a positive effect on the flowability, because less water in the mortars is necessary to achieve adequate flowability. In practice, this means that the microsilica types previously mentioned facilitate a higher resource efficiency than the rest of the microsilica types. Due to the high flowability, the dosage of the superplasticizer had to be reduced, as presented in section 7.3.2, Table 7.8.

According to the theoretical background section 3.2.1, the water demand is influenced by the particle size of the mineral admixture. The correlation between BET specific surface area and the flowability of the microsilica-mortars is therefore investigated.

Table 8.1: Flowability of mortars containing microsilica and BET specific surface area for the different microsilica types.

Microsilica	E1	E2	E3	E4	E5	E6	E7	E8	E9	E10
BET SA $[m2/g]$	16,9	27,74	16,65	18,16	24,21	24,62	24,69	24,57	17,15	18,94
Flowability $[mm]$	203,0	170,4	182,9	199,1	174,8	177,1	177,8	183,0	193,37	191,9

Table 8.1 presents the flowability of the mortars containing microsilica and the BET specific surface area of the microsilica types that have been presented in section 5 Materials, Table 5.4. Figure 8.14 illustrates the correlation between the specific surface area of the microsilica and the flowability of the mortars containing microsilica.
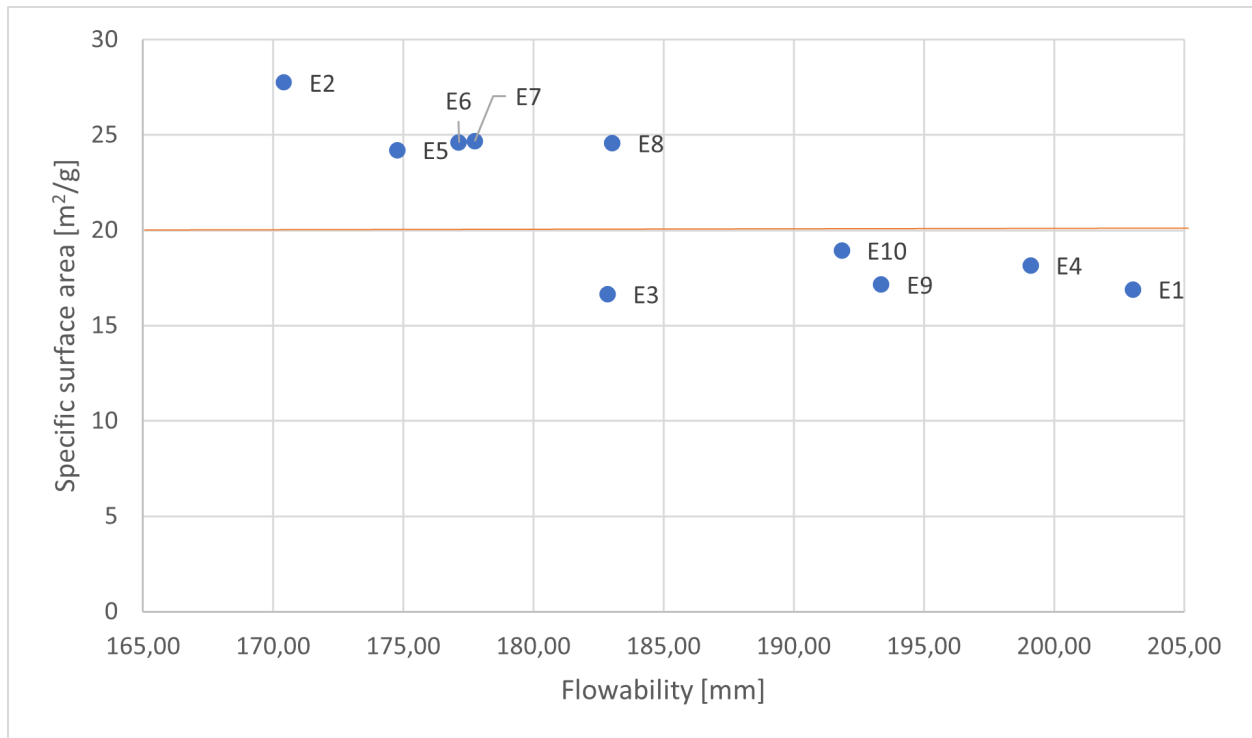
Figure 8.14: Flowability and specific surface area for mortars containing microsilica

The trend in Figure 8.14 illustrates that the mortars which contained microsilica that had a BET specific surface area $\leq 20 m^2/g$ (E1, E4, E9, and E10) gave higher flowability than the other mortars. According to the theoretical background, the increase in water demand is dependent on the surface area of the microsilica, and the water demand increases as the specific surface area increases. Hence, the low surface area of microsilica E1, E4, E9, and E10 has a positive effect on the flowability of the mortars.

Microsilica E3 also had a BET surface area lower than $20\,\mathrm{m}^2/\mathrm{g}$ but the mortar containing E3 microsilica gave lover flowability than the other mortars containing microsilica with a specific surface area $\leq 20 m^2/g$. As illustrated in Figure 8.14 the E3 mortar achieved the same flowability as the mortar containing E8 microsilica. E8 microsilica has a higher BET SA but the sample comes in the form of slurried microsilica, which means that the microsilica is already well dispersed in water. The same flowability and high dispersion of microsilica in the mortars may have been achieved due to the low specific surface area of E3 microsilica and already well-dispersed E8 microsilica particles in the slurry.

Based on the results it can only be assumed that the BET specific surface area of microsilica type E1, E3, E4, and E10 had a positive influence on the flowability

of the mortars when compared to the other mortars containing microsilica.

The relationship between the bulk density of the microsilica and the flowability of the mortars is illustrated in Figure 8.15. The form and the bulk density of microsilica are presented in Table 8.2 along with the flow test results for mortars containing microsilica E1-E10.

Table 8.2: Flow test results, and form and bulk density of microsilica E1-E10

Microsilica	E1	E2	E3	E4	E5	E6	E7	E8	E9	E10
Bulk density $[kg/m^3]$	348	330	360	167	228	638			681	252
Microsilica form (D/U/S)	U	U	U	U	U	D	S	S	D	U
Flowability $[mm]$	203,0	170,4	182,9	199,1	174,8	177,1	177,8	183,0	193,37	191,9
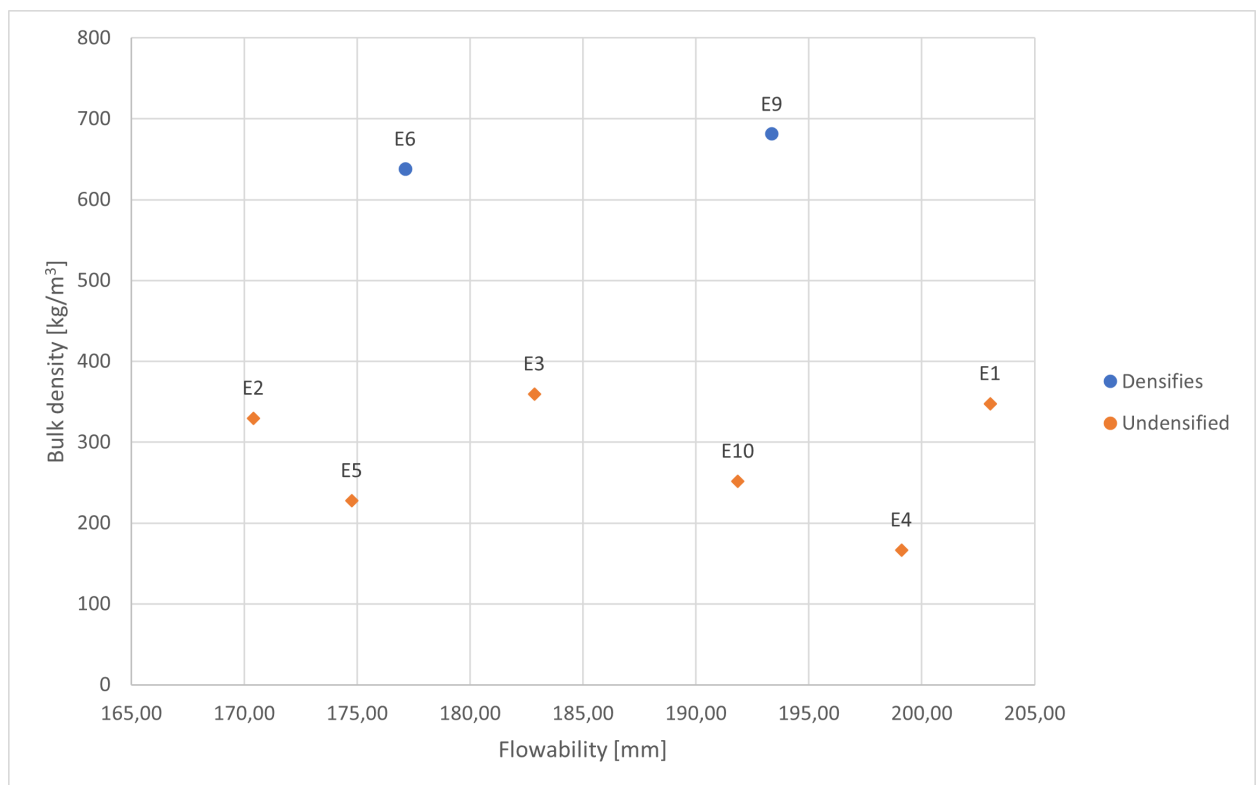
Figure 8.15: Diagram illustrating the relationship between the bulk density of microsilica and flowability.

The blue markers presented in Figure 8.15, represent the mortars containing densified microsilica, whereas the orange markers represent the samples containing undensified microsilica. The results indicate that the densification of microsilica on a general basis does not influence the flowability of the mortars.

The flowability of mortar is not only influenced by the densification process, there may also other many other factors affecting the flowability. Therefore the samples containing microsilica E9 and E10 have been individually compared to investigate if the densification of microsilica influences the flowability. The reason E9 and

E10 are compared is that the two microsilica types come from the same source and the only difference between the samples is the densification. Figure 8.16 presents flow test results of mortar containing E9 and E10 microsilica and the bulk density of each microsilica type.
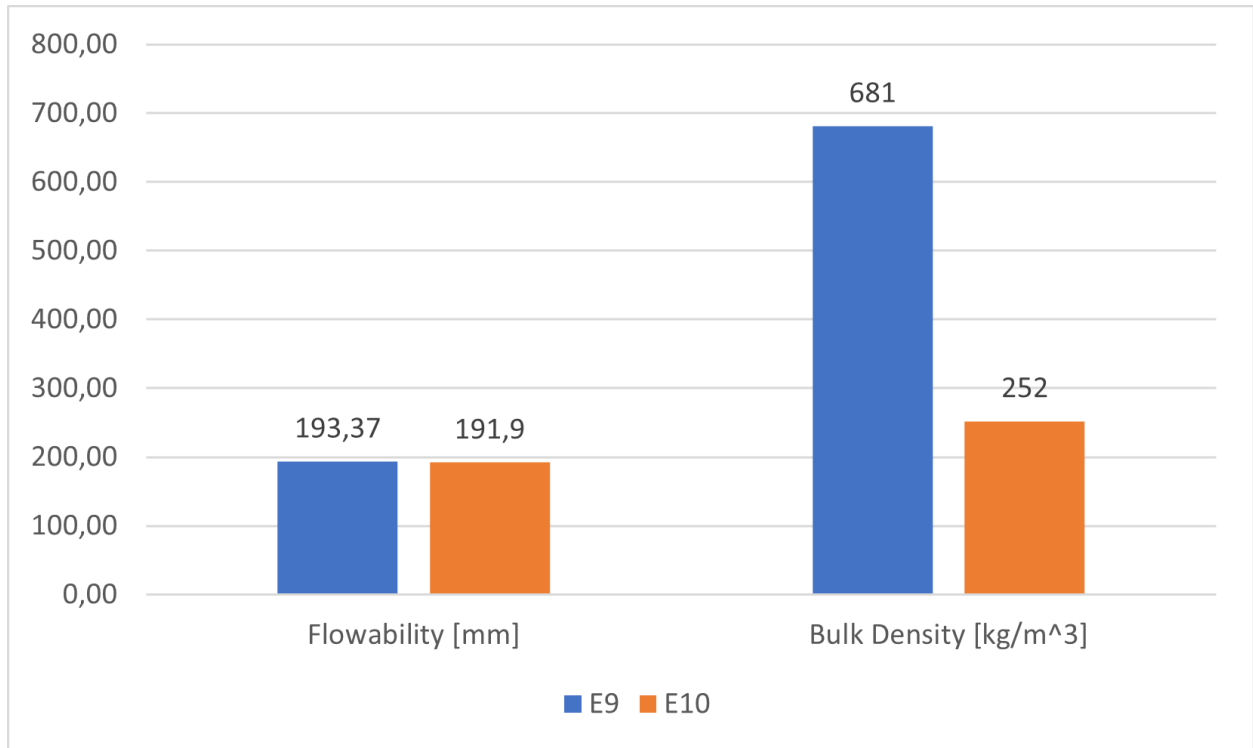
Figure 8.16: E9 & E10: Flow test results and bulk density.

From the results presented in Figure 8.16, it can be observed that the difference in flowability is insignificant and it can therefore be assumed that the densification of microsilica does not affect the flowability of concrete mortars.

The flowability of mortars containing microsilica and 0,9% superplasticizer and the influence of moisture in the microsilica powders have been investigated. Table 8.3 presents the moisture content of the microsilica and the flow test results, and Figure 8.17 illustrates the relationship between the two.

Table 8.3: Moisture of microsilica and flow test results of mortars containing microsilica and 0,9% SP

Microsilica	E1	E2	E3	E4	E5	E6	E7	E8	E9	E10
Moisture of microsilica [%]	0,63	0,45	0,88	0,46	0,65	0,72	-	-	0,7	0,76
Flowability [mm]	203,0	170,4	182,9	199,1	174,8	177,1	177,8	183,0	193,37	191,9
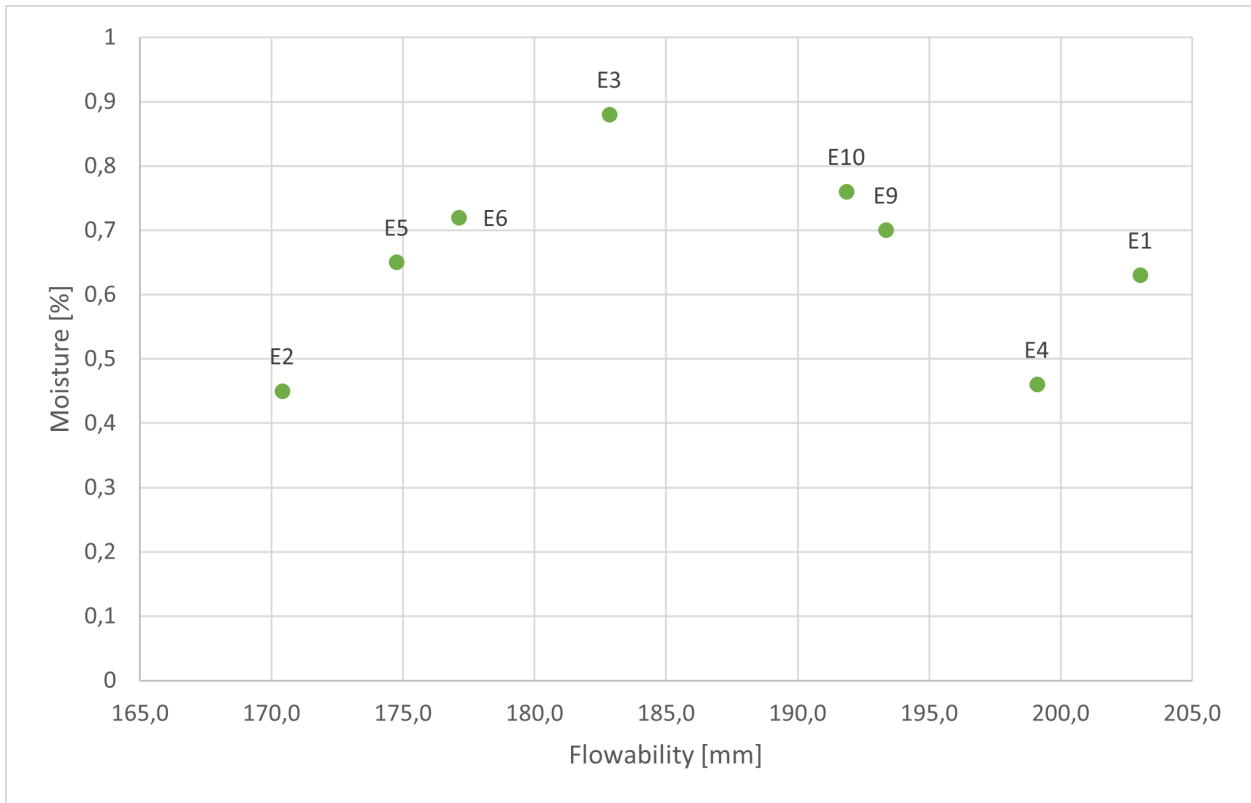
Figure 8.17: Diagram illustrating the relationship between moisture of microsilica and flowability.

No significant trend can be observed in Figure 8.17. This indicates that the moisture in the microsilica powders does not influence the flowability of the mortars that have been tested and compared.

8.3.3 Strength development

This section presents a discussion of findings in the report related to the hardening development of mortar and how it is affected by different microsilica samples. The final mortar compositions presented in 7.8 have been used for all test specimens in strength development tests.

Temperature logging technique
Temperature logging of mortars containing microsilica was executed to investigate the heat of hydration of the mortars. All mortars containing microsilica except the mortars containing microsilica type E7 and E8 were used for temperature logging. The temperature logging was done by using approximately 0.35L of mortar and the mortar was placed in a curing box that holds 15L of mortar. Temperature logging is usually conducted by using curing boxes that hold $1\,\mathrm{m}^3$ of concrete, which facilitates adiabatic conditions in the center of the concrete. Since the temperature logging of the mortars was conducted under diabatic conditions, the results can only be used for comparative purposes and not as generalized results. The results from temperature logging are presented in Figure 8.18.
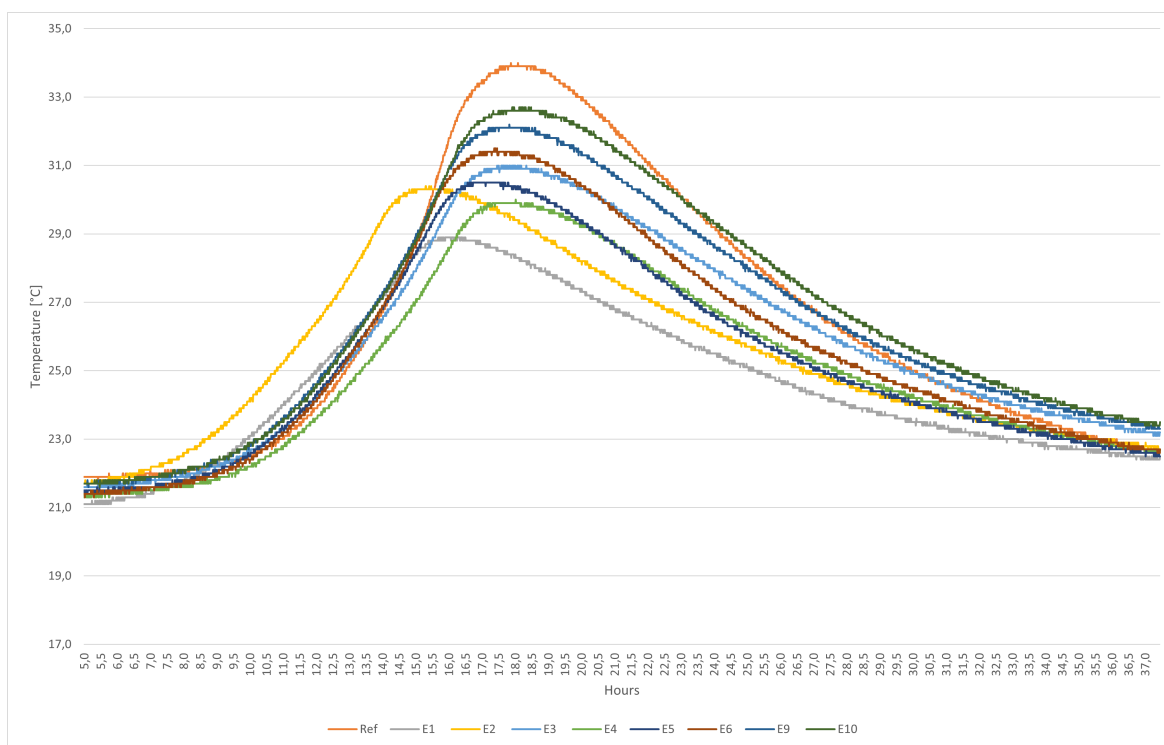
Figure 8.18: Temperature logging results showing logging results from 2,6h to 37h for mortars containing microsilica

Table 8.4: Complete setting time, maximum recorded temperature, and total heat release of all mortars used for temperature logging

Mortar type	Ref	E1	E2	E3	E4	E5	E6	E9	E10
Complete setting time $[h]$	18,0	15,6	15,3	17,4	18,0	16,5	17,3	17,8	17,9
Maximum temperature $°C]$	34	28,9	30,4	31	30	30,5	31,5	32,2	32,7
Total heat release $[°C * h]$	1184,2	1120,6	1154,0	1166,2	1133,8	1141,6	1153,3	1184,6	1193,2

The complete setting time of all samples containing microsilica occurs between 15 and 18 hours of hydration, see Table 8.4. According to chapter 3, section 3.1.2, the apex occurs 4–8 hours into the hydration process under adiabatic conditions. As the temperature logging was conducted under diabatic conditions, it can be assumed that a large amount of heat loss may have occurred.

The maximum recorded temperatures for all mortars used for temperature logging are presented in Figure 8.19.
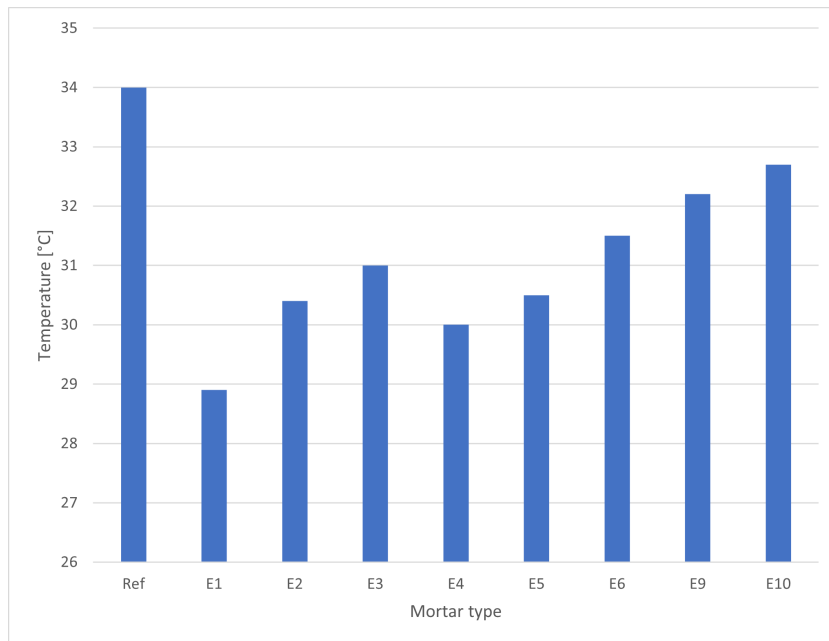
Figure 8.19: Maximum temperature recorded for all mortars used for temperature logging

As illustrated in the Figure above, the reference mortar achieved the highest temperature out of all the mortars. This can be explained by the lower cement content in the mortars where microsilica has been used as a pozzolanic additive. The lower content of cement will consequently reduce the maximum heat of hydration because there is a lower potential in the exothermic reaction that occurs in the hydration of the mortars. The slow hydration rate in the mortars containing microsilica can have been caused by the pozzolanic reaction where calcium hydroxide reacts with SiO_2 in microsilica to form C–S–H.

To investigate the total heat release of the mortars, the area beneath the temperature logging functions was calculated as an expression of the total heat release of the mortars, and the results are presented in Table 7.9.
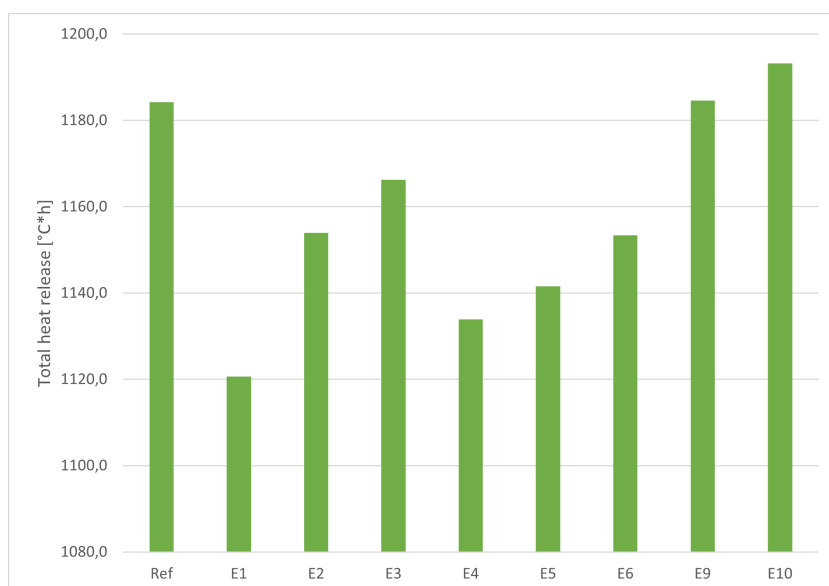
Figure 8.20: Total heat release for all mortars used for temperature logging

Even though the maximum temperature will be lower for the mortars containing microsilica, the total heat release value might not have been negatively affected by the microsilica. The reason for this is the pozzolanic reaction in the mortars occurs after the calcium hydroxide and water have reacted. According to observation from research conducted by Pundienė I, Pranckevičienė J, Kligys M, et al., it was observed that the total heat of hydration increased for the mortars containing microsilica. The observations from the temperature logging, therefore, contradict the research presented in chapter 7, section 7.3.1.

When investigating the Total heat release, no clear correlation is present. The mortars containing microsilica E9 and E10 gave significantly higher total heat release than the other mortars containing microsilica. To further investigate the cause of the high heat release, the chemical composition of the microsilica samples has been investigated. From Table 5.3 when comparing E9 and E10 to the rest, it is visible that the content of MgO, alkali ($Na_2O + K_2O$) and SO_3 is significantly higher for E9 and E10 and the Al_2O_3 content is significantly lower than the other microsilica samples. These chemical components could have influenced the total heat value of the mortars, but it is uncertain if this was the cause of the high rate of hydration.

According to Table 8.5, the microsilica samples had pH values ranging from 2,95 to 8,17. Due to this, it was decided that the relationship between the pH of microsilica and complete setting time would be investigated. Table 8.5 presents the complete setting time of the mortars and the pH value of the different types of microsilica.

Table 8.5: Complete setting time for all mortars containing microsilica and the pH of the microsilica types that have been used.

Mortar type	E1	E2	E3	E4	E5	E6	E9	E10
Complete setting time $[h]$	15,6	15,3	17,4	18,0	16,5	17,3	17,8	17,9
PH of microsilica	8,17	7,49	7,33	7,33	7,14	6,92	6,59	2,95

Figure 8.21 illustrates the relationship between the pH of microsilica and complete setting time.
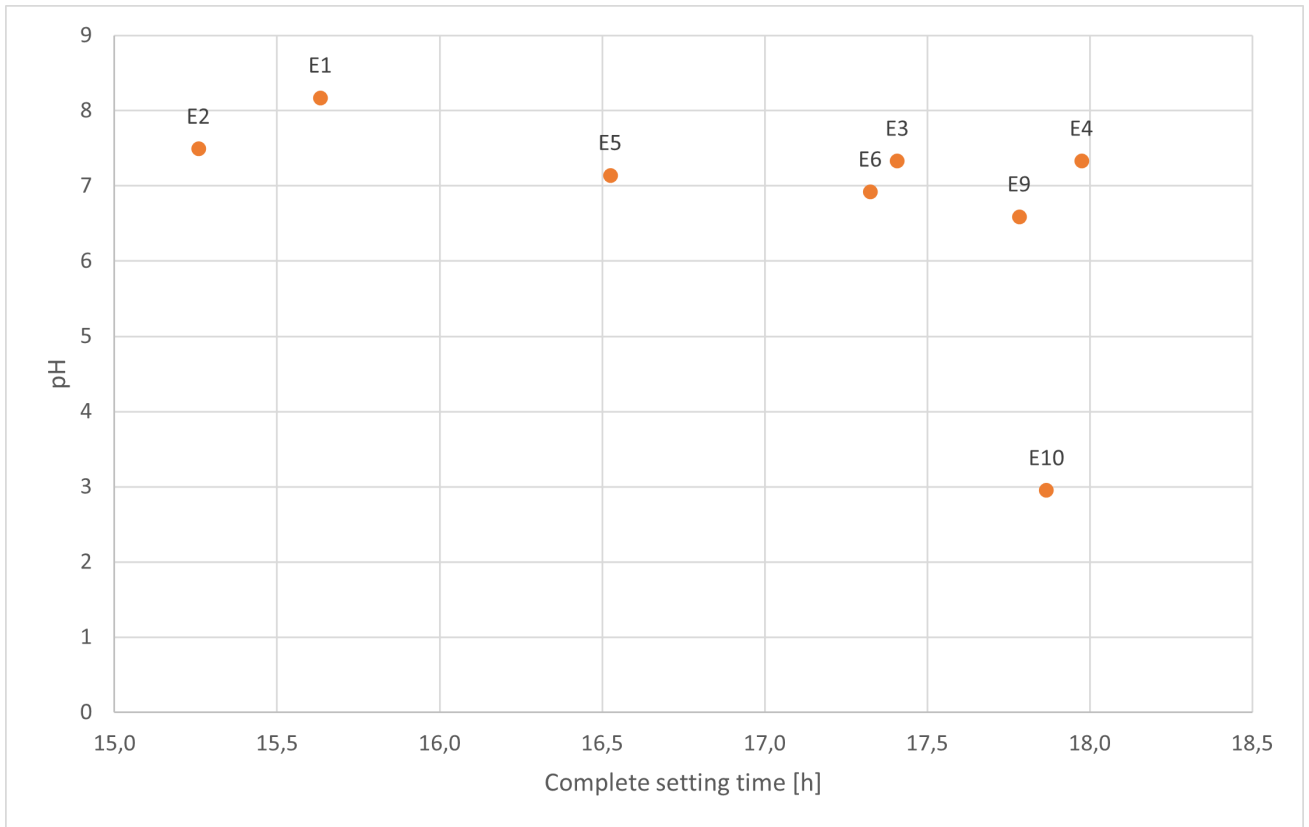
Figure 8.21: Relationship between complete setting time and pH of microsilica

When analyzing the data presented in Figure 8.21 no correlation between the pH of microsilica and the complete setting time can be observed. The results indicate that the pH of microsilica did not have any influence on the hydration of the mortars. If the pH would have affected the hydration, a high pH value would have accelerated the rate of hydration, and a low pH would have retarded the rate of hydration, which it did not.

The microsilica samples had alkali content ranging from approx. 0,4% to 2,5%. Alkali content of the microsilica samples and its influence on the time of the complete set has been investigated and the relationship between the two has been visualized in Figure 8.22.
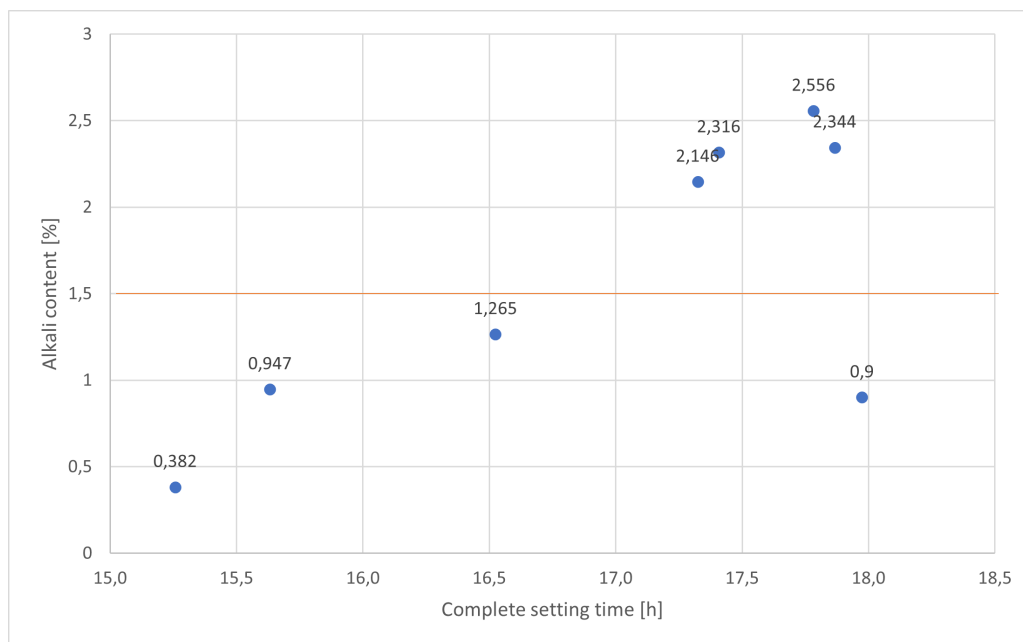
Figure 8.22: Relationship between complete setting time and alkaline content in the microsilica

Table 8.6: Alkali content of the microsilica samples and complete setting time for mortars containing microsilica.

Mortar type	E1	E2	E3	E4	E5	E6	E9	E10
Complete setting time $[h]$	15,6	15,3	17,4	18,0	16,5	17,3	17,8	17,9
Alkali content $(K_2O + Na_2O)$ microsilica $[\%]$	0,947	0,382	2,316	0,9	1,265	2,146	2,556	2,344

According to the data presented in Table 8.6 and the trend illustrated in Figure 8.22, it appears that there is a correlation between the alkali content of microsilica and the complete setting time of the mortars. It can be observed that a low alkali content of microsilica gave the mortars an earlier complete setting time than the mortars containing microsilica with high alkali content. According to information provided by Elkem ASA, a high alkali content of microsilica can cause retardation of the rate of hydration of concrete. Thus, one can assume that the rate of hydration in mortars containing microsilica may have been influenced by the alkali content of each microsilica sample.

This correlation was however not observed for the mortar containing microsilica type E4. The alkali content of microsilica E4 is 0,9 % and the complete setting time of the mortar containing microsilica E4 was approximately 18 h. The chemical composition of E4 has been assessed and there was a lack of correlation between the other chemical components of the microsilica and the retardation of the mortar. The cause of the deviation is therefore uncertain.

Temperature logging was conducted for mortars containing microsilica E9 and E10, and the results are presented in Figure 8.23.
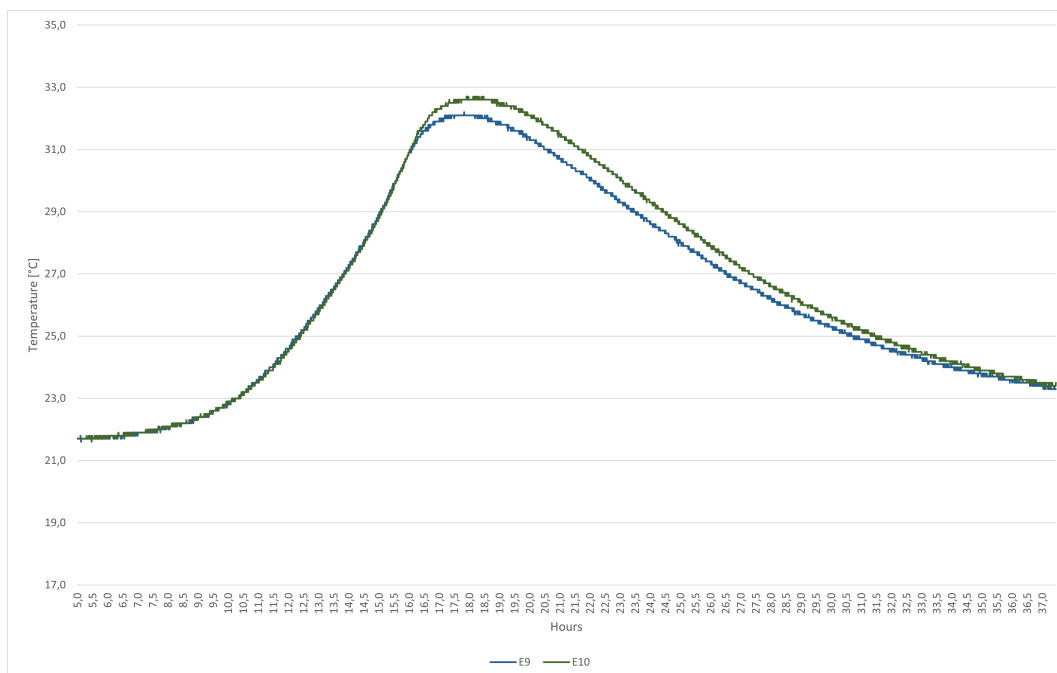
Figure 8.23: Temperature logging results for mortar containing E9 and E10 microsilica

The main difference between microsilica samples E9 and E10 is the densification of the microsilica powder. The complete setting time for the mortar containing E9 microsilica was 17,8h which is very similar to the complete setting time of the mortar containing E10 microsilica, which was 17,9h. There is also little difference between the maximum temperature achieved in both mortars. Based on these observations, it can be assumed that the densification of microsilica does not have a significant effect on the hydration of the mortars.

Densities of hardened mortars containing microsilica

The density has been calculated for all samples used for compressive and flexural tensile strength tests and the average density of each mortar composition has been presented in Figure 7.5.

As illustrated in Figure 7.5 presented in chapter 7, section 7.3.3, there was no significant difference in the density of the mortar samples. When comparing the samples containing microsilica to the mortar composition that was used for reference samples (R), no noticeable trend can be observed. These observations contradict the information presented in the theoretical background, section 3.2.1, and the observations from research presented as a result of the literature review. According to well-established research, concrete mortars containing microsilica give denser pore structures due to the packing effect caused by small spherical microsilica particles.

To further investigate if the densification of microsilica has influenced the density of mortar, a figure with an adjusted y-axis is presented to emphasize the difference between the samples, see Figure 8.24.
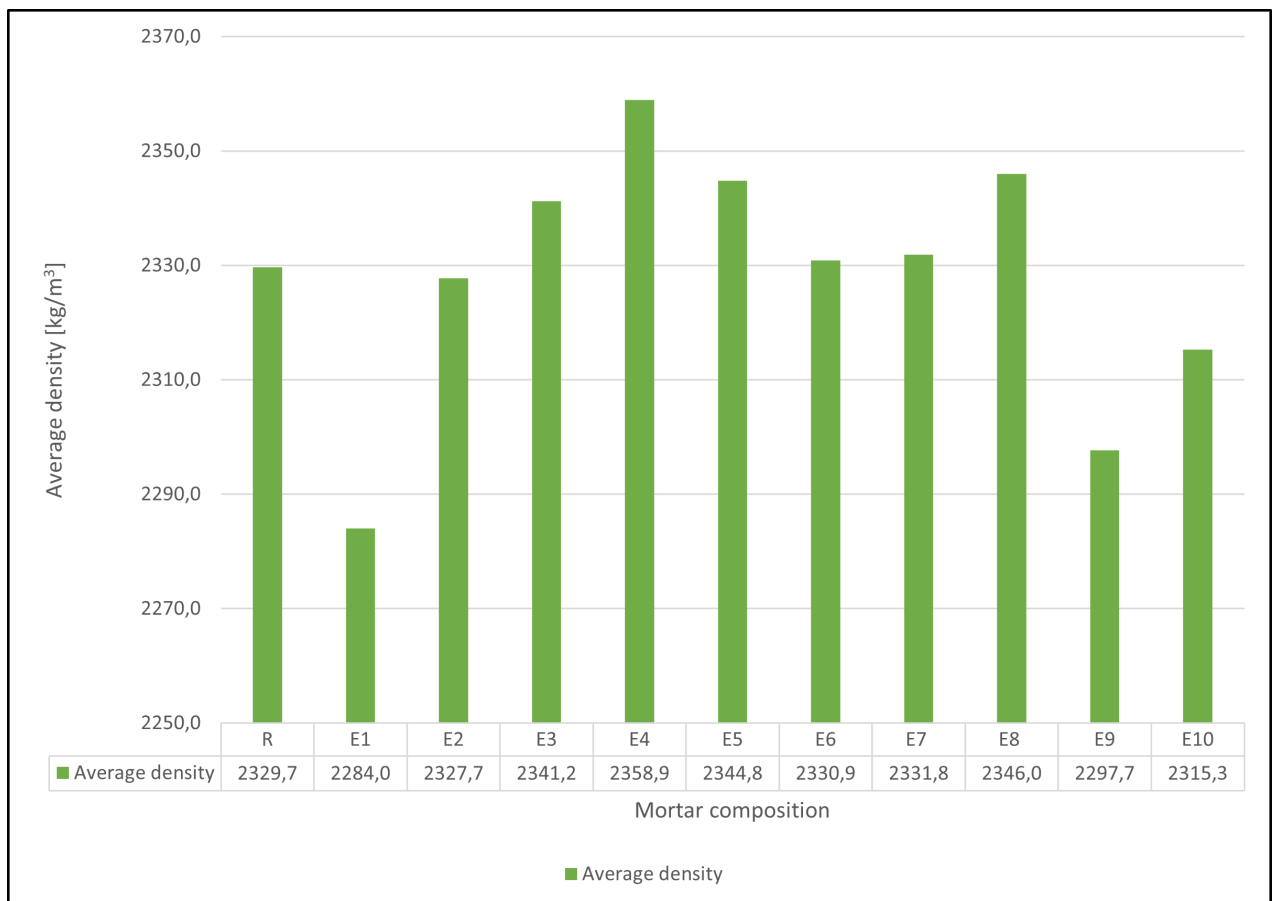
Figure 8.24: Densities of samples containing microsilica showing y-axis values 2250-2370 kg/m^3

In Figure 8.24 the difference in density between the samples has been emphasized by adjusting the y-axis. The results show no significant trend, and when assessing the influence of the densification of microsilica one can observe that

there is little difference between the densities of the densified microsilica mortars (E6 and E9) and the remaining undensified microsilica mortars (E1, E2, E3, E4, E5, E10). The inter-pore structure of the mortars containing microsilica E1-E10 has not been investigated. Thus, one can therefore not conclude anything about the influence of microsilica E1-E10 on the density of the mortars that have been tested.

Flexural tensile strength

The flexural tensile strength of the reference mortars and the mortars containing microsilica was done after 28 days of curing. As illustrated in Figure 7.6, the highest flexural tensile strengths were measured for the mortars containing microsilica E2, E5, and E8 at 11,4 MPa, 11,5 MPa, and, 11,6 MPa. These mortars gave an increase in flexural tensile strength of approximately 37%, 39%, and 40% when compared to the reference mortars.

In Figure 7.6 it was also observed that all samples containing microsilica gave higher flexural tensile strength than the associated reference samples, which indicates that microsilica E1-E10 enhances flexural tensile strength when used as a substitute for 10% of the cement mass in mortars. This behavior was expected and can be explained by the information in the theoretical background about mechanical strength enhancement caused by microsilica. The pozzolanic reaction causes the formation of more C-S-H than what can be achieved in the reference mortar and this is the cause of the strength enhancement. The observations of increased flexural tensile strength for the mortars containing microsilica E1-E10 also correlate with the observations from the literature review.

Compressive strength and pozzolanic activity index (PAI)

Compressive strength testing was executed as a part of the study to investigate if microsilica influenced the mechanical strength of mortar. The average compressive strength of reference mortar and each mortar composition containing microsilica has been presented in Figure 7.7.

The compressive strength results show that all mortars that contained microsilica gave higher average compressive strength than the reference samples. These observations correlate with the findings from the literature review. The research showed that all mortars containing microsilica showed higher compressive strength than the associated reference sample. The information presented in Chapter 3, section 3.2.1, also confirms that adding microsilica to concrete as a pozzolanic additive enhances the mechanical strength of the concrete.

A mechanical evaluation of the pozzolanic activity was conducted by measuring the compressive strength of the mortars containing microsilica E1-E10 and its reference samples after 28 days of curing. The pozzolanic activity index was calculated for all 10 microsilica mortar compositions as described in chapter 6, section 6.4.5, and the results are presented in Figure
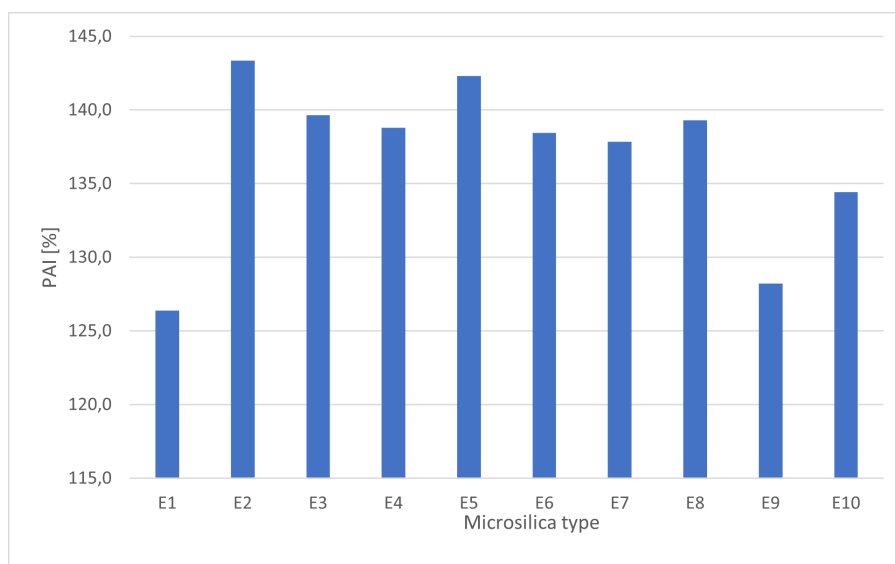
Figure 8.25: Average pozzolanic activity index for mortars containing microsilica E1-E10.

The mortars composition that showed the highest increase in compressive strength, hence the highest pozzolanic activity index was the mortars containing microsilica type E3 and E5. The average pozzolanic activity index of the mortars that contained microsilica E3 and E5 was 143,4% and 142,3%.

The pozzolanic activity index describes the reaction rate between the pozzolan and the calcium hydroxide in the concrete mortar paste. The reaction rate is therefore analyzed by investigating the correlation between the silicon dioxide (SiO_2) content of the microsilica samples and the average PAI of the mortars containing microsilica E1-E10. The relationship between the PAI and silicon dioxide content in the microsilica samples is visualized in Figure 8.26.
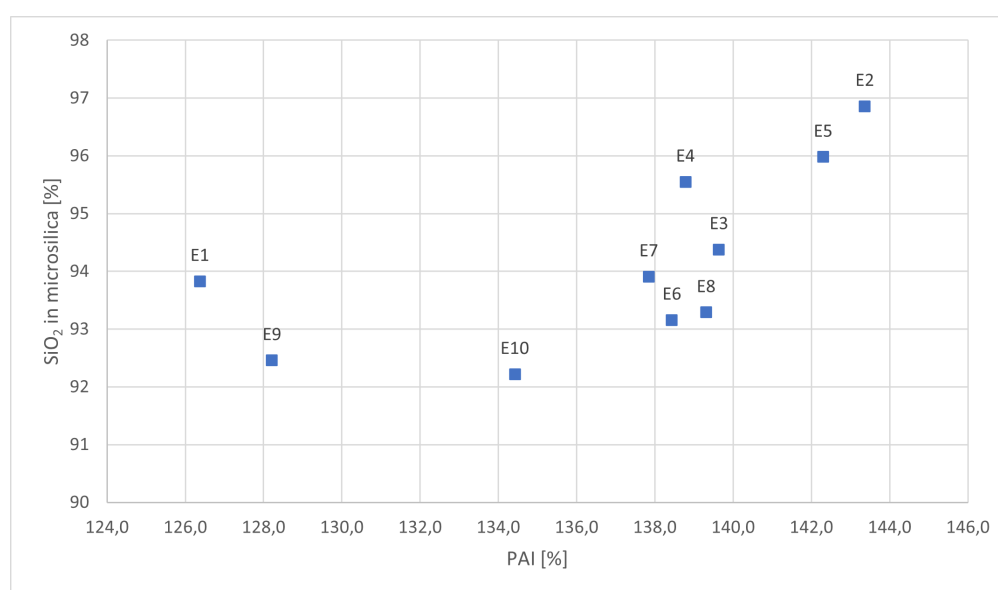
Figure 8.26: Average pozzolanic activity index for mortars containing microsilica E1-E10, SiO_2 content of the microsilica samples.

89

Table 8.7: Average PAI of mortars containing densified- undensified-, and slurried microsilica and SiO_2 content of each microsilica sample.

Microsilica type	E1	E2	E3	E4	E5	E6	E7	E8	E9	E10
Average PAI [%]	126,4	143,4	139,6	138,8	142,3	138,4	137,8	139,3	128,2	134,4
SiO_2 content of microsilica [%]	93,83	96,86	94,38	95,55	95,98	93,16	93,91	93,29	92,46	92,22
Form of microsilica	U	U	U	U	U	D	S	S	D	U

Table 8.7 presents the SiO_2 content of the different microsilica types and the average PAI values of the mortars containing microsilica E1-E10. As illustrated in Figure 8.26, a correlation can be observed between the SiO_2 content of the microsilica and the average PAI. Several of the samples with high silicon dioxide contents give a higher PAI than the microsilica samples that have a lower silicon dioxide content. According to information presented in chapter 3, section 3.2.1 the content of SiO_2 in microsilica can enhance mechanical strength due to the pozzolanic reaction present during the hydration process, see Table 3.3, for pozzolanic reaction equation. As presented in Table 8.7, E2 and E5 microsilica contained 96,86% and 95,98% SiO_2 which was the highest content of SiO_2 out of all the microsilica samples that have been tested. This indicates that the mortar containing the microsilica that had the highest content of SiO_2 gave the highest compressive strength, hence the highest reaction rate between the pozzolanic additive and the calcium hydroxide.

Mortars containing microsilica samples E3, E4, E6, E7, and E8 achieved a PAI of approx. 137%-139% and the microsilica samples contained 93,16%-95,55% silicon dioxide (SiO_2). The difference in PAI for the mortars containing the microsilica samples previously mentioned is insignificant and the impurity content of the microsilica samples is fairly low. It can therefore be assumed that there is a correlation between the content of silicon dioxide and the mechanical strength of mortars containing microsilica E1-E10.

However, when investigating the mortar containing microsilica E1, this behavior was not observed. The mortar containing microsilica E1 contains approximately the same amount of silicon dioxide as the mortars that achieved a high PAI. Despite this, the E1 microsilica mortar achieved the lowest PAI out of all the mortars containing microsilica E1-E10. When comparing the E1 microsilica to the remaining microsilica samples, the two chemical components that separate E1 microsilica from the others are the high Fe_2O_3 content (2,1%) and the high content of CaO (0,636%). The high content of these chemical components may have influenced the strength development, but the significance of the influence is uncertain.

The BET specific surface area is a physical property of microsilica that might

influence the strength development properties of concrete. BET specific surface area of the microsilica samples ranges from $16.9\,\mathrm{m^2/g}$ to $27.74\,\mathrm{m^2/g}$. It is therefore of interest to investigate if there is a correlation between the BET specific surface area of the microsilica samples and the pozzolanic activity index. The relationship between the two is presented in Figure 8.27.
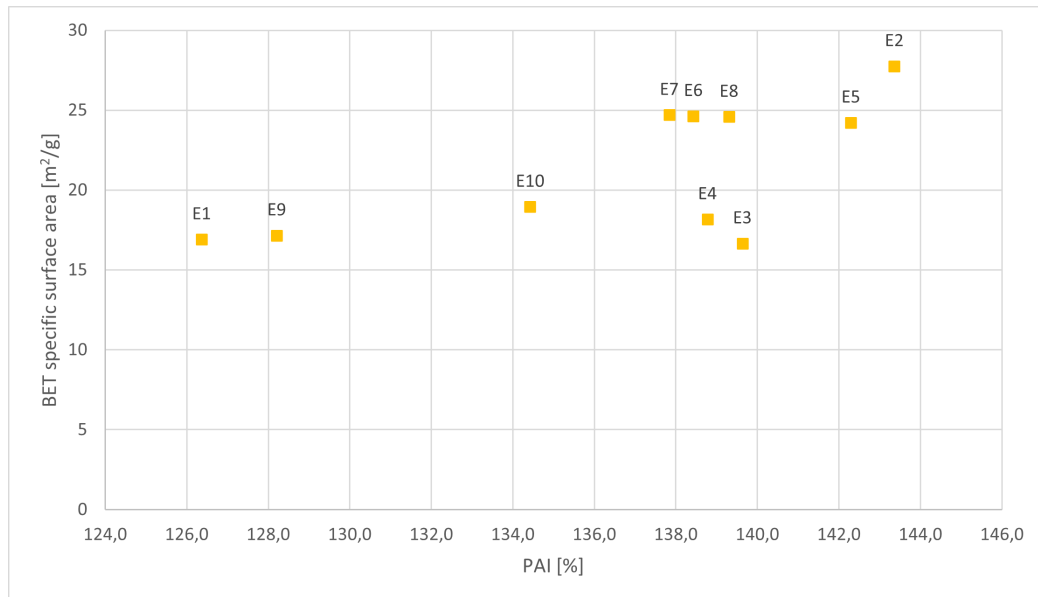
Figure 8.27: Average pozzolanic activity index for mortars containing undensified-, densified-, and slurried microsilica, and the BET specific surface area of each microsilica sample.

Table 8.8: Average PAI of mortars containing microsilica, BET specific surface area, and the form of each type of microsilica.

Microsilica type	E1	E2	E3	E4	E5	E6	E7	E8	E9	E10
Average PAI [%]	126,4	143,4	139,6	138,8	142,3	138,4	137,8	139,3	128,2	134,4
BET specific surface area $[m^2/g]$	16,9	27,74	16,65	18,16	24,21	24,62	24,69	24,57	17,15	18,94
Form of microsilica	U	U	U	U	U	D	S	S	D	U

The BET specific surface area of the microsilica sample is presented in Table 8.8 along with the Pozzolanic activity index of each mortar composition containing microsilica.

In Figure 8.27 it can be observed that there is a correlation between the two mentioned properties. From Table 8.8, it is visible that the three samples that achieved the lowest PAI had a BET SA $< 20\,\mathrm{m^2/g}$. The two mortars that contained microsilica E2, and E5 gave the highest PAI, and microsilica E2 and E5 have a BET SA $< 24\,\mathrm{m^2/g}$. These observations indicate that there is a strong correlation between the BET specific surface area and the PAI. Based on this relationship, it can be assumed that the PAI of mortars containing E1-E10 may increase as the

BET specific surface area decreases.

Microsilica comes in three different forms and as mentioned in the theoretical background, and the three forms are; undensified, densified, and slurried. The PAI of the mortars containing densified-, undensified-, and slurried microsilica is presented in Figure 8.28.
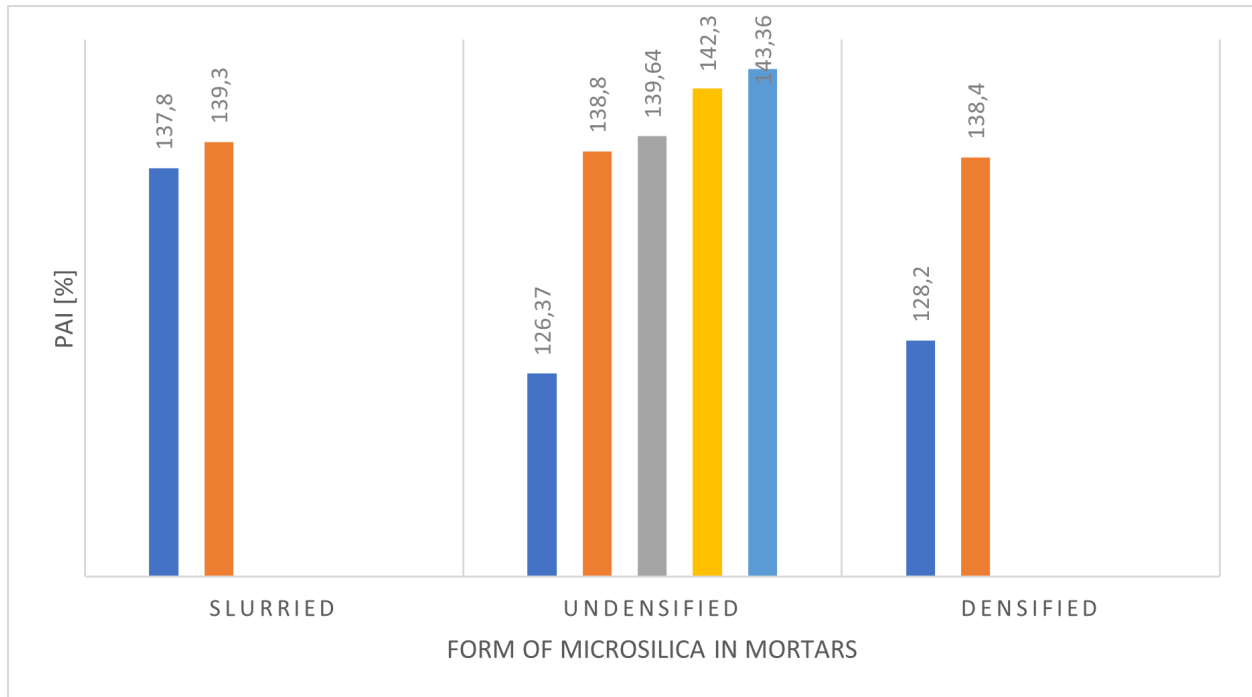
Figure 8.28: Average pozzolanic activity index for mortars containing undensified-, densified-, and slurried microsilica

Figure 8.28, shows that mortars containing densified, undensified, and slurried microsilica all achieved a PAI of approximately 138%. Based on this observation one can assume that the form of microsilica alone does not influence the pozzolanic activity index of the mortars that have been tested. Hence, it does not have a significant influence on the strength development of mortars containing E1-E10 microsilica.

According to the theoretical background, section 3.2, densified microsilica is the most commonly used form of dry microsilica. This is because it is easier to handle pneumatically than undensified microsilica. As the bulk density of microsilica is altered during densification, it is of interest to see if densification influences the mechanical strength of the mortars containing unidensified microsilica and densified microsilica. The correlation between the densification of the microsilica samples and the average PAI for each mortar composition containing microsilica has therefore been investigated. The relationship between the PAI and the bulk density has been illustrated in Figure 8.29.
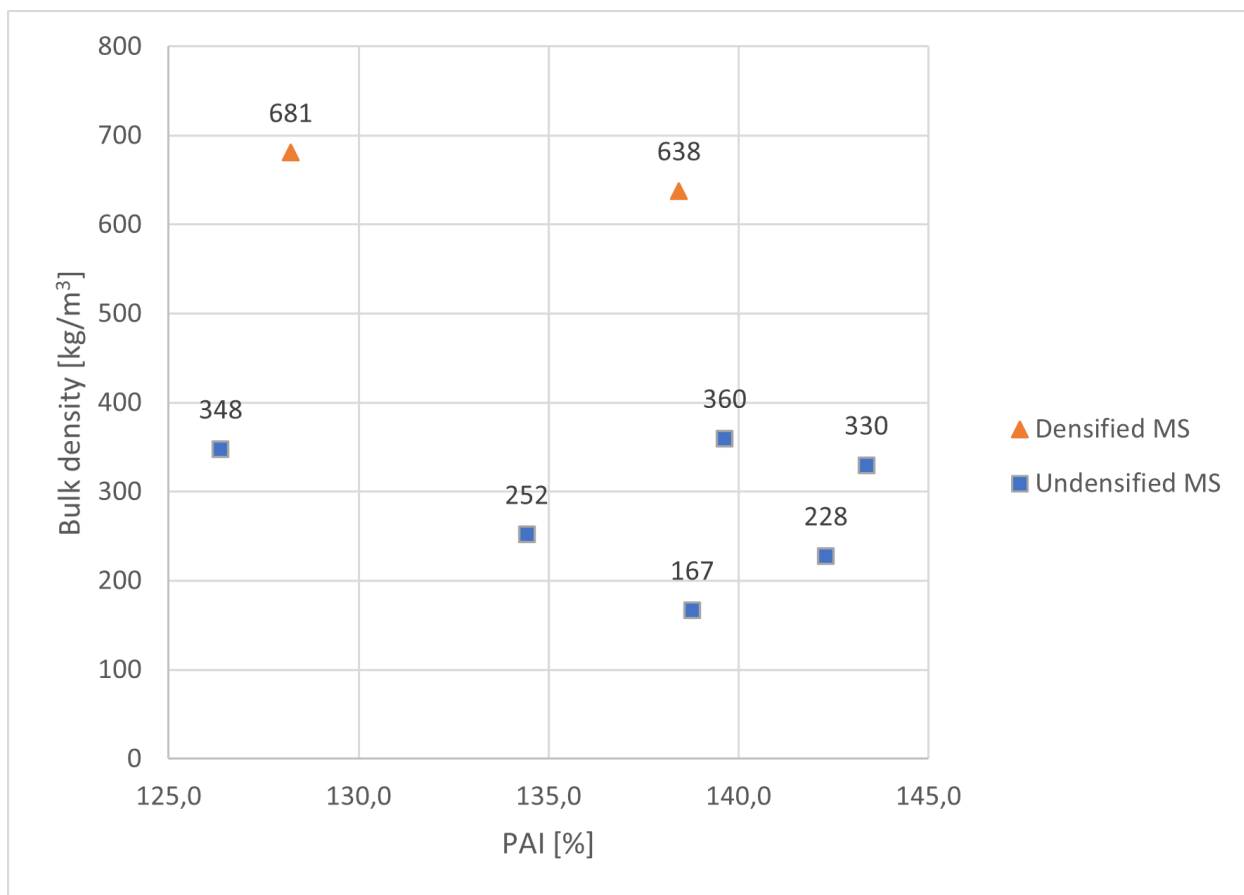
Figure 8.29: Average pozzolanic activity index for mortars containing undensified-, densified-, and slurried microsilica, and the bulk density of each microsilica sample.

Table 8.9: Bulk density of the microsilica samples, form of microsilica, and the average PAI of each mortar composition containing microsilica E1-E10

Microsilica type	E1	E2	E3	E4	E5	E6	E7	E8	E9	E10
Average PAI [%]	126,4	143,4	139,6	138,8	142,3	138,4	137,8	139,3	128,2	134,4
Bulk density [kg/m^3]	348	330	360	167	228	638	-	-	681	252
Form of microsilica	U	U	U	U	U	D	S	S	D	U

The bulk densities of the microsilica samples are presented in Table 8.9 along with the average PAI for each mortar composition used in strength development testing.

As illustrated in Figure 8.29 and presented in Table 8.9 the mortars that contained densified microsilica gave PAI of 128,2% and 138,4%. It was also observed that out of the two mortars containing densified microsilica, the mortar that achieved the highest PAI gave similar results as two of the mortars containing undensified microsilica. Based on these observations, it can be assumed that the densification of microsilica does not influence the strength development of the mortars that have been tested.

As mentioned in the earlier discussion, E9 and E10 come from the same source, and the only difference between the two samples is the bulk density. Due to this, the relationship between densification and PAI is further investigated by looking at the PAI of E9 and E10 microsilica, see Figure 8.30.
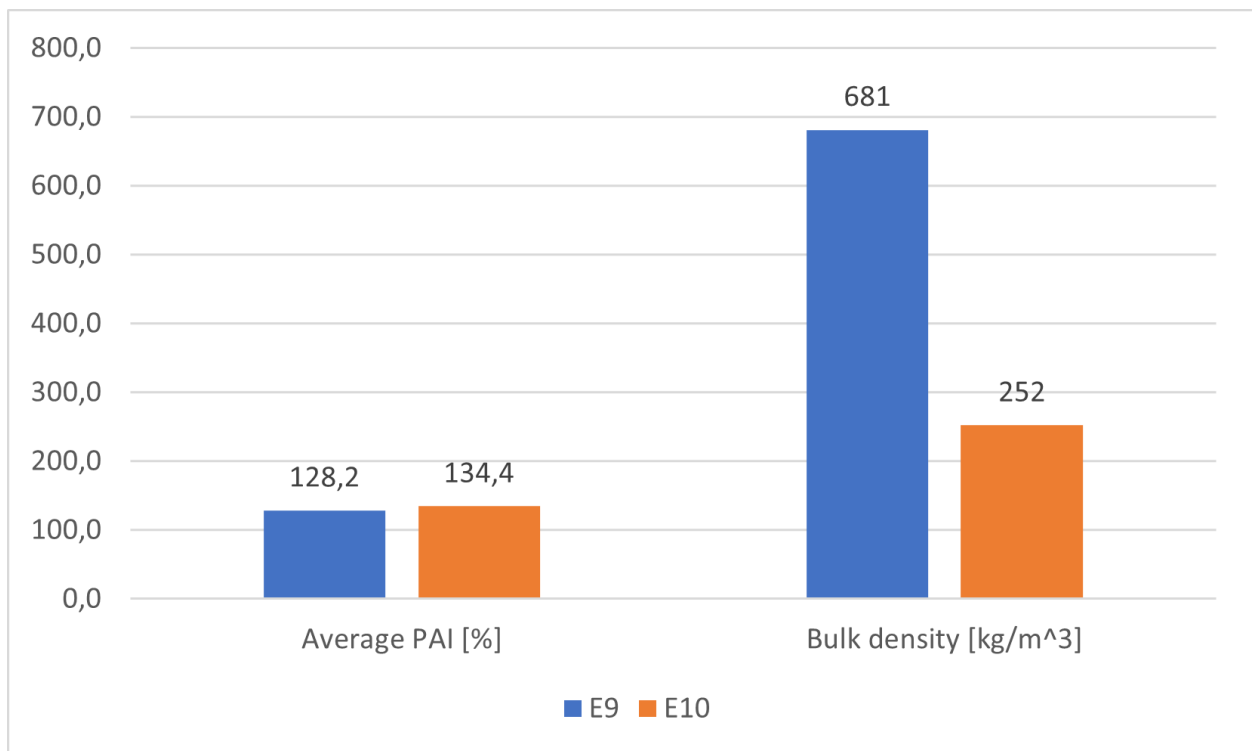
Figure 8.30: Average pozzolanic activity index for mortars containing E9 and E10 microsilica, and bulk density of the associated microsilica sample.

In Figure 8.30, it is visible that the two mortars containing E9 and E10 microsilica had pozzolanic activity indexes of approximately 128% and 134%. Due to small variations in the PAIs of the two mortars, it is not possible to conclude anything about the correlation between the densification of microsilica and the strength development of the mortars that have been tested. However, it can be assumed that if the correlation is present, it had a small impact on the mechanical strength of the mortars containing microsilica E9 and E10.

Chloride ion migration test of mortars containing microsilica

The NT BUILD 492 was conducted on 12 samples and the result had to be discarded for samples C.E2, C.E7, and C.E8. The test specimens containing microsilica E7 and E8 were discarded because they did not satisfy the mortar composition criteria presented in chapter 6, section 6.7.1. Sample C.E2 was discarded due to temperature measurements that were outside the temperature range of 20-25$°C$, given in the NT BUILD 492 test standard.

The test final results of the chloride ion migration test are presented in Figure 8.31. The non-steady-state coefficient is expressed by D_{nssm} x 10^{-12} m^2/s and it describes the degree of chloride ion migration in the samples. A high D_{nssm} value indicates high migration of chloride ions in the specimen.
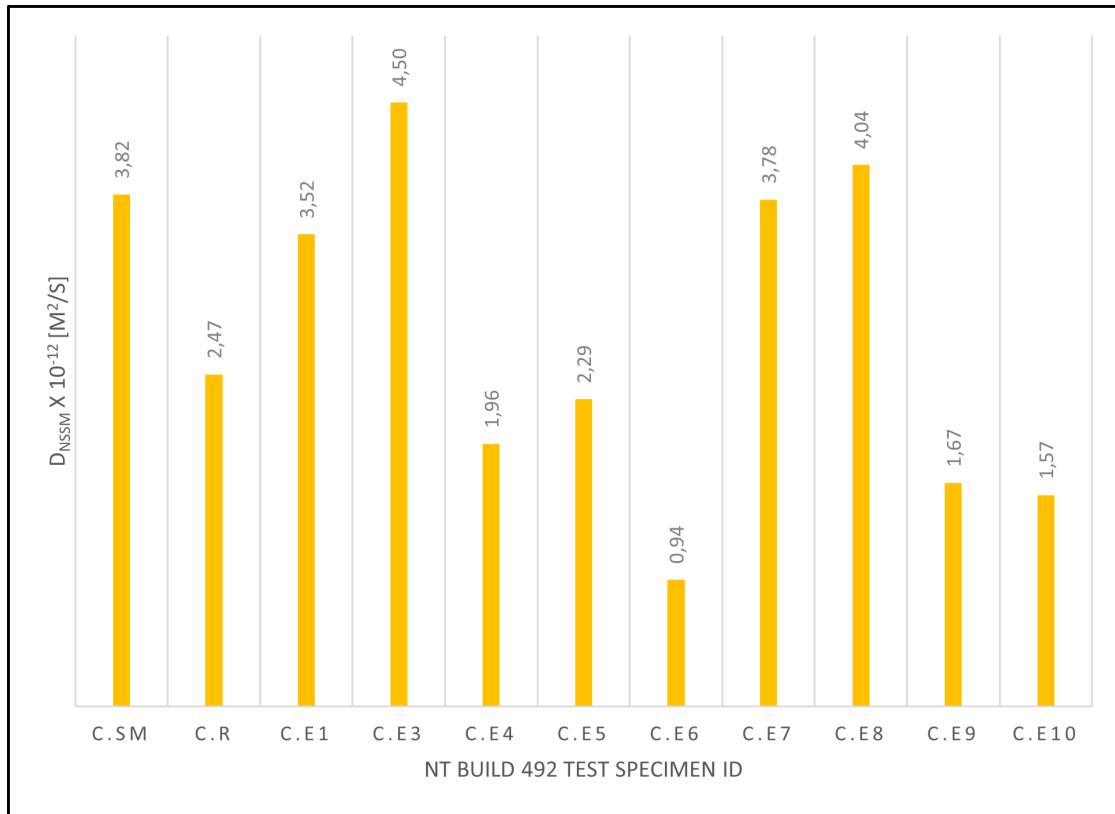
Figure 8.31: Non-steady-state migration coefficient for all samples used in NT BUILD 492 test.

As illustrated in Figure 8.31, the lowest chloride ion migration was observed in sample C.E6 containing microsilica E6. The highest chloride ion migration was observed for sample C.E3 which contained microsilica type E3, which was $0,68 * 10^{-12}$ higher than the standard mortar (C.SM). Five of the mortars containing microsilica showed a higher chloride ion migration resistance than the reference mortar (C.R). When analyzing the results containing microsilica, no significant trend can be observed.

Microsilica contributes to higher durability due to the "packing" of concrete according to the theoretical background and the observations for research presented in the literature review. The packing of the concrete is enabled by the small and spherical microsilica particles that contribute to decreased permeability according to the theoretical background, section 3.2.1. The test specimens containing microsilica showed big variations in the non-steady state coefficient and did not show a significant increase in resistance against chloride ion migration. Thus, one can assume that there is a source of deviation that has affected the results. This is because the test results contradict well-established research on the properties of concrete containing microsilica.

To investigate the potential sources of deviations in the test results, the densities of the specimens and the effect of manual compaction of the test specimens are assessed. Figure 8.32 presents the average density of test specimens containing microsilica used for mechanical strength tests and the density of the samples

used in the NT BUILD 492 test.
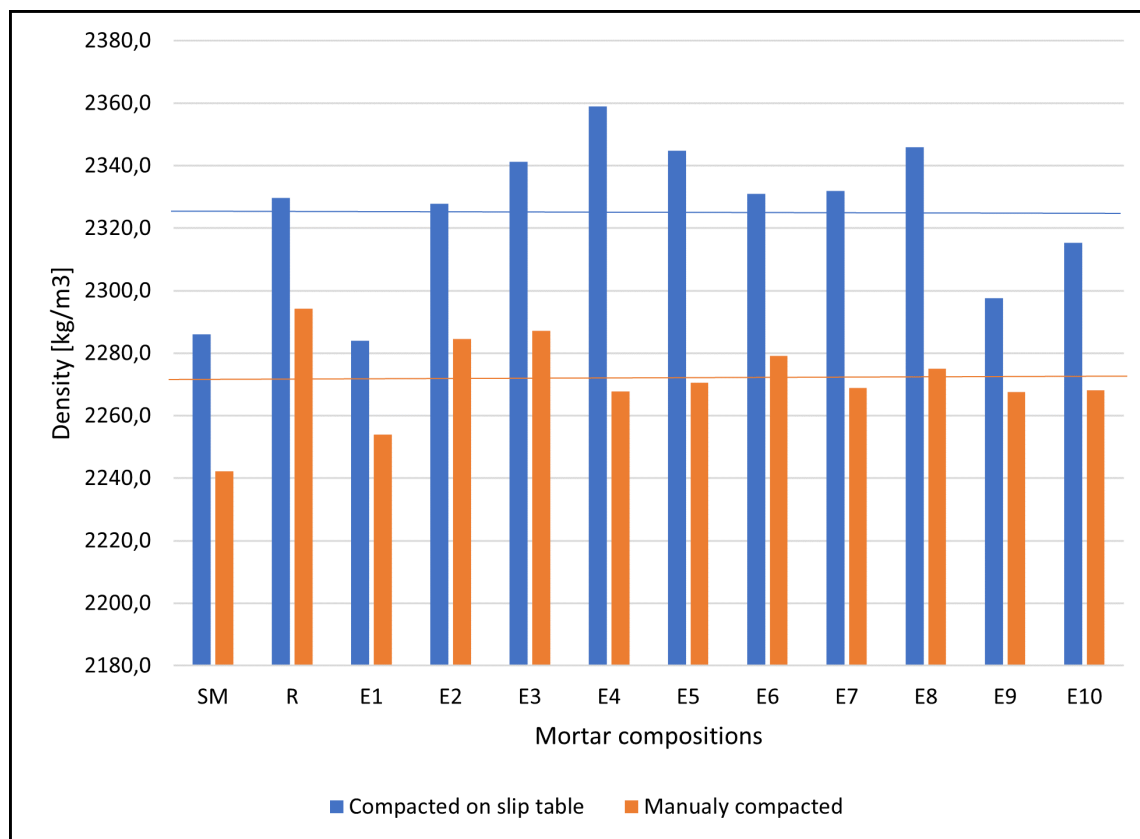
Figure 8.32: Density of specimens compacted using slip table and manual compaction

Figure 8.32 illustrated the difference in density between the samples that were compacted on a slip table and the samples that were manually compacted. The blue horizontal line marks the average density of all samples compacted on a slip table, which was approximately 2325kg/m^2. The chloride ion migration test specimens which were manually compacted show an average density of 2271kg/m^2. As one can see in Figure 8.32 the variation in the density between the samples used for strength tests and the ones used for chloride ion migration test are significantly high. Based on these observations one can assume that one of the sources of deviations in the test result could have originated from the manual compaction of the test specimens.

The chosen method of compaction could have affected the pore structure of the test specimens used in the chloride ion migration test. Manual compaction of the specimens may have caused a higher content of compaction voids and air pores in the pore structure when than what is expected of the specimens that were compacted on a slip table. According to the information presented in the theoretical background, section 3.1.6, porosity is closely related to the permeability of concrete. This is because the mass that penetrates the concrete travels through the pore structure of the material. Consequently, one can assume that the specimens which were used in the chloride ion migration test may have a lower resistance against chloride ion migration. To enable any conclusions about

the chloride ion migration resistance of the mortars containing E1-E10, new tests with new specimens are necessary.

Due to inconclusive test results from the NT BUILD 492 test, no general assumption can be made about the chloride ion migration resistance of the mortar compositions containing microsilica E1-E10.

8.4 Weaknesses in research method

The flowability of the mortars containing microsilica E1-E10 has been measured by conducting flow tests. Several of the mortars with the same mortar compositions gave very varying flow test results. The cause of the varying flow test results may have been the changing laboratory conditions, deviations in the mixing procedure, and low humidity in the laboratory, among other things, but the main reason for the big variations is uncertain. Using more than one method of measuring workability should therefore have been applied. Measuring several aspects of the flowability of the mortars would have provided more information about the fresh mortar properties of the mortar compositions.

Temperature logging was conducted in the laboratory at UiA using 0,35 l of mortar in insulated curing boxes that room 15 liters of mortar. Practically this means that calibration of the data was not possible and the results could only be used for comparative purposes.

When analyzing the data from the NT BUILD 492 chloride ion migration test, it became clear that the results were inconclusive and that there may have been several sources of deviations in the results. Due to this, it would have been beneficial to investigate the influence of more than one degradation factor on the permeability of mortars containing microsilica.

9 Conclusion

This section of the report presents the main findings and conclusions from the conducted study.

9.1 Secondary questions

How does microsilica affect the properties of fresh concrete mortar?
Flow tests were conducted to examine the impact of substituting 10% cement with microsilica on the flowability of mortars. The results reveal that microsilica samples with lower BET specific surface area exhibited enhanced flowability, leading to reduced water demand compared to samples with higher BET SA. Impacts on microsilica densification were investigated and the results showed no correlation between densification and flowability. The evaluation of the relationship between the moisture content of microsilica and flowability led to the conclusion that no significant correlation was observed between the two factors.

How does substituting 10% of the binder with microsilica affect the strength development of the mortars? As a result of conducted tests, it was observed that all mortars containing microsilica gave enhanced compressive- and flexural tensile strength when compared to the reference mortar. The relationship between microsilica BET specific surface area, SiO_2 content, and the PAI was investigated and it became clear that high BET SA and a high silicon dioxide content in the microsilica gave a high pozzolanic activity index, hence high compressive strength. By investigating the impact of microsilica densification on concrete mortars by comparing results from the mortars containing E9 and E10 microsilica, it has been determined that there is no correlation between densification and properties such as complete setting time, total heat of hydration, density, and pozzolanic activity index. The investigation also explored the form of microsilica, revealing no significant trend in the PAI of mortars containing slurried, densified, and undensified microsilica. When assessing the temperature logging results it was observed that there was no correlation between the complete setting time and the pH of the microsilica samples. However, a small correlation existed between microsilica alkali content and mortar complete setting time, with lower alkali content associated with an earlier complete set.

Which influence does the microsilica have on the durability of the mortars?
Chloride ion migration was investigated to analyze the influence of microsilica on concrete properties. The results were inconclusive, several potential sources of deviation were detected, and the observations contradicted well-established research on the topic. Due to this, nothing can be concluded about the influence of microsilica E1-E10 on the durability of concrete.

9.2 Research question

How does different compositions of microsilica affect the properties and characteristics of concrete?

As a result of the testing and comparative analysis, several observations about how microsilica influences concrete properties have been obtained. A common denominator in the observations for all tests was that the densification of the microsilica allegedly does not influence the properties of concrete. This is advantageous information for practical purposes because it means that densified microsilica, which is easier to work with pneumatically than undensified microsilica has not been alternated in terms of quality by the densification. The BET specific surface area of the microsilica influence both the flowability of the mortar as well as the pozzolanic activity index of the samples after 28 days of curing. Low BET SA (m^2/g) gave high flowability and an increase in PAI was observed for mortars containing microsilica with high BET SA (m^2/g). A low BET therefore may have a positive influence on the water demand of the mortars. The pozzolanic activity index of the mortars also showed an increase as the content of silicon dioxide in the microsilica increased. This makes the application of microsilica in high-strength concrete possible and beneficial. When assessing how the mortars were influenced by the pH of the microsilica samples, complete setting time was investigated and it was concluded that there was no correlation between the pH of microsilica and the complete setting time. However, there was a minor correlation between the complete setting time of the mortars and the alkali content of the microsilica samples, where low alkali content gave an early complete set. No correlation was observed when investigating the influence of moisture in the microsilica samples on the flowability of the mortars.

10 Recommendations for further work

For further research, it would be of interest to investigate the influence of additional samples of microsilica obtained from the same source. The aim when analyzing the results of these samples should also be on examining the impact of BET specific surface area and silicon dioxide on concrete properties. Furthermore, it would be of interest to analyze an expanded range of microsilica samples, including both densified and undensified variants.

Further exploration into the thermal properties of mortars incorporating microsilica would enhance comprehension regarding the influence of microsilica on the heat of hydration and the rate of concrete hydration. Consequently, conducting the Vicat test on microsilica-based mortars becomes a topic of interest. Acquiring more precise data on the exact initial and final setting times would significantly contribute to a deeper understanding of early strength development in mortars. Additionally, a comprehensive investigation into the strength progression over specific time intervals (1 day, 3 days, 14 days, 28 days) would prove valuable. Setting time and strength exhibit a close correlation, and insights derived from the Vicat test, in conjunction with strength test outcomes, offer valuable data on strength development and early strength characteristics. The practical application of microsilica in precast concrete would greatly benefit from the valuable information derived from these results.

The present report solely employs the BT BUILD 492 chloride ion migration test as the technique for investigating durability. However, it is imperative to explore multiple degradation factors in concrete containing microsilica types E1-E10. This is necessitated by conflicting test results and the limited measurement of only one degradation factor in the report. Durability assumes critical significance in concrete, particularly for structures located in marine environments. Existing research suggests that microsilica has a favorable impact on concrete durability, thus prompting the need to examine various degradation factors associated with concrete containing microsilica types E1-E10. Investigation into chemical- and physical actions, such as sulfate resistance, freeze/thaw resistance, water permeability, carbonization, and other relevant factors, is essential to provide comprehensive insights into durability aspects.

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A Appendix A - EN 13263-1:2005 pkt 5.3.3 Reference method

A.1 REFERENCE METHOD

EN 13263-1:2005 pkt 5.3.3

A.2 EQUIPMENT/CHEMICALS

A.2.1 Chemicals

Reference mortar:

> Test cement: 450g
>
> Standard sand: 1350g
>
> Water: 225g

Microsilica mortar:

> Test cement: 450g
>
> Microsilica: 45g
>
> Standard sand: 1350g
>
> Flow agent: Xg
>
> Distilled water: 225g - (water in ms slurry).

When correcting the amount of water, the solids in the ms slurry are always assumed to be 50,0%.

A.2.2 Equipment

- Hobart mixer with a 5 litre mixing bowl
- Scales with accuracy of ± 0,1 g
- Flow table according to ASTM C 230
- Slip table "TONI-Technik", 60 strokes/ cycle (55s), amplitude 14 mm
- Stop watch
- "TONICOMP III" Mortar press
- Plastic bowl
- 2 metal scoops / throwels for pouring of sand

- Ramming rod (D=40 mm, W=250 g)

- Sliding calliper

- Spatula

- Spoons

- Damp cloth

- Mould spout

- Spatula

- Mould, 3 prisms of 4 x 4 x 16 cm (EN 196-1)

Materials:

- Test cement CEM I 42.5 according to EN 13263-1 clause 3.30 (not older than 1 year)

- Microsilica

- Standard sand – CEN according to EN 196-1 clause 3

- Distilled water

- Flow agent (dry)

A.3 PROCEDURE

General:

1. Check that the equipment and materials required are available and functioning properly.

2. Check and note down the temperature in the laboratory. It should be 20oC, ± 2oC.

3. Testing is always initiated with a reference 0-mix (without microsilica).

4. For the 0-mix:

    - Weigh 450 g cement into a plastic bowl

    - Weigh 225 g water into the mixing bowl

    - Weigh 1350 g sand (one bag – not to be adjusted).

5. For the microsilica mix:

    - Weigh 405 g cement into a plastic bowl

    - Thereafter, weigh dry flow agent and 45 g microsilica and mix with the cement.

    - Weigh 225 g water into the mixing-bowl.

- (Alt. weigh ms-slurry into the mixing bowl with the water).

6. Weigh 1350 g standard sand in the metal scoops / throwels.

7. Mix:

    Pour the dry mix (without sand) and hoist up the bowl.

    At the same time, start the mixer and the stopwatch and run the mixer for 30 seconds at speed I. Note down the start time.

    During the next 30 seconds, add evenly standard sand.

    Stop the mixer, adjust the speed to II, and run for 30 seconds.

    Stop the mixer, lower the bowl and, for the next 30 second, scrape along the rim.

    Hoist up the bowl and cover with a damp cloth. Total pause: 90 seconds.

    Remove the cloth, start the mixer and mix for another 60 sec. Total mixing time: 4 minutes.

8. Flow measurements:

    Start to measure flow as soon as the mixing has been completed.

    Check that the cone is lying centred on the flow table.

    Fill the cone with 2 layers of mortar paste and ram each layer 10 times with a ramming rod; watch out so that the stabs do not penetrate deeper than the depth of the layer. Level the surface with a slice and remove excess paste around the ring. After 10-15 seconds lift the ring carefully.

    Start the motor of the flow table, and stop it after 15 strokes.

    Measure the diameter of the mortar spread in two directions perpendicular upon each other with the help of the sliding calliper. Note down the result to the nearest mm.

    The requirement in respect of flow measurements for microsilica mix is flow measurement for reference ± 5 mm. If the requirement cannot be met, start out with a new microsilica mix with a different amount of flow agent.

    When the flow measurements have been completed, put the paste from the flow table into the mould.

9. Casting of prisms:

    Check whether the prism mould is clean and lubricated. The casting is done in two layers. Fill up a layer of 2 cm of mortar into the mould, and insert the mould spout. Place the mould on the slip table and compact it with 60 strokes (1 series).

Fill up the rest of the mould with mortar. Compress with 60 blows.

Level the prisms using a slice (and remove any excess paste).

Mark the mould, using a water-resistant felt pen, with date and the number/ name of the mix.

Cover the mould with a glass plate. Leave the mould in a curing vessel with 90% RH (min.) and $20°C \pm 1°C$ for 24 hours.

Fill in the log forms

10. Storage of microsilica samples that have been tested:

    Keep the microsilica test samples shall for two years in case there is a need to repeat the test.

11. Determination of strength and density:

    Place a 10-litre plastic bucket on the scales next to the mortar press and fill it with water. Behind the bucket place a stand to be used when suspending the prisms in water.

    Remove the prisms from the water, dry with a paper towel and weigh. Note down the weight with one decimal.

    Thereafter, weigh the prisms when submerged in the bucket and suspended from the stand. Note down the weight with one decimal.

    After the prisms, have been weighed, proceed to measure flexural and compressive strength.

    IMPORTANT: 30 minutes before start-up of tests at least, switch on the mortar press. Check that the load application speed is correct - flexural strength shall be 50 N/s and compressive strength - 2.4 KN/s.

    To measure flexural strength, place the prism centred in the press. Start putting on load and note down the result with 2 decimals.

    IMPORTANT: The top of the prisms (uneven surface) should face towards the side. (Not up or down towards the pressure surface).

    Repeat the same procedure with the other prisms, taking care not to mix the parts of the different prisms.

    Switch off the flexural strength meter and switch on the compressive strength meter. Reset and place one half of the prism between the pressure holder so that the top of the prism (uneven surface) faces towards the side. Close the screen up front and start putting on load. Note down the result to one decimal.

    Clean the working surfaces of the press before the next load.

A.4 CALCULATIONS

Make 6 parallel measurements (compressive strength tests) with each sample. Work out the average. All measurements must be within 10% of average.

If one measurement lies outside average, it can be rejected. (If several lie outside, the whole series is rejected.) Work out a new average.

If the remaining 5 measurements lie within average (±10 %), the result can be approved. If not, the whole series is rejected and new prisms are prepared for a new test.

Calculate activity index according to method described in EN 13263-1 clause 5.3.3.

A.4.1 Reporting results

All results are stored in the database. Printouts of the results are also kept on file. It should be commented on if the results suggest inferior microsilica quality.

A.4.2 Specification

Climatic test chamber minimum 50 % RH, $20°C$, ± $2°C$.
Curing vessel minimum 90 % RH, $20°C$, ± $1°C$.
Water: $20°C$ +/- $1°C$.

A.5 REFERENCES

EN 196 – 1
EN-13263-1
ASTM C 230

A.6 ENCLOSURES

None

B Appendix B

B.1 Appendix B - Literature review logbook

B.1.1 Literature search 1

Table B.1: Parameters used in literature search 1

Parameters	Input
Search engine	ScienceDirect
Search words	Silicafume in concrete
Years	2023, 2022, 2021
Subject area	Material Science, Engineering, Environmental Science
Access type	Open access & Open archive

Output from the literature search was 5 articles, see Table B.2.

Table B.2: Results from literature search 1

Search results	
1.	Mechanical properties and microstructure of High-Performance Concrete with bamboo leaf ash as additive
2.	Data-driven compressive strength prediction of steel fiber reinforced concrete (SFRC) subjected to elevated temperatures using stacked machine learning algorithms
3.	Autonomous detection of concrete damage under fire conditions
4	High strength one-part alkali-activated slag blends designed by particle packing optimization
5.	Effect of glass microfibre addition on the mechanical performances of fly ash-based geopolymer composites

B.1.2 Literature search 2

Table B.3: Parameters used in literature search 2

Parameters	Input
Search engine	ScienceDirect
Search words	Silicafume AND Compressive strength
Years	2023, 2022, 2021
Subject area	Material Science, Engineering, Environmental Science
Access type	Open access & Open archive

Literature search 2 gave the same results as literature search 1, see Table B.2.

Table B.4: Results from literature search 2

Search results		Comments
1.	Mechanical properties and microstructure of High-Performance Concrete with bamboo leaf ash as additive	Contained little information about microsilica in concrete
2.	Data-driven compressive strength prediction of steel fiber reinforced concrete (SFRC) subjected to elevated temperatures using stacked machine learning algorithms	Not relevant
3.	Autonomous detection of concrete damage under fire conditions	Not relevant
4	High strength one-part alkali-activated slag blends designed by particle packing optimization	Might be relevant
5.	Effect of glass microfibre addition on the mechanical performances of fly ash-based geopolymer composites	Not relevant

B.2 Literature search 3

Table B.5: Parameters used in literature search 3

Parameters	Input
Search enging	Scopus
Search words	Microsilica AND compressive strength
Years	2023-2017
Subject area	Engineering Material Science Environmental Science Chemical Engineering
Keywords	Compressive strength Microsilica Silica Fume Silica Cement Concretes High Performance Concrete Durability
Language	Norwegian and English
Access type	All open access

Output from the literature search was 37 articles. Sort the results by relevance.

Number	Article	Comments
1	Systematic multiscale models to predict the compressive strength of cement paste as a function of microsilica and nanosilica contents, water/cement ratio, and curing ages	Not relevant

2	Effects of reinforced fiber and microsilica on the mechanical and choride ion penetration properties of latex-modified fiber-reinforced rapid-set cement concrete for pavement repair	Seems relevant
3	Non destructive studies on engineered cementitious composites using microsilica and polypropylene fibre	Seems relevant
4	Cement paste mixture proportioning with particle packingtheory: an ambiguous effect of microsilica	Seems relevant
5	Effect of GFRP rebars and polypropylene fibers on flexural strength in high-performance concrete beams with glass powder and microsilica	Seems relevant
6	Strength and durability of sustainable self-consolidating concrete with high levels of supplementary cementitious materials	Not relevant because they only vary the amount of fly ash.
7	Prediction of UCS and CBR of microsilica-lime stabilized sulfate silty sand using ANN and EPR models; application to the deep soil mixing	Not relevant
8	Relationship between splitting tensile strengths for self-compacting concrete containing nano- and microsilica	Not relevant
9	The effect of low-modulus plastic fiber on the physical and technical characteristics of modifies heavy concretes based on polycarboxylates and microsilica	Seems relevant
10	Effect of mixture proportioning of the high performance cementitious – limestone composites on the compressive strength	Relevant, a specific amount of microsilica increased the compressive strength
11	High performance concretes with modifying micro additives of microsilica and diopside	Seems relevant
12	Influence of recipe factors on the structure and properties of non-autoclaved aerated concrete of increased strength	Seems relevant
13	Laboratory investigation on the effect of microsilica additive on the mechanical behavior of deep soil mixing columns in saline dry sand	Seems relevant

14	Flexural behavior performance of reinforced concrete slabs mixed with nano- and microsilica	Seems relevant
15	Dependencies between cracking patterns and the physico-mechanical properties of microsilica modified cement matrix	Not relevant
16	Experimental study on the use of granite as fine aggregate in very-high-strength concrete	Not relevant
17	Insulation foam concrete nanomodified with microsilica and reinforced with polypropylene fiber for the improvement of characteristics	Seems relevant
18	Influence of polypropylene and steel fibers on the mechanical properties of ultra-high-performance fiber-reinforced geopolymer concrete	Not relevant
19	Effect of aggregate type on properties of ultra-high-strength concrete	Not relevant
20	Effect of basalt fibers on the parameters of fracture mechanics of MB modifier based high-strength concrete	Not relevant
21	Investigation of the structure of cement stone, obtaining and optimization of high-strength concrete on mechanically activated binder	Seems relevant
22	Comparison of alkali and silica sources in one-part alkali-activated blast furnace slag mortar	Not relevant
23	Effect of silica fume on high-strength concrete performance	Seems relevant
24	Heat treatment of basalt fiber reinforced expanded clay concrete with increased strength for cast-in-situ construction	Not relevant
25	Development of magnesium-silicate-hydrate (M-S-H) cement with rice husk ash	Not relevant
26	High-performance nano-modified concrete of increased strength and durability	Not relevant
27	Macroscopic and microstructural properties of engineered cementitious composites incorporating recycled concrete fines	Not relevant
28	Strain hardening magnesium-silicate-hydrate composites (SHMSHC) reinforced with short and randomly oriented polyvinyl alcohol microfibers	Not relevant

29	Mechanoactivation of Portland cement in the technology of manufacturing the self-compacting concrete	Not relevant
30	Pore structure analysis of various water-binder ratios ternary blended concrete made with	Seems relevant
31	Combination of polymeric superplasticizers, water repellents and pozzolanic agents to improve air lime-based grouts for historic masonry repair	Not relevant
32	Influence of silica fume on high-calcium fly ash expansion during hydration	Seems relevant
33	Study of the cource of cement hydration in the presence of waste metal particles and pozzolanic additives	Seems relevant
34	Performance of MgO-SiO2 system containing seeds under different curing conditions	Not relevant
35	Cement composites with waste incorporation under acid rain attack	Not relevant
36	Environmental and economic life cycle assessment of recycled aggregates concrete in the united arab emirates	Not relevant
37	Influence of boron carbide addition on performance and neutron shielding ability of cement mortar mix	Not relevant

Create a new list of articles that seemed relevant and sort the list by date (newest first).

Refining search

Look for findings on the following: Tensile strength, Compressive strength, Permeability, Durability, Packing.

Search for the word "microsilica or silica fume" to check relevance. Read sections containing these words. Read the conclusion and main findings to see if the articles are relevant.

Number	Article	Findings	Rele (yes/

1	Effect of GFRP rebars and polypropylene fibers on flexural strength in high-performance concrete beams with glass powder and microsilica	Using microsilica at 10wt% of cement decreases co2 emmissions by 95,4kg per ton of cement. Using microsilica alongside the WPG has enhanced concrete's microstructure behavior and reduced the number of microscopic cracks	No
2	Insulation foam concrete nanomodified with microsilica and reinforced with polypropylene fiber for the improvement of characteristics	Increased strength characteristics (compressive and tensile) when adding 10% microsilica to mixtures containing 1-3% fiber. Most reduced thermal conductivity with 10% microsilica content. Microsilica acts as a filler, it provides a denser packing of particles and also promotes the additional formation of calcium silicate hydrate(CSH).	Yes
3	Influence of recipe factors on the structure and properties of non-autoclaved aerated concrete of increased strength	"Adding microsilica showed higher strength compared to aerated concrete, where part of the cement was replaced by the addition of granulated blast-furnace slag and a complex additive." 16% MS gave the highest compressive strength. MS gave improved thermal conductivity	Yes
4	Influence of silica fume on high-calcium fly ash expansion during hydration	Not relevant because its about the prevention of cracking	No
5	Study of the cource of cement hydration in the presence of waste metal particles and pozzolanic additives	Mortar containing microsilica or metakaolin showed increased compressive strength. Adding microsilica or metakaolin decreased water absorption. Pozzolanic additives showed a less porous matrix and improved the contact zone between the cement matrix and the waste-metal particle fillers. Microsilica gave 39,1% increased heat release. (very reactive mixture).	Yes

6	The effect of low-modulus plastic fiber on the physical and technical characteristics of modifies heavy concretes based on polycarboxylates and microsilica.	Concrete with active silica showed higher values of density, frost resistance, and volumetric water absorption compared with the reference composition without midifiers, indicating higher characteristics of the operational reliability of products made of concrete with active microsilica. .	Yes
7	Laboratory investigation on the effect of microsilica additive on the mechanical behavior of deep soil mixing columns in saline dry sand	No interesting findings	No
8	Cement paste mixture proportioning with particle packing theory: an ambiguous effect of microsilica	Adding microsilica lead to decreased density and weight. It was shown that the addition of microsilica in cement paste improves the hydration kinetics of the cement, improving the compressive strength. In some of the samples, the microsilica was not fully dispersed and therefore lead to clusters of microsilica particles which caused cracking in the microstructure.	No
9	Flexural behavior performance of reinforced concrete slabs mixed with nano- and microsilica.	The use of nanosilica and microsilica showed a drastic increase of flexural tensile strength.	Yes

10	Pore structure analysis of various water-binder ratios ternary blended concrete made with	By using 5% microsilica and 15% fly ash, the pore diameter of the concrete was reduced from 19,121 mm to 3,386 mm. Using microsilica and fly ash in concrete can lead to dense and impermable microstructure. Also increased strength due to higher production of CSH and CAH. The ternary blended concrete mixes had very low chloride ion penetration which confirms its superior pore configuration.	Yes
11	Effect of silica fume on high-strength concrete performance.	Super relevant	Yes
12	Non destructive studies on engineered cementitious composites using microsilica and polypropylene fibre.	20% microsilica and 2% of polypropylene fibers induced to increase the range of the UPV. Increased compressive strength. More than 20% microsilica redulted in decreased compressive strength compared to the samples containing up to 20% microsilica. The study states that microsilica is more effective in concrete than in mortar due to the bond improvement in aggregate-paste associated with the formation of porous transition phase in lesser manner in microsilica concrete.	Yes
13	Effect of mixture proportioning of the high performance cementitious – limestone composites on the compressive strength	Compressive strength ratio versus the amount of microsilica and cement in mixture proportioning in the 100x100x100 mm cementitious - limestone compositest samples.	No

14	High performance concretes with modifying micro additives of microsilica and diopside.	Microsilica makes concrete stronger. MS also changes the microstructure of the material and leads to the acicular crystals formation of calcium hydrosilicates. Microsilica and diopside give the concrete a lower pore diameter and increased strength. The study shows that concrete with only MS had increased strength of 55% compared to the samples that did not have MS	Yes
15	Investigation of the structure of cement stone, obtaining and optimization of high-strength concrete on mechanically activated binder.	The study presents a detailed description of how microsilica reacts with CA(OH)2 and producec CSH in the form of needle shaped. Solid formation of connections. Also presents results that show that adding microsilica to the concrete increased the durability of hydrated cement from 26% to 40%.	Yes
16	Effects of reinforced fiber and microsilica on the mechanical and choride ion penetration properties of latex-modified fiber-reinforced rapid-set cement concrete for pavement repair.	Results show that adding microsilica led to a increased permability. compressive strength, flexural tensile strength increased as the microsilica substitution ratio increased. Target strength were satisfied after 28 days of curing. Decreased chloride ion penetration levels when microsilica was added.	Yes

Create new list with the relevant articles.

for the new selection: Allocate 1 point per topic of interest that is investigated in the article.

Topics of interest: Compressive strength, Flexural tensile strength, Density, Flowability, Chloride ion migration/penetration, Heat release during hydration, UPV, Microstructure and macrostructure, Particle size distribution of microsilica, Chemical composition of microsilica, Calorimetric test

Number	Article	Topics	Points
1	Insulation foam concrete nanomodified with microsilica and reinforced with polypropylene fiber for the improvement of characteristics	Compressive strength Tensile strength Particle size distribution of microsilica. Chemical composition of microsilica Density Thermal conductivity pore macrostructure	7
2	Influence of recipe factors on the structure and properties of non-autoclaved aerated concrete of increased strength	Compressive strength Thermal conductivity Microstructure Chemical composition of microsilca Density	5
3	Study of the course of cement hydration in the presence of waste metal particles and pozzolanic additives	Compressive strength UPV Total heat value Water absorption Calorimetric test Hydration process	5
4	The effect of low-modulus plastic fiber on the physical and technical characteristics of modified heavy concretes based on polycarboxylates and microsilica	Compressive strength Volumetric water absorption Frost resistance Density	2
5	Flexural behavior performance of reinforced concrete slabs mixed with nano-and microsilica	Density Compressive strength Flexural tensile strength	3
6	Pore structure analysis of various water-binder ratios ternary blended concrete made with	Chloride ion penetration Diffusion capability	1
7	Effect of silica fume on high-strength concrete performance	Compressive strength Flexural tensile strength Density	3
8	Non-destructive studies on engineered cementitious composites using microsilica and polypropylene fiber	Disqualified because of doubtful publisher	0
9	High performance concretes with modifying micro additives of microsilica and diopside.	Salt resistance Compressive strength Bending strength microstructure	3
10	Investigation of the structure of cement stone, obtaining and optimization of high-strength concrete on mechanically activated binder.	Compressive strength Water absorption Durability	2
11	Effects of reinforced fiber and microsilica on the mechanical and choride ion penetration properties of latex-modified	Compressive strength Flexural tensile strength chloride ion penetration abrasion resistance	5

B.2.1 The final list of articles

Number	Title	Points
1	Insulation foam concrete nanomodified with microsilica and reinforced with polypropylene fiber for the improvement of characteristics.	7
2	Influence of recipe factors on the structure and properties of non-autoclaved aerated concrete of increased strength.	5
3	Study of the course of cement hydration in the presence of waste metal particles and pozzolanic additives.	5
4	Effect of silica fume on high-strength concrete performance.	3
5	Effects of reinforced fiber and microsilica on the mechanical and chloride ion penetration properties of latex-modified fiber-reinforced rapid-set cement concrete for pavement repair.	5

C   Appendix C - Process development results

C.1   Flowability

Table C.1: Flow tests results for batch 1.1–1.5

Batch ID	Measurement A (mm)	Measurement B (mm)	Average (mm)
1.1	171,58	174,71	173,145
1.2	167,26	170,74	169,00
1.3	167,38	172,36	169,87
1.4	175,09	179,19	177,14
1.5	194,47	194,52	194,495

C.2   Density

Table C.2: Density calculation results for sample 1.1–1.4

Batch ID	Sample	Density (kg/m^3)	Average density (kg/m^3)	Standard deviation
1.1	A	2298,94	2300,54	1,53
	B	2300,70		
	C	2301,98		
1.2	A	2287,69	2286,64	2,15
	B	2288,06		
	C	2284,17		
1.3	A	2298,70	2299,85	2,76
	B	2297,86		
	C	2303,00		
1.4	A	2298,64	2301,01	2,45
	B	2300,85		
	C	2303,53		

C.3   Flexural tensile strength

Table C.3: Results from flexural tensile strength tests of sample 1.1–1.4

	Batch ID	Flexural tensile strength (MPa)			Average flexural tensile strength (MPa)	Standard deviation
		A	B	C		
Lab 1	1.1	8,6	8,0	8,2	8,3	0,31
	1.2	8,5	8,0	7,9	8,1	0,32
	1.3	8,3	7,7	8,4	8,1	0,38
	1.4	8,4	7,1	8,4	8,0	0,75

C.4 Compressive strength

Table C.4: Results from compressive strength tests of sample 1.1–1.4

	Batch ID	A (MPa)		B (MPa)		C (MPa)		Average (MPa)	Standard deviation
Lab 1	1.1	71,0	69,4	70,1	70,9	69,8	70,4	70,3	0,63
	1.2	73,3	70,7	71,4	73,3	74,1	69,4	72,0	1,82
	1.3	72,1	72,3	70,7	70,3	74,2	71,6	71,9	1,38
	1.4	68,1	69,8	69,3	71,6	66,4	70,6	69,3	1,85

D Appendix D - Preliminary study results

D.1 Flowability

Table D.1: Flow test results from preliminary study

Batch ID	Measurement A (mm)	Measurement B (mm)	Average (mm)
SM.1	167,51	170,1	168,805
EXP.1	104,32	105,86	105,09
EXP.2	110,79	109,4	110,095
EXP.3	167,32	167,58	167,45
EXP.4	108,02	109,47	108,745
SM.2	176,42	170,21	173,315
EXP.5	201,6	198,39	199,995
EXP.6	124,44	121,16	122,8
EXP.7	114,65	114,49	114,57
SM.3	186,45	191,58	189,015
EXP.8	175,65	176,88	176,265
EXP.9	110,43	112,39	111,41
EXP.10	115,44	114,38	114,91
SM.4	183,36	181,55	182,455
EXP.11	110,23	111,34	110,785
EXP.12	203,3	207	205,15
EXP.13	203,23	206,47	204,85
EXP.14	124,64	123,61	124,125
SM.5	168,2	170,52	169,36
EXP.15	155,92	153,95	154,935
EXP.16	169,72	164,43	167,075

D.2 Temperature logging
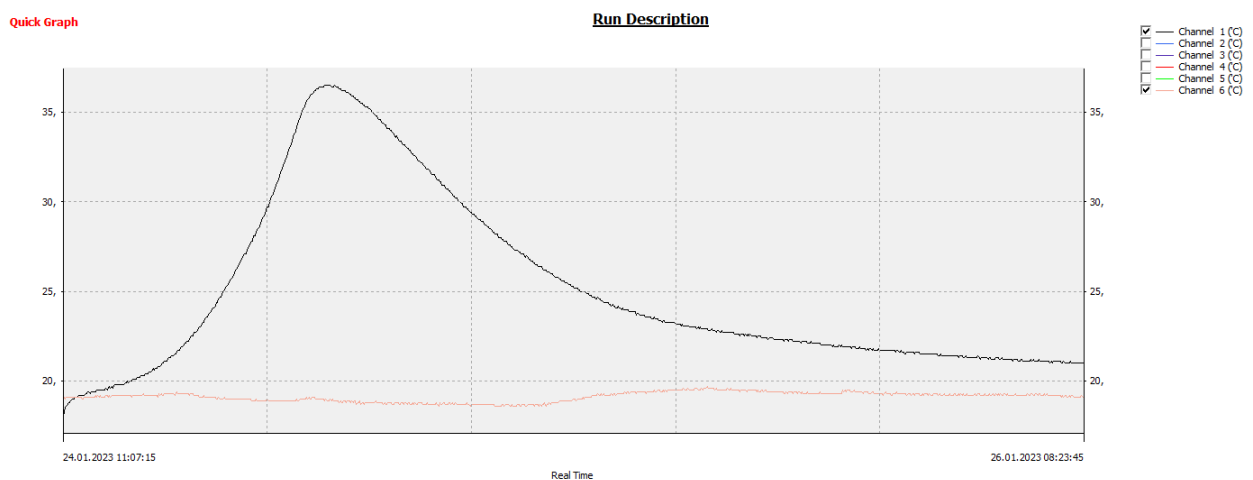
Figure D.1: Temperature logging of standard mortar (1.5)
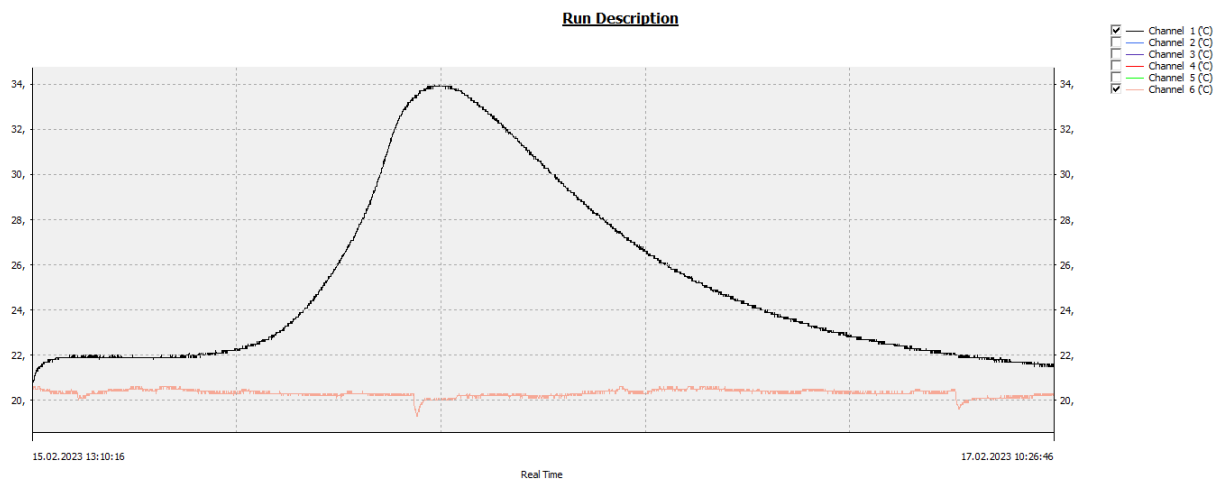
Figure D.2: Temperature logging of mortar with reduced W/C ratio and SP (EXP.17)

D.3 Density

Table D.2: Density calculation results from preliminary study

Batch ID	Sample	Density (kg/m^3)	Average density (kg/m^3)	Standard deviation
SM.1	A	2280,50	2281,69	1,78
	B	2280,83		
	C	2283,74		
EXP.3	A	2381,52	2381,12	0,70
	B	2381,52		
	C	2380,31		
SM.2	A	2280,52	2282,19	3,64
	B	2279,69		
	C	2286,38		
SM.3	A	2297,60	2295,74	3,81
	B	2291,35		
	C	2298,27		
SM.4	A	2286,16	2285,68	0,42
	B	2285,49		
	C	2285,38		
SM.5	A	2282,73	2284,98	2,15
	B	2285,21		
	C	2287,01		
EXP.15	A	2324,92	2325,62	1,64
	B	2324,44		
	C	2327,50		
EXP.16	A	2354,93	2356,39	1,46
	B	2356,40		
	C	2357,84		

D.4 Flexural tensile strength

Table D.3: Flexural tensile strength of specimens made in preliminary study

Batch ID	Flexural tensile strength (MPa)			Average flexural tensile strength (MPa)	Standard deviation
	A	B	C		
SM.1	7,3	7,1	7,4	7,27	0,15
EXP.3	8,0	7,5	7,8	7,77	0,25
SM.2	6,9	7,3	7,2	7,13	0,21
SM.3	6,7	7,0	7,1	6,93	0,21
SM.4	7,0	7,7	6,9	7,20	0,44
SM.5	7,3	6,8	7,2	7,10	0,26
EXP.15	8,5	7,8	7,4	7,90	0,56
EXP.16	7,9	8,0	7,8	7,90	0,10

D.5 Compressive strength

Table D.4: Compressive strength of specimens made in preliminary study

Batch ID	Compressive strength (MPa)						Average (MPa)	Standard deviation
	A		B		C			
SM.1	54,9	52,5	53,3	50,8	54,3	54,1	53,32	1,49
EXP.3	65,8	71,4	68,5	67,5	69,0	69,3	68,58	1,87
SM.2	56,1	54,6	56,9	55,9	55,3	57,4	56,03	1,02
SM.3	55,1	55,4	55,7	54,1	56,1	57,2	55,60	1,04
SM.4	54,6	55,2	53,3	55,6	52,9	54,8	54,40	1,07
SM.5	54,6	52,8	55,8	52,8	55,1	52,9	54,00	1,33
EXP.15	66,6	65,7	67,9	66,1	66,7	65,6	66,43	0,85
EXP.16	68,1	66,8	68,8	65,1	67,2	67,3	67,22	1,26

E Appendix E - Test results from research on microsilica

E.1 Laboratory conditions and mortar compositions

Mortar composition										
Mortar ID	**RF** [%]	**Temperature** [°C]	**Sand** [g]	**Cement** [g]	**Water** [g]	**SP** [%]	**SP** [g]	**W/C ratio**	**MS** [g]	**MS type**
R1.1	23,0	21,5	1355	450	176,8	0,9	4,0	0,40	0	-
E1.1	23,0	21,5	1355	405	176,8	0,9	4,0	0,40	45	E1
E1.2	23,0	21,5	1355	405	177,5	0,7	3,2	0,40	45	E1
E1.3	23,0	21,5	1355	405	179,0	0,4	1,6	0,40	45	E1
R2.1	22,0	21,0	1355	450	176,8	0,9	4,0	0,40	0	-
E2.1	22,0	21,0	1355	405	176,8	0,9	4,0	0,40	45	E2
E2.2	22,0	21,0	1355	405	176,8	0,9	4,0	0,40	45	E2
R3.1	24,0	21,0	1355	450	176,8	0,9	4,0	0,40	0	-
E3.1	24,0	21,0	1355	405	176,8	0,9	4,0	0,40	45	E3
E3.2	24,0	21,0	1355	405	176,8	0,9	4,0	0,40	45	E3
R4.1	33,0	20,5	1355	450	176,8	0,9	4,0	0,40	0	-
E4.1	33,0	20,5	1355	405	176,8	0,9	4,0	0,40	45	E4
E4.2	33,0	20,5	1355	405	176,8	0,9	4,0	0,40	45	E4
E4.3	33,0	20,5	1355	405	177,2	0,8	3,6	0,40	45	E4
R5.1	32,0	21,0	1355	450	176,8	0,9	4,0	0,40	0	-
E5.1	32,0	21,0	1355	405	176,8	0,9	4,0	0,40	45	E5
R5.2	29,0	20,5	1355	450	176,8	0,9	4,0	0,40	0	-
E5.2	29,0	20,5	1355	405	176,4	1	4,5	0,40	45	E5
E5.3	29,0	20,5	1355	405	176,8	0,9	4,0	0,40	45	E5
R6.1	34,0	20,5	1355	450	176,8	0,9	4,0	0,40	0	-
E6.1	34,0	20,5	1355	405	176,8	0,9	4,0	0,40	45	E6
E6.2	34,0	20,5	1355	405	176,8	0,9	4,0	0,40	45	E6
R7/8.2	26,5	20,0	1355	450	176,8	0,9	4,0	0,40	0	-
E7.2	26,5	20,0	1355	405	131,76	0,9	4,0	0,40	45	E7
E7.3	26,5	20,0	1355	405	133,56	0,4	1,8	0,40	45	E7
E7.4	24,0	20,0	1355	405	132,8	0,6	2,7	0,40	45	E7
E7.5	24,0	20,0	1355	405	132,48	0,7	3,2	0,40	45	E7
E7.6	24,0	20,0	1355	405	132,48	0,7	3,2	0,40	45	E7
E7.7	24,0	20,0	1355	405	131,76	0,9	4,0	0,40	45	E7
E8.2	24,0	20,0	1355	405	131,76	0,9	4,0	0,40	45	E8
R9/10.1	30,0	20,5	1355	450	176,8	0,9	4,0	0,40	45	-
E9.1	30,0	20,5	1355	405	176,8	0,9	4,0	0,40	45	E9
E9.2	30,0	20,5	1355	405	177,48	0,7	3,2	0,40	45	E9
E10.1	30,0	20,5	1355	405	176,8	0,9	4,0	0,40	45	E10
E10.2	30,0	20,5	1355	405	177,48	0,7	3,2	0,40	45	E10

E.2 Flowability

Table E.1: Flow test results for mortars used in the investigation of the influence of microsilica on fresh mortar properties.

Batch ID	Flow measurment A [mm]	Flow measurment B [mm]	Average flow [mm]
Flowability			
E1			
R1.1	155,32	158,57	156,95
E1.1	201,5	204,56	203,03
E1.2	205,13	198,53	201,83
E1.3	166,30	168,99	167,65
E2			
R2.1	153,19	151,61	152,40
E2.1	171,76	169,06	170,41
E2.2	174,59	171,5	173,05
E3			
R3.1	152,17	147,67	149,92
E3.1	183,74	181,96	182,85
E3.2	165,89	165,17	165,53
E4			
R4.1	155,37	152,85	154,11
E4.1	199,96	198,24	199,10
E4.2	184,94	186,8	185,87
E4.3	178,8	183,16	180,98
E5			
R5.1	170,27	169,79	170,03
E5.1	147,3	149,48	148,39
R5.2	140,16	139,59	139,88
E5.2	189,89	191,03	190,46
E5.3	171,55	177,98	174,77
E6			
R6.1	166,51	169,04	167,78
E6.1	177,22	177,04	177,13
E6.2	182,94	179,5	181,22
E7/E8			
R7/8.2	142,91	143,07	142,99
E7.2	202,05	201,39	201,72
E7.3	146,73	139,81	143,27
E7.4	155,52	160,05	157,79
E7.5	147,86	154,51	151,19
E7.6	154,51	154,05	154,28
E7.7	179,59	175,92	177,76
E8.2	182,42	183,64	183,03
E9/E10			
R9/10.1	153,08	155,17	154,13
E9.1	192,16	194,57	193,37
E9.2	171,04	173,33	172,19
E10.1	192,61	191,09	191,85
E10.2	181,3	179,96	180,63

E.3 Temperature logging
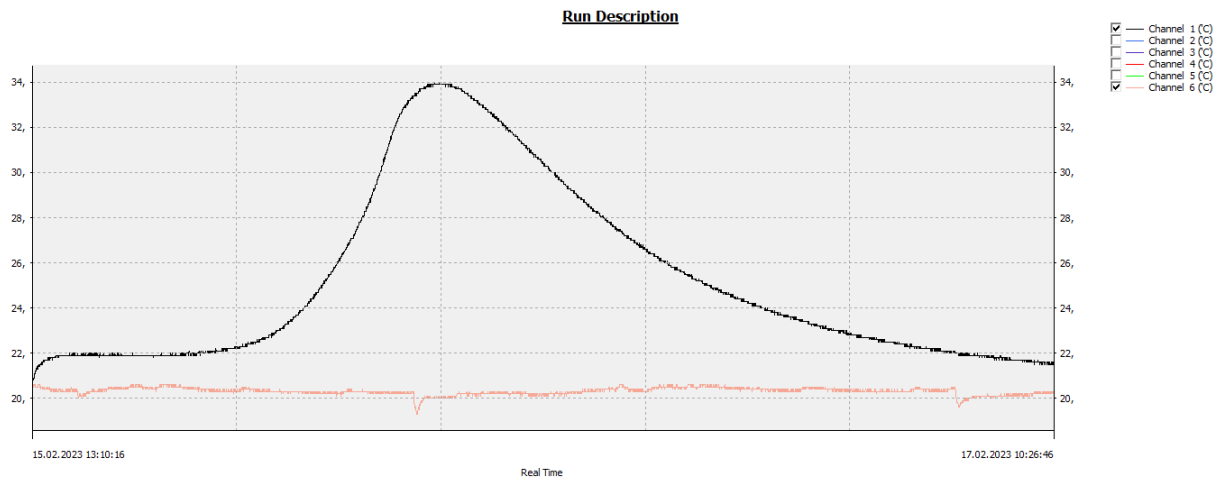
Figure E.1: Temperature logging of reference mortar with reduced W/C ratio and SP (EXP.17)

Figure E.2: Temperature logging of mortar containing E1 microsilica
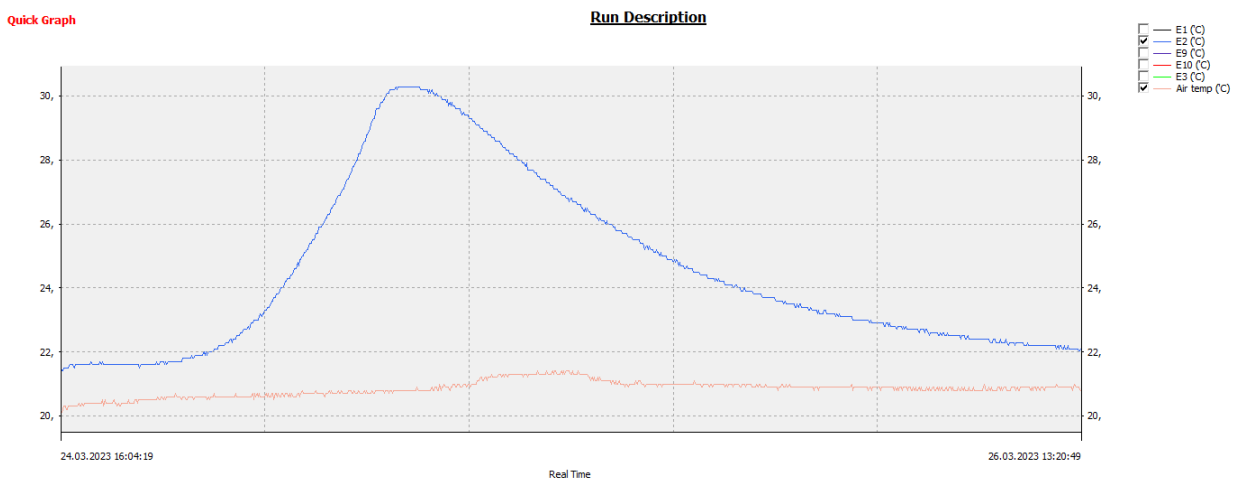
Figure E.3: Temperature logging of mortar containing E2 microsilica
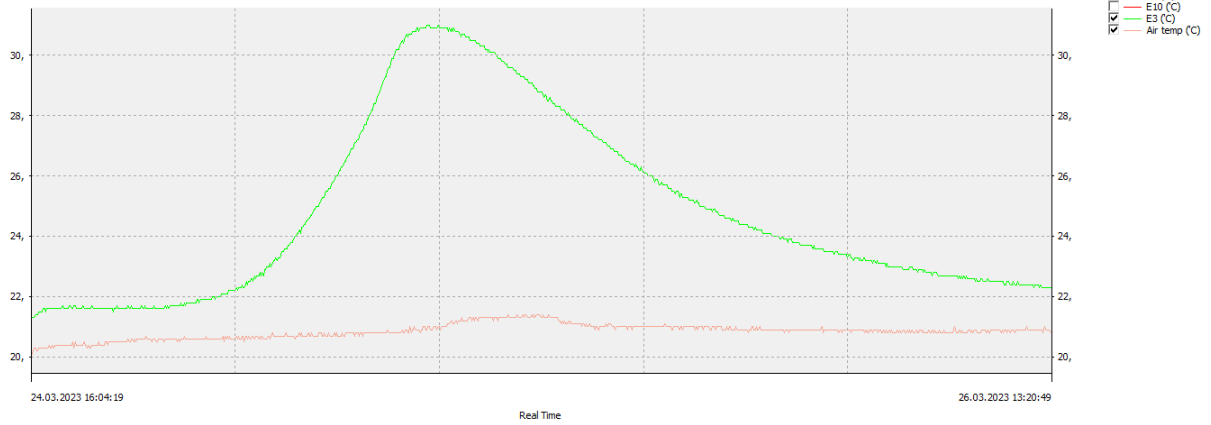
Figure E.4: Temperature logging of mortar containing E3 microsilica
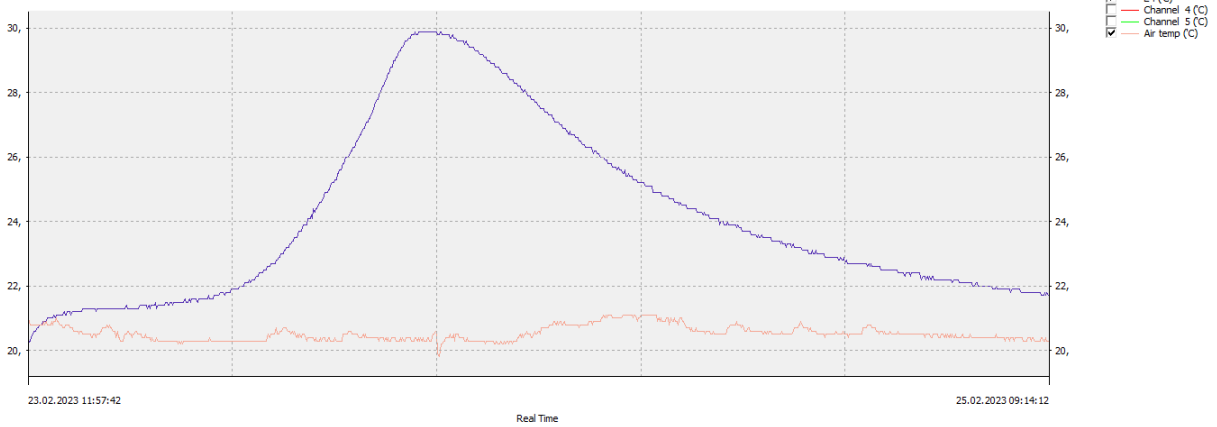
Figure E.5: Temperature logging of mortar containing E4 microsilica
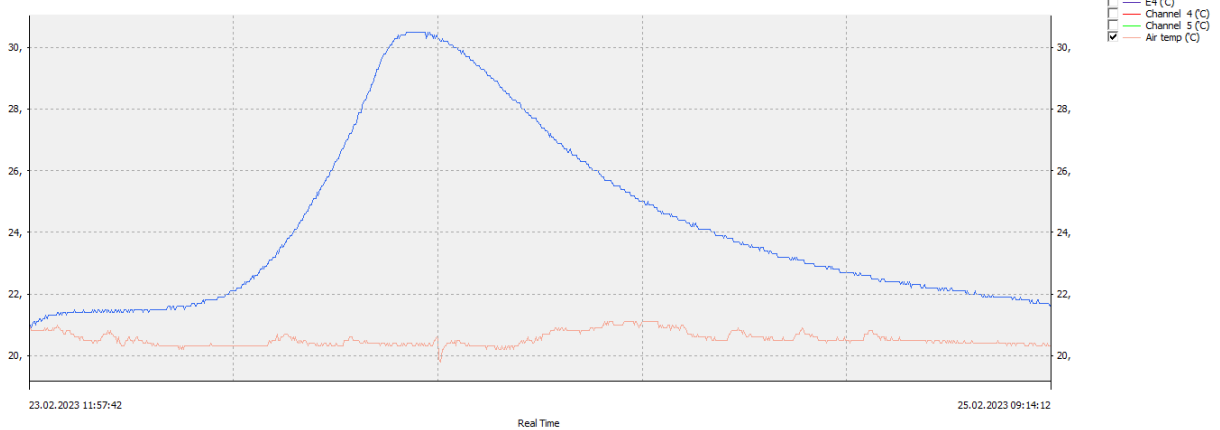
Figure E.6: Temperature logging of mortar containing E5 microsilica
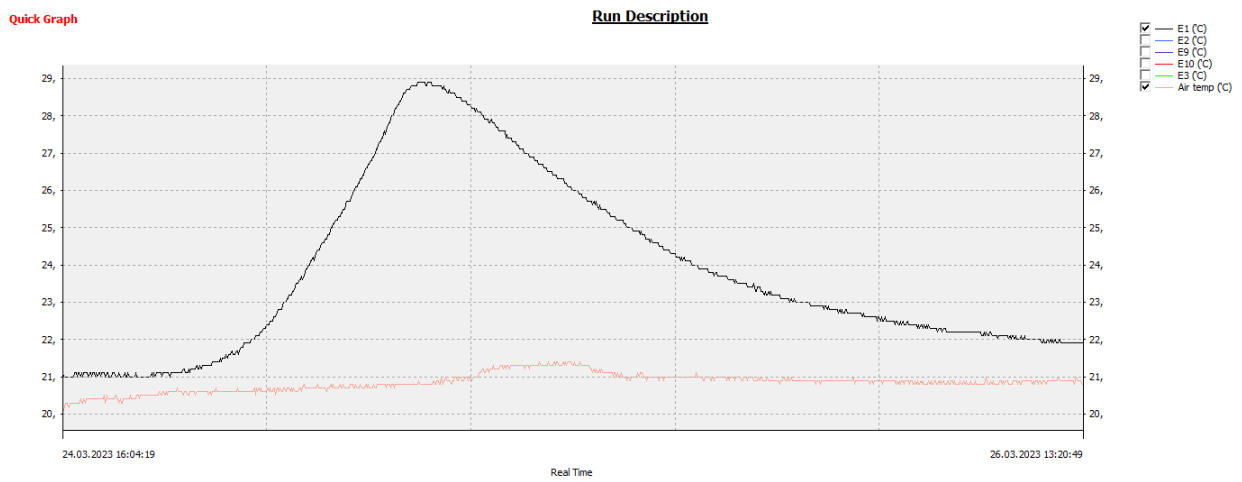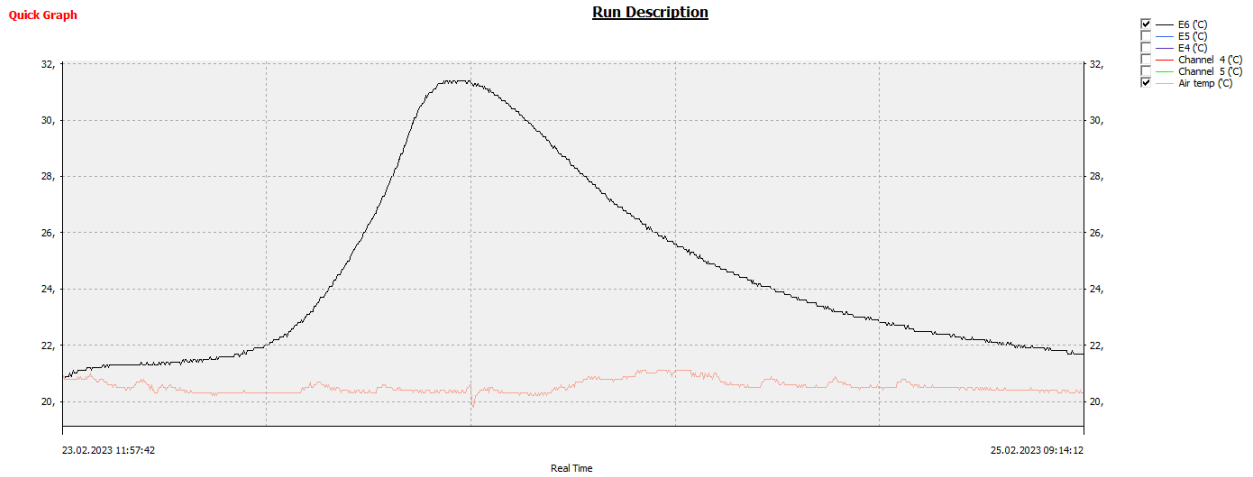
Figure E.7: Temperature logging of mortar containing E6 microsilica
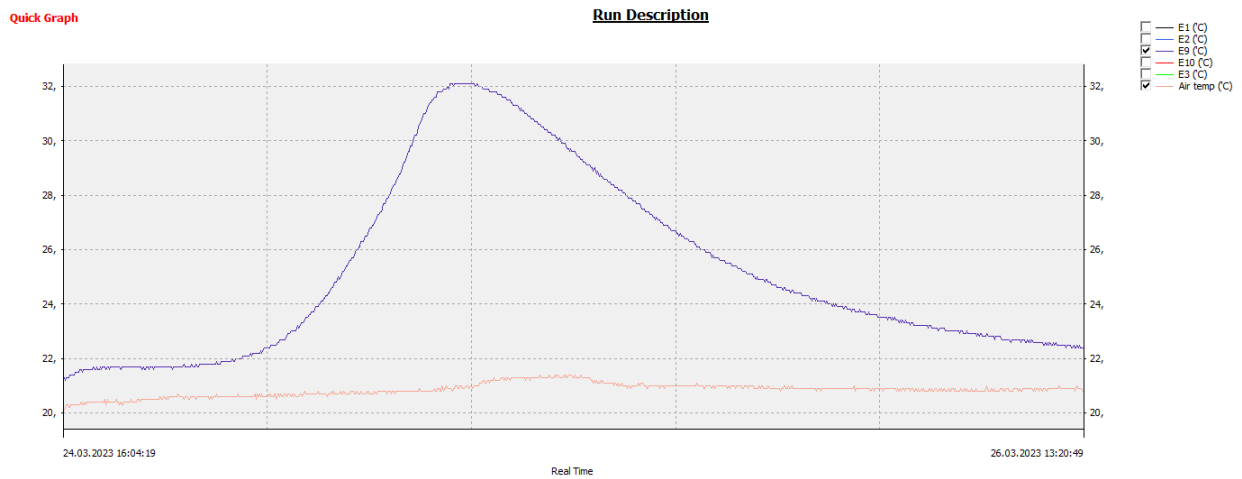
Figure E.8: Temperature logging of mortar containing E9 microsilica
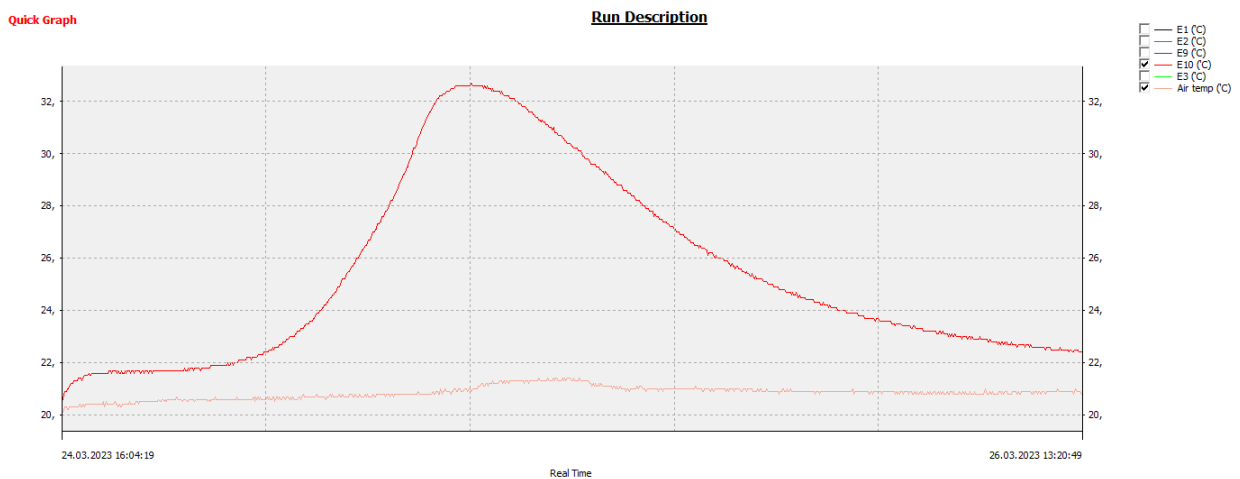
Figure E.9: Temperature logging of mortar containing E10 microsilica

E.4   Total heat value diagrams
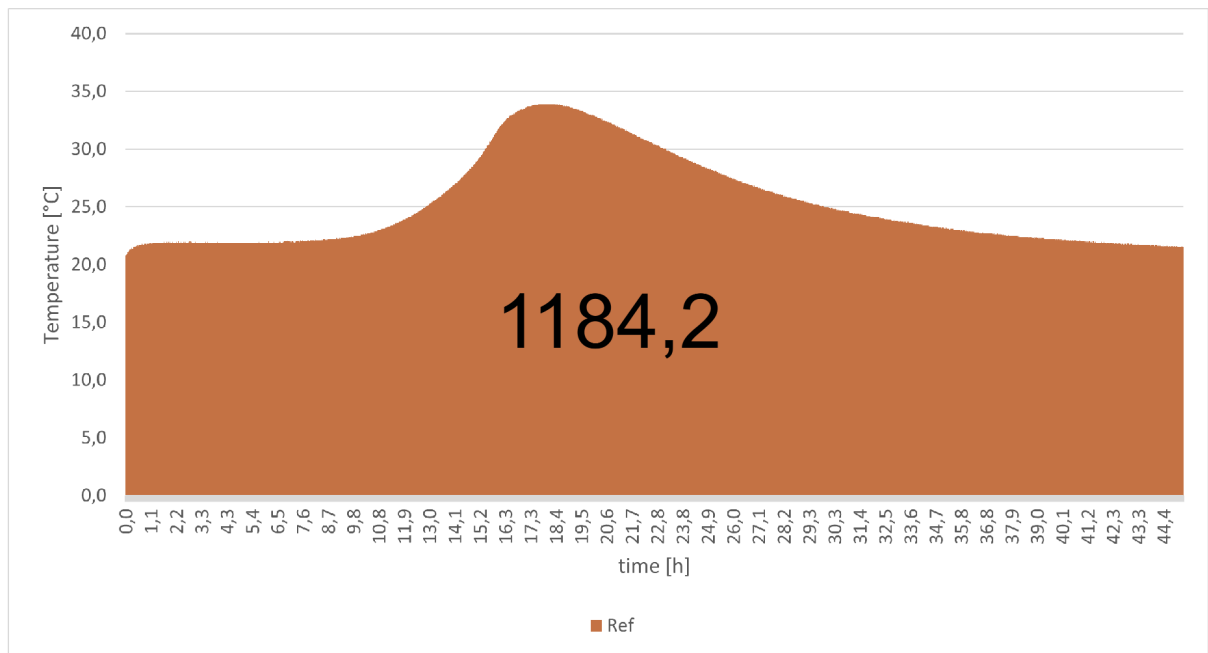
Figure E.10: Total heat value diagram of reference mortar

Figure E.11: Total heat value diagram of mortar containing E1 microsilica
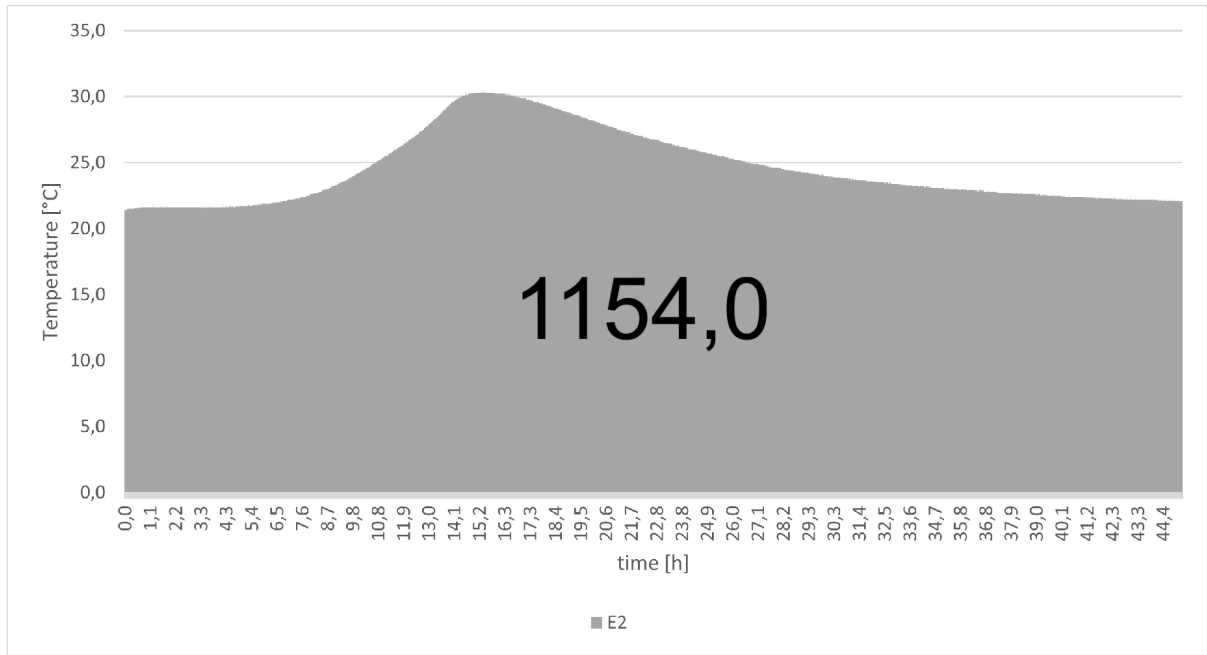
Figure E.12: Total heat value diagram of mortar containing E2 microsilica
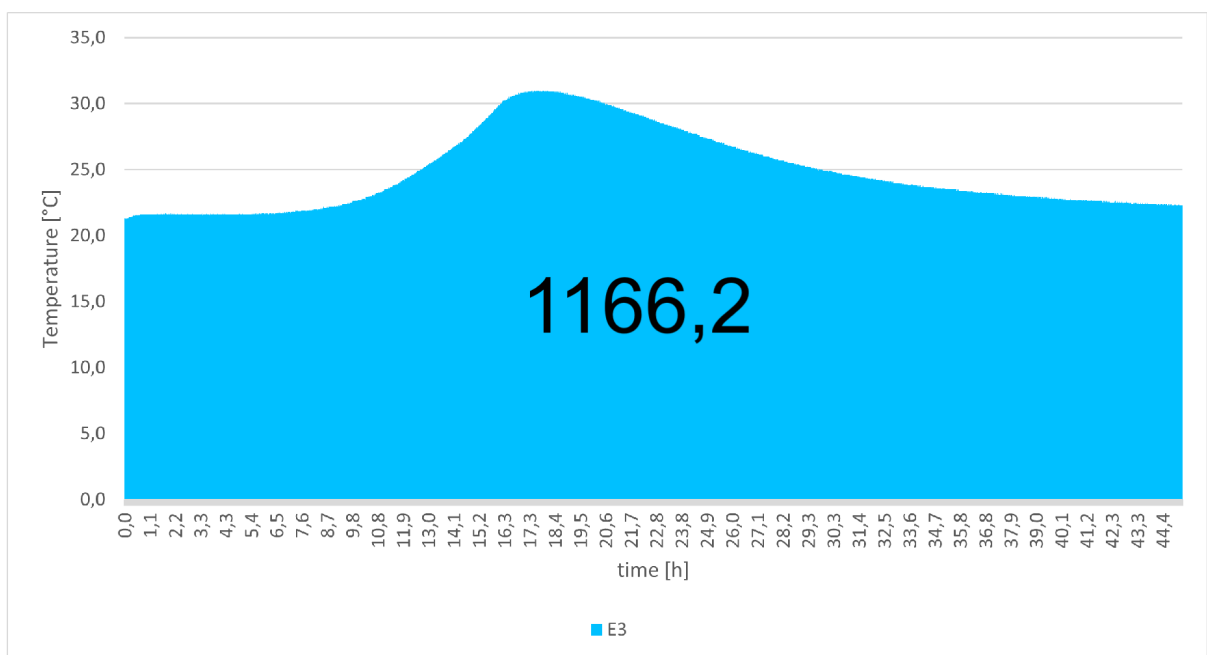
Figure E.13: Total heat value diagram of mortar containing E3 microsilica
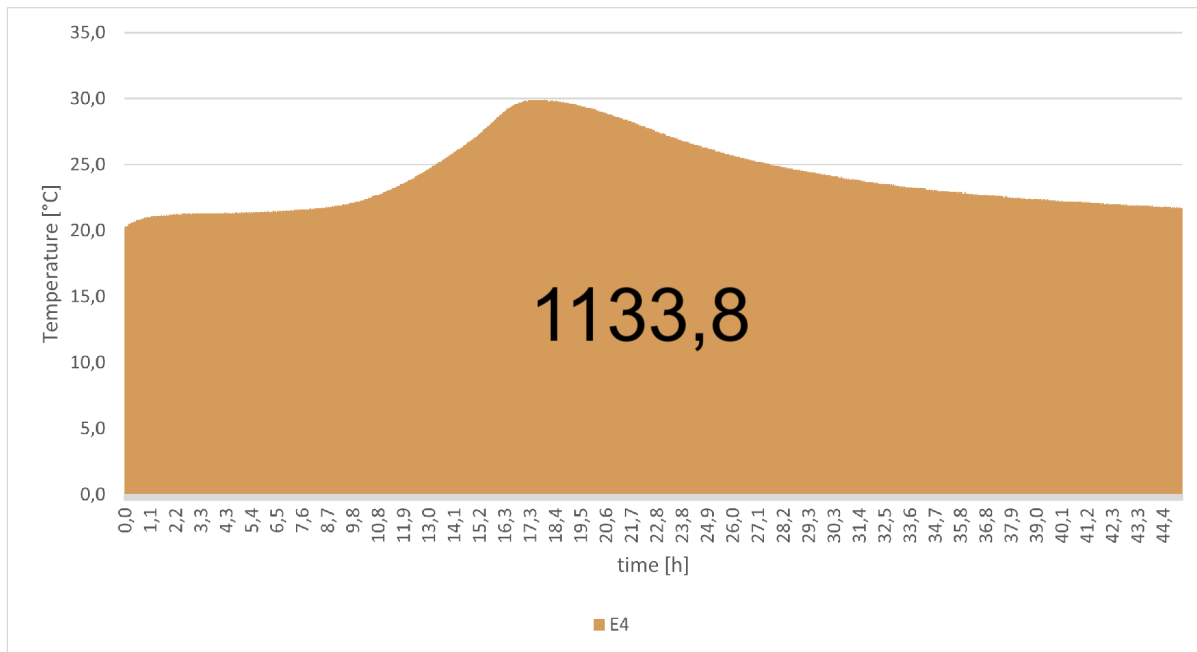
Figure E.14: Total heat value diagram of mortar containing E4 microsilica
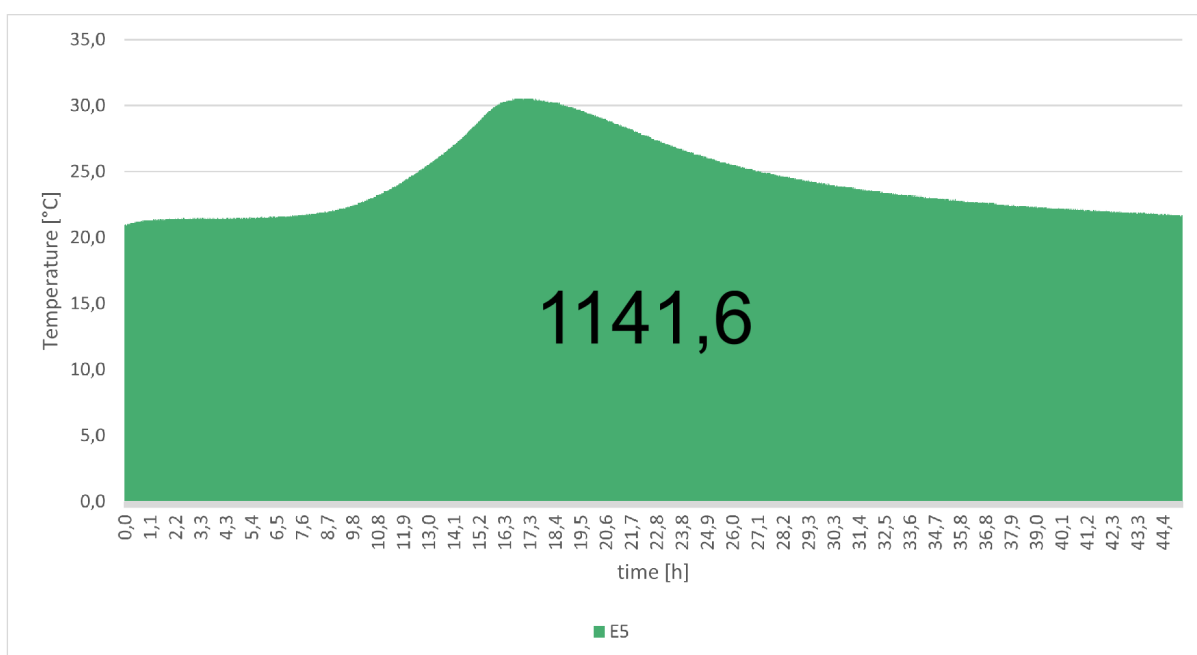
Figure E.15: Total heat value diagram of mortar containing E5 microsilica
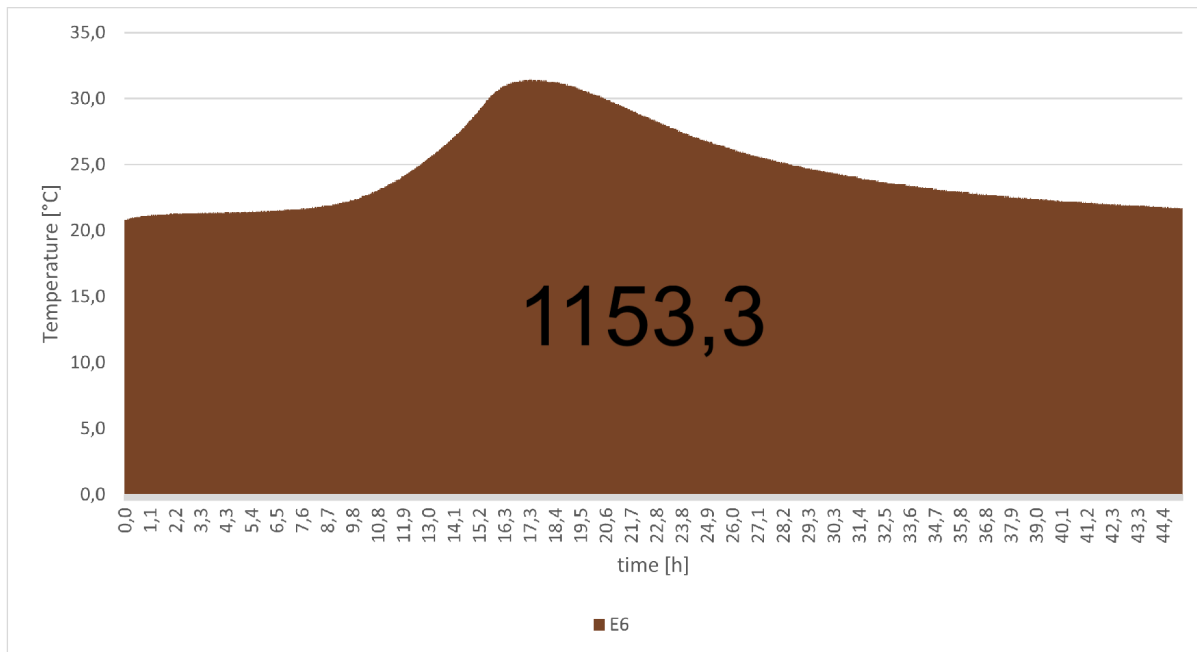
Figure E.16: Total heat value diagram of mortar containing E6 microsilica

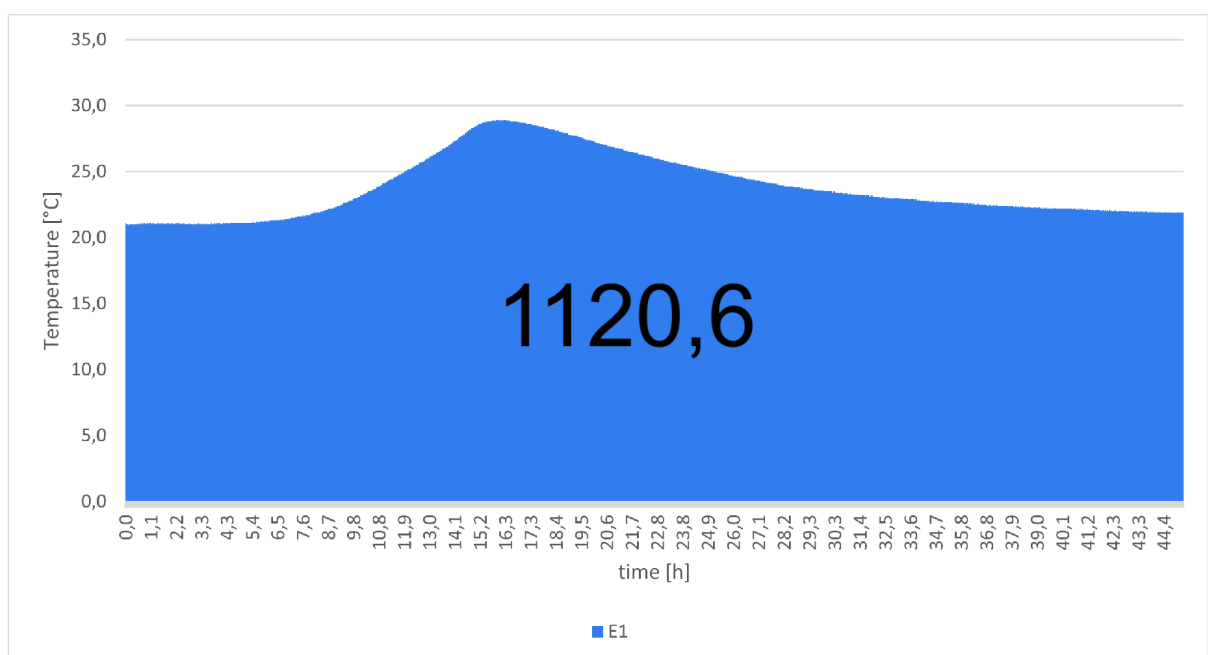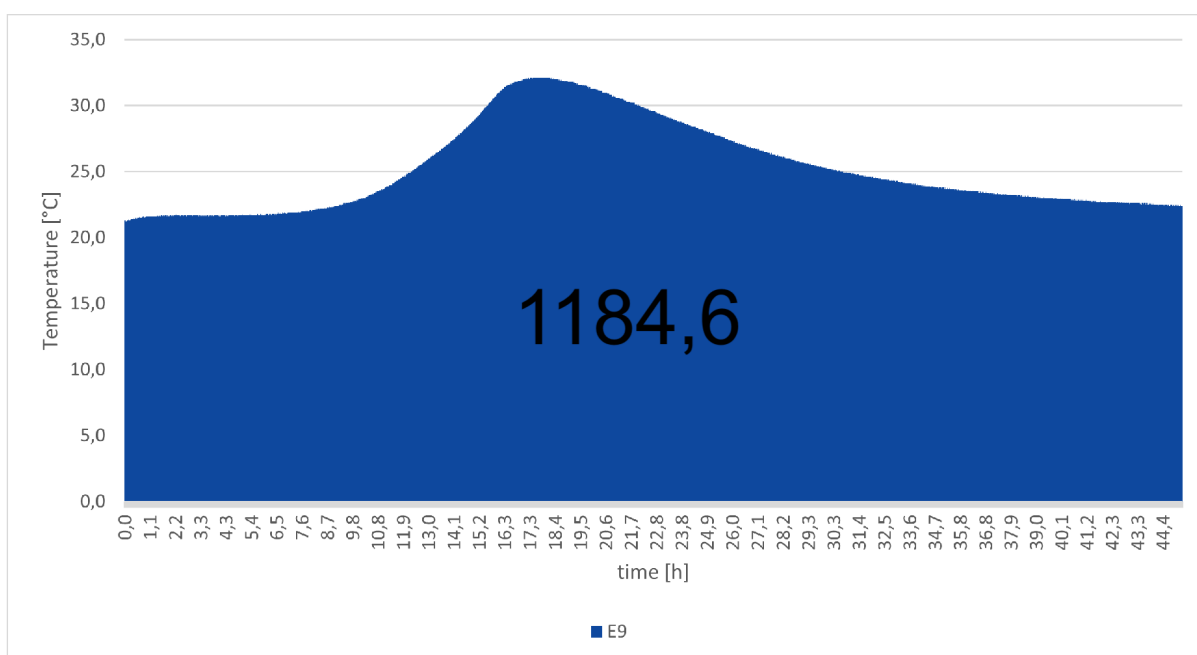Figure E.17: Total heat value diagram of mortar containing E9 microsilica
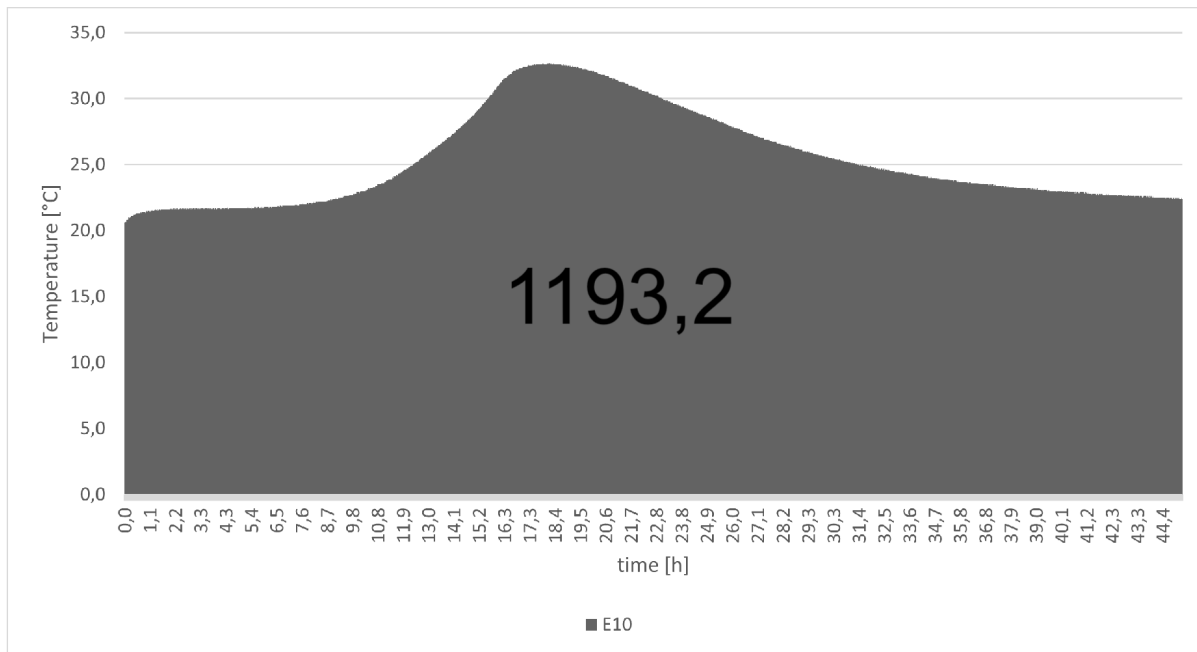
Figure E.18: Total heat value diagram of mortar containing E10 microsilica

E.5 Density

Table E.2: Densities of all specimens used for strength tests and chloride ion migration test

Specimen ID	Weigth dry $[g]$	Weigth sub. in water $[g]$	Volume $[dm^3]$	Density $[kg/m^3]$	Average density $[kg/m^3]$
E1					
R1.1A	599,9	342,1	0,258	2327,0	
R1.1B	598,6	341,4	0,257	2327,4	2329,36
R1.1C	599,3	342,5	0,257	2333,7	
E1.3A	577,3	324,5	0,253	2283,6	
E1.3B	578,4	324,5	0,254	2278,1	2283,99
E1.3C	581,5	327,6	0,254	2290,3	
E2					
R2.1A	596,7	339,1	0,258	2316,4	
R2.1B	591,0	335,6	0,255	2314,0	2316,76
R2.1C	598,3	340,4	0,258	2319,9	
E2.1A	593,5	339,0	0,255	2332,0	
E2.1B	595,8	340,0	0,256	2329,2	2329,98
E2.1C	593,6	338,7	0,255	2328,8	
E2.2A	596,3	339,6	0,257	2322,9	
E2.2B	599,7	341,6	0,258	2323,5	2325,48
E2.2C	600,2	342,6	0,258	2330,0	
E3					
R3.1A	593,2	336,9	0,256	2314,5	
R3.1B	594,7	337,8	0,257	2314,9	2315,62
R3.1C	594,9	338,2	0,257	2317,5	
E3.1A	601,9	344,5	0,257	2338,4	
E3.1B	600,9	344,0	0,257	2339,0	2338,86
E3.1C	602,8	345,1	0,258	2339,2	
E3.2A	597,3	342,4	0,255	2343,3	
E3.2B	605,5	347,0	0,259	2342,4	2343,61
E3.2C	599,2	343,7	0,256	2345,2	
E4					
R4.1A	599,9	342,6	0,257	2331,5	
R4.1B	600,1	342,3	0,258	2327,8	2329,75
R4.1C	600,2	342,6	0,258	2330,0	
E4.2A	601,5	346,7	0,255	2360,7	
E4.2B	599,9	345,7	0,254	2360,0	2358,00
E4.2C	598,7	344,3	0,254	2353,4	
E4.3A	607,5	350,0	0,258	2359,2	
					2359,81

E4.3B	606,2	349,3	0,257	2359,7	
E4.3C	607,6	350,2	0,257	2360,5	
E5					
R5.1A	601,1	345,2	0,256	2349,0	
R5.1B	601,1	345,1	0,256	2348,0	2348,52
R5.1C	602,4	345,9	0,257	2348,5	
E5.1A	603,2	345,6	0,258	2341,6	
E5.1B	604,5	347,0	0,258	2347,6	2345,76
E5.1C	605,1	347,4	0,258	2348,1	
R5.2A	607,1	347,5	0,260	2338,6	
R5.2B	604,6	346,2	0,258	2339,8	2339,56
R5.2C	604,5	346,2	0,258	2340,3	
E5.3A	603,8	347,2	0,257	2353,1	
E5.3B	604,8	347,6	0,257	2351,5	2353,96
E5.3C	606,3	349,1	0,257	2357,3	
E5.4A	597,9	341,8	0,256	2334,6	
E5.4B	595,5	340,5	0,255	2335,3	2334,77
E5.4C	595,5	340,4	0,255	2334,4	
E6					
R6.1A	603,7	345,9	0,258	2341,7	
R6.1B	605,4	346,7	0,259	2340,2	2342,10
R6.1C	607,9	348,6	0,259	2344,4	
E6.2A	596,3	340,6	0,256	2332,0	
E6.2B	597,6	341,4	0,256	2332,6	2330,90
E6.2C	596,7	340,4	0,256	2328,1	
E7/E8					
R7/8.2A	599,3	342,3	0,257	2331,9	
R7/8.2B	598,9	341,8	0,257	2329,4	2331,6
R7/8.2C	597,4	341,4	0,256	2333,6	
E7.7A	592,5	338,3	0,254	2330,8	
E7.7B	588,9	336	0,253	2328,6	2331,8
E7.7C	593,6	339,5	0,254	2336,1	
E8.2A	593,9	340,6	0,253	2344,7	
E8.2B	595,4	341,8	0,254	2347,8	2346,0
E8.2C	595,5	341,6	0,254	2345,4	
E9/E10					
R9/10.1A	588,9	335,2	0,254	2321,2	
R9/10.1B	593,4	337,2	0,256	2316,2	2319,82
R9/10.1C	596,3	339,5	0,257	2322,0	
E9.2A	587,4	331,5	0,256	2295,4	
E9.2B	588,6	332,5	0,256	2298,3	2297,67
E9.2C	587,0	331,7	0,255	2299,3	
E10.2A	587,9	333,8	0,254	2313,7	
					2315,29

E10.2B	589,4	334,8	0,255	2315,0	
E10.2C	589,5	335,1	0,254	2317,2	
Chloride ion micration test specimens (C)					
C.SM	499,1	276,5	0,223	2242,1	
C.SP	435,9	245,9	0,190	2294,2	
C.E1	426,9	237,5	0,189	2254,0	
C.E2	428,8	241,1	0,188	2284,5	
C.E3	424,5	238,9	0,186	2287,2	
C.E4	1010,7	565	0,446	2267,7	
C.E5	1006,8	563,4	0,443	2270,6	
C.E6	926	519,7	0,406	2279,1	
C.E7	964,3	539,3	0,425	2268,9	
C.E8	969,4	543,3	0,426	2275,1	
C.E9	1043,5	583,3	0,460	2267,5	
C.E10	1004,1	561,4	0,443	2268,1	

E.6 Flexural tensile strength

Table E.3: Flexural tensile strength results for mortars used in the investigation of the influence of microsilica on concrete properties

Batch ID	A [MPa]	B [MPa]	C [MPa]	Flexural tensile strength [MPa]	Standard deviation
Flexural tensile strength					
E1					
R1.1	8,6	8,6	8,2	8,47	0,23
E1.3	9,4	9,1	8,8	9,10	0,30
E2					
R2.1	8,3	7,9	8,1	8,10	0,20
E2.1	11,9	12,0	10,5	11,47	0,84
E2.2	11,6	10,9	11,2	11,23	0,35
E3					
R3.1	8,3	8,0	7,8	8,03	0,25
E3.1	11,3	10,4	9,9	10,53	0,71
E3.2	11,6	11,3	10,4	11,10	0,62
E4					
R4.1	8,3	8,1	8,1	8,17	0,12
E4.2	11,3	11,0	10,8	11,03	0,25
E4.3	10,3	11,5	11,0	10,93	0,60
E5					
R5.1	8,3	7,9	8,0	8,07	0,21
E5.1	11,5	11,4	11,2	11,37	0,15
R5.2	8,6	8,7	8,6	8,63	0,06
E5.3	11,9	10,8	12,1	11,60	0,70
E5.4	11,7	11,0	12,3	11,67	0,65
E6					
R6.1	8,3	8,3	8,5	8,37	0,12
E6.2	10,0	10,8	11,1	10,63	0,57
E7/E8					
R7/8.2	9,30	8,60	8,40	8,77	0,47
E7.7	10,2	10,3	10,2	10,23	0,06
E8.2	11,4	11,5	11,8	11,57	0,21
E9/E10					
R9/10.1	8,6	7,8	8,00	8,13	0,42
E9.2	9,80	10,70	10,70	10,40	0,52
E10.2	10,40	10,30	10,00	10,23	0,21

E.7 Compressive strength

Table E.4: Compressive strength of all specimens containing microsilica and its associated reference sample

	A		B		C		Compressive strength [MPa]	Standard deviation
Batch ID	**L** [MPa]	**R** [MPa]	**L** [MPa]	**R** [MPa]	**L** [MPa]	**R** [MPa]		
E1								
R1.1	66,1	65,9	66,0	65,8	65,9	66,9	66,10	0,40
E1.3	83,9	84,0	83,0	82,6	83,9	83,8	83,53	0,59
E2								
R2.1	66,4	65,8	65,0	64,9	66,3	65,8	65,70	0,63
E2.1	94,1	94,9	95,8	92,4	93,6	92,5	93,88	1,34
E2.2	94,6	93,2	94,2	96,7	92,9	95,4	94,50	1,41
E3								
R3.1	64,5	66,9	65,6	66,9	65,8	66,9	66,10	0,98
E3.1	90,6	91,9	92,0	92,9	92,7	92,0	92,02	0,81
E3.2	91,4	94,1	92,5	91,1	93,1	93,3	92,58	1,16
E4								
R4.1	66,9	67,8	65,3	66,3	66,6	67,9	66,80	0,98
E4.2	93,3	93,6	92,1	94,9	91,3	94,5	93,28	1,38
E4.3	94,8	91,8	92,1	90,4	92,4	91,3	92,13	1,48
E5								
R5.1	65,9	68,7	66,4	69,1	66,7	69,1	67,65	1,47
E5.1	94,6	97,5	96,1	97,4	93,9	96,5	96,00	1,47
R5.2	66,6	67,0	66,0	67,0	66,6	68,1	66,88	0,70
E5.3	94,3	98,4	96,8	94,6	94,4	99,3	96,30	2,20
E5.4	95,1	94,1	93,1	95,3	93,4	93,0	94,00	1,01
E6								
R6.1	68,4	67,7	67,2	67,2	67,8	67,6	67,65	0,45
E6.2	93,9	93,0	93,1	93,9	93,7	94,3	93,65	0,50
E7/E8								
R7/8.2	69,4	71,3	69,6	67,6	68,2	70,1	69,37	1,33
E7.7	95,4	95,9	97,6	94,1	95,3	95,4	95,62	1,14
E8.2	96,8	96,6	94,4	98,5	96,8	96,7	96,63	1,31
E9/E10								
R9/10.1	66,5	65,4	66,3	65,5	67,4	64,9	66,00	0,91
E9.2	86,4	86,1	80,3	83,6	87,0	84,3	84,62	2,48
E10.2	90,2	85,3	89,4	89,8	87,4	90,2	88,72	1,97

E.8   PAI

Table E.5: Pozzolanic activity index calculation results for mortars containing microsilica

Microsilica type	Ref specimen ID	Poz specimen ID	Sigma ref [MPa]	Sigma poz [MPa]	PAI [%]
E1	R1.1	E1.1	66,10	83,53	126
E2	R2.1	E2.1	65,70	93,88	143
	R2.1	E2.2	65,70	94,50	144
E3	R3.1	E3.1	66,10	92,02	139
	R3.1	E3.2	66,10	92,58	140
E4	R4.1	E4.2	66,80	93,28	140
	R4.1	E4.3	66,80	92,13	138
E5	R5.1	E5.1	67,65	96,00	142
	R5.2	E5.2	66,88	96,30	144
	R5.2	E5.3	66,88	94,30	141
E6	R6.1	E6.2	67,65	93,65	138
E7	R7/8.2	E7.7	69,37	95,62	138
E8	R7/8.2	E8.2	69,37	96,63	139
E9	R9/10.1	E9.2	66,00	84,62	128
E10	R9/10.1	E10.2	66,00	88,72	134

E.9   Chloride Ion Migration

Table E.6: Laboratory conditions and ingredients measurements for mortars used in NT BUILD 492 test and temperature logging

Batch ID	RF (%)	Temperature (°C)	SP (%)	SP (g)	Cement (g)	Sand (g)	Water (g)	Microsilica (g)	Microsilica type
C.SM	37,5	20,5	-	-	450	1355	225	-	-
C.SP	37,5	20,5	0,9	4,0	450	1355	176,8	-	-
C.E1	37,5	20,5	0,7	3,2	405	1355	177,5	45	E1
C.E2	37,5	20,5	0,9	4,0	405	1355	176,8	45	E2
C.E3	37,5	20,5	0,9	4,0	405	1355	176,8	45	E3
C.E4	37,5	20,5	0,8	3,6	405	1355	177,2	45	E4
C.E5	28	21	0,9	4,0	405	1355	176,8	45	E5
C.E6	28	21	0,9	4,0	405	1355	176,8	45	E6
C.E7	28	21	0,9	4,0	405	1355	154,26	22,5	E7
C.E8	28	21	0,9	4,0	405	1355	154,26	22,5	E8
C.E9	28	21	0,7	3,2	405	1355	177,48	45	E9
C.E10	28	21	0,7	3,2	405	1355	177,48	45	E10