



CHALMERS
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Use of Supplementary Cementitious Material in Concrete

Effect on Fresh Concrete Properties

Master's thesis in the Master's Program Structural Engineering and Building Technology

SUNIL GAUTAM

DEPARTMENT OF ARCHITECTURE AND CIVIL ENGINEERING
DIVISION OF STRUCTURAL ENGINEERING

CHALMERS UNIVERSITY OF TECHNOLOGY
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ABSTRACT

Minimizing the use of clinker content by using supplementary cementitious materials (SCMs) requires consideration of their influence on the fresh state properties as well as long-term strength and durability. This study investigated six different SCMs, both natural and industrial, i.e. ground granulated blast furnace slag (GGBS), fly ash (FA), calcined (Nova) clay, volcanic pozzolan from Iceland (VPI), pumice (Yalite) from Grekland and Boliden material (SCMentum) and compared their performance with CEM I 52.5R cement. Mortars containing 40% of SCM were analyzed in terms of water demand, workability, workability loss over 2 hours, bleeding, segregation, setting time, and hydration behavior. One-day strength was additionally determined replacing 20%, 40% and 60% of the cement. The standard test method was used such as mortar flow test using Hagermann cone for workability, Ultrasonic testing for setting time, calorimetry test for hydration behavior, compressive strength test according to EN-196-1.

The results illustrated that the type of SCMs considerably influences the balance between flowability and stability. Fly Ash demonstrated the highest flow and bleeding, while Nova Clay resulted in the lowest flow, but experienced the greatest workability loss, around 53% in two hours. VPI showed the most balanced overall performance including the highest one day strength. The initial setting time ranged from three to four hours, where Fly Ash and VPI started setting in 3 hours, and GGBS and Pumice started in 4 hours. All six SCMs exhibited lower early strength than the reference cement and strength decreased more with increasing SCM. In general, the results demonstrated that it is necessary to consider the fresh state properties and early strength when evaluating the suitability of SCM.

Key words: Supplementary cementitious material, workability, setting time, bleeding, segregation, early-age strength.

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SAMMANFATTNING

Att minska klinkerhalten genom användning av alternativa bindemedel, så kallade supplementary cementitious materials (SCM), kräver att deras inverkan på färskas egenskaper och tidig samt lång-tidsegenskaper och beständighet. I denna studie undersöktes sex naturliga och industriella SCM: mald granulerad masugnsslagg (GGBS), flygaska (FA), kalcinerad lera (NovaClay), vulkanisk puzzolan från Island (VPI), pimpsten (Yalite) från Grekland samt material från Boliden (SCMentum). Materialens egenskaper jämfördes med ett referenscement av typen CEM I 52,5 R. Bruk med 40% cementsättning undersöktes med avseende på vattenbehov, bearbetbarhet, bearbetbarhetsförlust under två timmar, vattenseparation, segregation, initial bindetid och hydratiseringsförlopp. Därutöver bestämdes tryckhållfastheten efter ett dygn vid ersättningsgrader på 20%, 40% och 60%. Standardiserade provningsmetoder användes, såsom bruksutbredningsprov med Hägermannkon för bestämning av bearbetbarhet, ultraljudsprovning för bestämning av bindetid, kalorimetrisk provning för utvärdering av hydrationsförloppet samt tryckhållfasthetsprovning enligt EN 196-1.

Resultaten visade att typen av SCM hade en betydande inverkan på balansen mellan flytbarhet och stabilitet. Flygaska gav den största utbredningen men även den mest omfattande vattenseparationen. NovaClay gav den minsta utbredningen och uppvisade samtidigt den största bearbetbarhetsförlusten, cirka 53% efter två timmar. VPI uppvisade den mest balanserade helhetsprestandan och gav dessutom den högsta endygnshållfastheten bland de undersökta SCM-blandningarna. Den initiala bindetiden varierade mellan tre och fyra timmar. Flygaska och VPI började binda efter tre timmar, medan GGBS och pimpsten började binda efter fyra timmar. Samtliga sex SCM-blandningar uppvisade lägre tidig hållfasthet än referenscementet, och hållfastheten minskade med ökande ersättningsgrad. Sammantaget visar resultaten att såväl färskas egenskaper som tidig hållfasthetsutveckling behöver beaktas vid bedömning av olika SCM:s lämplighet.

Nyckelord:

Cementsättningsmaterial, arbetbarhet, bindetid, blödning, separation, tidig hållfasthet.

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Preface

The master's thesis was conducted at Chalmers University of Technology in the Department of Architectural and Civil Engineering, which was part of the master's program in Structural Engineering and Building Technology. The work was carried out in the field of building materials that investigated the influence of different SCMs on fresh properties.

I am deeply grateful to Niklas Johansson (my industrial supervisor from MAPEI) and Arezou Baba Ahmadi (my academic supervisor and examiner) for their support, encouragement, suggestion, management, and motivation in every step from the beginning of the topic selection for the project to the end of submission of the final report. I am so grateful to have the kind and friendly supervisors like them.

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Göteborg, September 2026
Sunil Gautam

Notations

SCM	Supplementary Cementitious Material
FA	Fly Ash
GGBS/ GGBFS	Ground Granulated Blast Furnace Slag
VPI	Volcanic Pozzolan Iceland
NC	Nova Clay
SP	Superplasticizer

1 Introduction

The development of modern society is closely related to the advancement of construction materials where concrete continues to occupy the leading position. It is considered the backbone of the construction industry due to its availability, strength, and cost-effectiveness. For this reason, it is the material of choice in various applications in civil engineering. However, the excessive use of concrete raises the question of sustainability of its production process. Consequently, researchers have given more attention to the search for environmentally friendly materials.

1.1 Background

Rapid modernization, industrialization, and population growth resulted in the use of concrete. Concrete, composed primarily of a binder, aggregates, and water, is one of the most widely used materials in the construction industry. It serves as a fundamental structural and connecting material in the construction of a wide range of infrastructure, from small-scale buildings to high-rise structures. Due to its versatility, mechanical performance, durability, and availability, it is considered the material most used after water [1], so we are surrounded by concrete everywhere, from the streets to residential buildings. Although concrete plays a crucial role in improving the quality of modern life, its increasing use has also resulted in significant adverse environmental impacts. The binder commonly used in concrete is cement. Cement production involves calcination of limestone (CaCO_3), which is blended with other raw materials, such as clay, shale, sand, and iron-bearing materials, and heated to approximately 1450°C in a rotary kiln. During this process, limestone decomposes and releases carbon dioxide (CO_2). These process emissions account for roughly two-third of direct CO_2 emission associated with cement production [2].



In addition, fossil fuels are burned to provide the heat required for the operation of the kiln, accounting for a considerable amount of the total CO_2 emissions from cement production. Moreover, further low level emission is associated with electricity consumption and transportation. However, many cement producers have recently reduced their reliance on fossil fuels by adopting alternative fuels and more energy-efficient technologies. Carbon dioxide consists of one carbon atom and two oxygen atom. It is a greenhouse gas that absorbs outgoing infrared radiation, contributing to global warming as its concentration in the atmosphere increases. Today, one of the most serious issues that the world is facing is global warming due to climate change, which is caused by greenhouse gas emissions such as CO_2 gas. Anthropogenic CO_2 emissions primarily originate from fossil fuel combustion, industrial processes, and land-use change, with cement production representing a significant source of industrial CO_2 emissions. It is steadily increasing every year by around 2 ppm [1] and around 7% share of total emission of CO_2 is covered by cement production only [3]. These statistics might go up significantly in near future because the world population of around 8.3 billion in present will be around 9.8 billion & 11.2 billion by 2050 AD & 2100 AD, respectively, as projected by UN [4, 5]. At the same time, concrete structures typically have a service life of approximately 50–100 years, after which they may require significant renovation, repair, or replacement. Such interventions can lead to an additional demand

for concrete and cement, further increasing the consumption of these materials over the lifetime of a structure. In general, the demand for concrete is expected to continue to increase in the coming decades. Consequently, effective management of greenhouse gas (GHG) emissions is essential to mitigate the adverse impacts of climate change. Failure to reduce and manage these emissions in a timely manner could result in severe and potentially irreversible environmental and societal consequences. To reduce the annual rise of CO₂ by 1.5-2 PPM [6], several research projects are currently being carried out. This is because lowering the cement use can lead to a considerable percentage of CO₂ reduction [7]. In 2016, the UN formally launched the agreement stating threatening carbon emissions to living things, and 197 countries signed the agreement to minimize the production of carbon emission [8]. Moreover, several countries including the European union have committed Net Zero emissions by 2050 [9]. To meet these strategies, the Government of Sweden (which has the highest carbon tax in the world [10]) is slowly increasing the carbon tax to 138 EUR/ton CO₂ in 2026, which was 104 EUR/ton CO₂ in 2018. Due to this reason, the cement and concrete industries in the world, including Sweden, are forced to use other environmentally friendly material in cement and concrete to reduce the carbon tax ultimately reducing the carbon footprint. On the other hand, the growing number of industries are facing the problem of accumulation of industrial by-products as waste. Between these issues, researchers have found a way to utilize that waste by replacing cement by some percentage in concrete. Similarly, there are many other natural pozzolan that can be used as a replacement for cement. The materials to replace some fractions of cement are called Supplementary Cementitious Materials (SCMs) and the investigation to find multiple sources of these materials is increasing, and cement and concrete producers must choose which type of SCM they will use in their production. For cement and concrete manufacturer, it is increasingly important topic to know how those SCMs will affect the fresh concrete properties. Although the current use of SCM is limited, it is projected that this can potentially rise in coming years [11, 12]. So, in this paper, the effect of different SCMs on fresh concrete properties such as water demand, workability-loss, setting time, and stability replacing 40% of cement are systematically reviewed.

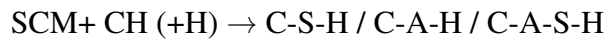
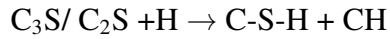
1.2 Supplementary Cementitious Materials

1.2.1 Concept, Classification and History

Supplementary Cementitious Materials (SCMs) are natural, industrial, or manufactured materials that are used to partially replace Portland cement or clinker in cement production due to their hydraulic and/or pozzolanic properties. The use of SCMs in cement and concrete production is one of the key strategies for reducing clinker content while maintaining or modifying the engineering properties of concrete. The incorporation of SCMs can influence a wide range of properties of both fresh and hardened concrete, with the nature and extent of these effects depending on the characteristics of the SCMs and their replacement level [3, 13, 14]. SCMs can be added either by blending them with clinker before cement production or substituting certain portion of cement during concrete/ mortar mixing. Depending on their reaction mechanism, SCMs are usually divided into two major types, namely pozzolanic materials and latent hydraulic materials. Despite the fact that both groups are involved in the formation of cementitious hydration product, their reaction mechanisms are not similar.

Pozzolanic SCM do not possess independent cementitious properties when mixing with

water on its own. Rather, they undergo a chemical reaction with calcium hydroxide formed from the hydration of calcium silicates in cement clinker, as illustrated in Figure 1.1. During the process, calcium silicate hydrate (C-S-H) along with some other hydration products like calcium aluminate hydrate (C-A-H) or calcium aluminosilicate hydrate (C-A-S-H) can be formed.



However, latent hydraulic SCMs possess the ability to react with water. The resultant products are similar to the product of hydration of cement, mainly C-S-H along with other calcium containing hydrates. Ground granulated blast furnace slag (GGBS) is one of the commonly used latent hydraulic SCM.

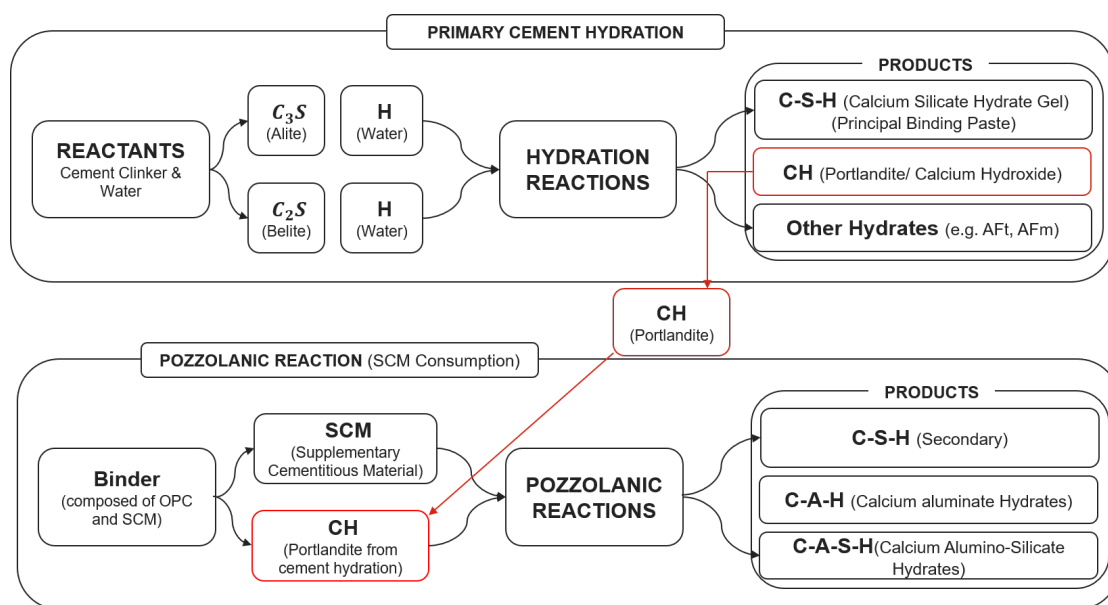
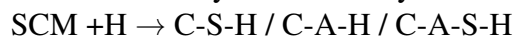


Figure 1.1: Reaction flow diagram of SCM

The reaction and hydration behavior of SCMs depend on their mineral composition, particle size distribution, fineness, specific surface area, and amorphous phase content, all of which influence their reactivity. Therefore, SCMs from different sources can exhibit different reaction rates and contribute differently to the hydration process, even when they are of the same type. These differences can affect both the fresh and hardened properties of concrete.

The use of pozzolanic materials in cementitious binders is not a modern concept. Long before the development of Portland cement, ancient Greek and Roman builders used natural pozzolans in combination with lime to produce durable construction materials. After the invention and patenting of Portland cement in 1824 by Joseph Aspdin, the application of SCMs started to shift from natural pozzolans to industrial by-products such as fly ash and ground granulated blast furnace slag. In recent years, the shift towards the production of low carbon construction materials has led to the emergence of many new SCMs such as calcined clay, volcanic pozzolans, metallurgical by-products, and other new cementitious materials. Meanwhile, it can be expected that the decline in the number of coal power plants will lead to a reduction in the amount of traditional

SCMs such as fly ash in the future. Thus, research on the development of new SCMs has become one of the active areas of investigation in the cement industry.

1.2.2 SCMs used in the project

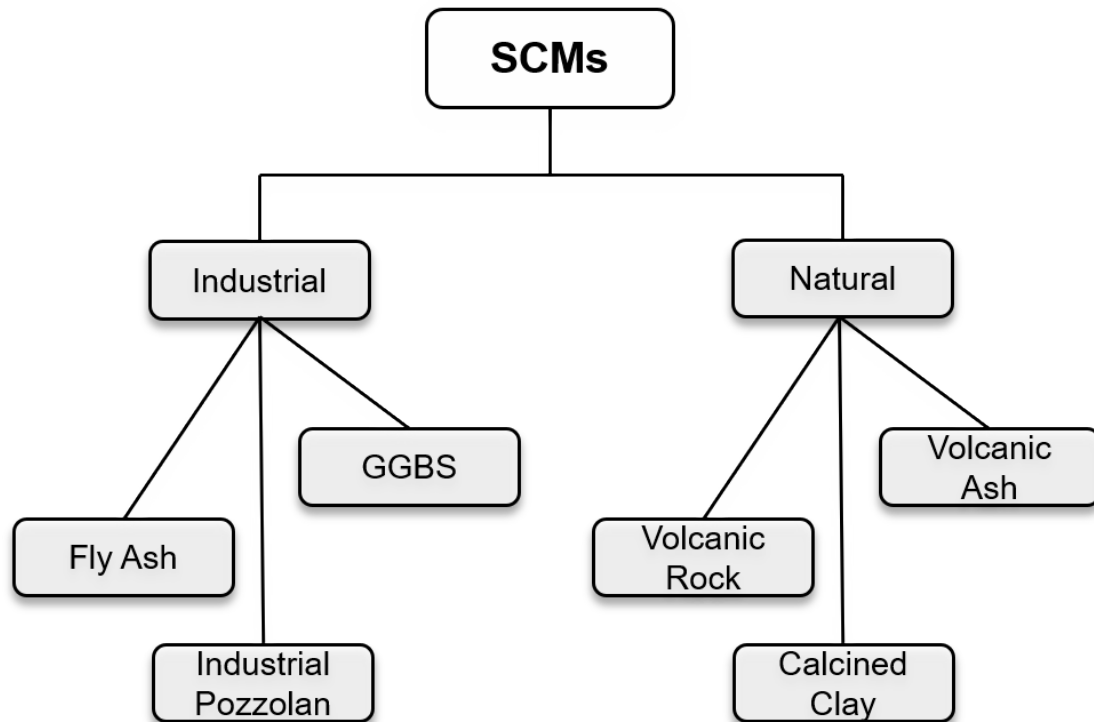


Figure 1.2: Types of SCM used in the project

1.2.2.1 Ground Granulated Blast Furnace Slag (GGBS/ GGBFS)

Ground Granulated Blast Furnace Slag (GGBFS) is a by-product of iron production in a blast furnace. The slag is then finely powdered [15, 16] to use as supplementary cementitious materials, partially replacing ordinary cement in concrete. Its latent hydraulic properties enable it to replace a substantial proportion of Portland cement clinker. To develop these properties, molten slag must be rapidly cooled, forming predominantly glassy materials. When GGBFS is blended with Portland cement, clinker hydration creates an alkaline environment that promotes slag dissolution and enables GGBFS to contribute to the formation of hydration products [13]. The rate and extent of the reaction depend on various factors, including the fineness of the slag and the glass content of it, the curing temperature, the percentage replacement of GGBFS, and the composition of Portland cement [17].

GGBS are usually lighter than cement, several papers have typically mentioned a specific gravity of around 2.85 to 2.91. The color of GGBFS can range from off-white to dark-gray depending on the moisture content. This distinctive property of GGBFS affects the fresh concrete property, in particular, workability, setting time, bleeding, and segregation. These properties are examined in this study.

1.2.2.2 Fly Ash (FA)

Fly Ash is defined as an industrial by-product produced by burning pulverized coal in a coal fired power station [18][19]. During the combustion process, the minerals contained in the coal are subjected to high temperatures, and thus are converted into fine particles that flow with the gasses from the combustion. The fine particles are then effectively separated from the flue gasses through electrostatic precipitators or other particulate control devices. Depending on the type and quality, the resultant product can be used as a supplementary cementitious material. Fly ash is generally classified as a pozzolanic material[20]. Unlike a hydraulic material, it typically does not harden through reaction with water alone. During the Portland cement hydration, clinker produces calcium hydroxide (CH), which reacts with the reactive component of fly ash (FA) in the presence of water. This pozzolanic reaction produce additional hydration product such as calcium silicate hydrate (C-S-H) and Calcium alumino-silicate hydrate (C-A-S-H) [21]. The pozzolanic reaction of fly ash begins after the hydration of Portland cement. As a result, formation of hydration products by FA is slower than the hydration of Portland clinker. The reactivity of FA is significantly dependent on the source and its properties. The main factors are the amount and chemical composition of its amorphous phase, the fineness of the particle, and the curing conditions [22]. Thus, different fly ashes belonging to the same material group may exhibit substantially different pozzolanic reactivities. Fly ash generally consists of fine, predominantly spherical particles [23], although some particles may have an irregular shape. The size of the particle may vary, and the small particle may occur individually or adhere to the surface of larger particles. The density and color vary according to the source of the coal, combustion conditions, and the content of unburnt carbon and other substances in FA. These variations may influence the fresh concrete properties that contain fly ash.

1.2.2.3 SCMentum (Boliden Material)

SCMentum is a novel supplementary cementitious material that Boliden develop from residual product of metal manufacturing in its smelters. According to [24], SCMentum is produced by processing residual material from Boliden's smelting operations. Its initial formulations consists primarily of slag from copper production and is intended for use as a partial replacement of Portland cement in concrete.

SCMentum is the recently developed supplementary cementitious material whose use in concrete is still being investigated. Boliden began collaborating with Thomas Concrete Group in 2023 to develop the material and evaluate its performance in concrete [25]. SCMentum's production concept is to turn the metallurgical residual into a usable cementitious substance rather than manufacturing a typical Portland clinker [24]. Being a newly established SCM, the availability of scientific information on the mechanism of the reaction and behavior of the material is limited compared to that of conventional SCMs.

1.2.2.4 Volcanic Ash (Volcanic Pozzolan Iceland (VPI))

Volcanic pozzolan Iceland (VPI) is a natural pozzolan sourced from Iceland for use as a supplementary cementitious materials in concrete [26]. The raw material use to produce VPI is extracted from the Lambafell and Litla sandfell quarries in Iceland [27]. The quarried material is hyaloclastite, a volcanic rock formed when lava comes in contact with water or Ice during eruptions beneath [28]. Rapid cooling of lava upon contact

with water or ice results in the formation of volcanic glass. After extraction, the material is screened to improve its uniformity, and transported from Iceland to Sweden for further processing. In addition, the volcanic materials are mechanically screened to obtain a more uniform material and shipped to Sweden from Iceland. The material is then dried and ground in the Degerhamn plant belonging to Heidelberg Materials to obtain a fine material that can be used as SCM. Unlike Portland cement clinker, VPI does not require high temperature kiln processing rather its pozzolanic properties comes from the volcanic material itself.

In combination with portland cement results in the possibility of reactive components of volcanic material to undergo a pozzolanic reaction with calcium hydroxide (CH) [21], formed during the cement hydration process. The reaction helps to form additional cementitious hydration products. The pozzolanic activity of natural volcanic materials is determined by various factors such as geology of the material, the proportion and properties of the glassy phase, the degree of crystalline, fineness, and the production process. It has been proven through research on Icelandic volcanic materials but several naturally occurring volcanic materials have enough pozzolanic activity for their application in cementitious system.

VPI is emerging SCM within the Nordic concrete industry. In present, it is commercially produced in Sweden as a type II addition for concrete, and Heidelberg Materials claims that it meets all the relevant Swedish requirements.

1.2.2.5 Volcanic Rock (Greek Pumice (Yalite))

The pumice used in the study, called Yalite, is a natural pozzolan sourced from Gyali island, Greece. The pumice from this island was formed by volcanic eruptions and contains a substantial glassy phase. When finely ground and incorporated into Portland cement, its reactive silica can react with calcium hydroxide released during cement hydration, forming an additional calcium silicate hydrate (C-S-H). The amount of amorphous silica, the fineness and the grinding process collectively decide the pozzolanic activity of Pumice. They are off-white in color [29].

1.2.2.6 Calcined Clay (Nova Clay (NC))

NovaClay is a high-quality calcined clay supplied by NovaClay A/S, Denmark, which is obtained through the controlled calcination process of Danish clay. The natural clay extracted is thermally activated to produce highly reactive pozzolanic material that can be used as a supplementary cementitious material (SCM). This method of activation is the widely reported effective method in the literature [30]. After the calcination process, the material is ground uniformly to a specific particle size and introduced into the cementitious system. According to the manufacturer, the production process provides consistency and high reactivity of the pozzolanic material.

In contrast to Portland cement, NovaClay does not undergo hydration independently on contact with water. Nevertheless, NovaClay acts as a pozzolonic material and undergoes reactions with the calcium hydroxide generated during the Portland cement hydration process, thus creating other cementitious hydration products and, consequently, densifying the cement matrix. Due to the high reactivity of NovaClay, this material allows substantial reduction the content of Portland cement without losing the properties of concrete. As noted in the product description, NovaClay meets all the requirements of DS 206 and is officially certified as equivalent to Portland cement for use in concrete

with 35% maximum cement replacement rate [31].

1.2.3 Use of SCMs in Concrete

I) K-value concept:

The concept of k-value provides a method for accounting for the contribution of certain supplementary cementitious materials (SCMs) when proportioning the concrete according to [32] and its Swedish application standard [33]. In this approach, the SCM content is multiplied by a material specific efficiency factor K, and added to the cement content to calculate an equivalent binder content.

$C_{eq.} = C + kA$, where C and A are the cement and SCM contents, respectively, in kg/m^3 . The permitted k-value and maximum amount of SCM that can be included in the depend on the type SCM and cement used, as specified in the relevant standard [32, 33].

II) Equivalent Performance of Cement Combinations (EPCC):

The equivalent performance of cement combinations (EPCC) concept allows a defined condition of cement and SCM to be assessed as a binder. Its suitability is established by demonstrating that the combination meets the applicable performance requirements, rather than by assigning the SCM a prescribed k-value. In Sweden, the requirements for applying this concept are set out in [33].

1.3 Fresh Properties

The fresh concrete properties describe the behavior of concrete from mixing until it begins to harden. They include workability, flow, consistency, viscosity, resistance to bleeding and segregation, and setting time. These properties affect how readily concrete can be mixed, transported, placed, compacted, and finished. They depend on the factors such as water to binder ratio, particle size distribution, aggregated characteristics, and the type and amount of admixture and SCMs [23, 20]. Partial replacement of cement with SCMs therefore alters the behavior of fresh concrete.

1.3.1 Workability

It is important to know that the higher the content of air voids in the mixture will lower the strength, so to increase the compaction and ultimately strength, generally, a higher water to binder ratio is adopted because water functions as the effective lubricant which eases the compaction process in the concrete. Thus, one of the main constituents of the concrete mix is water that is required for proper handling without any segregation and placing without changing the uniformity and homogeneity of the concrete mix and the compaction process for easy finishing of concrete. Concrete that meets all these requirements is said to be a workable concrete. Thus, the term Workability is operationally defined as the important property of fresh concrete which refers to ease of handling of concrete such as mixing, transporting, placing, including compaction and finishing maintaining uniformity after the addition of water in the mixture [23, 20]. The workability depends primarily on the water to binder ratio, the dosages of admixture, and the amount of SCM in the binder. All concrete works need proper workability to make the concrete operation more economical and durable. This can be divided into three distinct types: low, medium or highly workable concrete [34, 18, 13]. The use of supplementary cementitious materials (SCMs) in concrete/cement substantially alters the workability of the concrete and water demand. This depends on particle shape and

sizes, water absorption, etc. Those SCM which have a spherical particle shape can roll into each other and can increase the workability while the angular particle will consequently increase the friction due to interlocking and reduce the workability. When SCM particles are finer than cement particles, more water is typically required as a result of the increase in surface area. Also, it depends on the porosity as they will absorb more mixing water, leaving less free water. Furthermore, some SCM particles agglomerate during mixing with the water, which also reduces the workability.

1.3.2 Stability

Stability is the ability of fresh concrete to maintain a uniform distribution of its constituents during handling and placement. An unstable mixture may undergo segregation, in which coarse aggregates are separated from the mortar and settle, or bleeding, in which water rises to the surface as solid particles settle. Both processes reduce the homogeneity of the fresh concrete. Segregation and bleeding is promoted by excessive mixing water, unstable mixing proportions, or improper handling and placement of the concrete. Excess vibration during compaction further promotes the separation of water and solid particles, particularly in a mixture with a high water to binder ratio. Stability can be achieved by correctly proportioning the mix and properly handling, carrying, placing and finishing. Whenever segregation is seen while mixing, it can be improved by remixing [23, 20].

The stability of fresh concrete is influenced by the water content, aggregate grinding and the shape of the particle, paste cohesion, and the type and amount of supplementary cementitious materials. Excessive mixing water can reduce paste cohesion and increase the risk of segregation and bleeding. A cohesive paste helps aggregate particles to uniformly suspended, while a suitable aggregate grade can reduce their tendency to separate. SCM may reduce or improve stability depending on properties such as particle size, shape, surface area, and water demand [34, 13].

1.3.3 Setting Time

The concrete setting time is the time that the concrete begins to lose its plasticity. The standard way of measuring the setting time is using Vicat Apparatus in the laboratory. There are normally two types of setting time: initial and final setting time. The Final setting time is the time when the concrete loses its plasticity completely [23, 21]. However, for this thesis, a highly precise IP-8 ultrasonic measuring system was used to monitor the continuous measuring of the setting process. Normally, the addition of SCM will retard the setting time.

1.4 Limitation

Supplementary cementitious materials (SCM) are widely used to partially replace the ordinary Portland cement (OPC), thereby reducing the clinker content of the concrete and potentially lowering its associated green house gas emissions [13, 12]. However, various materials within the SCM class vary significantly in terms of their physical and chemical characteristics, resulting in a great difference in their behavior in the fresh state [13, 30]. Although, the fresh concrete behavior of established SCMs such as fly ash (FA) and ground granulated blast furnace slag (GGBFS) has been widely studied, less information available for other specific SCMs such as calcined clay, pumice, volcanic pozzolan Iceland (VPI) and SCementum which has high potential to be used in

future. Moreover, comparison of various SCMs under identical experimental condition is necessary to evaluate their impact on water requirements, workability, stability and other fresh concrete properties.

As the use of SCMs to reduce the cement consumption increases, it is important to understand how relatively high replacement levels affect fresh concrete. To address this gap that is why in the current study six aforementioned SCMs were investigated, paying attention to their effect on the fresh state properties of mortar with cement replacement level up to 40%. In addition, complementary investigations such as calorimetry test for 24 hours and 1 day compressive strength were conducted.

1.5 Aims and Objectives

The objectives of this research are:

1. To investigate and compare the effect of different SCMs on water demand and superplasticizer requirement.
2. To find out the initial workability and workability loss over time for 2 hours.
3. To evaluate the effect of SCM on fresh-state stability, particularly bleeding and segregation.
4. To check the effect of SCMs on the initial setting time.
5. To find out the early hydration behavior and one-day compressive strength.

1.6 Research Question

The research intends to answer the following research question: How do different natural and industrial supplementary cementitious materials affect the fresh concrete properties, hydration behavior, stability, and early-age strength of mortar when used as partial cement replacements?

In order to answer this questions, the following experiments were conducted: initial water demand by Hagermann cone, workability retention test, stability test, ultrasonic setting time test, isothermal calorimetry test and one day compressive strength test. Fresh property tests are the main subject of this study; calorimetry and compressive strength tests complement these tests in the interpretation of the hydration behavior of investigated binders.

2 Materials

2.1 Cement

SS-EN-197-1 specifies the composition and performance requirements of common cement, including CEM I to CEM V family. Figure 2.1 CEM I 52.5R from Heidelberg Materials was used as a Portland cement in all mixtures in this study. The properties of CEM I are mentioned in the Table 2.1

Using the same cement throughout the experimental period provided a consistent reference for comparing mixture with different SCMs and replacement levels. During cement hydration, calcium hydroxide is produced and can react with pozzolanic SCMs to form additional hydration products. This reaction provides a basis for examining differences in early-age behavior between the mixtures. Moreover, this is the cement widely used in research and industry, so it was used as a reference binder as a baseline to compare.



Figure 2.1: Rapid Hardening Cement Skövde

Table 2.1: Properties of CEM I 52.5 R

Property	Value
Cement type	CEM I 52.5 R
Manufacturer	Heidelberg Material
Standard	EN-197
Specific gravity	3.15
Initial setting time	>45 minute
28-days Compressive Strength	52.5 MPa

2.2 Sand

Normsand according to EN-196-1 was used in the whole experiment. The weight of 1 bag of sand is 1350 gram. The main reason for using was its standard particle size distribution.



Figure 2.2: CEN Standard Sand EN-196-1

2.3 Admixture

In some experiments, some superplasticizer as shown in the Figure 2.3 was used to increase the workability of the mixture. Polycarboxylate ether (PCE)-based superplasticizer, Dynamon SX-23 from MAPEI was used along with a higher water/binder ratio to check stability. Similarly, MasterGlenium SP is used to improve the workability of Nova Clay.

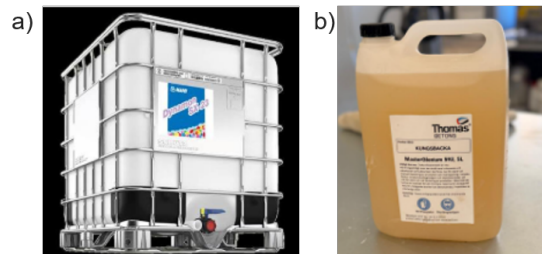


Figure 2.3: Superplasticizer a) Dynamon SX-23 from Mapei b) MasterGlenium

2.4 SCM

The study examines six supplementary cementitious materials (SCMs), shown in the Figure 2.4. They are selected on the basis of availability and potential for use as a cement replacement. The materials include both naturally occurring pozzolans and SCMs produced or processed through industrial activities. The SCMs of natural origin examined in this study are Volcanic Pozzolan Iceland, Pumice from Gyall, Greece, and Nova clay.

The other three SCMs examined in this study i.e. fly ash, Ground Granulated Blast Furnace Slag (GGBFS) and SCMentum are derived from industrial processes.

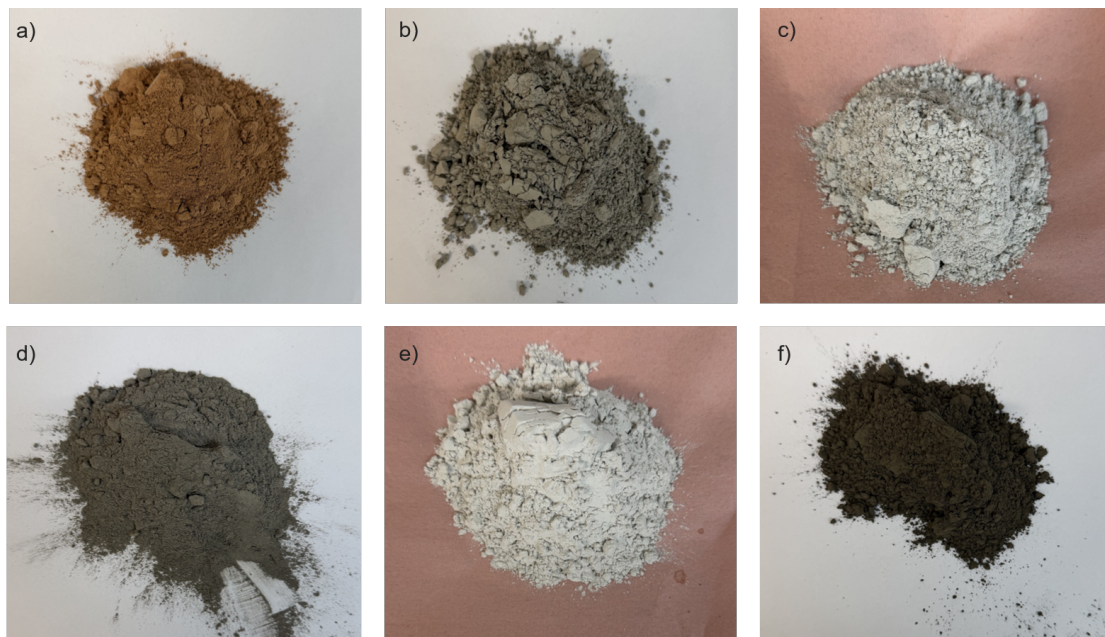
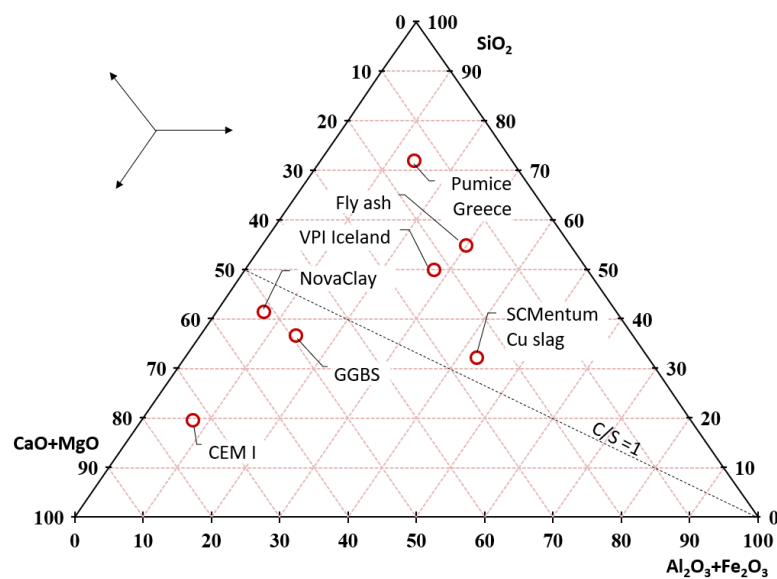


Figure 2.4: a) Nova Clay (Calcined Clay) b) Volcanic Ash (VPI from Heidelberg Material) c) Pumice (Yalite from Ridgehill Minerals) d) Fly Ash e) GGBFS (Slag Bremen from Thomas Cement) f) SCMentum (from Heidelberg material)

Table 2.2: Physical Properties of SCM

SCM	CEM I	Nova Clay	VPI	Pumice	FA	GGBS	Boliden
Colour	Grey	Light brown	Grey	Off-white	Grey	Off-white	Dark-grey
Fineness (μm)	7-10	10	-	4.78	-	-	-
Density (g/cc)	3.15	2.7	2.93	2.38	2.09	2.90	3.48

The six SCMs examined in this study differ in color, particle fineness, and density. Differences in chemical composition and fineness may affect their interaction with water and cement and, consequently, the behavior of fresh mixtures. Color provides a visible description of the materials. The density of each SCM was measured using a Micromeritics AccuPyc 1330 gas Pycnometer. The measure densities were lower than that of CEM I cement except for the Boliden sample.

**Table 2.3:** Chemical Composition of different SCM

Mineral	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	MgO	CaO	Na ₂ O+ K ₂ O
CEM I	19.6	4.5	3	3.5	63.5	1.5
Nova Clay	41.4	4.2	2.8	6.8	34	3.1
VPI	49.9	15.6	12.0	6.6	13.5	2.1
Pumice	71.9	12.7	1.13	0.32	1.5	7.75
FA	54.9	24.6	7.2	2.5	5.8	2.4
GGBS	36.6	13.6	0.5	8.5	39.1	1.0
Boliden	32.1	8.3	34.55	1.63	3.6	0.3

Table 2.3 presents the oxide composition of cement and SCM examined in this study. Pumice has the highest silica among SCMs (71.9%), while GGBFS has the highest CaO content (39.1%). The Boliden sample has notably high Iron oxides (34.5%).

3 Method

All experiments for this study were performed following this general procedure in which an experimental arrangement was set in the lab, this includes EN-196-1 Laboratory mortar mixture for mixing, a weighing balance for measuring quantity of material, Hagërmann cone and thin-smooth horizontal board of 60 cm /60 cm for workability test. First, the required amount of cement, sand, SCM, and de-ionized water were weighted according to the mixture proportions i.e. Table 3.1, Table 3.2, Table 3.4, Table 3.3, Table 3.5 and Table 3.6 for initial water demand, workability loss over time, initial setting time, stability, calorimetry and early age strength test, respectively. Before mixing and testing, tools for specific experiments such as the mixing bowl, mixing paddle, inner surface of Hagërmann cone, and the test plate to test flow were wiped with a damp sponge to reduce the adhesion of the mortar to their surfaces. To ensure homogeneity of the binder components, the weighted cement and SCM were first blended dry in the mixing bowl using a spatula. The weighted de-ionized water was then added to the dry cement-SCM blend in the mixture bowl. The time in which water was added was recorded as the start of mixing and the bowl was clamped to the mixture machine. The mixture was then mixed at low speed (140 rpm) for 30 s. Sand was gradually added over a next 30 s while mixing continued at the same speed. The mixture speed was increased to a high speed of 285 rpm for another 30 s, followed by a 90 s pause. During the 90 s pause, the material adhering to the sides of the mixing bowl was scraped with a spatula and incorporated into the mixture. The mixture was then restarted in a high speed of 285 rpm for 60 s, completing the 240 s mixing procedures.

3.1 Initial Water Demand

After mixing, the bowl was taken out of the machine and poured into the Hagermann cone placed on the test plate with a wider opening facing downwards and filled completely with the mortar of the bowl. The mortar on the top of the cone was leveled with the trowel and then carefully lifted the cone vertically upward to allow the flow to spread and settle. Once the mortar had stopped spreading, its flow diameter was measured in two perpendicular directions with ruler, and mean value was reported. The same mixing and flow test procedures were followed for every SCM mixture.

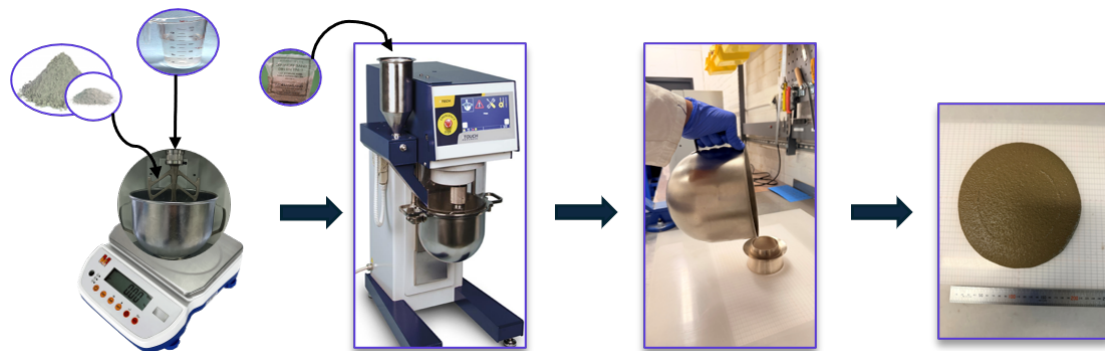


Figure 3.1: Steps for initial water demand

Table 3.1: Mortar Mixture proportions

Replacement	Materials by weight (gm)				w/b ratio
	Cement	SCM	Sand	Water	
20%	400	100	1350	350	0.7
40%	300	200	1350	350	0.7
60%	200	300	1350	350	0.7

3.2 Workability loss over time

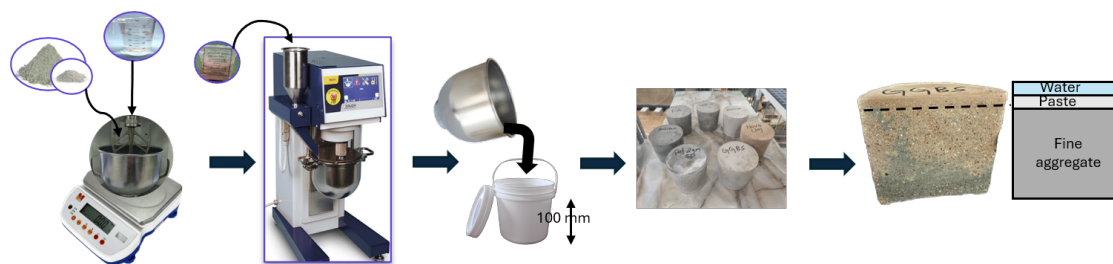
For this purpose, the water-binder ratio was reduced to 0.5 and a measured dose of superplasticizer (Dynamon SX-23) was added to the mixing water and stirred before the water was poured into the mixture. The superplasticizer dose for each SCM mixture was determined through preliminary trials, i.e. an iterative experimental approach.

The mortar flow diameter was measured at 5, 30, 60, 90 and 120 minutes after the initial addition of water. After each measurement, the mortar was returned to the mixing bowl and covered with a thin plastic film to prevent the water from evaporating. Before the next measurement, the mixture was stirred manually with a spatula for about 30 s, and the flow test was repeated, using the same procedure.

Table 3.2: Mortar Mixture proportions

Replacement	Materials by weight (gm)				w/b ratio
	Cement	SCM	Sand	Water	
40%	300	200	1350	250	0.5

3.3 Stability

**Figure 3.2:** Test procedure

The mortar was prepared using the general mixing procedures described above at a water binder ratio of 0.7 with no superplasticizer dose. The superplasticizer dose was adjusted in preliminary trials, i.e. iterative experimental approach to obtain the initial flow diameter of approximately 260 mm for each mixture, allowing the stability results to be compared at similar initial flow.

After mixing, the mortar was poured into a white bucket to a depth of 100 mm and vibrated for approximately 10 s. The bucket was covered and undisturbed. After 3.5 to 4 hours, water that had accumulated on the mortar surface was carefully collected with a pipette and its volume was measured.

The bucket was covered again and retained for 21 days. The hardened specimen was

then taken out and vertically cut into two halves. The cut surface was examined to determine the height of the segregated region.

Table 3.3: Mortar Mixture proportions

Replacement	Materials by weight (gm)				w/b ratio
	Cement	SCM	Sand	Water	
40%	300	200	1350	350	0.7

3.4 Setting time

The setting behavior was monitored using an ultrasound measurement system. Mortar was prepared using general mixing procedure described above. For Nova clay mixture, 2.2 and 1.2 gram of MasterGlenium superplasticizer were added at cement replacement levels of 40% and 20%, respectively, to increase workability.

while the mortar was being mixed, the ultrasound system was configured to record the measurement at 1 sec interval over 24 hours. Immediately after mixing, the mortar was placed in a silicone mould with a height and internal diameter of 50 mm. The mortar was carefully compacted and covered with a thin rubber sheet to limit evaporation. Two measurements of the same batch were made for each mixture. After 24 hours, the ultrasound curves in the screen were analyzed to determine the initial and final setting time and the mean value of two measurements were reported.

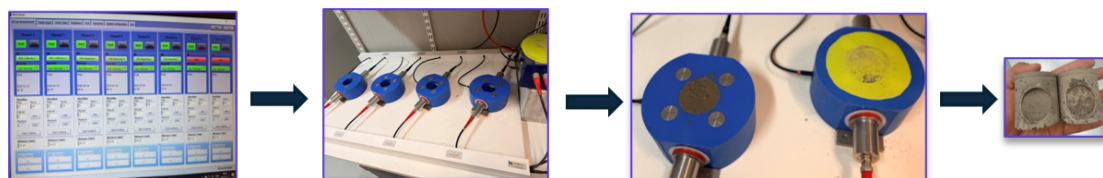


Figure 3.3: Step of Ultrasound test from setup to de-mould

An ultrasonic transmitter positioned on one side of the silicone mould sends a pulse through the mortar to a receiver on the opposite side. The system measures the pulse transit time and calculates the Ultrasonic Pulse Velocity (UPV) from the known distance between the transmitter and receiver.

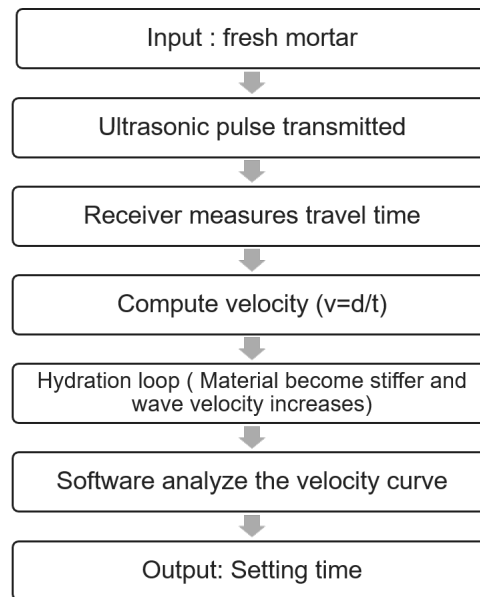


Figure 3.4: Flow diagram of Ultrasound test working principle

Immediately after mixing, the mortar has low stiffness and has not developed a continuous solid structure. As hydration progresses, products such as calcium silicate hydrate form and contribute to the development of a progressively stiffer structure. These changes generally increase the ultrasonic pulse velocity over time.

UltraTest lab software records the measurements at the selected intervals and displays the evolution of ultrasonic pulse velocity during setting and hardening. The first derivative of velocity-time curve describes the rate of change in velocity; its maximum identifies the time of the steepest increase. This characteristics point was used to compare setting behavior of the mixtures. The system also recorded the released temperature due to mixing.

Table 3.4: Mortar Mixture proportions

Replacement	Materials by weight (g)				w/b ratio
	Cement	SCM	Sand	Water	
40%	270	180	1350	225	0.5

3.5 Heat Evolution (Calorimetry)

Isothermal calorimetry was performed using Calmetrix calorimeter at the C-lab of Thomas Concrete Group AB, Gothenburg, Sweden, to monitor heat release during binder hydration. The instrument measured the heat flow from the sample relative to a reference maintained at the same temperature. The cumulative heat released is calculated by integrating the heat flow signal over time. After mixing as general mixing procedure mentioned above, 50 g mortar sample was transferred to the calorimetry container, which was then sealed. Cement hydration is a exothermic reaction. The calorimeter's heat flow sensors detected the heat release during hydration, and the instrument converted their signals into heat flow measurement. After 24 hours, the data were exported to excel and plotted as a heat flow against time.

Similarly to the setting time method, for nova clay mixtures, 2.2 g and 1.2 g of Mas-

terGlenium were added to increase the workability of the cement replacement level of 40% and 20%, respectively.

Table 3.5: Mortar Mixture proportions

Replacement	Materials by weight (gm)				w/b ratio
	Cement	SCM	Sand	Water	
40%	270	180	1350	225	0.5

3.6 Early-age compressive Strength (1-day)

The compressive strength test was conducted in the building laboratory of the Department of Architectural and Civil Engineering at Chalmers University of Technology. The mortar mixture was prepared as the general mixing procedure described above.

Immediately after mixing, the mortar was placed in three sets of three plastic cube moulds with an internal diameter of 40*40*40 mm. The inner surfaces were lubricated and the small opening in the center of each mould base was sealed with some sticky plastic before casting. The filled moulds were vibrated for around 10 s to reduce trapped air and the surface was leveled with a spatula. The moulds were then covered with thin plastic film to limit evaporation and stored for a day in room temperature. The same procedures were followed for all six SCMs at each of the three replacement levels. At an age of 24 hours (1440 ± 20 min) the samples were demoulded using air pressure and the compressive strength was tested. The three samples from each batch were tested for each mixture, and their mean compressive strength was reported.

Table 3.6: Mortar Mixture proportions

Replacement	Materials by weight (gm)				w/b ratio
	Cement	SCM	Sand	Water	
20%	400	100	1350	350	0.7
40%	300	200	1350	350	0.7
60%	200	300	1350	350	0.7

4 Results

4.1 Initial Water Demand

The figure 4.1 presents the initial mortar flow diameters at the cement replacement level of 20%, 40% and 60% by mass, represented by blue, brown and green bars, respectively. The dark horizontal line indicates the flow diameter of CEM I reference mixture (190 mm).

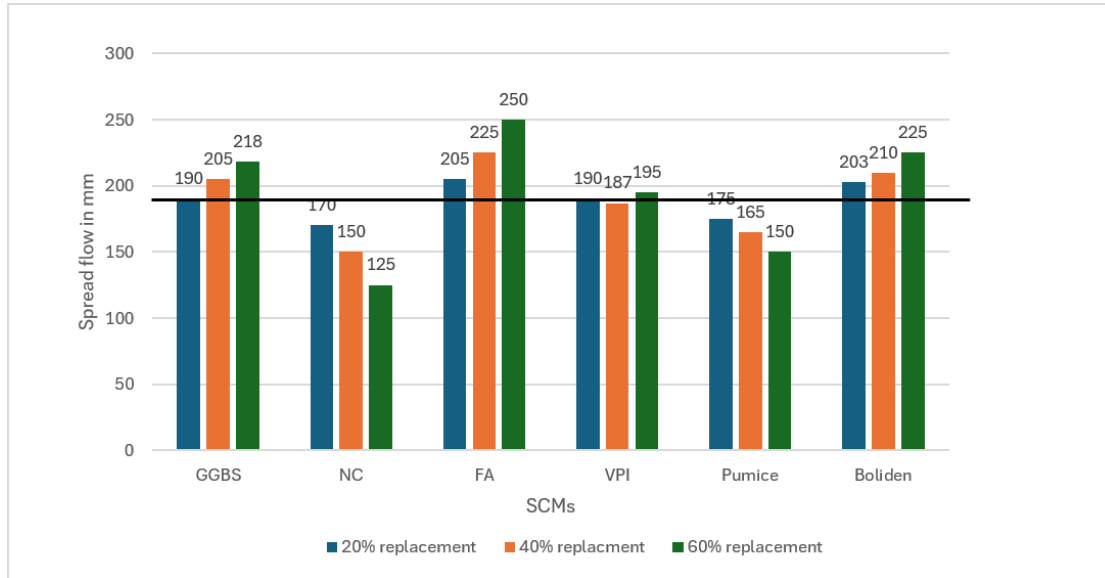


Figure 4.1: Initial water demand of different SCM

At 20% replacement, GGBFS and VPI produced flow diameters of 190 mm equal to that of the CEM I reference mixture. Increasing the replacement level from 40% to 60% increased the flow diameter of GGBFS, Fly ash and SCMENTUM mixtures from 190 to 216 mm, 205 to 250 mm, and 230 to 225 mm, respectively. In contrast, the flow diameter decreased from 170 to 125 mm for Nova clay and 175 to 150 mm for pumice. VPI showed comparatively little variation, with flow diameters ranging from 187 to 195 mm across the three replacement levels. Fly ash produced the highest flow diameter at each replacement level, while Nova clay produced the lowest.

4.2 Workability loss over time

The initial diameter was measured 5 min after the addition of water and the final diameter was measured at 120 min. The workability loss over time was expressed as the percentage reduction in the flow diameter.

$$\text{Workability loss (\%)} = \frac{\text{InitialDia}_{.5\text{min}} - \text{FinalDia}_{.120\text{min}}}{\text{InitialDia}_{.5\text{min}}} \times 100 \quad (4.1)$$

All measurement times were referenced to the initial addition of water.

The superplasticizer dose was adjusted for each mixture to obtain the initial flow diameter of 220 mm.

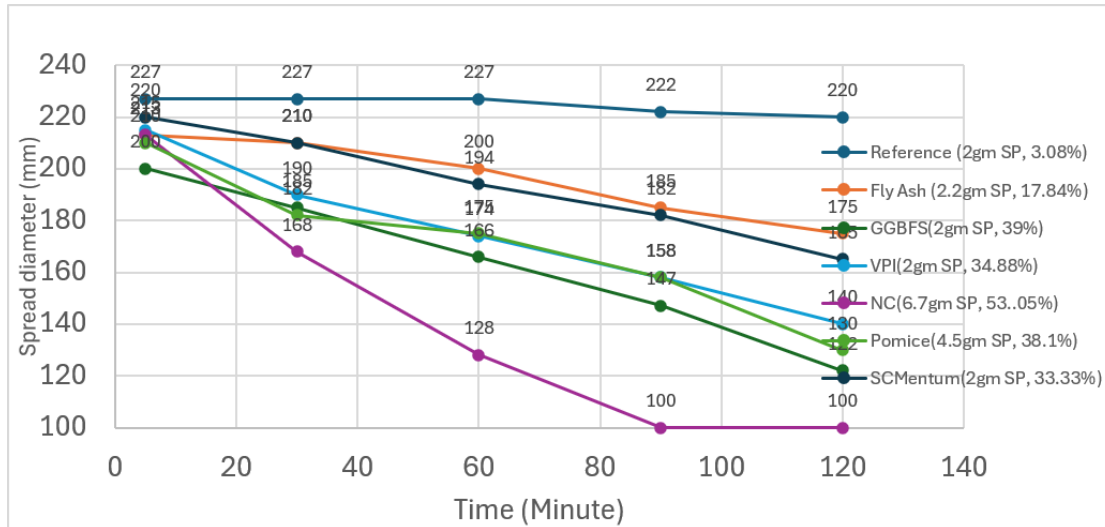


Figure 4.2: Workability loss over time for different SCMs

As shown in the figure 4.2, the mortar containing SCM exhibited an overall decrease in diameter during the measurement period, while the reference mixture remains comparatively constant. The reference mixture showed little change in flow diameter during the test, decreased by 7 mm, equivalent to a reduction of 3%.

Among the SCM containing mixtures, fly ash exhibited the highest flow retention. Its flow diameter decreased from 213 mm to 175 mm, corresponding to a reduction of around 18%.

Nova clay exhibited the greatest reduction in flow diameter. A superplasticizer dose of 6.7 gram, which is the highest dose among all, was required to achieve an initial flow diameter of 213 mm. The flow diameter decreased to 100 mm in 90 minutes, which was the lowest possible diameter in the Hagermann flow test, corresponding to an overall reduction of 53.05%.

GGBFS, Pumice, VPI and SCMentum exhibited intermediate flow retention. Their flow diameters decreased around by 39%, 38%, 34.5%, and 33%, respectively.

4.3 Stability

The superplasticizer dose was chosen according to the preliminary trials to get the initial flow diameter of around 260 mm to make the result comparable.

Table 4.1: results for Bleeding and Segregation

Materials	SP (gm)	Flow dia. (mm)	Bleeding (ml)	Segregation (mm)
CEM I	1.5	255	27	3
FA	0.5	273	39	3
GGBS	0.7	260	27.5	5
Nova Clay	3.8	255	8.5	1.5
VPI	0.8	255	24	3
Pumice	1.2	260	20	3
Boliden	0.6	255	37.5	3

The reference mortar produced 27 ml of bleed water and a segregation height of 3 mm.

These values provided the baseline for comparing the SCM-containing mixtures. Nova clay exhibited the lowest bleed water volume of 8.5 ml and the smallest segregation height of 1.5 mm, indicating the highest stability according to the two measured indicators.

Fly ash produced the highest bleed water volume of 39 ml, while its segregation height remained equal to the reference value of 3 mm. SCMentum also produced a comparatively high bleed water volume of 37.5 ml with a segregation height of 3 mm.

The GGBFS mixtures produced 27.5 ml of bleed water, close to the reference value, but exhibited the largest segregation height of 5 mm. VPI and Pumice produced the lower bleed water volume of 24 and 20 ml, respectively, while both retained segregation height of 3 mm.

4.4 Setting time

The data plotted in the Figure 4.3 of speed vs time and derivative of speed vs time, and the time for the average highest peak is the initial setting time. The black vertical line mark in the graph represents the highest average peak in a specific time.

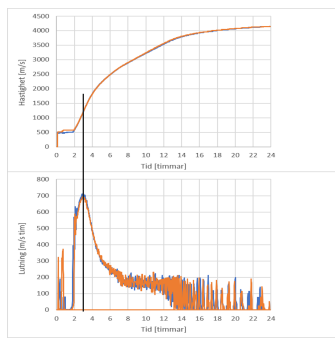
The Table 4.2 presents the initial setting times of the reference mortar and the mortar containing SCMs at 40% cement replacement by mass, together with the additional Nova clay mixture with 20% replacement. The reference mortar had the shortest initial setting time i.e. 174 min.

All SCM containing mixtures exhibited longer setting time than the reference. VPI started setting at 180 min, only 6 min later than the reference. Pumice exhibited the longest initial setting time, at 240 min, which is 66 min later than the reference.

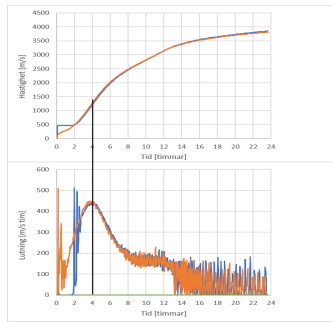
Fly ash and 20% Nova clay mixtures, both started setting at 198 min. Increasing the Nova clay replacement level to 40% increased the measured setting time to 204 min. GGBFS and SCMentum both reached initial setting at 228 min, corresponding to a delay of 54 min.

4.5 Heat Evolution (Calorimetry)

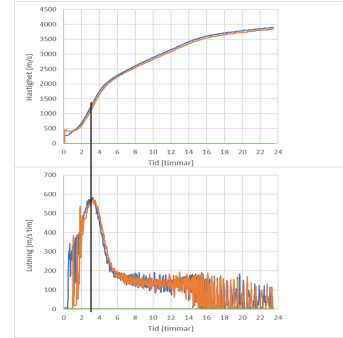
The heat flow curves and the cumulative heat release of the reference cement and the SCMs mixture for the first 24 hours of hydration are represented in figures 4.4 a) and b), respectively. It is clear from the graph of heat flow curves that the difference in the early hydration of the binder exists due to the use of SCMs, since the heat flow curve shows a similar trend as cement hydration such as the first peak, induction period, acceleration period, second (main) peak, and deceleration period.



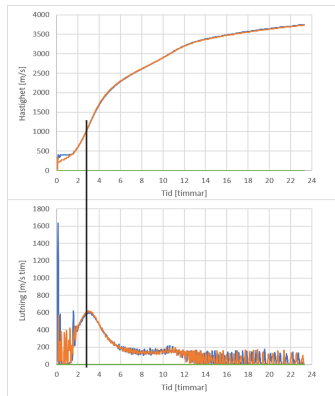
(a) CEM I



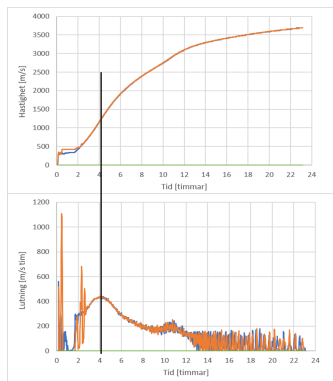
(b) GGBS



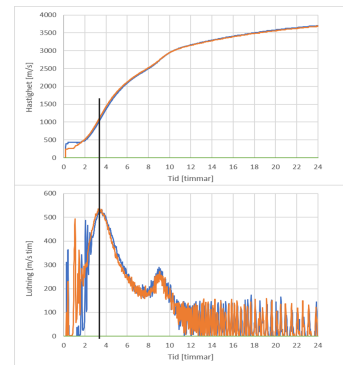
(c) Fly Ash



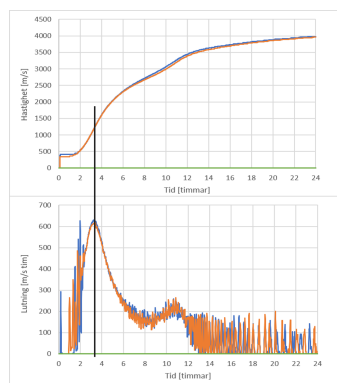
(d) VPI



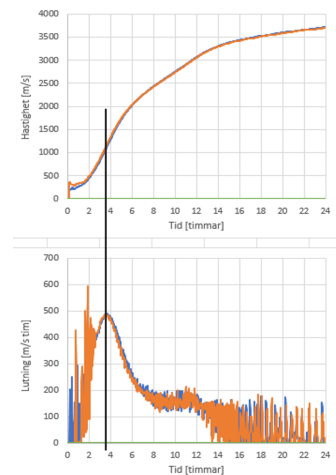
(e) Pumice (Yalite)



(f) Nova (Calcined) Clay 40%



(g) Nova (Calcined) Clay 20%



(h) SCMentum

Figure 4.3: Experimental results of setting time for the different samples

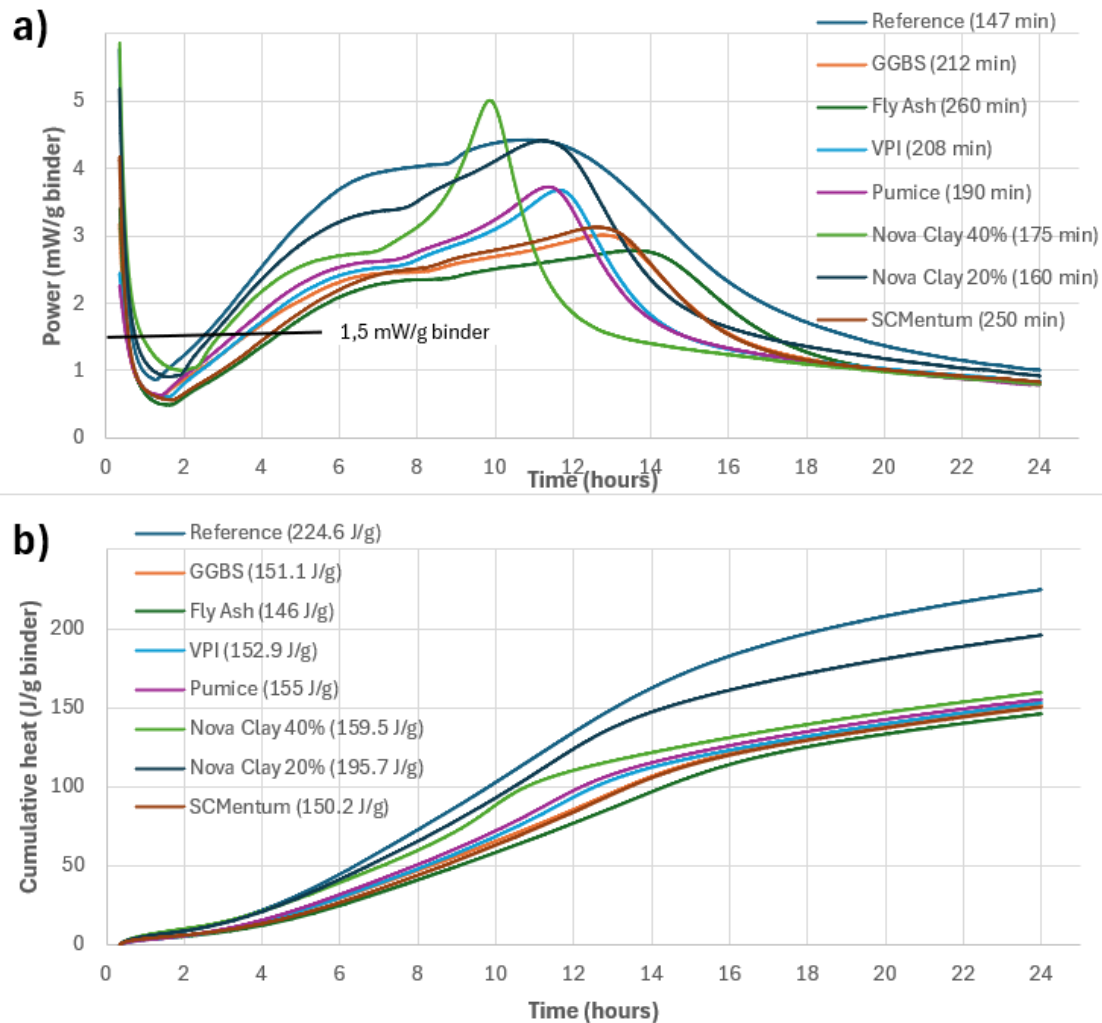


Figure 4.4: a) Heat flow as a function of time where heat flow reaches to 1.5 mW/g binder indicates initial setting time b) Cumulative heat development over a period of 24 hours

In this study, the initial setting time was estimated as the time at which the heat flow reached 1.5 mW/g. The reference mixture reached this threshold at 147 min, earlier than any other mixture. The Nova clay mixture was reached in 160 and 175 minutes for cement replacement levels of 20% and 40%, respectively. Increasing the Nova clay replacement level therefore increased the estimated initial setting time under tested conditions.

The pumice and VPI mixtures reached the threshold at 190 and 208 min, respectively, while GGBFS reached it at 212 min. SCMentum and Fly ash exhibited the longest estimated initial setting time, at approximately 250 and 260 min, respectively.

The reference mortar exhibited the highest cumulative heat release at 24 h, releasing 224.6 J/g of binder. All SCM containing mixtures released less heat per unit mass of binder than the reference. Among these, Nova clay with 20% replacement level released 195.7 J/g of binder, followed by Nova clay with 40% replacement level i.e. 159.5 J/g of binder and then Pumice (155.0 J/g), VPI (152.9 J/g), GGBS (151.1 J/g), SCMentum (150.2 J/g) and Fly Ash (146.0 J/g). Increasing the Nova clay replacement level from 20% to 40% reduced the cumulative heat release over 24 hours.

Table 4.2: Comparison of initial setting time of Calmatrix Calorimetry test and Ultrasound test

Materials	Calorimetry (min)	Ultrasound (min)
CEM I	147	174
GGBS	212	240
FA	260	198
VPI	208	180
Pumice	190	240
NC(40%)	175	216
NC(20%)	160	198
Boliden	250	222

Table 4.2 compares the initial setting time estimated using Ultrasound and calorimetry. Despite the different values of the initial setting times determined by two methods, there was a similar trend regarding the effect of the investigated SCMs on the setting process. The reference mixture demonstrated the lowest initial setting time using both methods, while the highest setting time delay was observed for Fly ash and SCMentum in Calorimetry test and GGBFS and Pumice in Ultrasound test. Nova Clay replacement from 20% and 40% increased the estimated setting time under both criteria. However, Nova Clay also received different doses of superplasticizer which might have affected the setting time.

4.6 Early-age compressive Strength (1-day)

The early age compressive strengths of the mortars with the six different SCM used at 20% , 40% (more focused) and 60% replacement of cement are presented in the bar graph. The compressive strength with pure cement was 12 MPa after 24 hours.

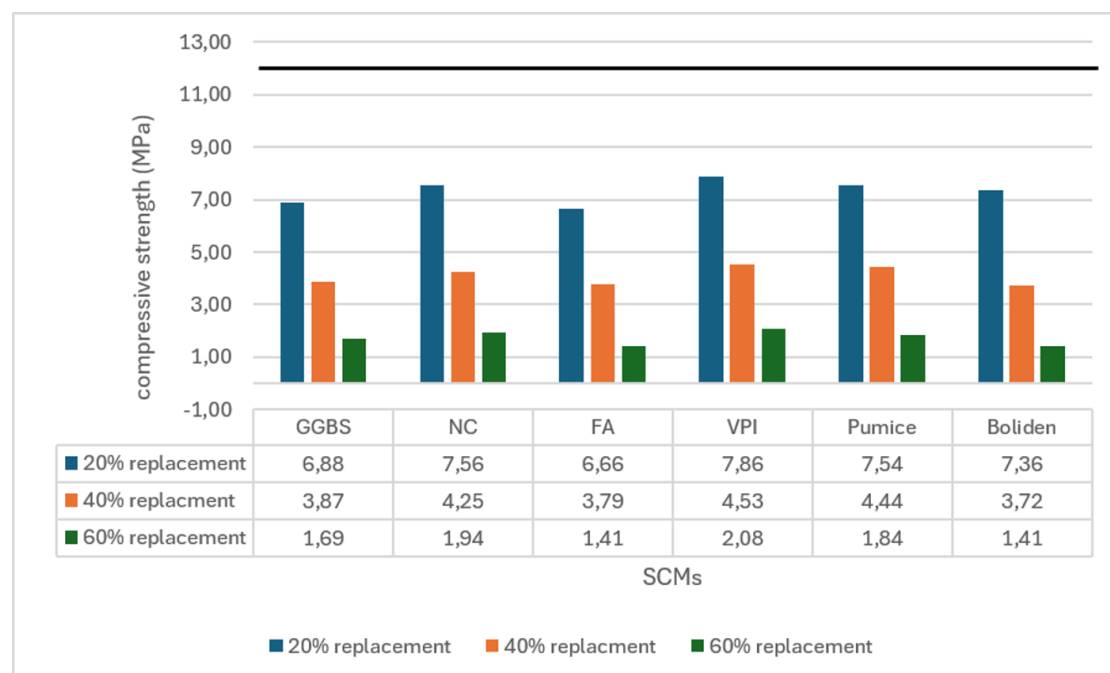


Figure 4.5: One day compressive strength test results with sample picture after the test

All SCM mixtures exhibited lower strength and decreased strength with increased replacement level. At 40% replacement, VPI produced the maximum compressive strength of 4.53 MPa followed by Pumice, i.e. 4.48 MPa, and Nova Clay i.e. 7.56 MPa. GGBS, Fly ash, and SCMentum produced a strength of around 3.8 MPa. VPI also exhibited the highest compressive strength among the SCM mixtures at a replacement level of 20% and 60% .

5 Discussion

The contrasting initial flow suggests that the SCMs affected the water demand and particle interactions differently. The higher flow of the Fly ash mixtures may partly reflect the predominantly spherical shape, which can reduce the inter-particle friction. In contrast, reduced flow of Nova clay may be associated with the surface area and morphology of calcined clay materials, while the porosity of pumice may increase its water requirement. This mechanism provides possible explanations, but their contribution cannot be established from flow measurements alone. The water to binder ratio was fixed and measurements indicate relative water demand rather than the water required to achieve a specified flow. Replacement by mass also introduces the differences in solid volume because SCMs and cement have different densities. Such differences may influence the particle packing and the volume of paste surrounded by sand. The increased flow observed with GGBFS and SCMENTUM should therefore be attributed to several factors rather than solely to a particle shape or chemical property.

The results of the workability loss over time indicate that a similar initial flow did not ensure a similar behavior over time. Nova clay required the highest superplasticizer dose but still exhibited the greatest flow loss. This suggests that the superplasticizer dose needed to obtain the initial flow did not provide the equivalent flow retention. Changes in particle interactions, hydration, and superplasticizer performance may have contributed to this behavior.

The stability results indicate that resistance to bleeding and resistance to segregation did not necessarily improve together. GGBFS produced a bleed water volume close to that of a reference but had the highest segregation height. This suggests that the mixture can retain water comparatively well, while still allowing solid particles to separate. Therefore, both measurements are needed to describe the stability of the mortars tested. The lower bleeding and segregation observed with Nova clay may be associated with greater paste cohesion and water retention. The surface area and morphology of the calcined clay particles could contribute to this behavior. The interpretation is also consistent with the lower initial flow and the higher superplasticizer required. Fly ash and SCMENTUM produced more bleed water without increasing the measured segregation height relative to the reference. Therefore, their higher bleeding does not imply a corresponding increase in particle segregation. In contrast, VPI and Pumice reduced bleeding while maintaining the reference segregation height. These differences suggest that the material affected water retention and particle separation in different ways.

The reason for the difference in the results of the initial setting time using Calmetrix based method and the Ultrasound based method may be the different nature of the physical principles used in each method. The calorimetry method uses the estimation of the initial setting time according to the heat flow equal to 1.5 mW/g of binder, which was considered to be the beginning of the development of the hydration process. At the same time, the determination of the setting time by the ultrasonic method is based on the increase of ultrasonic pulse velocity as a result of the formation of a continuous and solid structure inside the material. In most cases, the differences between the two approaches were around 20-40 min, which shows a good correlation in hydration and stiffness development. However, the difference between the results obtained with the help of the two approaches was more significant in the case of some types of SCMs such as Fly ash and GGBFS. In terms of the Fly ash mixture, the heat flow value was

reached later than the initial setting time determined by ultrasound, which shows that the rate of the reaction was relatively low and the stiffness had already formed enough to be measured by ultrasound. However, for the GGBFS mixture, the time it took to reach the criterion according to calorimetry was faster than the initial setting time by ultrasound, since heat evolution does not necessarily coincide with stiffness. In summary, it can be said that, in spite of similar results obtained, the two approaches gave complementary information about the reaction processes in question. The calorimetry based approach describes the reaction processes in detail, while ultrasound describes the structure formation.

Calorimetry and ultrasound measurements provide complementary information for interpreting the results of the one-day compressive strength. Although the three tests are for the first 24 hours, they assess the different aspects of early age behavior such as heat release during hydration, changes in the propagation of the ultrasonic wave, and resistance to compressive loading. The reference mixture exhibited both the highest cumulative heat release and the highest one day compressive strength. However, Nova clay exhibited the highest cumulative heat release among the SCM mixtures, whereas VPI achieved the highest compressive strength. Therefore, cumulative heat release alone cannot decide the strength. Heat release reflects hydration activity, while strength depends on the structure developed through hydration. Hydration product, particularly calcium silicate hydrate (C-S-H), contribute to the strength development, but their amount and distribution cannot be determined from calorimetry alone. But heat release is one of the factor to develop strength development. For instance, Fly ash showed the lowest total heat generation for 24 hours and one of the lowest compressive strength for 1 day. This might be due to the relatively low pozzolanic activity of Fly ash, which did not play a major role in the development of strength at an early age. However, Nova clay demonstrated relatively high heat generation at an early age, which might be due to its filler effect and specific surface area. Thus, Nova clay had a compressive strength relatively higher at an early age than Fly ash.

6 Conclusion

This study investigated effects of six supplementary cementitious materials GGBFS, Fly ash, Volcanic Pozzolan Iceland, Nova clay, Greek pumice and SCMentum on fresh state behavior of mortar prepared with CEM I 52.5R. Particle attention was given to 40% replacement by mass, with few additional comparisons at 20% and 60%.

The results demonstrated that SCM type and replacement level affected initial flow, flow retention, and stability differently. Increasing replacement improved initial flow of GGBFS, Fly ash and SCMentum, reduced it for Nova clay and Greek pumice, and produced comparatively little change for VPI.

Fly ash provided the highest initial flow and greatest flow retention among the SCM mixtures. However, it also produced the largest bleed water volume in stability test. Similarly, SCMentum improved initial flow but exhibited comparatively high bleeding. GGBFS increased initial flow and produced the bleed water volume close to the reference, although it showed greatest measured segregation height. These findings indicate that improved flow does not necessarily ensure greater stability.

Nova clay exhibited the lowest flow and greatest flow loss despite requiring the highest superplasticizer dosage in workability loss test. Conversely, it produced the lowest bleed water volume and segregation height. Its use therefore requires attention to the balance between flow, flow retention and stability. Greek pumice also reduced initial flow but produced less bleed water than the reference. VPI maintain the initial flow close to the reference across the tested replacement level. Therefore, it showed a favourable combination of properties under the tested conditions, although its flow retention was lower than that of reference cement.

All SCM containing mixtures exhibited longer initial setting times than reference under both adopted measurement criteria. Similarly, all SCM containing mixtures released less heat per gram of binder in 24 h than reference. One day compressive strength decreased with increasing replacement for every SCM.

7 Limitation and Future Scope

1. The findings are specific to the six SCM samples examined, and the mixture proportions and testing condition used. SCM properties may vary between sources and production batches. Therefore, the results cannot be assumed to represent all materials within the same SCM category.
2. This experiment involved the use of only one cement, Skövde SH cement (CEM I 52.5 R). Although this provided the consistent basis for comparison, the finding may differ with other cements because cement composition can influence hydration and interaction with SCM and superplasticizer.
3. The experiments were conducted on mortar rather than concrete. This allowed controlled comparison using smaller material quantities, but excluded the influence of coarse aggregate on flow, stability and setting. The observed trends therefore require validation in concrete.
4. Superplasticizer dosage was adjusted between mixtures in the workability loss over time and stability tests to obtain approximately comparable initial flow diameter. However, the dosages and achieved flow diameters differed between mixtures, which should be considered while comparing their stability and workability loss over time.
5. Initial setting time was estimated using Ultrasound test and calorimetry test. This estimate depends on the adopted criteria and was not independently validated against the conventional setting time test.

Future research could examine ternary binder containing Portland cement and two SCMs with complementary properties. Combining the SCM that improves flow with one that increases cohesion may help balance workability and stability. This potential should be evaluated experimentally, with particular attention to superplasticizer compatibility and workability loss.

Practical implementation requires considerations of material availability, consistency of supply, and processing requirements. Further studies should assess how grinding and where necessary activation affect water demand and fresh-state behavior.

The observed color differences suggest potential applications in architectural finishes. Further investigation should be evaluated color consistency between batches and appearance of finished surfaces, alongside the fresh properties required for placement and finishing.

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