Development of High Early Strength Grout System using Brick Dust for Preplaced Aggregate Concrete

By

Hamza Ali

2021-NUST-MS-Structural Engineering 00000361420

NUST Institute of Civil Engineering

School of Civil and Environmental Engineering

National University of Sciences & Technology (NUST)

Islamabad, Pakistan

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Thesis Supervisor: Dr. Junaid Ahmad

School of Civil and Environmental Engineering

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Signature: ____________________

Supervisor: Dr. Junaid Ahmad

Date: 1/11/2024

Signature: ____________________ HoD Structural Engineering

Head of Department: Dr. Muhammad Usman

Date: 5-11-2024

Signature: ____________________ Dr. S. Muhammad Jamil Associate Dean NICE, SCEE, NUST

Associate Dean: Dr. S. Muhammad Jamil

Date: 05-11-2024

Signature: ____________________

Principal & Dean (SCEE-NICE): Prof. Dr. Muhammad Irfan

PROF DR MUHAMMAD IRFAN Principal & Dean SCEE, NUST

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We hereby recommend that the dissertation prepared under our Supervision by Hamza Ali (000003614200)

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Examination Committee Members

1. Name: Dr. Muhammad Usman Signature:

2. Name: Dr. Azam Khan Signature:

Supervisor's name: Dr Junaid Ahmad Signature:

Date: 1/11/2024

Head of Department
HoD Structural Engineering
NUST Institute of Civil Engineering
School of Civil & Environmental Engineering
National University of Sciences and Technology

(Associate Dean)
Dr. S. Muhammad Jamil
Associate Dean
NICE, SCEE, NUST

COUNTERSIGNED

Date: 06 NOV 2024, 2024

Principal & Dean SCEE
PROF DR MUHAMMAD IRFAN
Principal & Dean
SCEE, NUST

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Student Name: Hamza Ali — Signature: ____

Examination Committee:

a) GEC Member 1: Dr. Muhammad Usman
Associate Professor (SCEE, NUST) — Signature ____

b) GEC Member 2: Dr. Azam Khan
Professor (SCEE, NUST) — Signature ____

Supervisor Name: Dr. Junaid Ahmad — Signature: ____

Name of HOD: Dr. Muhammad Usman — Signature: ____

HoD Structural Engineering
NUST Institute of Civil Engineering
School of Civil & Environmental Engineering
National University of Sciences and Technology

Name of Associate Dean: Dr. S. Muhammad Jamil — Signature: ____

Dr. S. Muhammad Jamil
Associate Dean
NICE, SCEE, NUST

Name of Principal & Dean: Prof. Dr. Muhammad Irfan — Signature: ____

PROF DR MUHAMMAD IRFAN
Principal & Dean
SCEE, NUST

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DEDICATION

This thesis is dedicated to my parents, whose unwavering support, encouragement, and sacrifices have been the driving force behind my success and have played a pivotal role in my academic journey. I am forever grateful for your love and trust.

To my esteemed professors, whose guidance, expertise, and mentorship have shaped my intellectual curiosity and research pursuits - I thank you for your invaluable contributions to my growth.

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LIST OF SYMBOLS, ABBREVIATIONS AND ACRONYMS

ACI	American Concrete Institute
ASTM	American Society of Testing of Materials
BD	Brick Dust
BD-C	Brick Dust Commercial
BD-S	Brick Dust as Received
CAC	Calcium Aluminates Cement
CH	Calcium Hydroxide
CSH	Calcium Silicate Hydrate
CASH	Calcium Sulfoaluminate Hydrate
C_2S	Dicalcium Silicate
C_3S	Tricalcium Silicate
C_3A	Tri-Calcium Aluminate
C_4AF	Tetra Calcium Alumino Ferrite
FA	Fly Ash
FA-K	Fly Ash from Karachi

FA-S	Fly Ash from Sahiwal Coal Power Plant
FS	Final Set
HAC	High Alumina Cement
IS	Initial Set
LC	Lithium Carbonate
OPC	Ordinary Portland Cement
PAC	Preplaced Aggregate Cement
SCC	Self Compacting Concrete
SCCS	Self-Compacting Cementous Systems
SCG	Self-Compacting Grout
SCM	Secondary Cementitious Materials
SCP	Self-Compacting Paste
SLG	Self-Leveling Grout
SRM	Secondary Raw Material
SP	Super Plasticizer
W/C	Water Cement Ratio
WD	Water Demand

ABSTRACT

This study investigates the use of brick dust (BD) as a supplementary cementitious material (SCM) for high early strength grout systems, specifically designed for rapid repairs of civil and military infrastructure where open time is limited. A comprehensive evaluation of BD's pozzolanic activity and its effects on fresh and hardened state grout properties was conducted through powder characterization, flow, flexure, compressive strength, strength index, modified Chapelle's test, and BET test. The results demonstrate that BD improves strength, durability, and making it a suitable SCM for high early strength grout systems. Notably, formulations F11, containing 5% BD, 30% fly ash (FA), and 10% ordinary Portland Cement (OPC) in replacement of Calcium Aluminate Cement (CAC), exhibit promising results with 28 MPa compressive strength achieved in just 1 hour. This offers a potential solution for immediate repairs where rapid strength gain and reduced open time are critical. XRD and SEM analysis reveal that the addition of these SCMs increases the availability of silicate sites, leading to the production of more calcium aluminate silicate hydrates, which governs the reduction of strength degradation factors associated with CAC. The incorporation of BET test results further supports the improved pozzolanic activity of BD, showcasing its potential to enhance grout performance in demanding applications. The findings of this study contribute to the development of sustainable and efficient repair materials for critical infrastructure."

Keywords: Calcium Aluminate Cement, Fly Ash, Brick Dust, Pozzolanic Activity, Secondary Cementitious Materials, High Strength Grout Systems

CHAPTER 1: INTRODUCTION

1.1 Introduction

Ultra-High Early Strength Grout is a grout specifically designed for a particular purpose. It includes High Early Strength cement, which is made from specially processed Portland cement clinker and gypsum, together with other components. High Early Strength Cement is a suitable substitute for general purpose cement in all applications. However, it is typically recommended for use in situations that demand higher than average early strengths. High-early-strength concrete, often known as fast-track concrete, attains its designated strength at a younger age compared to regular concrete. The duration required to attain a particular level of strength can vary from a few hours (or even minutes) to several days. High-early strength in concrete can be achieved with the use of conventional components and processes, although there may be instances where specific materials or techniques are required. High-early-strength can be achieved by increasing the amount of cement used, reducing the ratio of water to cementing material, employing chemical admixtures, incorporating silica fume, or using a special type of cement that hardens quickly. The specific method chosen depends on the desired strength that needs to be reached and the parameters of the project.

1.2 Self-consolidating Concrete

As per ACI PRC-237.2-21, Self-consolidating concrete (SCC) is a type of concrete that has a high flowability and does not separate. It may easily spread into position, fill the formwork, and cover the reinforcement without the need for mechanical consolidation.

Grout is often composed of water, cement, and sand with varying grades. Its composition varies depending on its intended purpose. The self-consolidating grout exhibits a notable degree of fluidity, with reduced viscosity and excellent resistance to segregation. [1]

Currently, the desirable characteristics of self-consolidating grouts are achieved by including chemical and mineral admixtures. Chemical and mineral admixtures have the ability to decrease the viscosity of the mixture without raising the water to cement ratio. Although the use of chemical and mineral admixtures in self-consolidating grout is advantageous, it necessitates the expertise of a proficient Material Engineer. [2M]

1.3 Historic development

Until the 1900s, engineers did not actively engage in optimizing the strength of concrete or incorporating new technology into its production, despite concrete being used as a building material for millennia. The definition of high strength was updated with each subsequent development. According to ACI 363 R, high strength concrete is defined as concrete with a compressive strength exceeding 41 MPa. ACI defines high strength concrete as having a compressive strength more than 6000 psi (41 Mpa). The number was initially employed in 1984 by ACI, but it is not absolute due to ACI's acknowledgment that the notion of high strength is contingent upon geographical considerations. Professor J. Francis Young [1] from the University of Illinois Urbana Champaign has created a classification strength "Table 1.1".

Table 1 Concrete Strength Classification [2]

	Conventional concrete	High Strength Concrete	Very High Strength Concrete	Ultra-High Strength Concrete
Strength, MPa (psi)	< 50 (7250)	50 - 100 (7250-14,500)	100 - 150 (14500-21,750)	> 150 (21,750)
Water cement ratio	> 0.45	0.45-0.30	0.30-0.25	< 0.25
Chemical admixtures	Not necessary	WRA/HRWR*	HRWR*	HRWR*
Mineral Admixtures	Not necessary	Fly Ash	Silica Fume	Silica fume
Permeability Coefficients (cm/s)	> 10^{-10}	10^{-11}	10^{-12}	10^{-13}
Freeze Thaw Protection	Needs Air Entrainment	Needs Air Entrainment	Needs Air Entrainment	Needs Air Entrainment

*WRA= Water Reducing Admixtures; HRWA =High Range Water Reducers

The compressive strength of the concrete at the building site was approximately 25 MPa in the 1940s and increased to approximately 34 MPa in the 1950s. In 1970, experts believed that the maximum achievable compressive strength of ready mixed concrete would not surpass 43 MPa. The compressive strength of concrete is primarily determined by the degree of internal packing, porosity, continuous grading, and water-cement ratio. Grading the aggregate and binder phases consistently, especially when there are a lot of particles, can decrease porosities. However, this would also increase the quantity of water needed, leading to lesser strength and reduced durability. The dimensions of structural elements (columns, beams, slabs) are enlarged by employing low-strength concrete, which fails to meet the specifications of a high-rise building. If the dead loads exceed the occupancy loads, the bearing capacity of the foundation would need to be higher, resulting in a lesser number of stories. In the early 1980s, following the development of super plasticizers in Japan and Germany, it became possible to decrease the water-to-cement ratio while still achieving the appropriate level of fines incorporation in high performance concrete and self-compacting concrete. Several years ago, the builders were able to construct two buildings in Seattle, Washington using concrete with a compressive strength of 131 MPa.

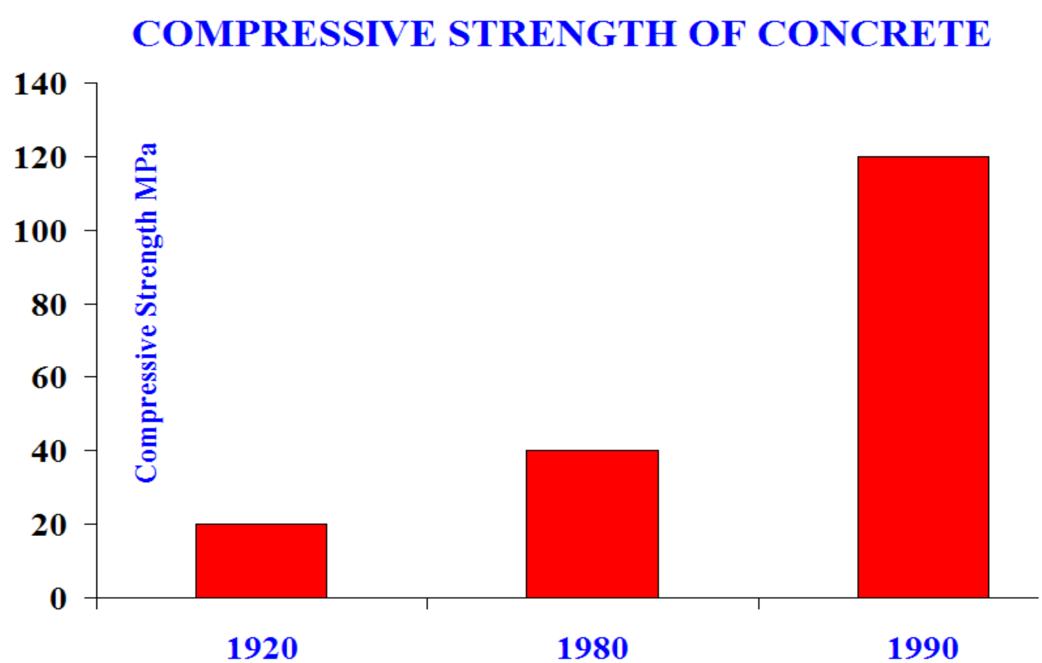

Figure 1 Strength Enhancement of Concrete through Modern Concrete Engineering[3]

1.4 Pozzolans

Pozzolan, as defined in ACI 237 R, is a material that is siliceous or aluminous. It does not have much cementitious value on its own. However, when it is finely divided and in the presence of moisture, it chemically reacts with calcium hydroxide (CH) produced during cement hydration at normal temperature. This reaction forms compounds that have cementitious properties [4].

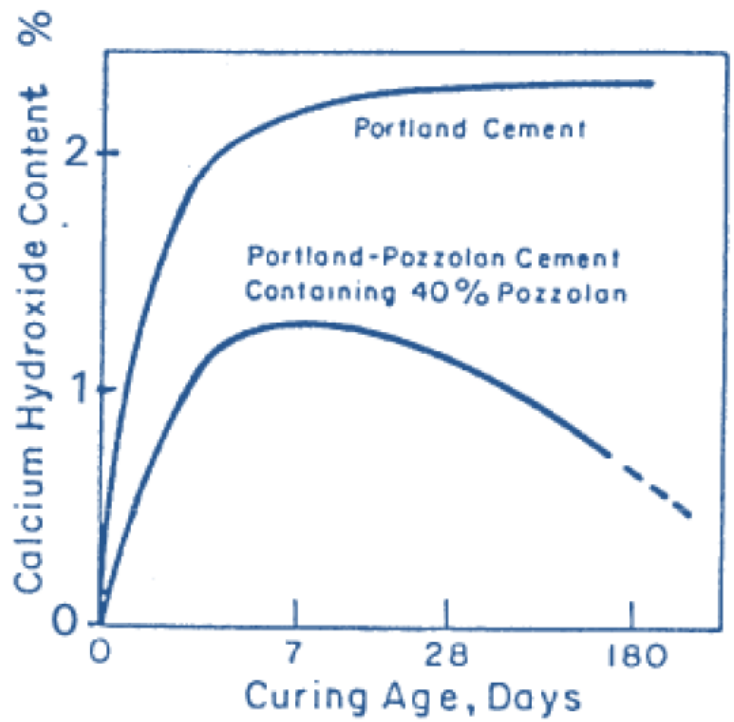

Figure 2 Changes in Ca $(OH)_2$ content of a hydrating portland-pozzolan cement [4]

1.5 Superplasticizers

Super plasticizers are incorporated to enhance the workability of the mixture without altering its composition. They also help decrease the quantity of mixing water, hence reducing the water-cement ratio and ultimately enhancing the strength and durability of the combination. In addition to lowering creep, shrinkage, and thermal stresses induced by the heat of cement hydration, they are also utilized to minimize both water and cement content, hence reducing costs [5]. Super plasticizer is incorporated into concrete to enhance its flowability. In order to ensure that the fluidity remains unchanged, it is important to assess the retardation of the hydration reaction caused by SP.

1.6 Admixtures

Accelerating admixtures are incorporated into concrete with the purpose of enhancing the speed at which the concrete gains strength in its early stages, or to reduce the time it takes for the concrete to set, or both. They are utilized to expedite the removal of work, shorten the time required for curing, accelerate the readiness of a structure for use, counteract the delaying impact of low temperature, and facilitate emergency repairs. Accelerators consist of various chemical compositions, including inorganic chemicals like soluble chlorides, carbonates, silicates, and fluosilicates, as well as organic molecules like triethanolamine [5]

1.7 Preplaced Aggregate Concrete (PAC)

PAC, as specified in ACI 116R, refers to a type of concrete that involves arranging the coarse aggregate in a form and then injecting a combination of cement, sand, and often admixtures to fill any voids. PAC is highly advantageous for underwater construction and locations with tightly positioned reinforcement. The repairs to the concrete and masonry are intended to contribute to stress distribution, particularly in areas where significant weight is involved. This includes the use of high-density concrete, high lift monolithic sections, and situations where low volume change in the concrete is necessary [6]. PAC, or Placed Aggregate Concrete, is a type of concrete where the coarse aggregate is directly placed in the forms, with point to point contact. This is different from standard concrete, which contains a higher percentage of coarse particles but is contained in a flowable plastic mixture. The characteristics of PAC are thus mostly influenced by the coarse aggregate. As a result, the modulus of elasticity of the material has been determined to be greater, and the drying shrinkage to be less than half, compared to traditional concrete [7]. Shrinkage is reduced by 50 to 100% compared to standard cast-in-place concrete.

1.8 Research Objectives

The objective of this research is to identify an optimal blend of calcium aluminate cement (CAC) and ordinary Portland cement (OPC) with the addition of fly ash (FA) and Brick Dust (BD) in order to produce a repair grout with very high early strength,

- To develop a high early age compressive strength grout system which can be used for the repair or construction of civil and military construction applications (such as rigid pavements or for stability of slopes etc.) where open time is very less.
- To develop a grout which has the ability of self-levelling and will create a smooth surface to fill voids and cavities without the need for manual compaction.
- To enhance the ability of the grout to resist degradation and maintain its strength and properties over time by using brick dust (Nano and micro particles) with other chemical admixtures.

CHAPTER 2: LITERATURE REVIEW

2.1 `General

High Early Strength Grout system is specifically designed for immediate repairs and other applications [7]. High-early strength in concrete can be achieved with the use of conventional components and processes with specific materials and techniques[8]. Cong Ma et. al have conducted research on high-performance grouting mortar. An experimental evaluation was conducted to assess the impact of mineral admixtures on several properties of mortar, including fluidity, setting time, expansion, strength, and others. The optimal parameters for gypsum-bauxite grouting mortar were determined to be a water-to-binder ratio of 0.3, a mineral admixture content of 15%, and a molar ratio K of 2. The gypsum-bauxite grouting mortar anchor exhibited a 39.6% improvement in its ultimate bearing capacity compared to the conventional mortar anchor. The gypsum-bauxite grouting mortar exhibits excellent fluidity, rapid setting, slight expansion, early strength, and high strength properties [9]. Extensive research has been conducted in recent years on the formulation and application of grouting mortar. The fluidity, water retention, and strength of mortar have been greatly enhanced by including a certain quantity of silica fume, volcanic ash, and other admixtures [10–15]. In the early 1980s, following the development of super plasticizers in Japan and Germany, it became possible to decrease the water-to-cement ratio. Several years ago, the builders were able to construct two buildings in Seattle, Washington using concrete with a compressive strength of 131 MPa. [3]. Adding a superplasticizer can enhance the strength and flowability of grouting mortar, but it will cause a reduction in the volume of cured cement pastes[16–19].

Grout is often composed of water, cement, sand and other varying contents. The self-consolidating grout exhibits a notable degree of fluidity, with adequate viscosity and excellent resistance to segregation [9], [20]. The desirable characteristics of self-consolidating grouts are achieved by including chemical and mineral admixtures. Chemical and mineral admixtures have the ability to adjust the viscosity of the mixture at same mixing water content. Although the use of chemical and mineral admixtures in self-consolidating grout is advantageous, it necessitates the expertise of a proficient Material Engineer [21].

2.2 Ordinary Portland Cement (OPC)

Cement is a substance with cohesive and adhesive qualities that can bind together various construction materials[22]. Ordinary Portland cement is the predominant type of hydraulic cement that is produced and utilized worldwide. The manufacturing process involves the combination of raw materials that have a high concentration of lime, silica, and alumina. This blending occurs at elevated temperatures within cement rotary kilns. Rotary kilns generate an intermediary substance known as "clinker." Clinker is pulverized to generate cement. Gypsum, comprising 5% of the mixture, is incorporated into the cement clinker to enhance the solidification process of the clinker. Portland cements with different qualities can be produced by making modest changes in the composition of the raw material mix and adjusting the manufacturing temperature to some extent.

2.3 Calcium Aluminate Cement (CAC)

Calcium aluminate cements (CAC) are recognized for their ability to survive harsh conditions such as bacterial or acid attacks. They exhibit exceptional resistance to abrasion and impact when combined with suitable aggregates. The primary distinction between Portland cement and CAC (Calcium Aluminate Cement) resides in the characteristic of the active phase that initiates the process of setting and hardening. Mono-calcium aluminate (CA) is the primary reactive component in CAC cement. It undergoes a chemical reaction with water to form calcium aluminate hydrates. ,[23–26]. The mechanical properties and hydration reaction of CAC can be affected by several parameters, including the amount of water, the percentage of Li_2CO_3, and the age of the formulations. CAC has been investigated as a viable substitute for Portland cement (PC) with the aim of promoting sustainability [27–29].

2.4 Chemistry and mineralogy of CACs

The primary chemical phases of CAC consist of mayenite ($C_{12}A_7$) and calcium aluminate (CA), whereas calcium di-aluminate (CA_2) and gehlenite (C_2AS) are present in smaller amounts [30,31]. In this context, C represents CaO, A represents Al_2O_3, H represents H_2O, and S represents SiO_2. The attractiveness of CAC is further enhanced when we consider its rapid strength gain. This is due to the quick hydration of CAC, resulting in the 1-day and 7-day strength of the CAC binder being equal to the 7-day and 28-day strengths of their PC equivalents. [32–34]. Throughout the process of hydration of calcium aluminate cement (CAC), many intermediate phases are generated that are in a metastable state. The phases are referred to as CAH_{10}, C_2AH_8, and C_4AH_x, with "x" representing either 11, 13, or 19, depending on the relative humidity [35,36]. Subsequently, these stages undergo a transformation into C_3AH_6, also known as hydrogarnet, and AH_3, also known as gibbsite [30]. The occurrence of these metastable phases is influenced by temperature. C_AH_{10} is the sole substance that is generated when temperatures are below 15°C [30]. At higher temperatures, the presence of C_2AH_8 becomes evident in the CAC binder [37]. At around 40 °C, the primary product of hydration is C_2AH_8, in addition to alumina gel [38]. At a temperature of 60 °C, the compounds C_3AH_6 and AH_3 are produced without the formation of any unstable phases [30,37,38]. When silica is present in the CAC, it may lead to the formation of C_2ASH_8 (stratlingite) [31]. Stratlingite is a phase that enhances the compressive strength of calcium aluminate cement (CAC). The procedure of converting phases has a substantial impact on the compressive strength of CAC. During the transformation of low-density phases (C_2AH_8, CAH_{10}, and C_4AHx) into the high-density phase (C_3AH_6), the cement's porosity rises and its compressive strength falls [33,39]. The primary degrading process observed in calcium aluminate cement (CAC) is the conversion of hexagonal calcium aluminate hydrate to cubic form, which is both inevitable and irreversible [40,41]. This transformation typically leads to an elevation in porosity, which is governed by the varying densities of these hydrates, resulting in a subsequent decrease in strength. Several instances of deterioration in concretes made with calcium aluminates cement were documented in Spain over a prolonged period. In 1990s in Spain, an incident of fatality caused by falling of building made with CAC had raised questions about the use of CAC [42,43].

$$3\ CAH_{10} \rightarrow C_3AH_6 + 3AH_3 + 9H$$

$$3\ C_2AH_8 \rightarrow 2C_3AH_6 + AH_3 + 9H$$

2.5 Mitigation of Strength Reduction

A compelling method to mitigate hydrate conversion and strength reduction is to substitute a portion of calcium aluminate cement (CAC) with Blast Furnace Slag (BFS) or pozzolanic materials such as metakaolin, micro silica and Brick Dust by providing additional silicate sites for additional calcium aluminate silicate hydrates [44–47].

2.6 Brick Dust

Brick dust is an abundant waste material that is produced as a by-product in brick kilns and construction sites. This material is disposed of by dumping it and using it in landfills, which is a hazardous for the environment. Researchers worldwide utilize various inventive and discarded waste materials in concrete to address environmental challenges. These waste materials yield comparable or almost identical concrete qualities[48–50]. Scientists are employing several substances as substitutes for cement in order to examine the characteristics of concrete [11]. According to the research from the Cement Sustainability Initiative [51], the production of 1 ton of cement results in the emission of roughly 1 ton of CO_2 along with other dangerous gases. Aliabdo et. al has incorporated crushed clay bricks into concrete and subjected it to non-traditional testing such as XRD, thermo-gravimetric analysis (TGA), and microstructural analysis. Based on empirical observation, it was deduced that the strength is diminished, while the heat resistance, economic implications, and environmental factors should be considered [52]. According to Heidari and Hasanpour, brick dust possesses pozzolanic qualities that can be utilized as a substitute for cement in concrete. They also determined that the utilization of brick dust has negligible impact on the reduction of strength [53]. Khan et al has examined the potential of using brick dust and marble powder as substitutes for cement. The findings indicate that the combination of both materials in specific proportions enhances workability. However, the compressive strength decreases when the brick dust concentration exceeds 10% replacement [48].

2.7 Fly Ash

Fly ash consists of fine particles that are accumulated during the combustion process of pulverized coal in electrical power producing plants. During the process of combustion, the mineral impurities found in coal, such as clay, feldspar, quartz, and shale, melt while suspended and are expelled from the combustion chamber together with the exhaust gases. As the molten material ascends, it undergoes cooling and solidification, resulting in the formation of glassy particles known as fly ash. Fly ash is captured by electrostatic precipitators from the emissions of exhaust gasses. Fly ash is utilized as a raw material in the manufacturing of cement clinker. It is either interground with the clinker or blended with the finished cement [54]. The primary reason for the pozzolanic activity of fly ash is its high glassy composition, which combines with lime in the presence of water. ASTM 618 C defines two distinct categories of fly ash: Class C and Class F fly ash. The primary distinction among these groups lies in the varying levels of silica, calcium, aluminum, and iron present in the ash. The chemical characteristics of fly ash mostly rely on the chemical composition of the burned coal, such as anthracite, bituminous, or lignite. Class C fly ash contains a higher percentage of $SiO_2+Al_2O_3+Fe_2O_3$, above 70%, while Class F fly ash has a lower percentage of these oxides, exceeding 50%. Class C fly ashes are derived from the combustion of subbituminous coal or lignite. Class C fly ash exhibits both pozzolanic qualities as well as cementitious properties. The relationship between the water binder ratio and the water cement ratio in Fly ash cement-based systems is expressed as follows [55]. The pozzolanic activity of fly ash is contingent upon the particle size, with smaller particles exhibiting more reactivity. When the water binder ratio remains constant, increasing the amount of Fly ash in concrete results in a higher effective water to cement ratio at a fixed mixing water to cement ratio. Fly ash (FA) has distinct behavior in both enclosed and exposed environments. Systems that incorporate fly ash exhibit increased bleeding and delayed setting, as indicated by research.

2.8 CAC with Secondary Cementitious Materials (SCMs)

Duby and Porwal has found that incorporating fly ash and brick dust as admixtures in concrete can reduce the cost of cement by up to 20% while maintaining the same level of strength [50]. Bharti and Patel has found that the substitution of cement with 15% silica fume and 10% brick kiln dust resulted in the highest compressive and tensile strength when utilizing a water-to-cement ratio of 0.50 [49]. Majumdar demonstrated that using a concrete mixture containing equal proportions of calcium aluminate cement (CAC) and blast furnace slag (BFS), and curing it at either 20°C or 38°C, resulted in a continual rise in compressive strength over a one-year period. This is in contrast to control samples that did not contain BFS, which exhibited a drop-in strength due to conversion. These concrete materials have also demonstrated excellent chemical resistance and a decreased temperature increase during the curing process. [56,57]. The reaction that circumvents the conversion process can be generated as follows [56,58,59]. The inclusion of minerals with high silica concentration would react with calcium aluminates, preventing the synthesis of C_2AH_8 initially and subsequently converting it into C_3AH_6. Instead of the cubic phase, a hexagonal hydrated compound called startlingite or gehlenite (C_2ASH_8) is produced. Majumdar et al. has hypothesized that the quantity of C_2ASH_8 is contingent upon the ability of mineral addition to liberate silica [45]. Roger et al (1984) proposed that the solution's composition should be in the state of supersaturation with regard to C_2AH_8 after five minutes of mixing. The composition of the solution shifts towards supersaturation in relation to CAH_{10}, leading to the initial production of C_2AH_8, followed by the subsequent precipitation of CAH_{10}. Damitot et al (1996-97) proposed that the presence of lithium shortens the time it takes for a reaction to start by interacting with aluminum hydroxide. Adding a little quantity of lithium to aluminum hydroxide is enough to speed up its nucleation rate and decrease the duration of the induction period [60].

2.9 Self-Leveling Grout system

Self-leveling grout (SLG) is a cohesive and stable mixture that can be consolidated without the need for segregation, vibration, or compaction. The grout retains its homogeneity, ensuring a constant property throughout without any segregation. The composition consists of cementitious materials, aggregates, water, and admixtures that provide fluidity and stability to achieve the required performance standards. The quantity and dimensions of the coarse aggregate should be restricted to prevent it from obstructing or forming a barrier as it flows through densely packed reinforcement and narrow gaps, while yet remaining suspended in the paste [60]. High-performance superplasticizers are utilized to attain a paste or mortar system with optimal fluidity. SLG is a grout system that exhibits exceptional endurance as a result of its low water cement ratio. The self-compatibility of a grout system necessitates a high level of deformability in the paste or mortar, as well as resistance to segregation between the coarse aggregate and mortar.

2.9.1 Properties required from SCC

The SCC should have the following characteristics in its fresh state.

- The flow of concrete should evenly distribute over all sections of the formwork due to gravity.
- Concrete should be able to pass through formwork and reinforcing barriers smoothly without causing any obstruction.
- The concrete should possess sufficient cohesiveness and viscosity to prevent bleeding and segregation.

2.10 State of the art

This research involved creating fast-penetrating grouts with a very short open time for urgent strategic repairs. The chosen approach was to use full preplaced aggregate concrete (PAC). PAC is also known as two-stage concrete, and was initially used in the 1930s. As the name implies, PAC is made in two distinct processes [61,62]. First, a clean, gap-graded coarse aggregate is placed inside the formwork. Then, a specialized grout with enough flowability is utilized to fill the gaps and spaces in the course aggregate matrix. Typically, admixtures are included to enhance the characteristics of PAC, particularly its workability [63,64]. In contrast, traditional concrete is created by combining all the elements and subsequently pouring the mixture into the formwork. PAC contains a higher proportion of coarse aggregate, making up 60% to 70% of the overall volume. In traditional concrete, the course aggregate content comprises only 40% to 50% of the entire volume [65,66]. Thus, the reduction in volume of polymer-modified asphalt concrete (PAC) is significantly smaller compared to traditional concrete [6]. Moreover, PAC exhibits a larger density matrix because to increased pressure and direct contact between the coarse aggregate particles, resulting in enhanced strength [67]. In addition, the production cost of PAC is 25% to 40% lower than that of traditional concrete [64].

2.11 Research Significance

Most researchers suggest BD as pozzolanic material based on X-Ray Fluorescence (XRF) and X-Ray Diffraction (XRD) only but it is not the actual case. This paper allocates pozzolanic materials after qualifying XRF, XRD, SEM, Strength Index Test (SIT) and Modified Chapelle's Test (MCT). These tests will ensure the start and level of activation of pozzolanic properties and will be an addition to existing information. Furthermore, this study aims to create self-leveling grout systems with a high initial strength by utilizing the proven pozzolanic activity of brick dust and other secondary raw materials (SRMs). These systems are crucial in construction because they can offer effective and long-lasting solutions, especially in projects with strict time constraints.

CHAPTER 3: METHODOLOGY

3.1 Characterization of materials and experimental methods

3.1.1 Cement

Ordinary Portland Cement (OPC) of Grade 52.5, Type-1 conforming to ASTM C150-07 [68] was used in this research. X-ray Fluorescence (XRF) analysis was conducted to determine the chemical composition. The results can be found in Table 3.

3.1.2 Calcium Aluminate Cement (CAC)

CAC, CA50-600 was used in this research. The CAC refers to High Alumina Cement, which promotes rapid initial hydration of C_3A and C_4AF compounds when combined with lithium accelerator salts.

3.1.3 Fly Ash (FA)

Fly ash of class F was utilized to accomplish the desired workability (penetration speed) because of its smooth and spherical texture, which may be difficult to get with other supplementary cementitious materials (SCMs) that have irregular shapes, such as rice husk ash (RHA). Initially, FA from two different sources were obtained. First one is obtained from a local vendor from Karachi this Fly Ash was named as FA-K and second type was bought directly from coal power plant Sahiwal and is named as FA-S as shown in figure 3 (a) and (b) respectively.

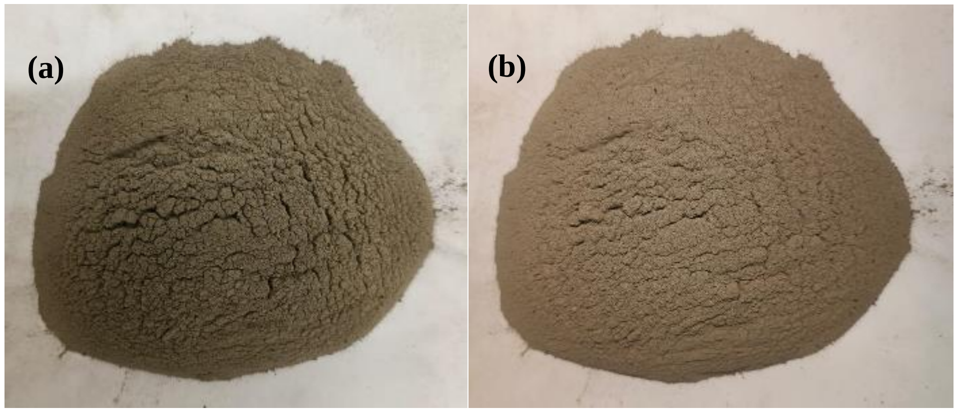

Figure 3 Powder images of a) FA-K, b) FA-S

3.1.4 Brick Dust (BD)

Brick dust is a finely powdered material obtained from crushed bricks or waste obtained from Brick Kilns. It is a rich source of silica and alumina, making it a suitable SCM for construction applications, including high-strength grout systems, concrete, and mortar. BD was also obtained from two different origins. First one is obtained from a Brick Kiln and named as BD-S while BD was also commercially available and is brought to study and was named as BD-C as shown in figure 4 (c) and (d) respectively.

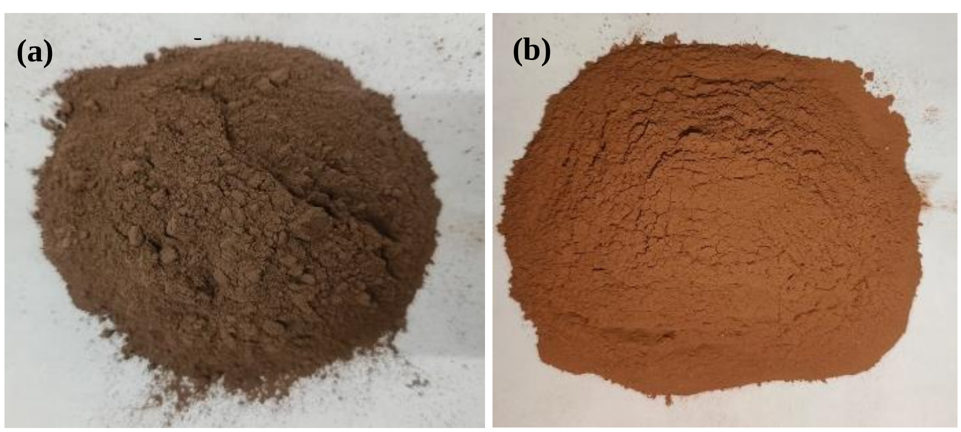

Figure 4 Powder images of a) BD-S and b) BD-C

3.1.5 Superplasticizer

Melflux 2651F, a very efficient water reducing agent, was utilized to produce self-leveling Grout (SLG) specimens. This super-plasticizer is classified as a third-generation poly-carboxylate ether (PCE) and was imported from BASF industries in Germany. For optimum results, the manufacturer suggests a dosage range of 0.05 to 1.00%. The third generation PCE Super plasticizers were first developed in Japan and Germany during the late seventies. [69].

3.1.6 Lithium Carbonate

Different kinds of accelerators have been explored to determine the most suitable option for facilitating CAC hydration. Out of all these substances, it has been discovered that lithium salts speed up initial hydration of CAC. In this research, Lithium Carbonate (Li_2CO_3) was utilized as an accelerator. The solution composition of cement undergoes hydrolysis, resulting in the rapid precipitation of lithium aluminate from the liberated aluminate. Aluminate is solubilized only when lithium is eliminated through precipitation [70].

3.1.7 Hemihydrate

Gypsum is the commonly used name for naturally occurring calcium sulphate dihydrate. The process of removing water from calcium sulphate dihydrate results in the formation of calcium modifications, occasionally referred to as calcium sulphate hemihydrate. [71,72]

$$CaSO_4.2H_2O + Heat \rightarrow CaSO_4.\ 0.5\ H_2O + 1.5H_2O \text{ [73]}$$

3.1.8 Seashore Pit Sand

Seashore pit sand is a quality material for construction, extracted from coastal areas. Its unique properties, such as high silica content, low silt and clay content, and good gradation, make it an ideal component for high-strength grout systems. The use of seashore pit sand in grout formulations enhances its flowability in self leveling grout systems. It also enhances compressive strength, and durability, allowing for superior bonding and resistance to chemical attacks, making it a vital component in demanding applications like preplaced aggregate concrete and high-performance grouting.

3.2 Formulations

In order to achieve the desired outcomes within the self-levelling grout system, various formulations of OPC and CAC were employed, as shown in Table 2. These formulations involved the utilization of different admixtures and raw materials, such as fly ash and brick dust to improve the characteristics of the grout systems.

3.3 Mixing Regime and Casting

The mixing regime adopted was as described below and was applied uniformly to all types of formulations. For a particular formulation, we put all the materials after weighing in a Hobart mixer. First dry mixing was done for 30 seconds so that any lumps if made were broken to powder form and mixed uniformly. Then we add approximately 70% of both water and superplasticizer and start mixing at low speed of 140 ± 5 rpm for 30 seconds. After this, we had stopped the mixer for 30 seconds and had scrap the walls of jar. By adding remaining 30% of water and superplasticizer, we had started mixing it again at medium speed of 280 ± 5 rpm for 90 seconds. Once all mixing was done, sample was taken for casting. Total duration for mixing was 3 minutes. Prisms with dimensions of 40 x 40 x 160 mm^3, as specified by BS EN 196-1[74], were created through casting. Figure 5(b) displays the casted prism samples.

Table 2 list of Self-Leveling Grout (SLG) Formulations

Formulation #	CAC %	OPC %	Fly Ash %	BD %	SP %	SAND %	w/b ratio	Detail Tag
F-1	100	0	0	0	1	50	24	F1-1C-0P-0F-0B
F-2	100	0	30	0	0.9	50	24	F2-1C-0P-0.3F-0B
F-3				5	0.94	50	24	F3-1C-0P-0.3F-0.05B
F-4			40	0	0.88	50	24	F4-1C-0P-0.4F-0B
F-5				5	0.91	50	24	F5-1C-0P-0.4F-0.05B
F-6	95	5	30	0	0.91	50	24	F6-0.95C-0.05P-0.3F-0B
F-7				5	0.94	50	24	F7-0.95C-0.05P-0.3F-0.05B
F-8			40	0	0.87	50	24	F8-0.95C-0.05P-0.4F-0B
F-9				5	0.92	50	24	F9-0.95C-0.05P-0.4F-0.5B
F-10	90	10	30	0	0.91	50	24	F10-0.9C-0.1P-0.3F-0B
F-11				5	0.95	50	24	F11-0.9C-0.1P-0.3F-0.5B
F-12			40	0	0.89	50	24	F12-0.9C-0.1P-0.4F-0B
F-13				5	0.93	50	24	F13-0.9C-0.1P-0.4F-0B

3.4 Characterization of powders

The powders were analyzed for particle characteristics, including size, shape, surface morphology, and interior porosity, using scanning electron microscopy (SEM), X-Ray fluorescence (XRF), X-Ray Diffraction (XRD) analysis, Laser Particle Size analysis (LSP) and Brunauer–Emmett–Teller (BET) surface area analyzer. The findings were also utilized to elucidate the relationship between water and SP demand, flow characteristics, strength, hydration kinetics, and microstructure of binder blends in the self-leveling grout system.

3.5 Flow Measurements

To achieve a target flow of 35 ± 1 cm to make our grout self-leveling as shown in figure 5(a), many trials were conducted using Hagerman's mini slump cone apparatus, which has cone dimensions of 10 x 7 x 6 cm^3. The calculation of the SP demand, which primarily regulates the flow of the self-compacting grout systems, was determined by experimental trials for each formulation.

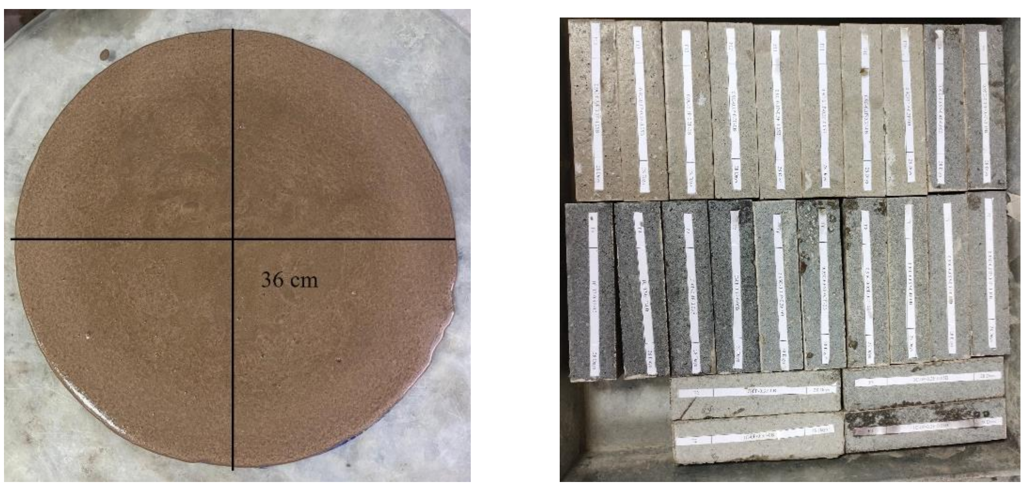

Figure 5 a) Flow through Hangerman Mini Slump Cone and b) Casted Prisms

3.6 Penetration Speed Test

The speed of penetration of the self-compacting paste and mortar (grout) system was determined by inserting ¾ inch preplaced aggregate into a graduated jar and subsequently pouring the paste or mortar from the top as shown in figure 6. The duration required for the material to descend to the base of the aggregate was computed in order to ascertain the velocity at which the self-compacting paste or grout system infiltrates.

Figure 6 Glass Jar for Penetration Speed

3.7 Hydration Kinetics

The hydration kinetics of blended binders were analyzed by measuring heat release using the FCAL 8100 Field Calorimeter as shown in figure 7, in order to investigate the hydration kinetics of various formulations. During the first reaction stage, a substantial amount of heat was generated as a result of the hydration of the aluminate phase. This was followed by a notable decrease in heat release and a period of inactivity. Subsequently, there was a gradual increase in heat release known as the acceleration stage, which was then followed by a decrease in the rate of heat release, known as the deceleration stage.

Figure 7 F-Cal 8100 for Hydration Kinetics

3.8 Shrinkage Strains

Shrinkage leads to the formation of small cracks in the SLGs. The determination of volume changes or shrinkage was conducted using the German Schwindrine equipment, which has a channel dimension of 4 x 6 x 25 cm^3 as shown in figure 8. The initial reactions were documented within the initial 24-hour period for each mixture. The laboratory had a relative humidity of 55% and a temperature of 24°C.

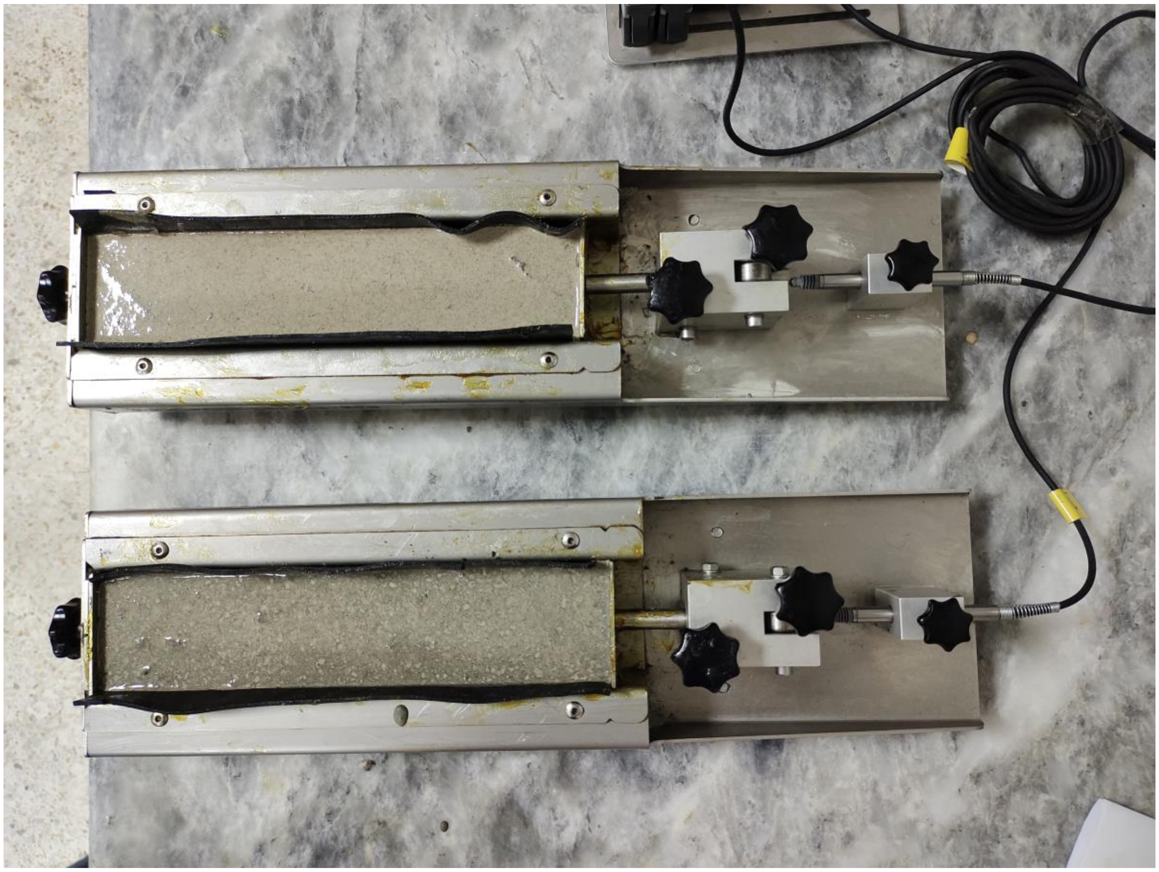

Figure 8 Shrinkage Drain for Shrinkage strains

3.9 Strength Properties

The mechanical properties, specifically the flexural and compressive strength, were measured at the ages of 1 hour, 3 days and 28 days, following the guidelines of EN 196-1. The samples were removed from the moulds after 40 minutes and cured by immersing them in water at a temperature of 20±2 degrees Celsius as shown in figure 9. The flexural strength was determined by taking the average value of three specimen prisms at the necessary ages, while the compressive strength was determined by taking the average of five specimens.

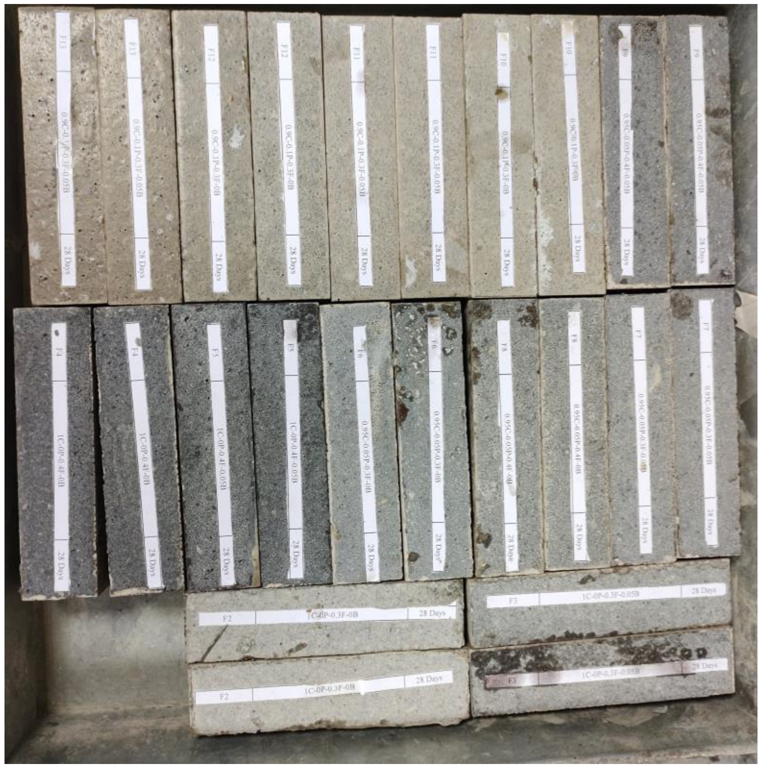

Figure 9 Fresh Samples taken out from mould

3.10 Modified Chapelle's Test

The modified Chapelle test[75] is a laboratory test used to evaluate the pozzolanic activity of supplementary cementitious materials (SCMs) like brick dust (BD). The test involves mixing the SCM with calcium hydroxide and measuring the volume reduction of the mixture over time. The pozzolanic activity value is calculated based on the volume reduction and is expressed in ml/50g. The test provides a quick and reliable method to assess the reactivity of SCMs and their potential to improve the strength and durability of cementitious mixtures. Apparatus setup is shown in figure 10.

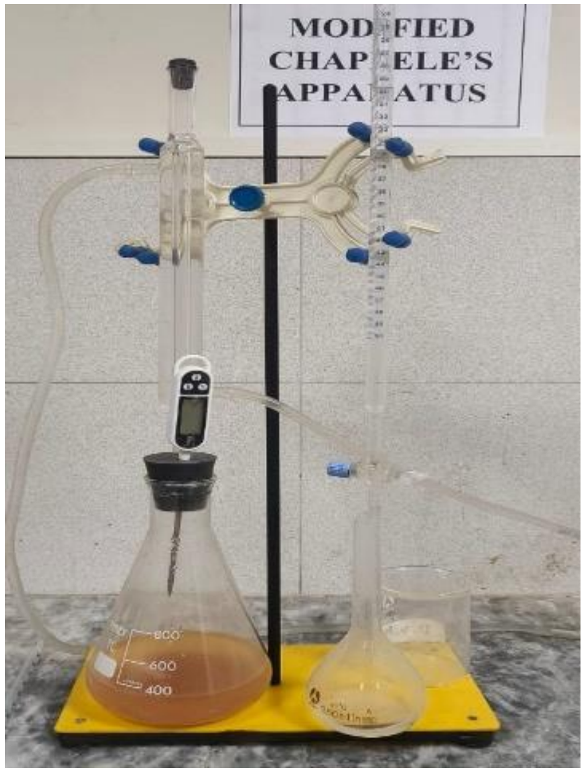

Figure 10 Modified Chapelle's Test Apparatus

3.11 Brunauer-Emmett-Teller (BET)

The Brunauer-Emmett-Teller (BET) test was conducted to evaluate the specific surface area and pore size distribution of the brick dust (BD) and its blends with other supplementary cementitious materials (SCMs). The BET test measures the amount of nitrogen gas adsorbed onto the surface of the particles, providing insight into the material's surface area, pore volume, and pore size distribution.

3.12 Compressive strength of preplaced aggregate concrete

The compressive strength of the preplaced aggregate and preplaced mortar system was determined using square molds measuring 4" x 4". Position the aggregate with a size of ¾ inch on top of a layer of paste measuring 3/4 inch. Proceed to pour self-compacting mortar and paste from the top until the mold is completely filled. Complete the surfacing of the specimen and maintain it within the mold for a duration of 12-15 minutes as shown in figure 11. After demolding samples were submerged in water, and then a compressive strength test is conducted at a specific time.

Figure 11 Preplaced Aggregate Concrete (4 inch cube)

CHAPTER 4 : RESULTS & DISCUSSIONS

4.1 Chemical and Physical Properties of powders

XRF analysis had been done on different powders used in this study to look into the chemical composition of these powders as shown in Table 3. In order to be classified as pozzolanic according to ASTM C618, the sum of the quantities of SiO_2, Al_2O_3, and Fe_2O_3 of any material should be greater than 70% [76]. From the results, it's clear that both types of brick dust and fly ash fall in this category and can be used as pozzolanic material as the sum of these oxides is greater than 70%. Average particle size had been determined through laser particle size analyzer and is also shown in Table 3. Particle size of Fly Ash is very fine and that also play vital role in strength enhancements due to filling effect.

Table 3 Chemical and Physical Analysis of Powders

Chemical Composition		OPC	CAC	BD-S	BD-C	FA-K	FA-S
SiO_2	**%**	20.63	12.46	49.91	61.35	35.86	48.78
Al_2O_3	**%**	5.69	51.29	15.54	12.91	21.89	27.18
Fe_2O_3	**%**	4.35	2.45	12.02	6.19	12.23	4.09
CaO	**%**	59.77	36.8	5.7	5.38	10.69	8.59
MGO	**%**	2.43	1.7	1.69	2.17	3.81	1.52
K_2O	**%**	0.7	0	1	2.22	0	0.35
Na_2O	**%**	0.05	1.1	1.52	1.8	4.42	0.35
SO_3	**%**	2.92	1.82	12.65	7.88	10.35	2.31
CL	**%**	0.006	0.1	0.004	0.005	0.03	0.03

D_{50}	**µm**	2.04	2.34	2.135	2.133	0.44	0.48
Surface Area	**m^2/g**	-	-	-	1.3628	-	4.5656

4.2 X-Ray Diffraction (XRD) of Powders

Usually a powder can either be amorphous or crystalline. These compounds were identified by using XRD analysis and results are shown in Figure 12. Xpert-Highscore and Origin Lab was used for processing of raw XRD data. From the results we can clearly identify the compounds present in that material and their crystallographic nature. Results shows that BDS has high amount of crystalline Quartz (SiO_2) as compared to BDC. This leads us to exclude BDS for further use in this study as any material to be used as a pozzolanic material should have more amorphous phases than crystalline phases. Same is the case with FA-K which had more amount of crystalline quartz. Final materials selected for further formulations and casting were therefore BD-C and FA-S with other powders.

4.3 Scanning Electron Microscopy (SEM) of Powders

SEM analysis was done to get more information about morphology and insights of materials. Figure 13 shows SEM results of BDS, BDC, and FA. These images are the confirmation of XRD results. In BDS image, one can clearly see multiple crystalline phases while in BDC, less crystals are visible and more soft structure can be seen which pointed towards the amorphous nature of material. FA has round spherical particle which can be seen in Figure 13c**.** These round particles are responsible for increasing workability of the system.

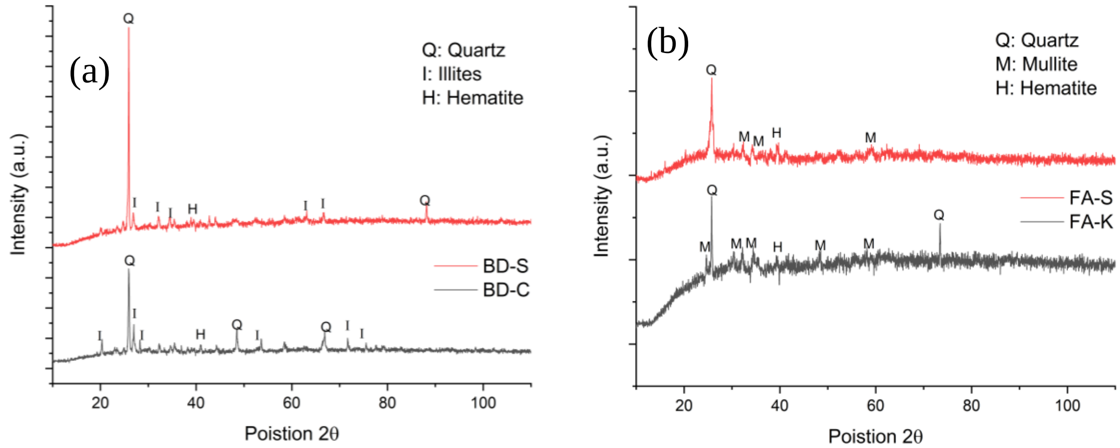

Figure 12 XRD Analysis of a) BD and b) FA

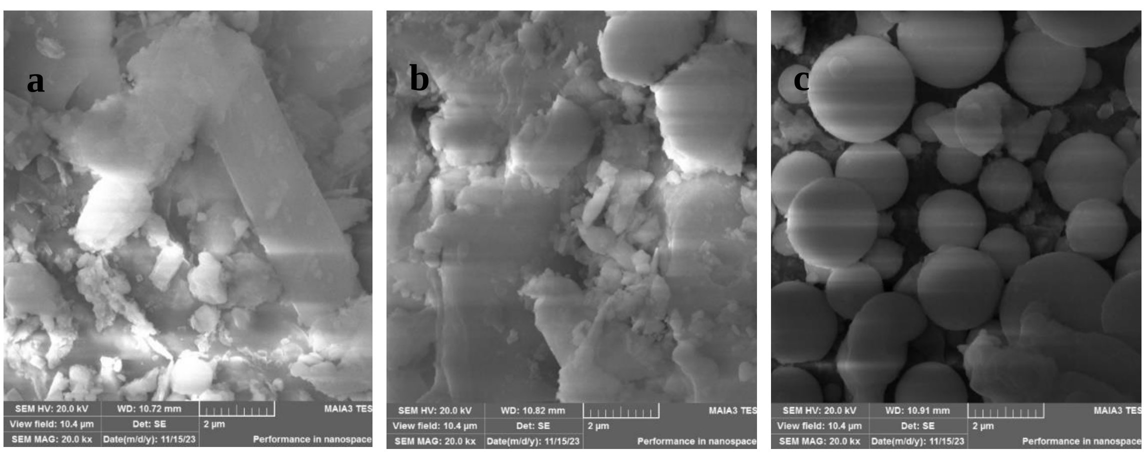

Figure 13 SEM Analysis of powders a) BDS b) BDC and c) FAS

4.4 Surface Area Analysis

Brunauer–Emmett–Teller (BET) surface area analyzer was used to find out the surface area of selected powders as shown in Table 3. Absorption and desorption curves were also plotted as shown in figure 14. Desorption hysteresis, which is a difference between the adsorption and desorption curves, provides significant insights on the pore structure and connectivity of the material. The presence of a small hysteresis loop in the FA curve indicates the presence of well-connected pores, which allows for easy access to adsorption sites and reversible adsorption. On the other hand, the large hysteresis loop observed in the BD curve suggests the presence of poorly connected pores or "ink-bottle" pores, which makes it difficult to access adsorption sites and leads to irreversible adsorption. The decline in the final value of the desorption curve of the BD curve shows the presence of trapped gas within the material, which is indicative of the existence of mesopores and inadequate pore connectivity. The curves demonstrate that FA possesses a pore structure that is more spacious and easier to enter, whereas Brick Dust has a pore structure that is more intricate and limiting, which affects its effectiveness in many applications such as adsorption and catalysis.

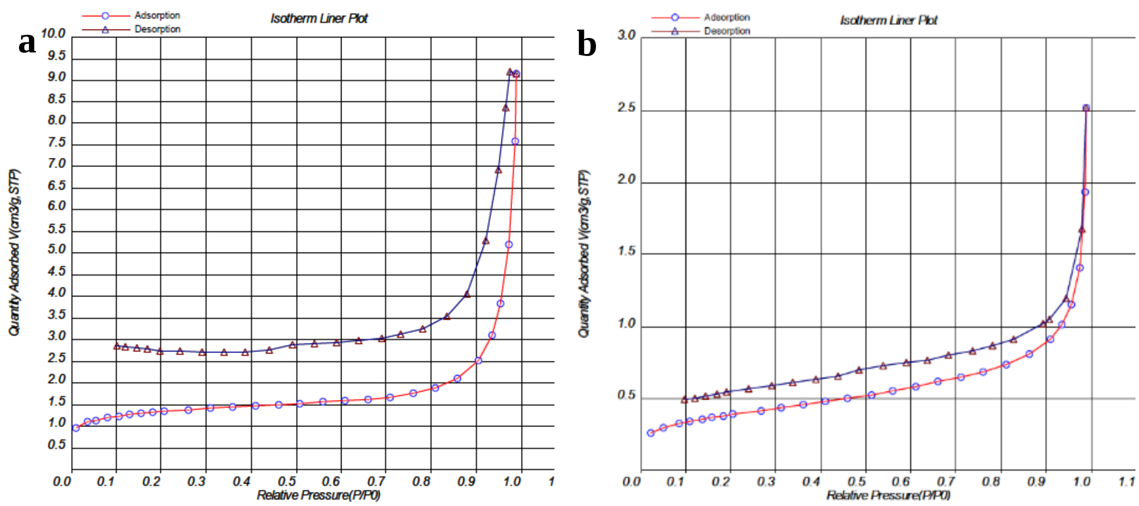

Figure 14 BET Analysis of a) BDS and b)FAS

4.5 Sieve Analysis and Fineness Modulus of Sand

Sieve analysis of seashore pit sand was done in accordance with ASTM C136 [77] and particle size distribution curve had been plotted to find out the average particle size (D_{50}) of sand as shown in figure 15. The fineness modulus (F.M) comes to be 2.56 for the sea shore pit sand which indicates that the sand has a relatively coarser particle size distribution compared to regular sand, which may affect the performance of our self-leveling grout system. The larger particles may lead to a slightly reduced flowability and workability of the grout. However, the coarser particles may also provide improved strength and durability to the grout, which would be beneficial in our application.

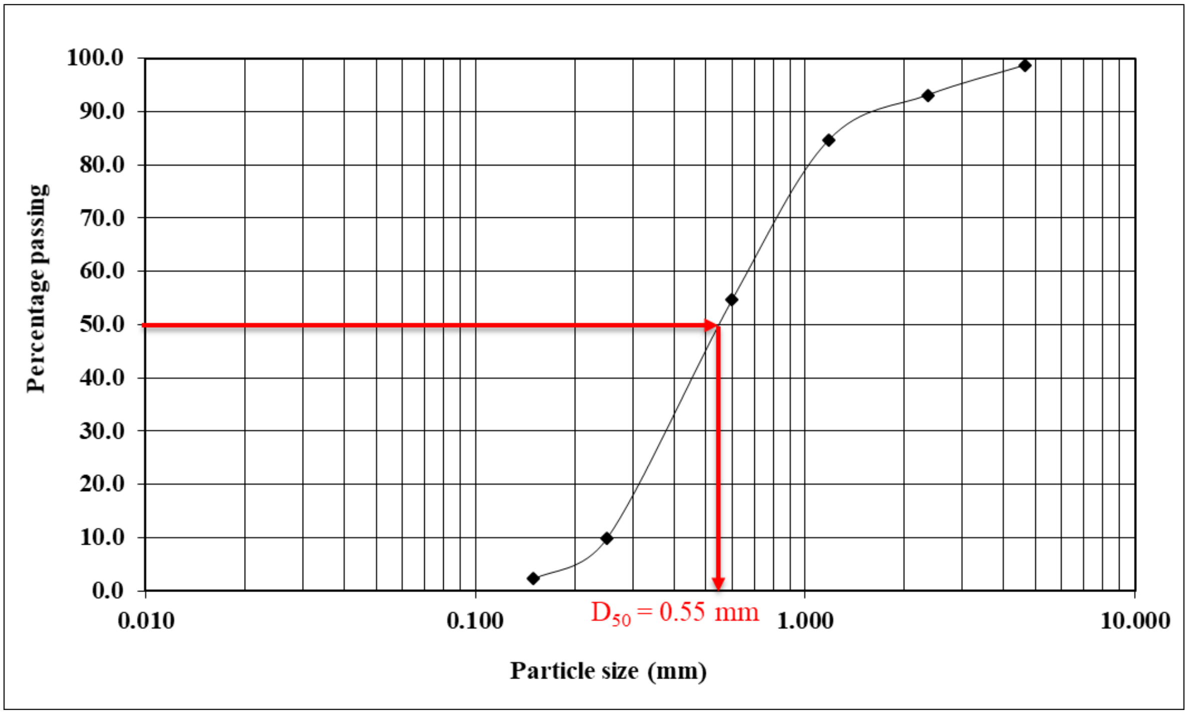

Figure 15 Particle Size Distribution Curve of Seashore Pit Sand

4.6 Superplasticizer Demand of SLGs Formulations

The Superplasticizer (SP) demand varies across the different formulations due to the distinct properties of each component as shown in Figure 16. In general, any changes to the formulation that alter the mix's water demand, particle size distribution, or surface chemistry can either increase or decrease the SP demand, depending on the specific properties of the added or replaced components. The addition of FA-S decreases the SP demand because its spherical shape and pozzolanic activity improve the mix's workability and reduce the water demand, making the mix more cohesive and requiring less Superplasticizer. On the other hand, the addition of BD-C increases the SP demand due to its irregular shape and high-water absorption, making the mix more fluid and requiring more Superplasticizer to maintain workability. Similarly, the replacement of CAC with OPC increases the SP demand because OPC has a different particle size distribution and surface chemistry than CAC, affecting the mix's water demand and workability.

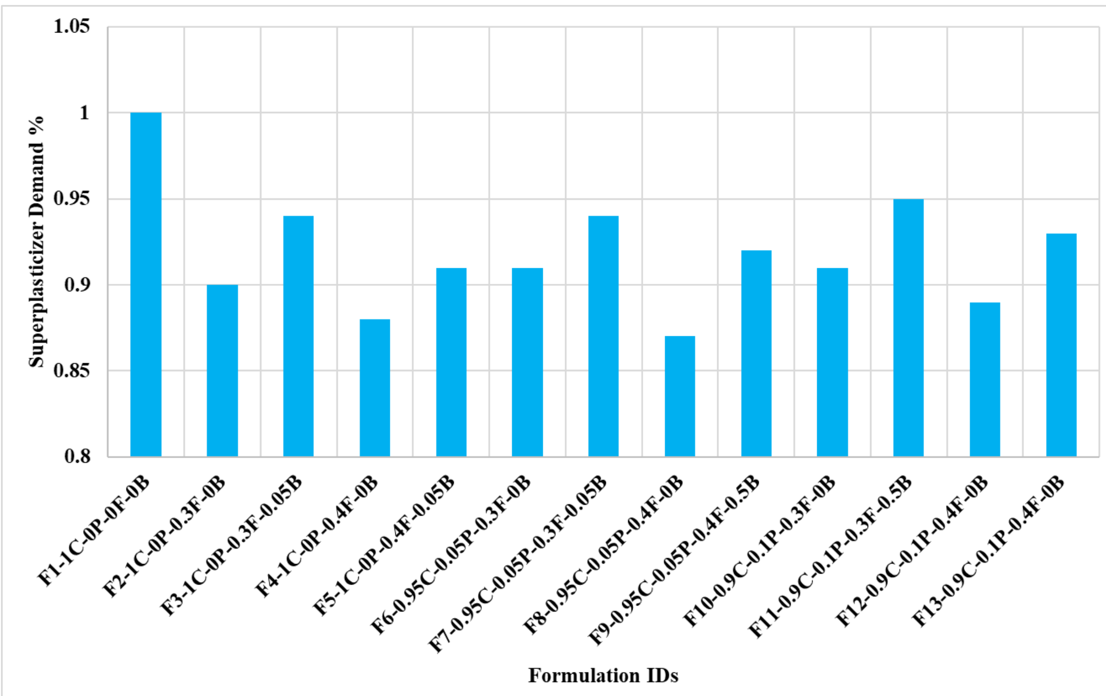

Figure 16 Superplasticizer demand of SLG's Formulations

4.7 Setting Times of SLGs Formulations

The setting times of self-leveling grout systems formulations vary depending on the composition as shown in Figure 17. As OPC is replaced with CAC, the initial setting time shortens due to CAC's faster reactivity. The addition of FA further reduces setting times as its finer particles enhance the grout's early strength development. In contrast, the introduction of BD slightly increases setting times, as its coarser particles slow down the grout's early strength gain. Overall, the proportion of CAC and the addition of FA and BD influence the setting times, with CAC's faster reactivity driving the shortenings of initial setting times.

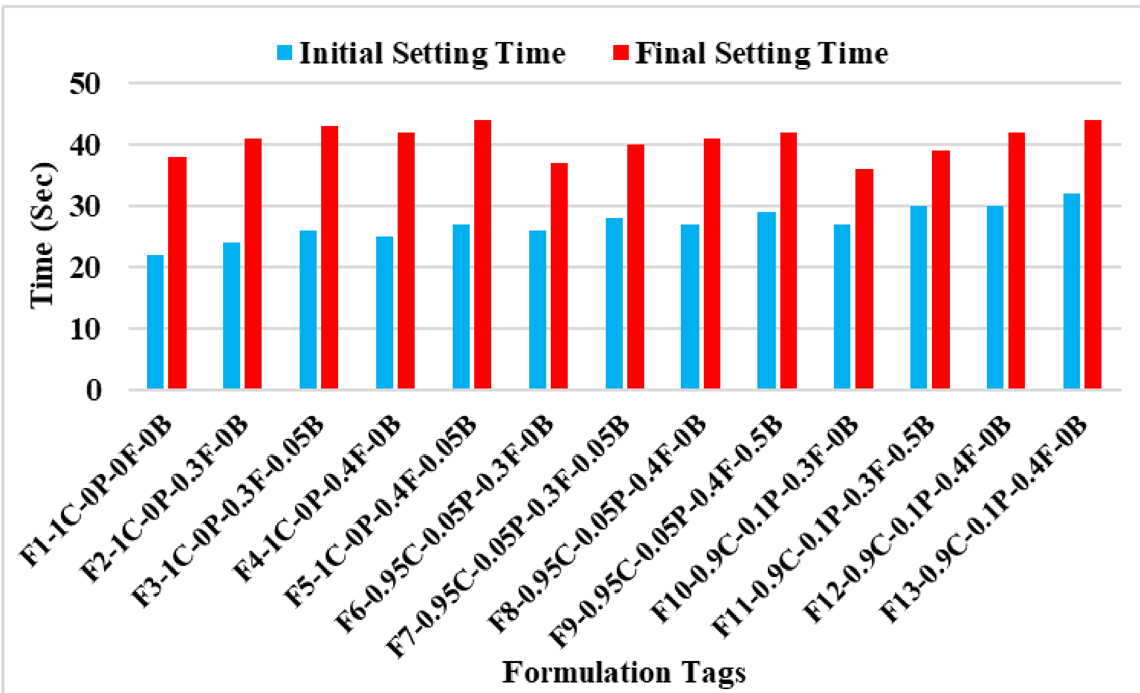

Figure 17 Setting Times of SLG's Formulations

4.8 Compressive and Flexure Strength of SLGs Formulations

The compressive and flexure strength of the formulations is influenced by the interactions between the different components. Results are shown in Figure 18 & Figure 19. The addition of FAS reduces the early strength (1 hour and 3 days) but increases the later strength (28 days) due to its pozzolanic activity, as seen in formulations F2-F13. However, the inclusion of BDC leads to a reduction in compressive strength at initial ages (1 hour and 3 days), likely due to its high-water absorption and low reactivity, as observed in formulations F3, F5, F7, F9, and F11 but have increased later strength due to late pozzolanic activity of BD. On the other hand, replacing Calcium Aluminate Cement (CAC) with Ordinary Portland Cement (OPC) increases the compressive strength at all ages, as seen in formulations F6-F13, likely due to OPC's higher reactivity and faster hydration rate. Overall, the control mix (F1) with 100% CAC shows high early strength but lower later strength, while the replacement of CAC with OPC and the addition of FA-S and BD-C improves the later strength, indicating the complex interactions between these materials in cementitious systems. F11 shows best results both in terms of compression and flexure due to the incorporation of FA-S, BD-C and 10% OPC in replacement with CAC. And the major phenomena for this strength enhancement at 28 days strength is the pozzolanic activity of FA-S and BD-C.

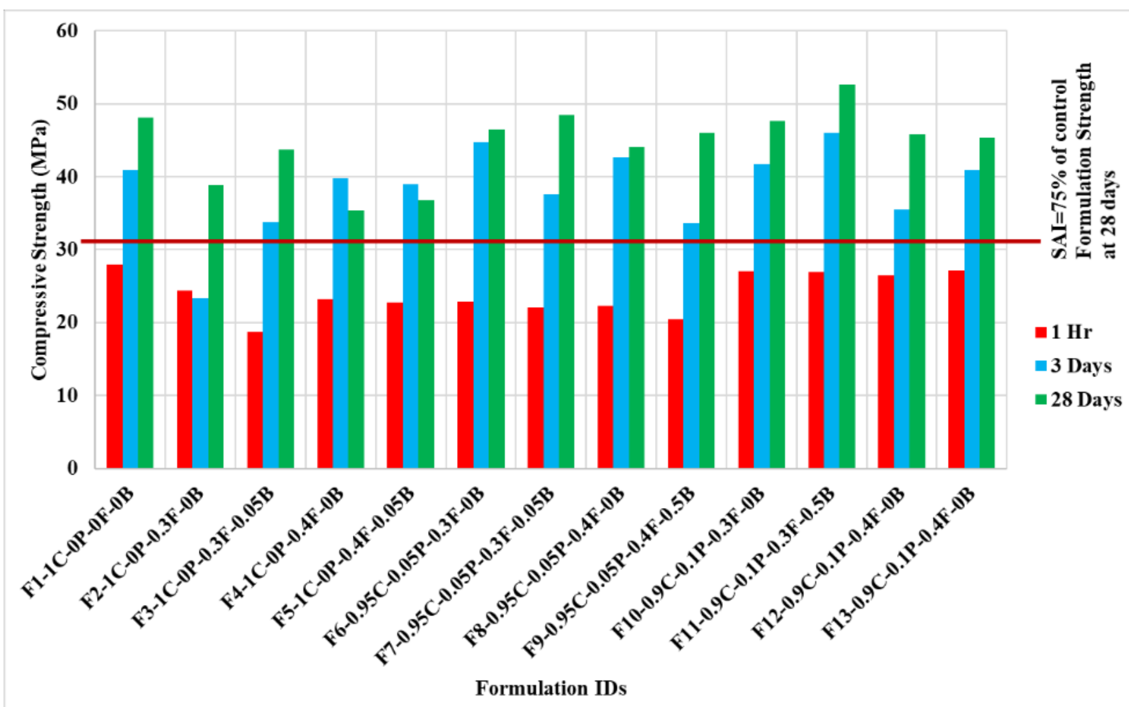

Figure 18 Compressive strength of SLG's Formulations

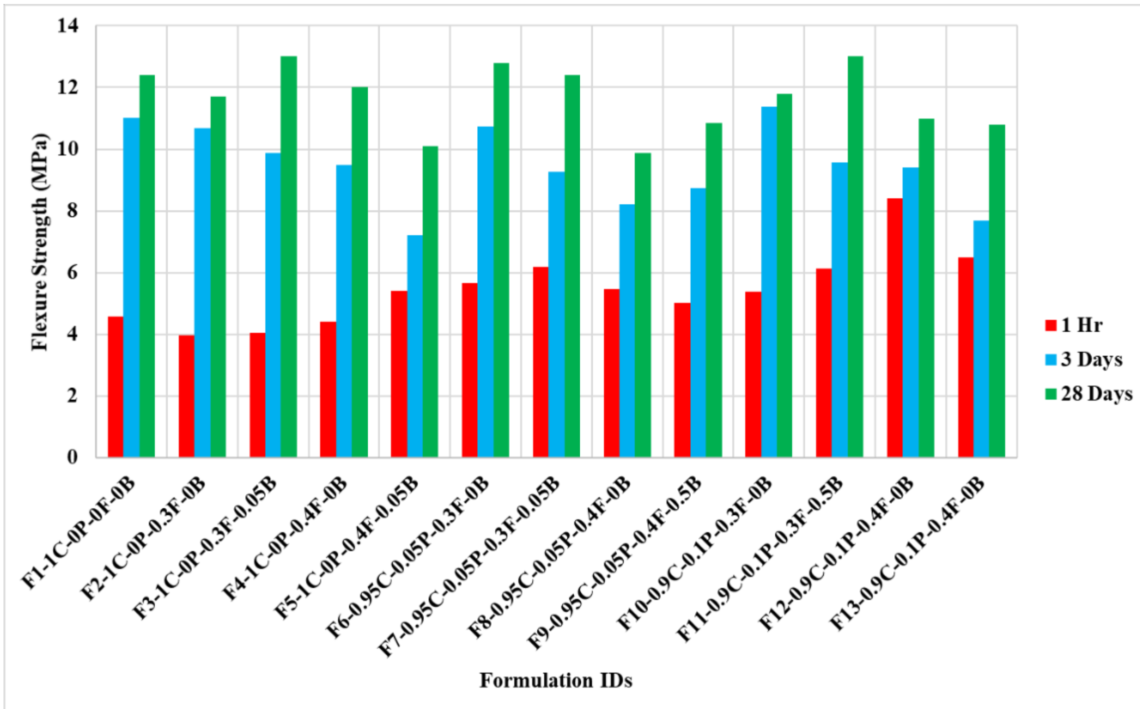

Figure 19 Flexural Strength of SLG's Formulations

4.9 Strength Index Test

The compressive strength results at 28 days, which are all greater than 75% of the control formulation as shown in Figure 18, indicate that BDC exhibits pozzolanic activity. This is evident from the strength index test, which evaluates the ability of a SCM to contribute to the strength of a cementitious mixture [76]. The BD-C containing formulations (F3, F5, F7, F9, and F11) demonstrate a significant strength gain, with values exceeding 75% of the control formulation (F1), indicating a high level of pozzolanic activity. This suggests that the BD reacts with the calcium hydroxide produced during hydration, forming additional calcium silicate hydrates and thereby increasing the compressive strength of the mixture. The pozzolanic activity of BD is further supported by its ability to improve the later-age strength (28 days) of the mixtures, which is characteristic of SCMs with high pozzolanic activity. Overall, the strength index test results confirm the pozzolanic activity of BD, highlighting its potential as a supplementary cementitious material for improving the strength and durability of concrete.

4.10 Hydration Kinetics of SLGs Formulations

The calorimeter curves as shown in Figure 20 and Figure 21 reveal the heat of hydration of the formulations, with F1 (1C-0P-0F-0B) exhibiting a high cumulative temperature peak due to its high content of CAC, a highly reactive and heat-generating component. In contrast, F10 (0.9C-0.1P-0.3F-0B) displays an intermediate curve, as the addition of OPC and Fly Ash moderates the heat of hydration, introducing a more balanced reactivity. Meanwhile, F11 (0.9C-0.1P-0.3F-0.5B) shows a significantly lower curve, as the introduction of Brick Dust, an inert material, further reduces the heat of hydration, resulting in a more subdued thermal response. This gradual decrease in heat of hydration from F1 to F11 is a direct consequence of the progressive replacement of CAC with OPC, Fly Ash, and Brick Dust, each contributing to a more tempered reactivity and thermal profile.

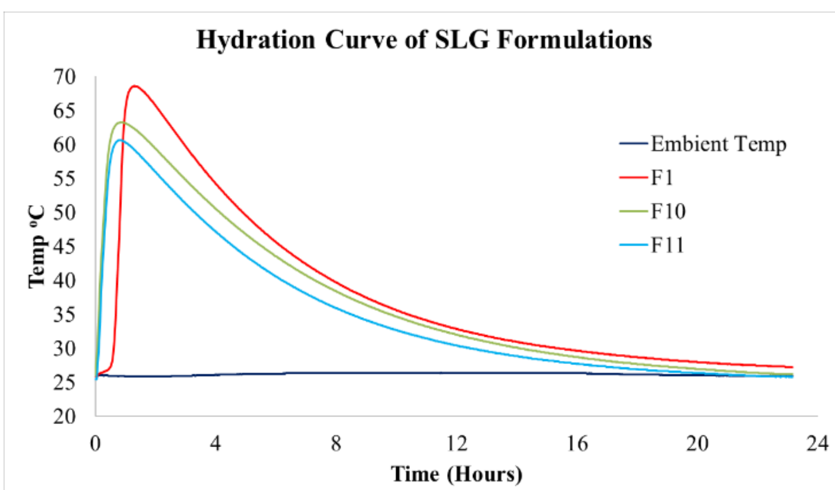

Figure 20 Hydration Kinetics of SLG's Formulation

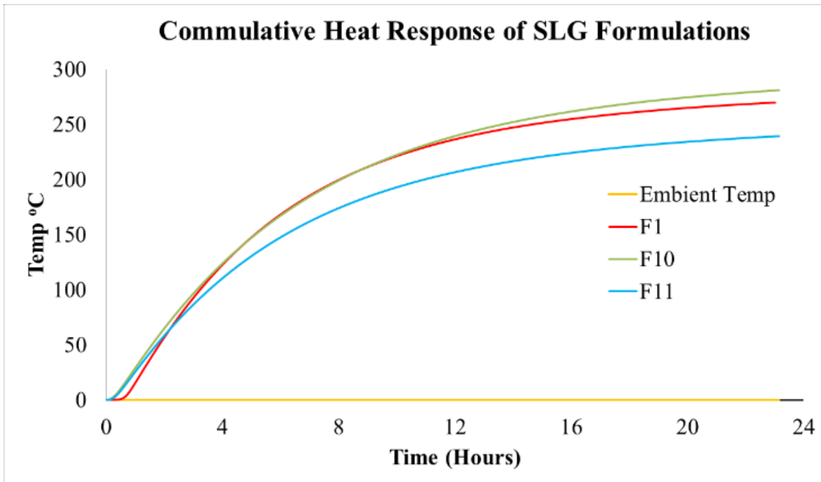

Figure 21 Cumulative curves of SLG's Formulation

4.11 Shrinkage Response of SLGs Formulations

The total early-age linear shrinkage responses as shown in Figure 22 reveals that F1, with its high CAC content, exhibits the most pronounced early age linear shrinkage and cracking, likely due to the high heat of hydration and rapid hydration rate, which generates significant internal stresses and shrinkage strains. In contrast, F10, with its balanced composition of CAC, OPC, and Fly Ash, displays a moderate shrinkage response, as the more tempered hydration kinetics and heat of hydration reduce the internal stresses and shrinkage strains. Meanwhile, F11, with its high content of inert Brick Dust, exhibits the least shrinkage and cracking, as the reduced reactivity and heat of hydration minimize the internal stresses and shrinkage strains, resulting in a more stable and less shrinkage-prone material. This progression from F1 to F11 reflects the impact of compositional changes on the hydration kinetics, heat of hydration, and ultimately, the shrinkage response of the formulations.

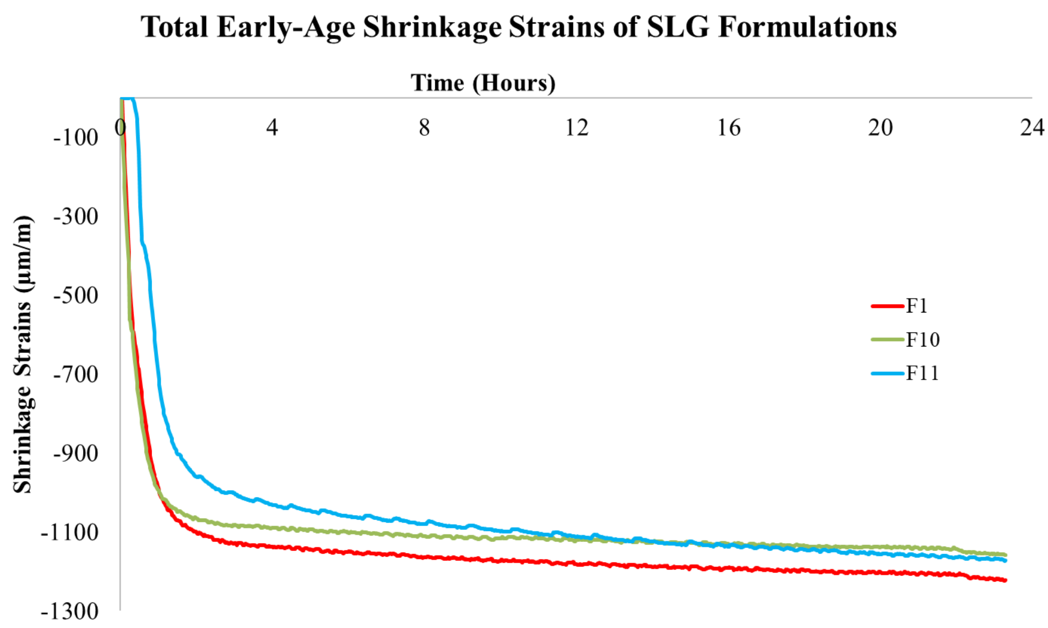

Figure 22 Shrinkage response of SLG's Formulations

4.12 XRD ANALYSIS

The XRD analysis as shown in Figure 23-25 revealed the presence of various phases in the cementitious mixtures of F1, F10, and F11 at different ages of 1 hr, 3 days, and 28 days. At early ages (1 hr), the XRD patterns showed a predominance of calcium aluminate hydrates (CAH) and calcium oxide (CaO), while at later ages (3 days and 28 days), additional phases such as calcium aluminate silicate hydrates (CASH), calcites, cowlesite, gibbsite (AH), killalaite ($C_2H_6S_{10}$), stratlingite ($C_2A_2S_7H_8$), wollastonite, and xonotile (C_6SH_2) were found. The increase in crystalline count of these phases with age suggests a progressive strengthening of the mixtures, contributing to the compressive strength. The development of the phases over time indicates a pozzolanic activity of BD, which reacts with calcium aluminate hydrates to form additional CASH phases, leading to a denser microstructure and improved durability.

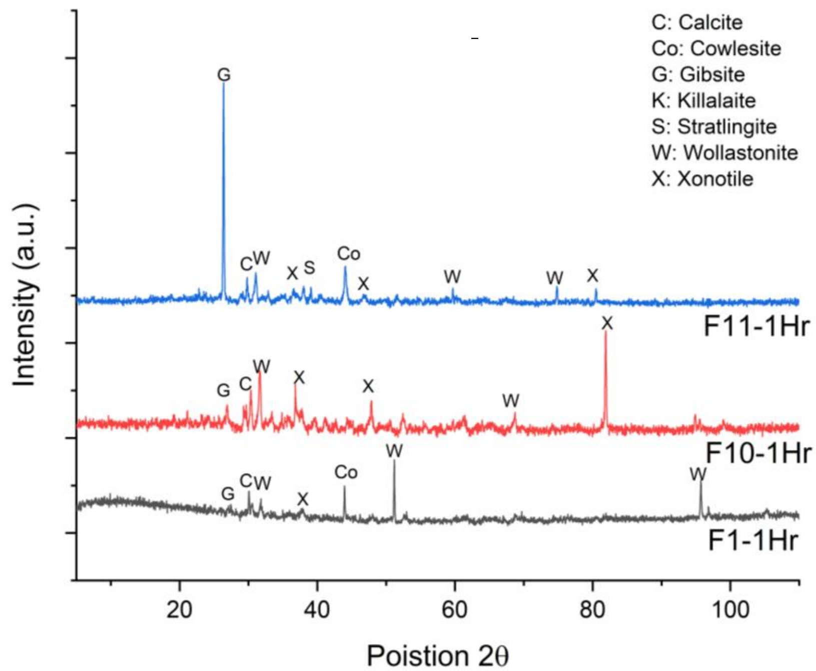

Figure 23 XRD Analysis of SLG's formulations at 1 hr

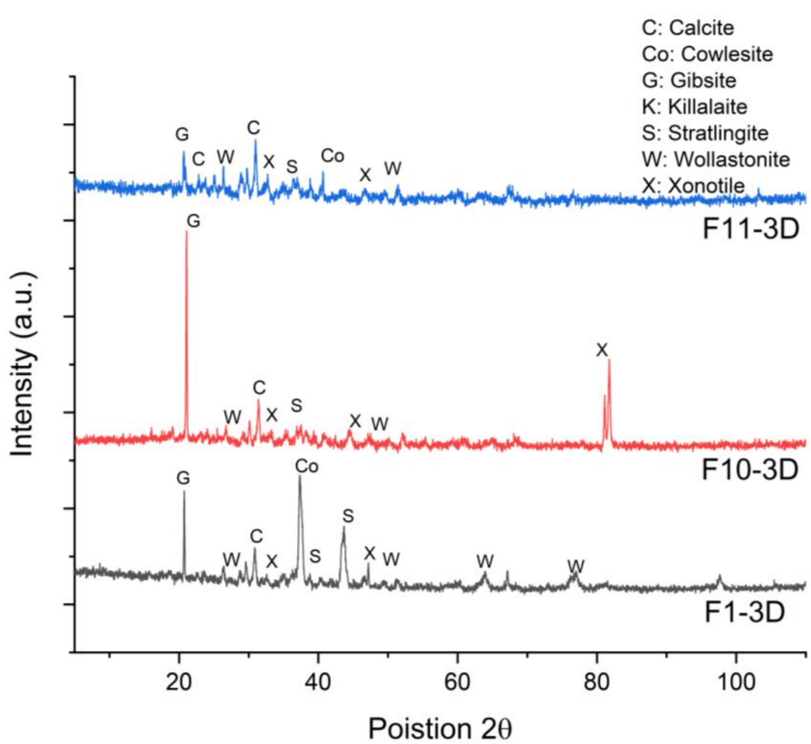

Figure 24 XRD Analysis of SLG's formulations at 1 3 Days

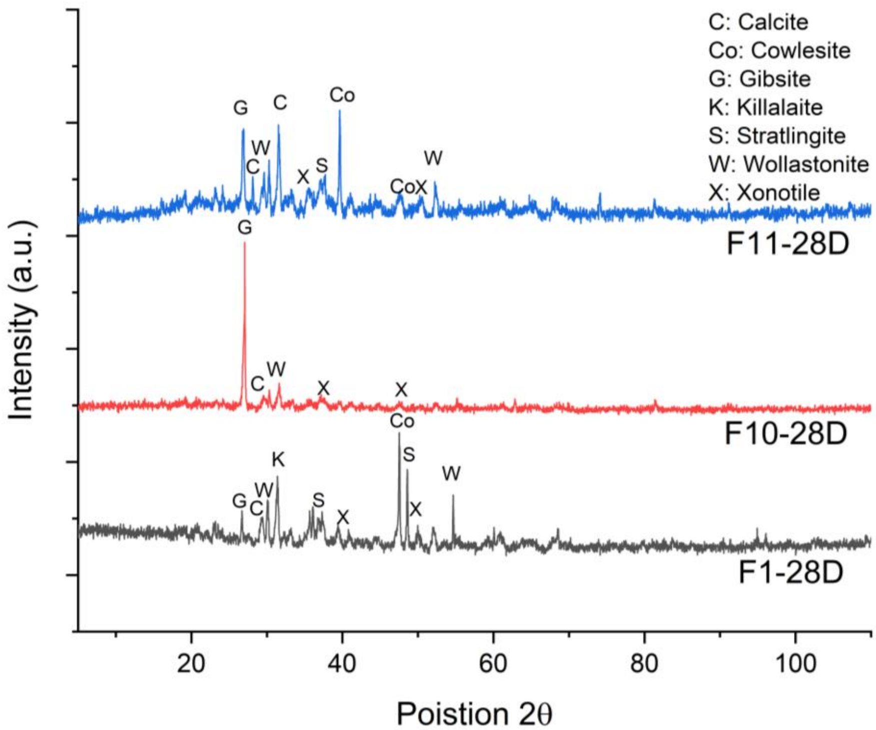

Figure 25 XRD Analysis of SLG's formulations at 28 Days

4.13 SEM Analysis of SLG’s Formulations

The SEM analysis as shown in figure 26-28 revealed a diverse microstructure and morphology of the elements in the cementitious mixtures of F1, F10, and F11 formulations at different ages of 1 hr, 3 days, and 28 days. At early ages (1 hr), the microstructure showed a more porous and disordered arrangement of calcium aluminate hydrates (CAH), while at later ages (3 days and 28 days), a denser and more organized microstructure with visible BD particles was observed. The BD particles appeared to be intimately mixed with the CAH, indicating a strong interfacial bond. The development of the microstructure over time suggests a progressive strengthening of the mixtures, contributing to the compressive strength. The morphology of the elements, such as the spherical shape of calcites and the fibrous structure of wollastonite, can provide a favorable microstructure for load transfer and resistance, thereby enhancing the compressive strength.

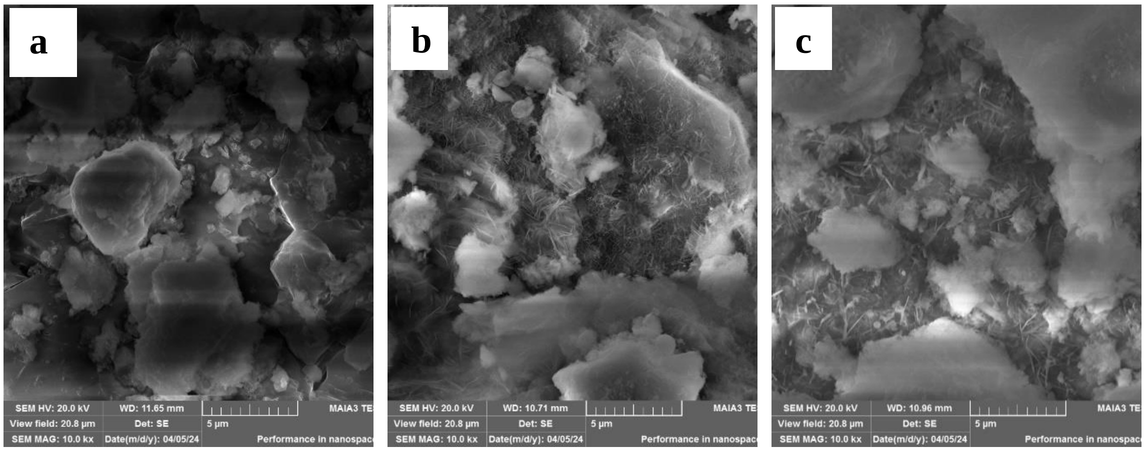

Figure 26 SEM Analysis of a) F1 b) F10 and c) F11 formulations at 1 hr

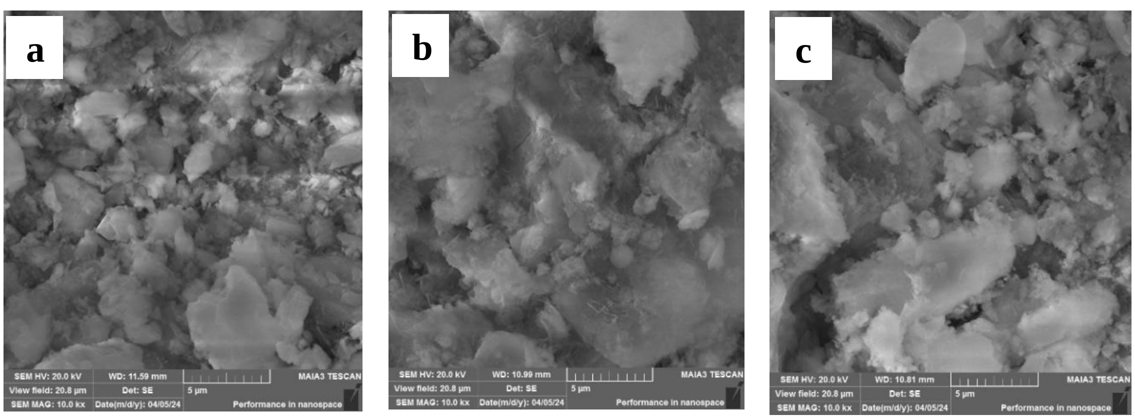

Figure 27 SEM Analysis of a) F1 b) F10 and c) F11 formulations at 3 Days

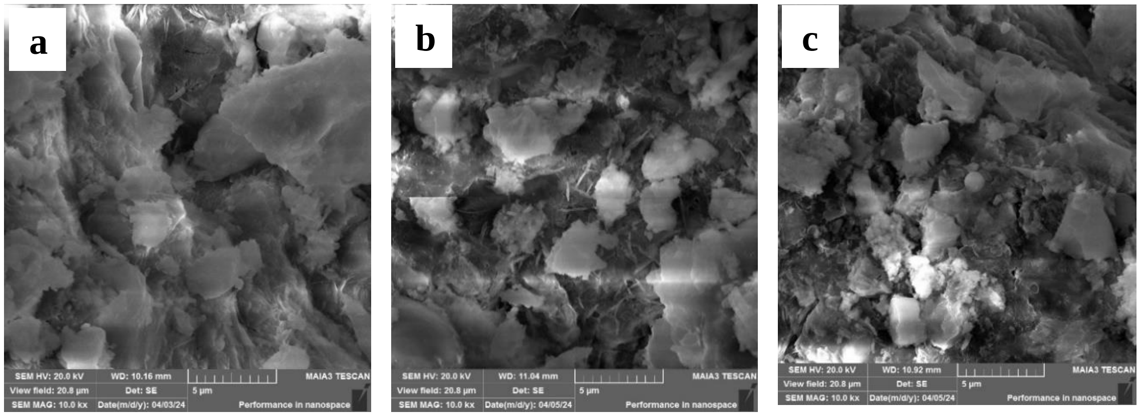

Figure 28 SEM Analysis of a) F1 b) F10 and c) F11 formulations at 28 Days

4.14 Modified Chapelle's Test of BD

The modified Chapelle test results indicate a pozzolanic activity value of 1057 for the BD-C, which is significantly higher than the standard value of 850-950 for a typical pozzolan. This suggests that the BD exhibits high reactivity and potential to react with calcium hydroxide, leading to the formation of additional calcium silicate hydrates and improved strength and durability. The blank sample (V1=10 ml) served as a control, while the BD sample (V2=6 ml) showed a substantial reduction in volume, indicating a high level of pozzolanic activity. This result confirms the XRD and SEM analysis, which showed the formation of calcium aluminate silicate hydrates and a denser microstructure at 28 days as show in figure 15 (c) and figure 18 respectively. The high pozzolanic activity value of 1057 supports the use of BD as a SCM to enhance the properties of the cementitious mixtures.

4.15 Penetration test of SLGs formulations

A penetration speed test was conducted to ensure that the paste and mortar have completely permeated and that no honeycombing has occurred. The analysis focuses on the penetration speed of various formulations based on their specific requirement for SP. The desired penetration speed was set at 1 m/s and was successfully reached at a rate of 0.9 m/s, which is in close proximity to the target. A speed penetration test ensures complete penetration of paste into preplaced aggregate.

4.16 BET of SLG's Formulations

The results of the BET test revealed that the addition of BD increased the specific surface area of the blend, indicating a higher reactivity and potential for improved pozzolanic activity. Furthermore, the pore size distribution analysis showed a shift towards smaller pores, suggesting a more refined microstructure and enhanced durability. The BET test results complemented the XRD and SEM analysis, providing a comprehensive understanding of the material's physical and chemical properties and their impact on the grout's performance.

CHAPTER 5 : CONCLUSIONS

In conclusion, the comprehensive investigation of Brick Dust (BD) as a Supplementary Cementitious Material (SCM) has demonstrated its potential to enhance the properties of high early strength grout systems, particularly for preplaced aggregate concrete applications where open time is limited. Some other supports conclusions are as follows.

- The chemical composition and crystalline structure of BD, as revealed by XRD and XRF analysis, show its suitability as a SCM. The presence of silica and alumina in BD's chemical composition contributes to its pozzolanic activity, which is further confirmed by various tests.
- BD's pozzolanic activity is evident from the results of the strength index test, modified Chapelle's test, and BET test. The BET test, in particular, highlights BD's increased specific surface area and refined pore size distribution, indicating its potential to enhance the grout's mechanical properties.
- The interfacial bond between BD and cement hydrates, as observed through SEM analysis, is strong and contributes to the improved strength and durability of the grout. The refined microstructure resulting from this bond leads to enhanced mechanical properties.
- Formulation F11, containing BD-C and FA-S, shows promising results, achieving 28 MPa compressive strength at 1 hour and about 52 MPa compressive strength at 28 days. This makes BD a viable SCM for high early strength grout systems, particularly in applications where rapid strength gain is critical.

Overall, formulations F10 and F11 are potential candidates for further development and application, offering a potential solution for preplaced aggregate concrete applications where rapid strength gain and reduced open time are essential.

CHAPTER 6 : FUTURE RECOMMENDATIONS

Some of the future recommendation that can be carried through this research is as follows.

- Investigate the optimal dosage and combination of BD with other SCMs to further enhance the properties of high early strength grout systems.
- Explore the potential of BD in other applications, such as self-consolidating concrete, high-performance concrete, and sustainable construction materials.
- Conduct further research on the long-term durability and sustainability of BD-based grout systems, including its resistance to chemical attacks, freeze-thaw cycles, and abrasion.
- Investigate the feasibility of using BD in combination with other innovative materials, such as nanomaterials, to develop advanced construction materials.
- Develop a comprehensive life cycle assessment (LCA) of BD-based grout systems to evaluate their environmental impact and sustainability.
- Investigate the effects of BD on the rheological properties of grout systems and its impact on pumpability and workability.
- Develop a guideline or standard for the use of BD as a SCM in high early strength grout systems, including recommendations for dosage, mixing, and application.

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