AMERICAN UNIVERSITY OF BEIRUT

EVALUATION OF SUSTAINABLE CONCRETE INCORPORATING CERAMIC HYBRID BINDERS

by
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AN ABSTRACT OF THE THESIS OF

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Title: Evaluation of Sustainable Concrete Incorporating Ceramic Hybrid Binders

Concrete incorporating ceramic hybrid binders is a sustainable material prepared by partial replacement of Portland cement with a proper dosage of ceramic powder and mineral admixtures or pozzolanic materials. On one hand, the production of Portland cement causes depletion of natural resources, consumes large amounts of energy, and has negative environmental impact since it is responsible for around 5 to 7% of the global carbon dioxide emissions. On the other hand, the ceramic industry which produces tiles, bricks, and sanitary ware generates 3 to 5% waste in the different production stages. Recycling ceramics waste in the production process in the ceramic plant is costing more than producing ceramics from raw materials, the reason such wastes are dumped in landfills and causing environmental pollution. The problem persists in Lebanon and world-wide. Recycling the ceramic waste material by reusing it in the concrete industry has been investigated in many research studies that were reported in the literature in the last 10 to 15 years. It was found that the replacement of different percentages of Portland cement with ground ceramic powder decreased the mechanical strength properties of concrete. The hypothesis to be tested in this research is whether a certain percentage of replacement of Portland cement with blast furnace slag would overcome the reduction in the mechanical properties of concrete incorporating ceramic powder.

The proposed research program will be conducted on four stages: microstructure and powder characterization, pozzolanic performance, mortar scale and concrete-scale. The microscale aims at studying the physical properties of the powders though specific gravity and BET tests as well as the mineralogical properties by performing XRD and the morphological properties through SEM and TGA tests. The assessment of the pozzolanic activity of the pozzolans will be tackled through direct methods (Frattini test, saturated lime test, XRD, TGA, and SEM) and indirect methods (Strength index and electrical conductivity). Moreover, the mortar phase includes testing the compressive strength of the slag and ceramic mortars as well as assessing the mortar's fire resistance through fire refractory test which consists of heating mortar specimens at different temperatures (100˚C to 800 ˚C).

In the mesoscale, concrete batches will be prepared in three series. The main objective behind the first series is to quantify the effect of including ceramic as a replacement of cement targeting a compressive strength of 30 MPa with the following level of replacement (10%, 15%, and 20%). In the second series similar ceramic replacement levels was investigated on slag cement rather than Portland cement. Lastly, in series (3) the main target was to study the behavior of ceramic high strength concrete of 60 MPa mix design. These objectives were targeted by conducting the following tests: slump, compressive strength, splitting tensile strength, flexural strength, and modulus of elasticity. Durability was targeted through freezing and thawing and thermal conductivity tests. The wide scale testing will result a better understand of the hybrid material and aim to find an optimum sustainable concrete material while recycling and reusing different wastes without any negative impact on the hardened mechanical properties. The results indicate that the ceramic is considered as a pozzolan material. In addition, the inclusion of slag improved the deficiency caused by the ceramic. Unpredictably, the slag is the most durable material among the studied powders. Further, it was found that ceramic have high thermal resistivity however this material has shown negative effect when exposed to freezing and thawing.

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CHAPTER 1

INTRODUCTION AND BACKGROUND

1.1 Introduction

In recent years, many scholars worked on utilizing byproduct materials in concrete because of the increasing demand for integrating sustainable materials in construction. And by sustainability, the usage of new materials that cause no harm to the environment is addressed. In line with this trend, several studies targeted construction demolition wastes. The composition of construction wastes includes: steel, copper, glass, tiles (ceramics and granite), wood, sanitary fixtures, rubble (concrete and masonry), and hazardous materials (fluorescence and asbestos) as specified by Tamraz et al. (2011). In the last couple of years, researchers in the American University of Beirut targeted mostly the recycled aggregate concrete and its potential to be included in concrete and asphalt and none targeted the ceramics. Therefore, the focus of this study is to highlight on two sustainable materials: ceramic powder and blast furnace slag. Ceramic is classified as a material of extreme hardness which has been used in many applications such as cutting tools, milling and grinding metals. Slag is a byproduct of steel production and is a well-known pozzolan material used as a partial replacement of cement. This study aims at investigating the use of sustainable materials, in particularly ceramics and slag as a substitute of cement.

1.2 Ceramic raw material and production

Ceramic is one of the most ancient fabricated products on earth. Its production goes back to early 24,000 BC (Figure 1.1). According to the American ceramic Society, Eileen (2014) stated that ceramic production started initially by firing slurry which is a semiliquid clayey material. The first manufactured ceramic tile was established in India 14,000 BC. It is also believed that the glazing material were discovered 5000 BC in Egypt. Moreover, in 1550, furnaces were used to facilitate production and increased the ceramics high temperature resistance. Then Porcelain electrical insulator were manufactured in mid-1800's. The evolution of ceramic continued, that the product becomes a technical ceramic, that has many forms, usages, and properties nowadays.

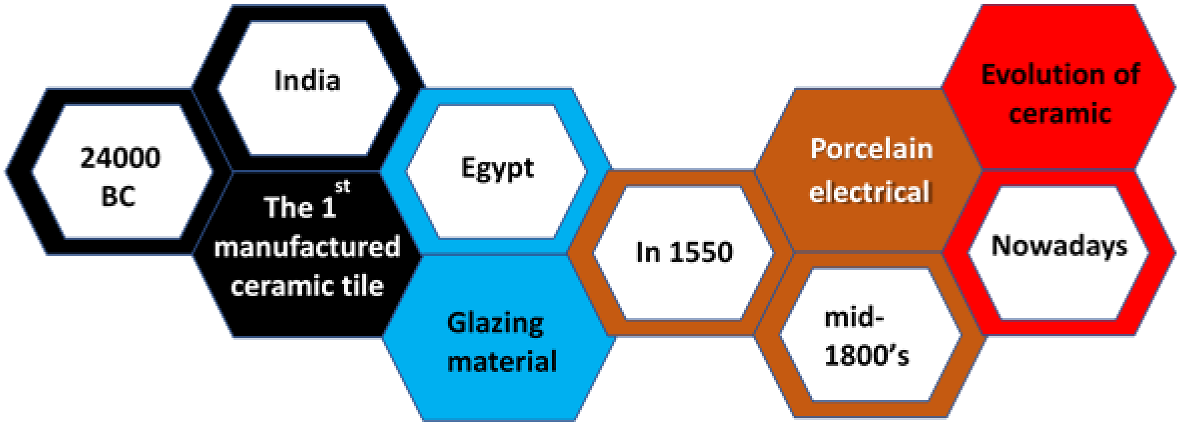


Figure 1.1 Ceramics evolution

Ceramics raw materials are all natural resources and well known. However ceramic tiles can differ according to the source of production. Where each company has their own proportions of making ceramics according to specific standards. These proportions are confidential to the manifacturing company.

The raw materials of ceramics are:

- Potash Feldspar /Soda Feldspar
- Quartz Powder (silica sand)

- Ball Clay, Kaolin
- Talc Powder

Worral et al. (1982) specified that 95% of feldspar consumption is for ceramic production. Feldspar and clay are the two major components that form ceramic. Moreover, feldspar plays an important role as a flux in the mix, since it accelerates the melting of quartz. So that when feldspar melts at 1100 degree, it affects the melting point of the quartz that drops from 1600 degrees to 1250-1400 degrees depending on the type and the amount of the feldspar available in the mix. The higher the temperature the more the texture of the ceramics change from dusty to polished. At low temperature ceramic can be very weak and breaks easily. However, hardening at a very high temperature strengthen the ceramic tiles.

The potash feldspar has a white color, whereas the sodium feldspar has a brownish color. The selection of raw material affects the fired final product coloration. Clay and kaolin are acknowledged for the strength, composition, and plasticity of ceramics. The proportions of the mixture differ and depend on the manufacturing company itself. Where high clay content makes ceramics easily shaped while high feldspar content makes the ceramic glasslike. The chemical and physical properties of ceramics' raw material are listed in the Tables 1.1 and 1.2. It is important to notice that feldspar has almost the same chemical composition of ceramics the reason it is considered as ceramic raw powder.

Table 1.1 Chemical composition of ceramics raw materials

	Molecule	**Chemical composition**							
		SiO_2	Al203	Fe_2O_3	K_2O	Na_2O	MgO	CaO	LOI
Potash Feldspar	$KAlSi_3O_8$	68.00%	18.00%	0.08%	11.50%	2.00%	0%	0%	0.40%

Sodium Feldspar	NaAlSi3O8	68.00%	18.00%	0.08%	1.50%	9.00%	0%	0.50%	0.40%
Quartz (sand)	SiO_2	99.80%	0%	0%	0%	0.00%	0%	0%	0.10%
Ball Clay	Al203-2Si02-2H20	53.80%	28.50%	0.83%	0.70%	0.06%	0.12%	0.41%	10.00%
Kaolin (china clay)	Al2O3·2SiO2·2H2O	45.30%	33.40%	0.30%	0.44%	0.27%	0.25%	0.05%	0.14%
Talc powder	3MgO.4SiO2.H2O	63.70%	0%	0%	0%	0%	31.88%	0%	3.00%

Table 1.2 Physical properties of feldspar and clay

Material	Physical properties	
	SG	melting range
Feldspar	2.6	1100-1150
Clay	2.65	1650

Broad studies proved the effectiveness of ceramic raw materials utilized in concrete mixes. Quartz/silicate sand has a hexagonal crystal structure. It is insoluble in water and typically works as a filler in concrete since the coarse aggregate and the paste are responsible for concrete strength capacity. Kaolinite/china clay has no pozzolanic reactivity but when heated at a temperature of 550˚C, dihydroxylations occurs in the china clay. Increasing the temperature will recrystallize the structure of the material forming metakaolin that is considered as a pozzolanic material capable of substituting cement partially. Overheating the Metakaolin to a temperature above 850 ˚C can cause sintering, forming a dead non-reactive material (Ding and li 2002).

It is worth noting that none of the studies targeted the usage of feldspar in concrete. So, a small study is established to investigate the feldspar properties. Feldspar was brought from Lecico, the biggest national company that produces Ceramics in Lebanon. Lecico company imports the Kaolinite from England, Feldspar from turkey, and lastly quartz from local sources. The company used to recycle and reuse the broken ceramics in the production process. Unfortunately, recycling was stopped since the cost of melting and reshaping of the wastes cost more than dumping it or selling it as waste to clients that are usually interested in making artworks from ceramics.

In the American University of Beirut construction and Material Lab, a study was done to investigate whether feldspar can be used to replace cement or sand in concrete. Further, five mortar mixes (20CF0, 20SF0, 20CF6, 20SF6, and the control mix) were made according to ASTM C109. Each mix consists of two replicates. The mix proportions by weight for the mortar is selected according to ASTM C109 code Which specifies one part of cement to 2.75 parts of sand and a water to cement ratio of 0.5. The samples were removed from the molds one day after pouring, then the weight of the sample was taken directly prior the curing stage which involved soaking the specimens in water for 28 days and lastly tested using Universal Testing Machine. The average of the samples densities and compressive strength are displayed in the Table 1.3. The testing results shows that heating feldspar had no effect on activating the material into a pozzolanic one. On the other hand, feldspar, in general, can replace the sand successively since results shows no change in strength. As for the density of the mortar, feldspar decreased the mortar density when replacing cement, however density remained steady when it replaced sand.

Table 1.3 The average of the sample’s densities and compressive strength

Sample	C : F : S : W	F'c	Ratio	Density
Control	1: 0: 2.75: 0.5	41.5	1	2.13
20CF0	(0.8: 0.2): 2.75: 0.5	30.5	0.73	2.07
20SF0	1: (0.55: 2.2): 0.5	40.5	0.98	2.13
20CF6	(0.8: 0.2): 2.75: 0.5	32.0	0.77	2.10
20SF6	1: (0.55: 2.2): 0.5	41.9	1.01	2.14

Where:

“F0” terms for non-heated feldspar powders and “F6” terms for feldspar powders heated at 600 degrees. Moreover, (20C) terms for cement replacement and (20S) as sand replacement.

Production of ceramics passes through multistages (Figure 1.2). The raw materials must be selected and proportioned according to the company criteria. Then mixing is done and formed in special molds making a green ceramic. The green material terms for the raw unfired materials which are soft and precede the hardening and calcination that occur after firing. Ceramics are fired twice, once after forming and second after glazing.

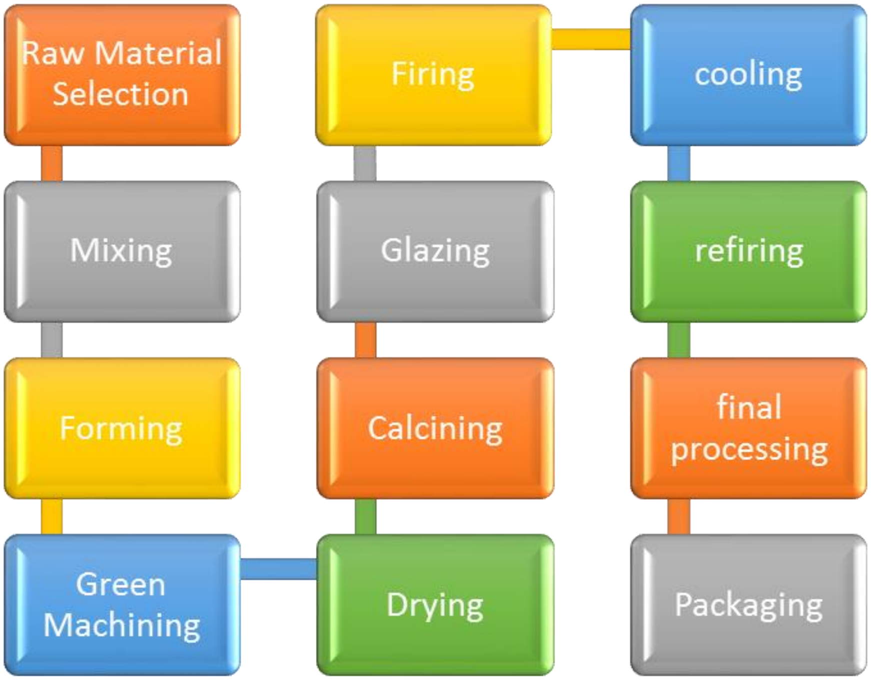


Figure 1.2 Ceramics manufacturing process

Ceramics can take different forms and have many types. In this research, two types of ceramics are to be investigated Terracotta and Porcelain. The first is mainly a brownish-red earthenware, consists of fired clay, glazed with a porcelain layer. While the latter is a full body of low porous ceramic that is heated at a temperature of 1400° C.

1.3 Ceramic Quantification

As the war in Syria appears to continue, the number of the destroyed houses during the war increases. According to a privately funded study, the number of the destroyed houses is exceeded a half million (535000) and valued about $68 Billion.

Abdullah Dardari, the head of UN Economic for western Asia revealed that more than 400’000 buildings were destroyed and around 300’000 Houses were severely damaged.

In a previous study conducted at AUB, Tamraz et al. 2012 declared that the composed wastes from destroyed buildings, are classified to the following categories: Steel, copper, glass, tiles, wood, sanitary fixtures, rubble, and hazardous material. The Ceramic wastes are estimated to be 3% of the demolition wastes. Tamraz et al. also derived a simplified empirical equation to estimate the weight of the demolished wastes (DW).

$$W_{DW} = Nbr\ of\ Demolished\ Buildings * building\ areas * 0.73\ m^2 * 2.25\ {}^{t}/_{m^3}$$
$$W_{Ceramic} = 3\% * Nbr\ of\ Demolished\ Buildings * building\ areas * 0.73\ m^2 * 2.25\ {}^{t}/_{m^3}$$

Assuming that (i) the building area is 1000 m2 which is conservatively small and close to Zalka’s specified building area by Tamraz et al., (ii) the Number of destroyed buildings is 535000 and (iii) Ceramic wastes is 3% out of the construction demolished wastes.

$$W_{Ceramic} = 0.03 * 535000 * 1000 * 0.73 * 2.25 = 26\ Million\ Tons.$$

The estimated number of ceramic wastes is 26 million Tons which is enormous and such quantity is never easy to recycle. The old practice of solving such issues is to damp the accumulated waste in the sea and coastal areas as the Lebanese government did after 2006 war. The provided research provides a plausible solution of consuming such quantities in concrete.

Furthermore, wars not only outcome a vast amount of wastes, but also leave empty areas that needed to be constructed. Construction of such areas requires large quantities of cement. And since cement makes 15% of concrete weight, replacing cement partially by ceramics and slag powders will double solve the waste problem and the need of producing vast cement quantities.

1.4 Slag

Ground granulated blast-furnace (GGBS) is a byproduct of iron production. Iron is made of a mixture of iron ore, coke and limestone fired to a temperature of 1,500 degrees in a blast furnace. It is a nonmetallic material consisting essentially of silicates and aluminosilicates of calcium developed in a molten condition simultaneously with iron at a temperature of about 1500°C in a blast furnace.

Different forms of slag products are produced depending on the method used to cool the molten slag:

- Air-Cooled Blast Furnace Slag: the molten slag is poured into beds and then crushed and screened after cooling.
- Expanded or Foamed Blast Furnace: the slag is controlled by steam and controlled quantity of water.
- Slag Pelletized Blast Furnace Slag: the slag is added to a spinning drum cooled by water.
- Ground Granulated Blast-furnace Slag (GGBS) is formed by rapid chill water cooling. This process results in the formation of sand size (or frit-like)

In the market, the most commonly used type of slag is GGBS (rapidly quenched in water then dried then ground to powder).

The granulated slag size must have almost the same cement size according to ACI standards while European standards specifies that Slag must be finer than cement. The specific gravity of the slag falls in general between 2.85 and 2.95.

Slag was first established in Germany in 1853 (Malhotra 1996). The inclusion of slag as a pozzolanic material in concrete started in the beginning of the 1900s (Abrams 1925).

Ground granulated blast-furnace slag for use in concrete and mortar standard (ASTM C989) classifies the slag in three strength grades: Grade 80, Grade 100, and Grade 120 according to its performance in the slag activity test. The test consists of preparing 2 mortar mixes according to ASTM C109. The control mix must be proportioned as follow (500g cement, 1375g sand, and 250g water) and the slag mix is similarly made, however in this mix slag replaces 50% of cement weight. Compressive cubes must be test at 7 and 28 days. The strength activity index is calculated by dividing the compressive strength of the slag cement cube to control cube. Then slag can be classified according to the results (as shown in table xxx). It is important to mention that Grade 120 is the most powerful slag, Grade 100 is the closer to cement at 28 days, and grade 80 is the weakest. In general, the role of slag is to lower the heat of hydration of cement which will result a drop in the compressive strength at early days and will result an increase in the compressive strength at later days.

1.5 Research Objectives and Scope of Work

This Study is composed of multiple levels and is based on literature reviews. The research fills different limitations that are found in each level. As a start, the research aims to compare different types of ceramics namely terracotta and porcelain that reflect the traditional and the modern ceramic tiles that exist nowadays. Further, the microstructure of the ceramic and slag pastes morphology, mineralogy, and thermal properties are limited with no available studies highlighted on possible occurrence of a diffusion between powder materials that need to be checked. The pozzolanic reactivity testing for new materials has been a hot topic lately the reason it is worth to conduct multi-tests to ensure the potential of such hybrid materials as a cement substitute. Next, Ceramic is a well-known material for its high heat resistance the reason it is worth investigating ceramic concrete under different thermal testing and compare it to slag concrete and the conventional concrete made of cement. In addition, most of the published literature only studied the mortar level. The experimental plan of concrete covers a wide range of testing for two different compressive strengths (30 and 60 MPa) and cover 11 different mixes that will be provided in the study

1.6 Research Significance and Local Context

This study explores the use of recycled ceramic tiles and slag in the concrete mix. The proposed study provides possible alternatives of cement. Such practice has a positive impact on the environment. Cement is composed 95% of clinker and 5% of gypsum. Clinker production consumes enormous amount of energy since it is burnt at a very high temperature exceeding 1400˚C. Such energy releases large CO_2 emissions that harm the environment. The CO_2 emissions from clinker production are estimated to be 5 to 7% of global anthropogenic CO_2 emissions. In addition, each 1 Mt of clinker requires 1.7Mt of raw materials which are all-natural resources (limestone, clay, shale, and quartz sand). So that cement production not only causes air pollution but also depletion of natural resources. Further, regionally, the demolition wastes from destroyed buildings increase as the war continues in Syria. The estimated number of destroyed buildings during the war exceeds half a million which will produce huge quantities of ceramic wastes that will be dumped without being properly recycled. Next, the challenge is to make a sustainable concrete that satisfies strength requirements and make it durable under different conditions. Ceramic and slag are considered as sustainable building materials expected to (i) reduce energy and resources depletion from cement production, (ii) make a sustainable concrete that satisfies strength and durability requirements, (iii) provide a solution for the encountered ceramics wastes not subjected to proper recycling. The significance of this research is to check the following hypothesis, whether a certain percentage of replacement of Portland cement with blast furnace slag would overcome the reduction in the mechanical properties of concrete incorporating ceramic powder.

1.7 Research Methodology

The work in this thesis is comprised of a comprehensive experimental testing program that consists of four levels: powder characterization, evaluation of pozzolanic reactivity, mortar level, and lastly meso level. The main target behind the experimental program is to (1) study the mineralogy, morphology, and thermal properties of the powder types through (XRD, BET, SEM, and TGA) (2) compare the pozzolanic reactivity through multiple methods (strength index, Frattini test, lime test) (3) Study the two types of ceramics (Terracotta and Porcelain) and the fineness effect of the ceramic powder used on compressive strength of mortar according to ASTM C109 in addition to the fire effect on mortar (4) Apply the science on real concrete samples and study their fresh and hardened mechanical properties of the hybrid concrete.

1.8 Thesis Outline

The thesis is divided into eight chapters. Chapter 1 is an introduction to the topic of Hybrid ceramic slag concrete, and a summary of the research objectives and methodology. Chapter 2 presents background and literature review on both micro and macro test levels. Chapter 3 details the material, sample preparation, and presents an overview of the experimental program. Chapter 4 explains the microstructure and powder characterization of cement and slag. Chapter 5 discusses the evaluation of pozzolanic performance of supplementary cementitious materials. Chapters 6 and 7 respectively examine the mortar and concrete levels of testing methods and results of the experimental investigation. Chapter 8 concludes the research and gives recommendations.

CHAPTER 2

LITERATURE REVIEW

2.1 Relevant Literature - General Context

The potential use of ceramic in concrete as substitute of cement is garnering more interest in the material and structural community. This interest in ceramics has generated a number of research initiatives and experimental testing programs aimed at investigating the effect of adding such material on the mechanical properties of concrete. The studies on ceramic usage in concrete are still theoretical and not applied in the industry which requires more investigations which bring the need for more experimental studies to become applied.

Numerous studies have explored the behavior of ceramics and slag. Some literature includes characterization of the materials studying its morphological and mineralogical properties through several physical and chemical testing (ex. Lavat et al. 2009, Dima et al. 2017, Ay et al. 2000, Farhina et al. 2017, Zhang et al. 2017, Van Deventer et al. 2014, Steiner et al. 2015…). Others include reports and findings from a number of experimental studies that investigated the response of ceramic in concrete on the fresh and hardened properties of concrete (ex. Asiwaju-bello et al. 2012 Heidari and tavakoli 2013, Vejmelkova et al. 2012, Raval et al. 2013, Serkan et al. 2017, Samad et al. 2017…).

Previous investigation has revealed that ceramic and slag substantially improve the sustainability of concrete by lowering the cement content responsible for high CO_2 emissions and high-energy consumption.

2.2 Studies involving material characterization and mortar level

Lavat et al. 2009 explored the impact of glazing for ceramic powders on the pozzolanic reactivity of the three ceramic types: natural glazed ceramics (E), black glazed ceramics (N), and non-glazed ceramics (T). Ceramic powders were produced by crushing, milling, then sieving through a #325 mesh. The experimental plan included Frattini test and lime consumption test to measure the pozzolanic reactivity in addition to XRD and SEM to study the minerology of the ceramic types and compressive strength test that was made on mortar specimens (40x40x160mm) made from the three ceramic types. The results of Frattini test showed no difference in result for the three types of ceramics where 30% ceramic replacing cement resulted the same concentration of [Ca^{2+}] and [OH^-] (Figures 2.1 and 2.2) . In contrast, the ceramic Type E consumed the most of $Ca(OH)_2$ which indicates that Type E is the most pozzolanic material among the three types since the SiO_2 content from the ceramic reacted with the calcium hydroxide which produced CSH strength gel. As for the compressive strength results, at 28 days, the addition of 30% of ceramics for the types E, N, and T resulted in a reduction in strength respectively of 24%, 25%, and 12.5%. Therefore, the non-glazed ceramic yielded the highest strength among ceramic types and that can be explain due to the negative effect that glazing brings to the bond and cement matrix. The results are backed up through the mineralogical testing.

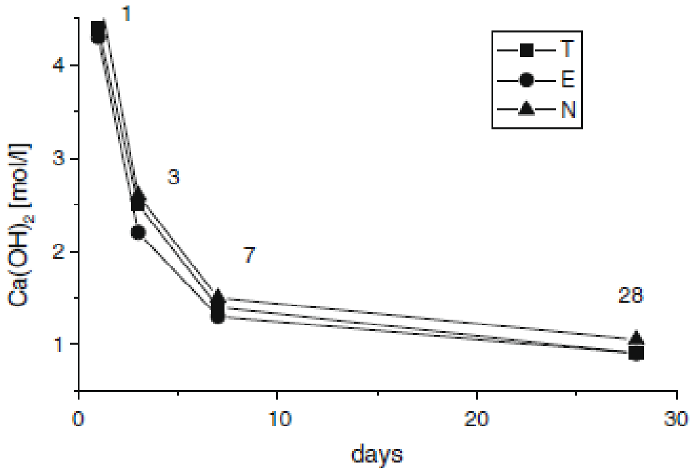


Figure 2.1 Saturated lime test result (Lavat et al. 2009)

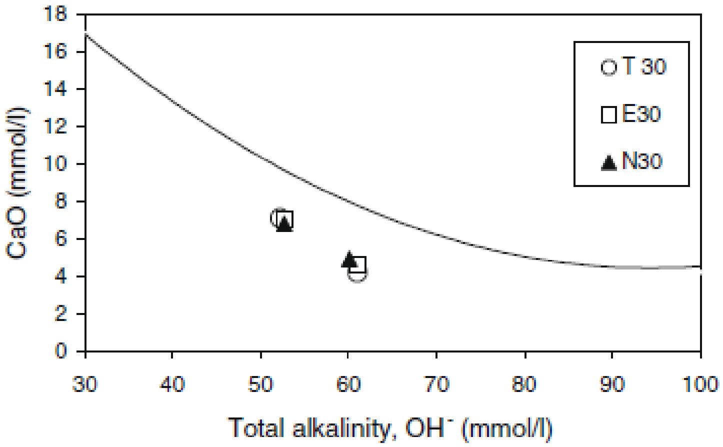


Figure 2.2 Frattini test (Lavat et al. 2009)

In a study illustrated by Dima et al. (2017), different chemical tests were performed to characterize the ceramic as well as to prove its pozzolanic reactivity. 10 to 40% of ceramic powders were evaluated as cement replacement. Ceramics were ground to a surface area of 0.55 m^2/g. The experimental plan includes the following tests: electrical resistivity test, pores permeability test, X-ray diffraction (XRD), scanning electron microscope (SEM), thermal gravity meter analysis (TGA), differential scanning calorimeter (DSC) and Frattini test which measures the reactivity of the material. The chemical testing showed that ceramics at 40% improved the electrical resistivity by 9 times. As for TGA and DSC tests, ceramic pastes show a slight reduction in mass compared to cement paste, which denotes that hydration component is almost the same for the two materials. Further, the SEM test displayed that the ceramic has angular and irregular shapes closed to cement particles while XRD displayed a presence of higher SiO_2 and CSH peaks and less CH peaks when ceramic is included in the paste which can be explained by the fact that the silicon content inside the ceramics is reacting with CH creating more CSH gel in the paste. Lastly, Frattini test measures the removal of Ca^{2+} ions that in turn attributes to pozzolanic activity. Preparation of the test requires making a sample made of 100 ml distilled water and 20g in a bottle. Cement will settle and harden in form of a layer in the bottom of the bottle. When hydration of cement starts, leaching will occur at the surface of the sample. The test consists of double titration once with HCL and other with EDTA to calculate the alkalinity (OH- concentration) and hardness (Ca^{2+}) concentration. As shown Figure 2.3, the results for 20 and 40% replacement indicated that ceramics had a pozzolanic reactivity and can be considered as pozzolan. In other words, the experiment confirmed that ceramic played a double role as a tough filler in the concrete as well as a reactive pozzolanic material.

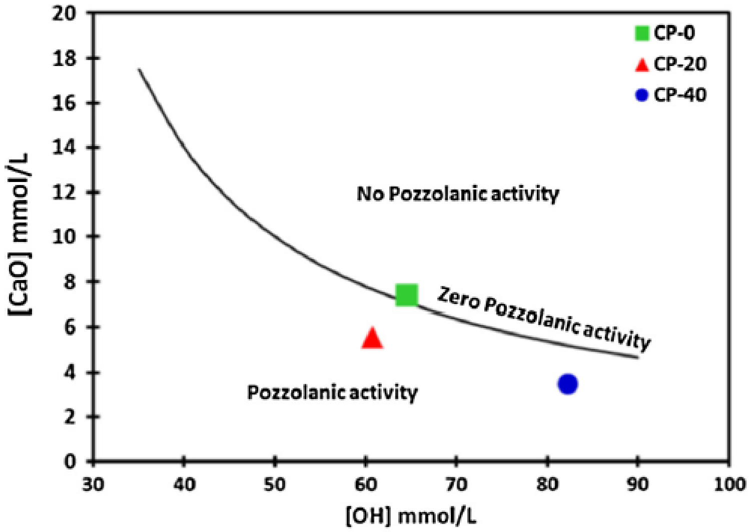
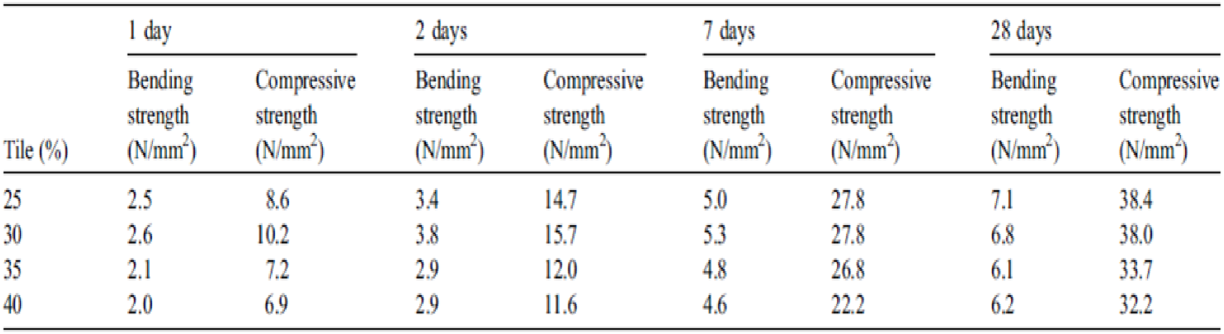


Figure 2.3 Frattini test (Dima et al. 2017),

Ay et al. (2000) investigated the use of ceramic tiles in cement production. Ceramic powders were prepared by crushing ceramic wastes in a jaw crusher and then grinding the particles in a ball mill for 55 minutes. Ceramic powders were then blended with cement in a ball mill (by weight ratios of 25%, 30%, 35%, and 40%) for 30 minutes. Four batches were prepared out of the four new blended cement for pozzolanic activity test according to Rilem cembureau method: one cement particle is mixed with three sand particles and half particle of water. Mortar prisms (of dimension 40x40x160mm) were tested at 1, 2, 7, and 28 days. The results (Table 2.1) of the compressive strength indicated that up to 30% ceramics the compressive strength is still in the acceptable range. It was concluded that ceramic can be considered as a pozzolan and that its usage in cement production could be beneficial in reducing ceramic wastes, increasing the sustainability of a concrete mix and cutting the cement production cost.

Table 2.1 Experimental testing results of Ay et al. (2000)



	1 day		2 days		7 days		28 days	
Tile (%)	Bending strength (N/mm^2)	Compressive strength (N/mm^2)	Bending strength (N/mm^2)	Compressive strength (N/mm^2)	Bending strength (N/mm^2)	Compressive strength (N/mm^2)	Bending strength (N/mm^2)	Compressive strength (N/mm^2)
25	2.5	8.6	3.4	14.7	5.0	27.8	7.1	38.4
30	2.6	10.2	3.8	15.7	5.3	27.8	6.8	38.0
35	2.1	7.2	2.9	12.0	4.8	26.8	6.1	33.7
40	2.0	6.9	2.9	11.6	4.6	22.2	6.2	32.2

Farhina et al. (2017) implemented a testing program on mortars of different volumetric proportions incorporating ceramics. Reduction of cement volume was made by replacing 20% of cement with ceramics as well as by changing the volumetric cement to sand ratio of the mortar mix as follow: 1 to 4, 1 to 5, and 1 to 6. The fineness of ceramics used in the experiment passed 149 microns. Decreasing the cement content led to a critical decrease in strength specially for the 1:6 ratio's mix, but the interesting part was that the 20% substitution drove an improvement in both 1:5 and 1:6 ratios' mixes.

Zhang et al. (2017) evaluated the deterioration by freeze-thaw and carbonation of mortars incorporated with slag activated by 4% of lime. The experimental investigation revealed that the frost resistance and carbonation resistance decreased as the slag ratio increased by weight in the concrete. Since the low heat of hydration leads to a lower CH amount in concrete it encourages the carbonation progress. The lime incorporation improved the compressive strength; however, it had a negative effect on frost resistance.

Steiner et al. (2015) examined the potential of ceramic powder produced from polishing process of ceramic to become a cement substitute. The powder combination was carried out through several samplings of two polishing residues that are originated from ‘porcellanato’ tiles and ‘monoporosa’ tiles. The study aimed to investigate the effectiveness of polishing residues as a supplementary cementitious material. The experimental plan included Laser diffraction, X-ray fluorescence, X-ray diffraction to study the chemical and physical properties of the powder in addition to compressive strength, pozzolanic activity index, and thermal behavior to study its pozzolanic activity. The average particles diameter was 9 microns which is small with respect to cement size (45 microns). The XRD analysis showed that the ceramic is composed of SiO2 and amorphous phase. The mortar compressive strength test indicated that the incorporation of polishing residue as 20% replacement decreased the compressive strength by 10% at 28 days. The pozzolanic activity index showed 85%,101%, and 104% at 28,100, and 120 days respectively which can be explained by the fact that ceramic gains strength at a very low rate. The thermogravimetric test showed that the addition of ceramic in the paste reduced the loss in mass by 5 %. The differential thermal analysis showed that at 120 days, the calcium (CH) of cement paste is estimated to be 4.7% by mass. The inclusion of ceramics reduced the CH content to 2.18% and that can be explained by that the SiO_2 content reacted with the CH forming calcium silicate hydrate (CSH).

Jannie S.J van Deventer et al. (2014) created a blended system to fully replace the cement. It consisted of making a hybrid blended 50% slag with 50% fly ash. These binders were mixed with an activator solution dose of 8 g Na_2SiO_3 per 100 g of (anhydrous weight of binders). Ordinary cement paste was also produced for comparison purposes. Similar water/ binder (w/b) ratios to those specified for the concretes were adopted for preparing these pastes. The strength obtained from hybrid was comparable to the concrete one.

2.3 Studies involving ceramic and slag in concrete

Asiwaju-bello et al. 2012 studied the effect of curing concrete samples with salty water. Ceramic powders were grinded to a size of 150µm. The percentages of ceramic which replaced cement were 5% to 30%. The compressive strength of concrete specimens was tested on cubes (150x150x150 mm) at different stages 7, 28, 56 and 90 days. The outcomes revealed that salty water accelerated the early days compressive strength of the conventional concrete with no effect on 28 days strength. Also, the salty water improved both early and late compressive strengths for the ceramic concrete. Hydration is retarded when ceramic is added, thus the salty water accelerates the curing rate ensuring a higher gain for both early and late strengths. It is important to mention that the slump decreased with the addition of more ceramics.

Heidari and tavakoli (2013) investigated the usage of ceramic powder incorporating Nano silica as a replacement of cement (type II) which is well known for its moderated low heat of hydration. The ceramic tiles were crushed by a jaw crusher, then ground with an air jet mill and sieved to a size passing number 200 (particles size is smaller than 75 microns). The experimental plan was divided into two phases. In the first phase, the aim was to study the effect of ceramics as cement replacement on the compressive strength of concrete. The parameter of interest in this phase was the percentage of ceramics replacing cement: 10%, 15%, 20%, 25%, 30%, and 40%. In the second phase only 10 to

25% of ceramics percentages were selected for the study. The aim was to improve the compressive strength of the ceramic concrete by adding Nano silica particles. Nano silica is the same material of silica fume, the only difference is its fineness where the surface area of Nano silica is 230 m2/g (almost 200 times larger than cement). The percentage of Nano silica used in this phase were 0.5% and 1% of cement size. Concrete cubes (150x150x150mm) were prepared for both phases and were tested at at 7, 28, 56, and 90 days. The results indicated that the ceramic concrete samples have a close compressive strength compared to control at 90 days whereas at early days it showed a higher drop. This finding initiated a second phase that focused on adding Nano silica as an additive to concrete to enhancement the concrete performance at early days with small dosage of 0.5% and 1% of the cement. In fact, Nano SiO_2 was very effective in improving strength that 10% ceramic with 1% Nano silica concrete gained 110% as compared to the control concrete strength. The ceramic concrete has a very low heat of hydration even lower than the standard concrete made out of cement type II, thus such material needs to be activated in order to participate in gaining strength.

In 2012, Vejmelkova et al. started an experimental on durability characteristics of high performance concrete with fine-ground ceramics replacing Portland Cement of ratios up to 60%. Durability testing covered: frost resistance test, thermal conductivity test, and water absorption test. Mechanical testing included compressive strength test and three-point bending test to measure the facture toughness. Frost resistance test Results indicated that ceramics improved the frost resistance of concrete up to 40% replacement. Further, the addition of ceramics decreased the thermal conductivity of the concrete and had insignificant effect on the water transporation and absorption. As for the mechanical testing, the compressive strength fell in the acceptable range up to 20% replacement level. Lastly, ceramic inclusion decreased the fracture energy and fracture toughness compared to control. It is worth mentioning that 40% replacement level led to highest fracture energy and toughness among ceramic concrete mixes.

In 2013, Raval et al. performed a study investigating the use of ceramic powder generated as waste during the polishing process of ceramics. The waste was estimated to be 15 to 30% of raw material weight. The aim of the study was to explore financial aspect behind utilizing ceramics in the mix along with studying the mechanical behavior of the ceramic concrete of percentage replacement (10 to 50%). The findings were in line with previous studies. The addition of ceramics reduced the compressive strength dramatically after 20% replacement level where 50% replacement caused a drop of 40% in strength. The incorporation of 10 and 20% replacement resulted in a decrease of 8 and 10% in compressive strength, respectively. In spite of this, replacing 20% and 50% of cement by ceramics could save up to 8.45% and 21% of concrete cost in one cubic meter respectively. Thus, concrete incorporating ceramics could be used in multiapplication where strength is not an issue.

Serkan et al. 2017 conducted a comprehensive testing of self-consolidating concrete including ceramic powders. The ceramic fineness used was 125 microns which is larger in size than cement particles (45 microns). To study the fresh concrete properties, slump flow, L-box, and J-ring tests were performed. In addition, the compressive strength, splitting tensile, flexural strength, and bond strength tests were studied to evaluate the mechanical concrete properties. Further, the pulse ultrasonic velocity test was added to perceive whether this test was still valid when ceramics are included in the mix. The outcomes indicated that ceramics improved the consistency of concrete and that was explained by the large particles of ceramic where less surface area leads to higher workability. Further, the compressive and flexure tests showed that up to 15% replacement, there was insignificant change in the compressive strength and flexure strength results. However, ceramics inclusion caused a reduction observed in the bond strength. Moreover, pulse velocity showed an excellent indication of strength when the new ceramic material was induced in the concrete.

Samad et al. (2017) investigated the effect of blast furnace slag under different curing conditions with different percentages of replacement: 40%, 60%, and 70% of the cement. Concrete cubes (100x100x100 mm) were cured under three different regimes. The first regime was summer curing where samples were stored and sealed in plastic sheets at a temperature of 20 2 degrees. Next, the second regime was Winter curing where samples were sealed and stored but at a temperature of 7 degrees. The last regime was to immerse the samples in water chamber that is controlled at a temperature of 20 degrees. In the early days (1 to 5 day), in both winter and summer curing regime, slag concrete of 30% replacement indicated the highest compressive strength among the slag concrete mixes. In contrast the result of the compressive strength slag concrete made of 40% replacement indicated the highest among the mixes at 7, 28, and 56 days. This phenomenon was explained by that slag has low heat of hydration which delayed the strength development at early days. Winter curing dropped the strength dramatically compared to Summer curing. However, this drop decreased with time so that at 56 days the control concrete had same compressive strength of 70 MPa in both curing regimes. Further, slag was more affected by the curing regime, where at 56 days, slag mixes in winter regime gained almost 90% of the compressive strength of the summer regime. As for the comparison between slag concrete and the conventional concrete, slag mixes at 28 days achieved 85% to 97% of control in winter regime and 98% to 104% in summer curing. The performance of slag concrete improved in 56 days where the compressive strength of slag concrete passed the control concrete in summer and showed percentages of 104% to 115% as compared to the control. Moreover, in winter regime, the compressive strength for the slag concrete achieved 88 to 99% of the control. The highest strength at 56 was recorded 81.5 MPa for the 40% slag during summer condition.

2.4 Summary of Findings from the Experimental Literature Review

The aforementioned studies and others conducted on ceramics and slag point to some commonalties in the findings in some aspects of behavior and to inconsistencies in other aspects. Some of the findings which are relevant to the objective of this study are summarized below:

- The ceramic powder has potential to be a supplementary cementitious material according to different studies (Lavat et al. 2009, Dima et al. 2017, Steiner et al. 2015).
- Ceramics contains high content of SiO_2 which helps in reacting with Calcium hydroxide (CH) gel creating Calcium Silica hydrate (CSH) (Lavat et al. 2009, Dima et al. 2017, Steiner et al. 2015).
- Ceramics reduce the density of concrete.
- Inclusion of ceramics in concrete reduces the consistency of concrete.
- Ceramic concrete gains strength slowly at early age and develops strength with time.

- The addition of ceramics in concrete decreases the compressive strength of concrete. However up to 20% level of replacement, this deficiency falls in the acceptable range (Ay et al. 2000, Haidari and tavakoli 2013, Vejmelkova et al. 2012, Raval et al. 2013, Serkan et al. 2017, Samad et al. 2017).
- Incorporating ceramics in concrete can improve the durability of the concrete in resisting chemicals, frost, thermal (Vejmelkova et al. 2012 and Serkan et al. 2017).
- The performance of slag, that is considered as a pozzolanic material, is highly affected by temperature (Samad et al. 2017).
- Slag has low heat of hydration which is reflected by lowering the compressive strength of concrete at early days however the strength gain continues even after 28 days (Samad et al. 2017).

2.5 Limitations addressed in Literature

The investigation of the published experimental studies on ceramics and slag lead to the identification of the following possible limitations:

The first limitation is that the majority of the studies investigated the polishing residue produced from the polishing process rather than grinding the whole tile material. The aim of this study is to recycle the ceramic waste produced from construction demolishing waste and reuse it in concrete. A recent worldwide awareness and interest in sustainability concepts have pushed towards favoring practices aimed at impeding further global warming, climate change, and depletion of natural resources. In this study, two types of ceramics will be targeted the terracotta (traditional ceramic tiling) and the porcelain (the modern ceramic).

Recent studies have used different ceramic size in their studies. Where some authors implanted ceramic powder of size finer than cement (9 and 13 microns). Others used ceramic of comparable particle size to cement. Most practical studies tackled the usage of passing N200 (45 microns) in order to reduce the cost and energy needed to grind the material to a finer final size. The usage of finer size of ceramic could contribute to a higher compressive strength since higher fineness leads to a higher surface area available for hydration. In this study, a mortar scale phase is designed to study the fineness effect of ceramics on concrete.

As for thermos-gravimetric test, the results of Dima 2017 et al. showed that ceramics increased the loss in mass. However, Lavat et al. 2015 showed the opposite knowing that both studies were established on polishing residue. Ceramic is very stiff material and is noted for its thermal shock resistance. Therefore, investigating the effect of ceramic under thermal testing is very important. Thermal experimental studies will include the thermogravimetric test on several powder materials and pastes, in addition to fire refractory test on mortar and thermal conductivity test on concrete slabs. In addition, the microstructure behavior of the ceramic paste is not fully understood, the reason why more testing is required to be made on pastes to study the hydration and composition of CH and CSH gels on micro level for the ceramic paste as well as for the hybrid slag ceramic paste. Mixing two powder materials would result in a presence of new elements in the composition of the mixture created from the diffusion between elements.

Most of the studies that investigated the effect of ceramics on concrete, proved that ceramics reduce the compressive strength of concrete. Heidara et al. 2013 study was the only one that included the addition of new pozzolanic material (Nano silica) beside ceramics in order to improve such deficiency in concrete compressive strength. The study included the usage of a new pozzolanic material (slag), in a way to improve the deficiency in the compressive strength of concrete caused by ceramics inclusion.

Further, the recent studies included several concrete durability tests (frost resistance, permeability, shrinkage, chemical resistance) to study ceramics effect on the durability of concrete (Vejmelkova et al. 2012, Raval et al. 2013, Serkan et al. 2017, Samad et al. 2017). However, few targeted the thermal and freezing and thawing testing that are presented in this study.

CHAPTER 3

TEST MATERIALS

3.1 Introduction

Based on the literature review presented in Chapter 2 of this thesis, it is obvious that the mechanism that governs the behavior of ceramics and slag is not fully understood. Such an understanding is required in order to further develop design methodologies for structural systems that involve ceramics.

The experimental program in this research study was designed to supplement the limited data available in the literature. In compliance with sustainability criteria, ceramic and slag were the materials of choice. The main scope in this thesis is to study the characteristics of the materials and its pozzolanic reactivity. As such, two scales (mortar and concrete) were adopted as they provide a more realistic testing technique to understand ceramics response when incorporated in concrete.

In this chapter, the materials and sample preparations (mortar and concrete scales) used in the testing program are described in detail, including ceramics, slag, cement, sand and coarse aggregates.

3.2 Test Materials

The materials section includes a brief description of ceramics, slag, cement, sand and coarse aggregates.

3.2.1 Ceramic

Ceramic is majorly used in works related to tiling. Different types of ceramic tiles can be found in a building. The most common two types are the porcelain ceramic which is fully made from ceramics and the Terracotta ceramic that is made of clay with a thin layer of ceramic on top. Both ceramic types were brought from a local source in Lebanon (Metatrade company located in the industrial zone of bichamoun) originally imported from Spain. The brought ceramic boxes contained each 1.215 m3 of ceramics (3 tiles 45x90cm) weighing 27 kg (Figure 3.1).

For sustainability concerns, the usage of ceramic as cement replacement in concrete was investigated. Moreover, validating the effectiveness of sustainable ceramic composite will encourage the recycling of the encountered waste produced from construction and war zones. To have an efficient replacement, ceramic powder must have a fineness comparable to cement. Hence, in this study the ceramic powder processing wemt through multi stages. At first tiles were broken by a hammer to pieces (aggregate) size in order to feed them into the crushing machine as shown in Figures 3.2 and 3.3. Then the crusher will process them into particles smaller than ½ inch as shown in Figure 3.4. Next, the half-inch particles must be sieved through sieve #4 prior to feeding them into the bico pulverizer (Figure 3.5). The input size of the bico machine is 3/8 inches but it is recommended to go to a less particle size since ceramic is a very stiff material and can harm and deteriorate the disks. The output of the pulverizer is also comparable to cement size. The last step is the Sieving step, which is essential to exclude all sizes larger than #200. The reason #200 was chosen as an output (Figure 3.7) is because processing ceramic to lesser sizes requires a lot of energy and expensive sophisticated pulverizer.

It is worth noting, that the output to input ratio of the ceramic process is 1 to 8 for a powder size output of passing #200 and this ratio drops to 1 to 14 when powder is of cement size (passing #325). Precautious measurements must be taken when dealing with the pulverizer. The gap between the two grinding disks (Figure 3.7) should be minimal to ensure a finer powder output (Figure 3.8). Further, always check the disks alignment and if the disks are not aligned the disks should be filed with a hand file metal. Frequently, lubricate the bearing of the machine by rotating the grease cup.

Figure 3.1 Ceramic box

Figure 3.2 Broken ceramic by hammer

Figure 3.3 Crushing machine

Figure 3.4 Product of the crushing machine

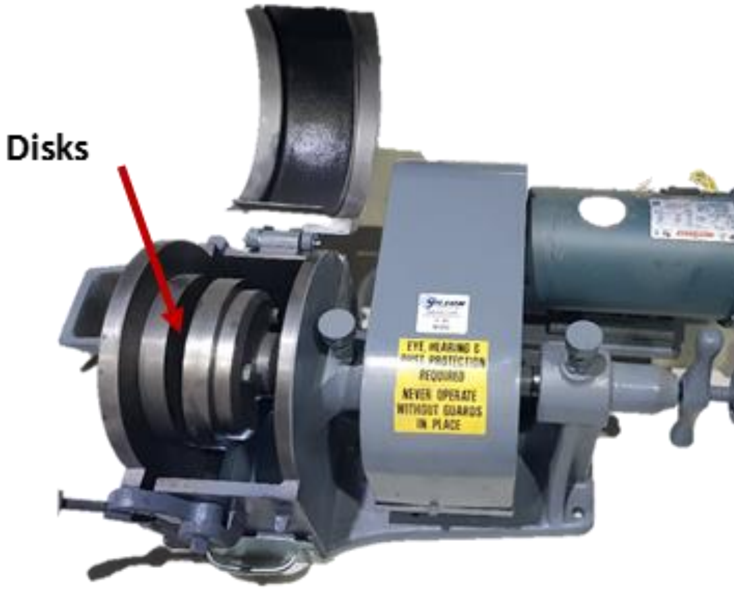


Figure 3.5 Bico pulverizer machine

Figure 3.6 Cast Iron disks

Figure 3.7 Pulverized ceramic powder

3.2.2 Slag

Slag is a pozzolanic material produced by cooling the molten byproduct of the iron production. Lebanon is one of the countries that import iron and steel from the region, thus slag material does not exist. Importing slag to Lebanon is banned since slag is considered as a waste byproduct and Lebanon is facing many issues concerning their own wastes. Only cement factories have the permission of getting the slag material. Two types of slag were selected in this study: A blended type (40% slag 60% cement) from the cimenterie national company El Sabeh which is the largest company in manufacturing cement in Chekka, and the raw type which is imported from Turkey was brought from Araco Company located in Biel (refer to Figure 3.8).

Different forms of slag product are produced depending on the method used to cool the molten slag as explained in chapter 1. In general, the role of slag is to lower the heat of hydration of cement, which will result a drop in the compressive early age strength but will result an increase in the compressive strength at later age. The granulated slag size must have almost the same cement size according to ACI standards while European standards specify that Slag must be finer than cement. The specific gravity of the slag falls in general between 2.85 and 2.95.

Figure 3.8 Blended and Raw slags

3.2.3 Cement

The Portland cement used in this study is brought from Holcim plant located in Chekka (North of Lebanon). The cement used is PL42.5, conforming to EN 197 European norms (CEM II /A-L) and to Lebanese standards (LIBNOR). Holcim is the second largest company that manufactures cement according to sustainability criteria. New cement bags are frequently used since the CaO from cement reacts with oxygen from the air which can lead to modification in the cement properties where cement is considered oxidized.

3.2.4 Sand

Sand is needed for two different applications in the experimental program. It is needed for the mortar level and for the concrete level. The mortar specimens require the usage of Ottawa sand as specified in the ASTM C778 standard. Two types of Ottawa sand exist in the standard: the graded and the 20-30 type. The type used in the mortar mix is the graded one. As for the concrete, two types of sand were investigated in the study: Sand from local Lebanese source and Egyptian sand. ASTM C33 specifies that the sand gradation must fall between the upper and the lower limits as shown in Figure 3.9. Results showed that Egyptian sand almost lies in the acceptable range while the local sand showed a very fine distribution that might have a negative effect on workability (requires higher water content due to its high fineness). Therefore, the whole concrete mixing was made using the Egyptian sand.

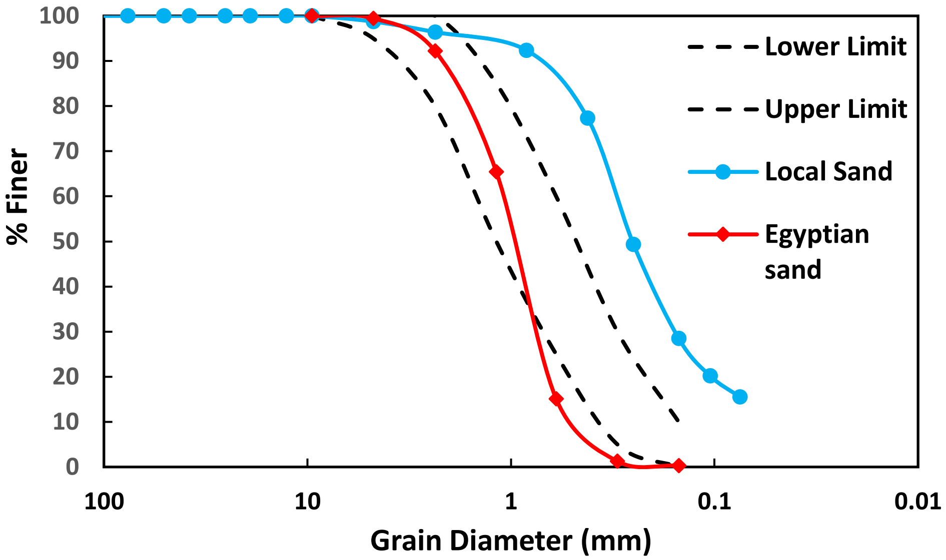


Figure 3.9 Grain size distribution of the Sand used

The specific gravity and the absorption capacity tests for the fine aggregate were conducted and tabulated along with the coarse aggregates properties in Table 3.1.

Table 3.1 Material Properties of fine and coarse aggregates

Properties		
Material	**CA**	**FA**
BSG dry	2680	2640
Absorption	1.74%	0.60%
Gama rodded	1600	-
FM	-	3

An example of a cone test used for calculating the bulk specific gravity is illustrated in Figure 3.10.

Figure 3.10 Cone test example

3.2.5 Coarse Aggregate

The coarse aggregate was also brought from a local source. According to ASTM C33, the gradation of the aggregates depends on its nominal size as mentioned in Table 9.6

in the Appendix. The boundaries for the coarse aggregate gradation were selected according to sieve #6 (Table 9.6 Appendix). The coarse aggregate gradation is presented in Figure 3.11. It was noticed that the distribution is almost similar to the upper limit.

It is important to estimate the absorption capacity and bulk specific gravity of sand and coarse aggregates before including them in the mix as specified in ASTM C127 and C128. So that concrete mix design is based on volumetric proportions and requires the usage of both bulk specific gravity of coarse and fine aggregates.

The bulk specific gravity and absorption capacity values for the fine and coarse aggregates used are presented in Table 3.1. Before testing, washing coarse aggregates is necessary for removing dirt impurities, which would affect the strength (Figure 3.11). This will be elaborated more in the concrete preparation section.

As for the mortar scale, two tests will be performed: compressive strength test and fire refractory test. The materials and the mix proportions for both tests are similar. The only difference is the procedure of mixing such that the compressive strength test is according to ASTM C109 and the fire refractory test is according to ASTM C1012.

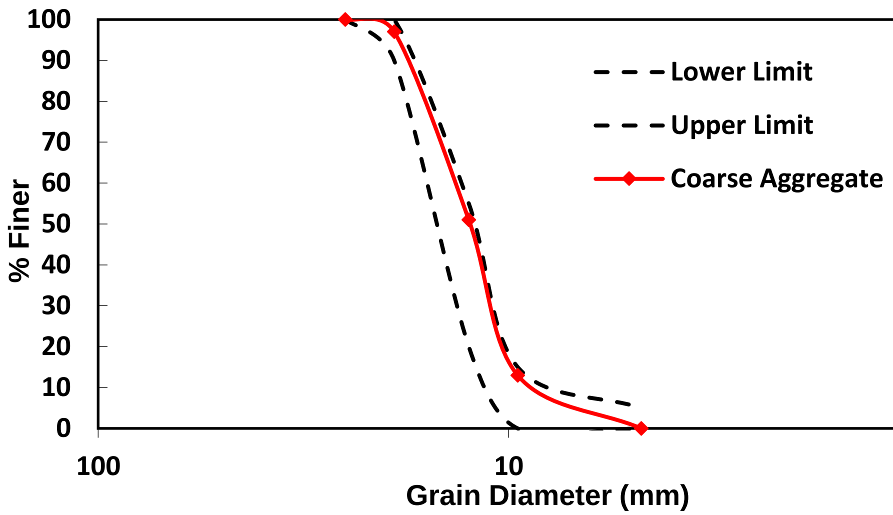


Figure 3.11 Coarse aggregate gradation

Figure 3.12 Washing coarse aggregates to remove impurities

3.2.6 Superplasticizer

The superplasticizer, Sikament NN (High Range Water-Reducing), was purchased from Sika brand and is highly recommended for concrete mixing specially for high strength concrete. Sikament NN complies with ASTM C 494 type F and B.S. 5075 part 3 for superplasticizers. In addition, Sikament NN has a density of 1.2 T/m3 at 25°C. Sikament NN is a highly effective dual action liquid superplasticizer. The dosage of the superplasticizer as specified in the data sheet of Sika is bounded between 0.6 – 2.5% by weight of cement depending on desired workability and strength required. In the study, the superplasticizer dosage used for the 30 MPa and 60 MPa mixes was 0.6% and 2.5 %, respectively.

3.3 Specimen Preparation

The experimental plan consists of four levels as previously discussed. And each section requires its own sample preparation. The terms found in this section are: powder, paste, mortar and concrete. A powder is the material passing sieve Number 200. A paste is a mixture of cementious material and water. The mortar is mixture of paste and sand. Lastly, a concrete is mortar with coarse aggregate.

In the first level, processing of powder is only required in order to characterize the material. Further, in the second level, the paste is made simply by blending cementious materials to water with a ratio of 2 to 1 by weight. The percentage of replacement and the test procedure will be explained in chapters 5,6 and 7 for each scale.

Chapter 4

MICROSTRUCTURE AND POWDER CHARACTERIZATION

4.1 Introduction to microstructures

The microstructure relationship with the actual macro scale mechanistic performance is the heart of the modern material science. Concrete is a highly heterozygote material made of complex microstructures. The term microstructure refers to a magnification of a microscopy portion of an element. The resolution of a human eye is limited to 200 microns. Observing the particles and elements below that range can give a better understanding of the material behavior. At macroscopic level, the concrete is observed to have two phases: aggregates and matrix of cement paste that typically affect the concrete performance. However, at microscopic level, even the two phases are heterogeneous and are made of several elements.

The microstructure of aggregate plays a less important role compared to the microstructure of the paste. The response of the aggregate in concrete is predominantly affected by the physical properties of the aggregates such as volume, size, distribution of pores, and shape of the aggregate. The shape can affect the interfacial transition zone between the two phases since the more the aggregates are flat and elongated, the more they have tendency to accumulate films of water that weaken the transition zone.

4.2 Powder Characterization

In order to examine the potential of a material to become a cementitious material, studying the powder properties is required. Many factors can affect the performance of a material in the paste, mortar and concrete levels. These factors are classified as powder characteristics. Powder has several characteristics categorized in four folds: physical, chemical, mineralogical, and morphological. The physical characteristics can be evaluated by measuring the moisture content, specific gravity, particle size distribution, surface area, and loss of ignition. X-ray fluorescence, Fourier transform, and wet chemical analysis can be used to determine the chemical composition of a material and thus characterize its chemical properties. Moreover, the X-ray diffraction is the typical test used to study the mineralogical characteristics and SEM (scan electron microscopy) is used to study the morphological characteristics of the powder.

The powder characteristics can give preliminary indication whether the material has potential to replace cement. For instance, the presence of reactive silicious material in the powder can help in forming new compounds that have cementitious properties. The powder characterization scheme is illustrated in Figure 4.1.

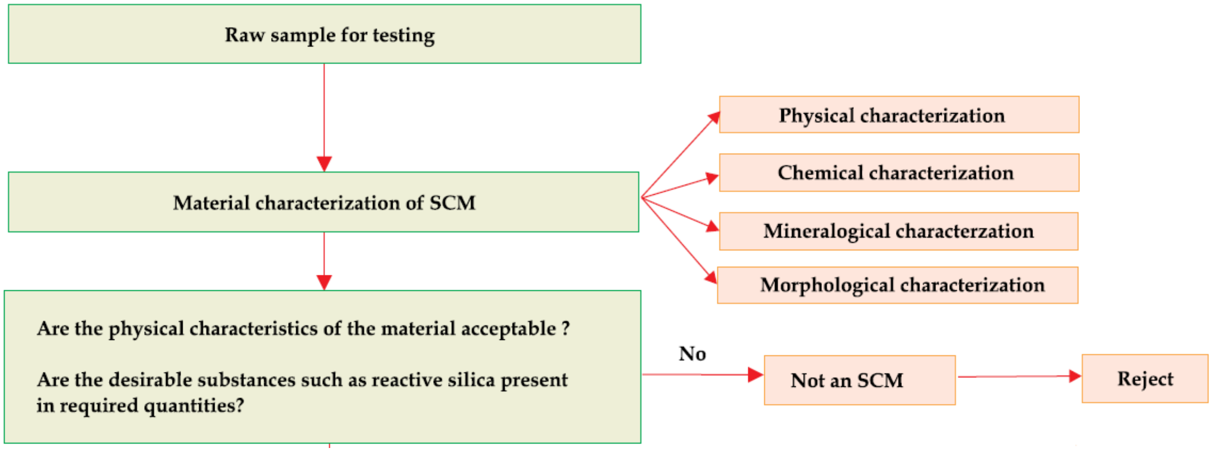


Figure 4.1 Powder characterization scheme

4.3 Testing Plan

In this section, the test procedures for the powder characterization plan are discussed briefly. The powders selected for the following study are cement, slag cement, Terracotta and porcelain. To characterize the properties of the powder material several tests were conducted. For the physical testing, specific gravity and surface area analysis were tested. Characterization of the chemical testing will be skipped since the X-ray fluorescence test is unavailable at AUB. Further, the mineralogical properties will be investigated through XRD (X-ray diffraction) and the morphological properties through SEM (scanning electron microscopy) and TGA (thermal gravimetric analysis).

4.4 Physical Testing Analysis and Results

4.4.1 Specific gravity

Specific Gravity of a material is the ratio of the density of a particular material to that of water having the same volume at a specified temperature. Cement is known to have a specific gravity of 3.15, which means that cement is 3.15 times heavier than the water of an equivalent volume. The specific gravity of a powder can be calculated using Equation 4.1. It is worth mentioning that pozzolanic material reacts with water, which brings the need to use different liquid such as kerosene that has a specific gravity of 0.807 since kerosene does not react with cement.

$$SG = \frac{(w_2 - w_1)}{(w_2 - w_1) - (w_3 - w_4) * SG_{Liquid}} \qquad \text{(Eq. 4.1)}$$

Where W1 is weight of the flask empty (250 ml), W2 is the weight of flask plus 50g of cementious material, W3 is the weight of flask filled with weighed cement and kerosene added till the mark, and W4 is the weight of the flask filled with kerosene up to the top. The results of the Specific gravity test shown in table 3.1 indicate that the ceramic powders are lighter in weight than the cementious materials (cement and slag) which indicates that the usage of ceramic will result in reducing the unit weight of the concrete.

Table 4.1 Specific gravity SG of the used materials

Material	Cement	Slag cement	Slag	Porcelain	Terracotta
SG	3.15	2.93	2.83	2.65	2.60

4.4.2 BET (Surface Area)

Brunauer–Emmett–Teller (BET) is used to determine the surface area and the volume of the pores for the powder. The procedure of running a BET is shown in Figure 4.2. At first degassing must be made at a constant temperature of 140 degrees to ensure no moisture persists in the sample. As a second step, vacuum is applied to tube, then Helium is added to the sample after the tubes are immersed in liquid nitrogen of -196 degrees followed by absorption and desorption by nitrogen.

The specific surface area of a powder material is measured by calculating the adsorbed gas on the surface of the particle with respect to a monomolecular layer on the surface.

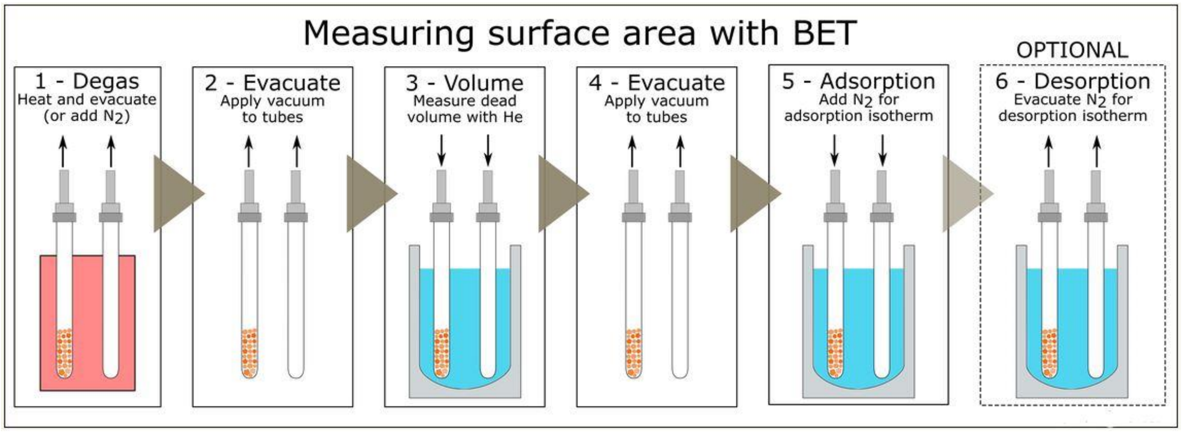


Figure 4.2 BET surface area

The BET results for the different materials utilized are presented in Table 4.2.

Table 4.2 Results of the BET test

Materials	Cement	Slag cement	Slag	Porcelain	Terracotta
Surface Area (m^2/g)	0.513	0.616	0.523	0.364	0.437
Volume of large pores (cm^3/g)	0.00044	0.00024	0.0003	0.00026	0.00032
Volume micropores (cm^3/g)	0.0067	0.001484	0.001	0.00148	0.000554

The Powders selected in this experiment are considered of low porosity. It is important to notice that the Terracotta ceramic is more porous and has a higher surface area as compared to the porcelain ceramic. Further, the slag cement has a higher surface area than cement. As for the porosity, the distribution of pore sizes differs between slag cement and cement, where both have almost same total pores volume however slag cement has high micropores and cement has larger pores.

4.5 Mineralogical Testing Analysis and Results

4.5.1 X-ray Diffraction (XRD)

X-ray powder diffraction is used to identify unknown crystalline materials. Determination of unknown solids is critical to study the mineralogical science of a material. The intensity of X-ray is continuously recorded for the sample from the scattered elements while the detector is moving with an angle of 2θ. X-ray diffraction (XRD) measurements were conducted using the Burker X-ray D8 advance. The operation of this system functioned under the open attenuator of 40 kV and 40 mA with an optimization for scattering angles θ of 5 to 55 degrees. The aim of the test is to compare the compositions of the ceramic and slag to that of cement and to look for the siliceous element in the material.

The XRD patterns for the cement, slag cement, and ceramic powders are illustrated in Figure 4.3. The cement and slag cement are formed almost from the same compounds showing high peaks of Alite (C_3S), Belite (C_2S), ferrite (C_4AF), and gypsum with cement showing an additional peak of basanite. It can be observed that the cement shows higher peaks of Alite and Belite whereas slag cement shows higher intensity of

Ferrite. As for the ceramic, it is mainly composed of mullite ($2SiO_2.Al_2O_3$), quartz (SiO_2), and anorthite ($Ca[SiO_2.Al_2O_3]$) with highest intensity observed for quartz.

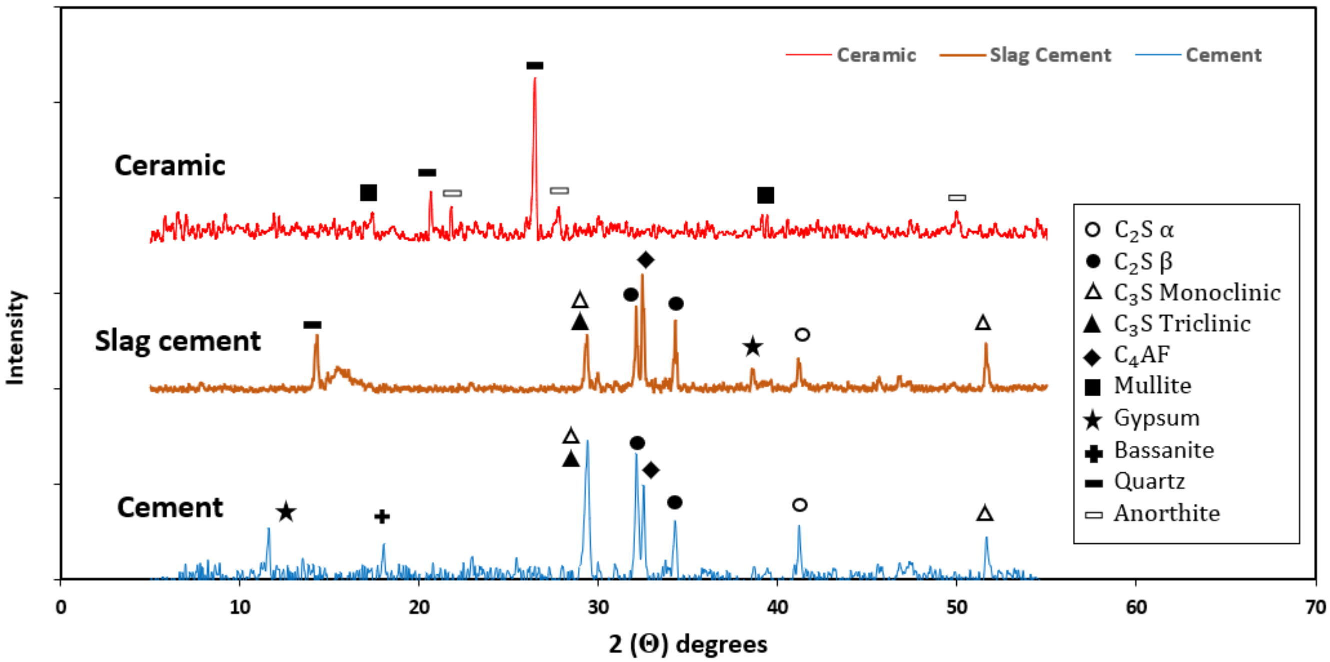


Figure 4.3 XRD test for cement, slag cement and ceramic

4.6 Morphological Testing Analysis and Results

The morphological testing analysis and results for different utilized powders will be presented in detail in this section.

4.6.1 Scanning Electron Microscopy (SEM)

TESCAN, VEGA 3 LMU, Scan Electronic Microscope (SEM) was used to characterize the physical surface characteristics of the five powders (Cement, Slag, Slag Cement, Terracotta, and Porcelain). SEM shows the true texture and shape of the fillers providing a better understanding of the size, angularity, and porosity of the powder particles. Coating and the resolution of the images plays an important role in showing the true shape and texture at the microstructure level.

Follow the following procedures when making scanning through SEM:

- Coat the samples with platinum with the thickness of 30 nanometer.
- Make sure the stage far from the objective.
- Set the value of Wd and Z to 15
- Vent the chamber
- Put the samples in the chamber (Figure 4.4)
- Pump the chamber
- Set the voltage to 5kV
- Turn Beam on and select SE.
- The chamber has a capacity of 7 cells. On the tescan software click on the cell you want to study.
- Right click and select the minimum magnification
- Click on Auto brightness
- Mag till 50 microns (size of cement particle size)
- Use Wd and mag to get the proper image and scale required.
- Zoom out and select adjustment autogun then adjustment manual centring
- Change pad spot to zero and WD to 5mm.
- Focus WD with F11 and F12 and the ball
- Scroll down in the image window to lower the rate

- Save the image.

Figure 4.4 shows the SEM chamber in where samples are inserted.

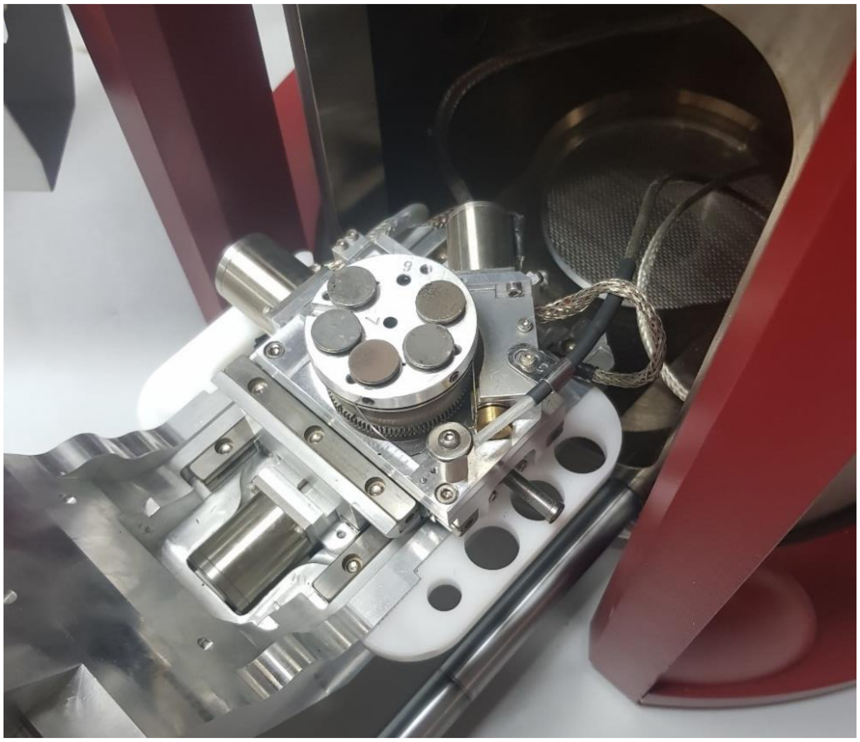


Figure 4.4 SEM chamber

The SEM morphology results for the different powder types are presented in Fig. 4.5. The SEM images clearly illustrate that porcelain ceramic has the closest texture to cement. The size of the porcelain particles is also comparable to cement. In addition, both slag types are formed from clanged particles which seem to be smaller in size compared to cement. All powders consist of angular elements.

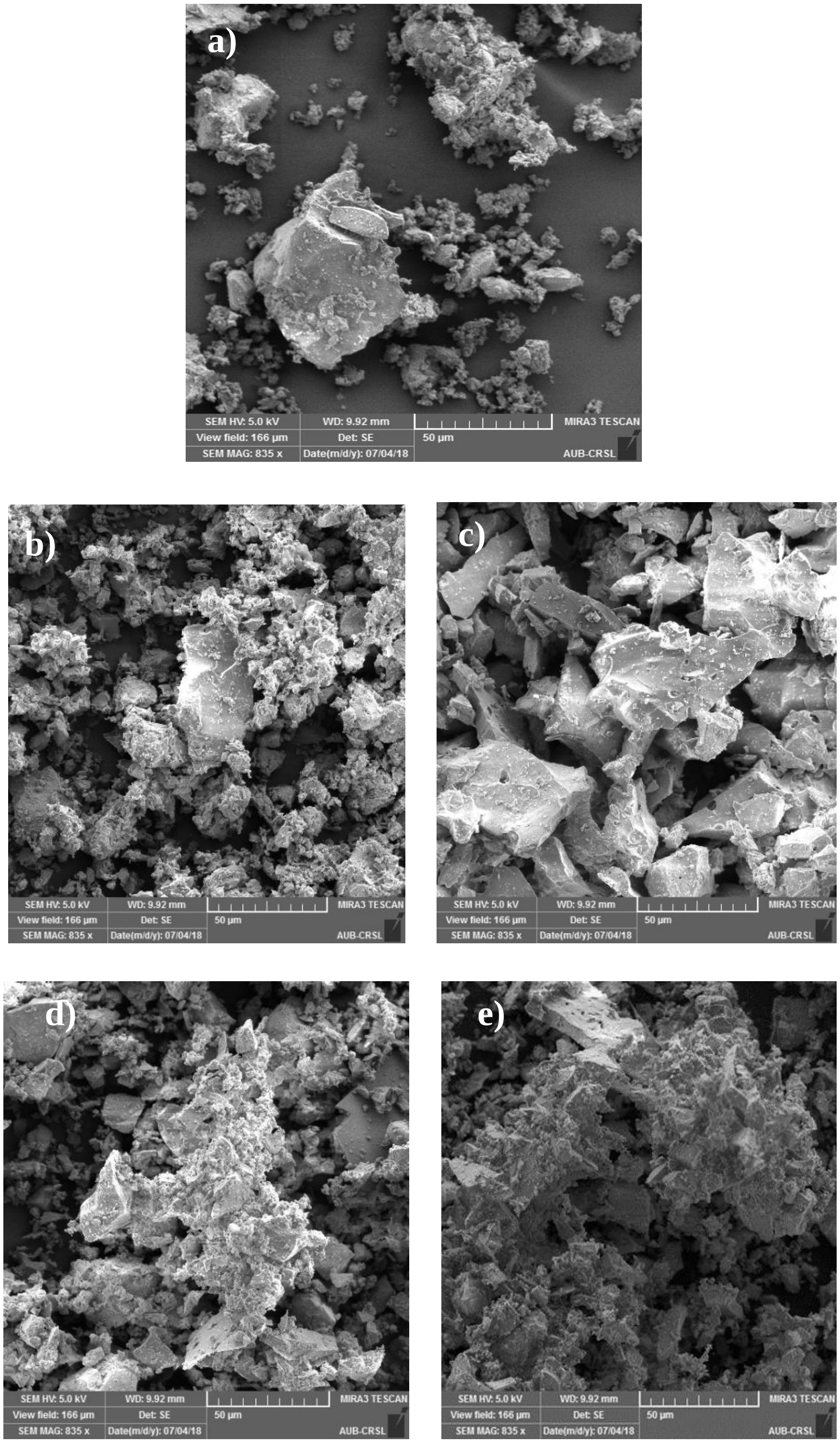


Figure 4.5 SEM morphology results for the different powder types a) Cement b) Terracotta c) Porcelain d) Blended slag e) Raw slag

4.6.2 Thermal Gravimetric Analysis (TGA)

The thermal gravity test was performed to study the mass stability of the powders under heat using the Netzsch machine (Figure 4.7). Since ceramic is classified as a material of extreme hardness, it is important to characterize its thermal property. Thus, powder samples were heated at a constant rate of 10°C/min from 30 to 1000°C.

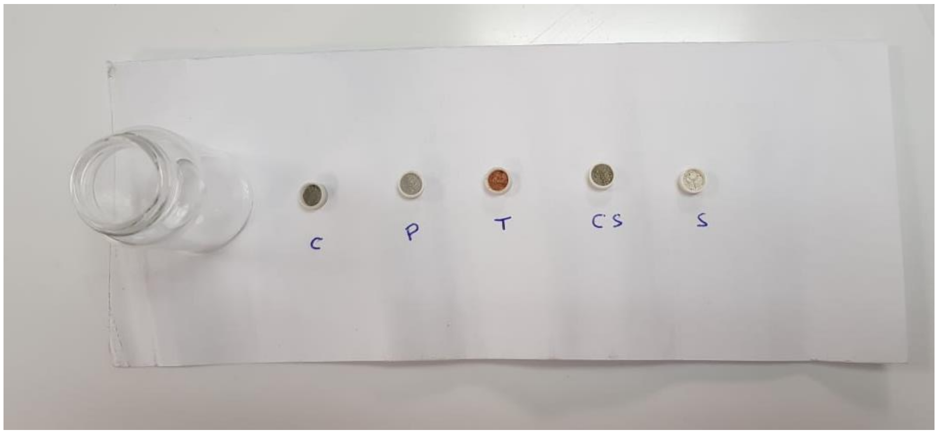


Figure 4.6 TGA samples in crucibles

Figure 4.7 TGA machine

The results of the thermal gravimetric test on powders are represented in the Figure 4.8. The porcelain and terracotta ceramic materials showed the least mass loss under heat. It can be noticed that the porcelain showed zero loss of mass while terracotta indicated 1% of mass loss. The blended slag cement showed more stability than the slag. Slag cement lost 1.7% of its weight while slag lost 3.9%. Further, cement is the weakest material among the powders showing a loss of 9.7%. It is important to mention the major loss in weight of the slag, slag cement, and cement occurred between 650 and 780 ^{0}C.

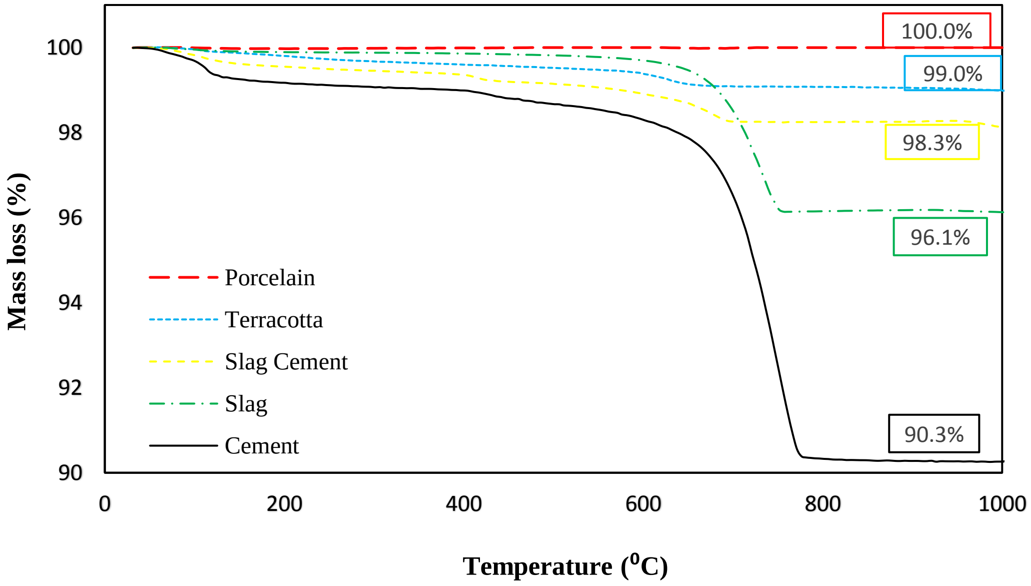


Figure 4.8 Thermal gravimetric analysis TGA powder results

4.7 Summary

Based on the powder characterization tests the following conclusions can be drawn:

1. Ceramic powder is lighter in weight than the blended slag cement and cement which makes the material useful in making lightweight concrete.

2. The BET test revealed that the ceramic powder has a lower surface area are than cement and slag cement and this is expected since the ceramic used in the study is only sieved through sieve #200. In other words, ceramic has particles size less than 75 microns which is considered coarser than cement and slag cement (less than 45 microns).
3. X-ray diffraction test revealed that cement and slag cement have a similar composition, however ceramic has high content of silicon which indicate that ceramic has potential of becoming a pozzolanic material.
4. The SEM images showed that ceramic is angular and has a texture close to cement and slag cement
5. The TGA test revealed that ceramic is a very stable material under high heat. In addition, slag is more stable than cement.

Chapter 5

POZZOLANIC PERFORMANCE

5.1 Definition of Pozzolan

Assessment of the pozzolanic activity of sustainable materials has been increasing in the last decade because of the necessity of finding new materials to replace cement which harms the environment in several ways. A pozzolanic material as defined by ASTM C125 as a material that has siliceous (SiO_2) and aluminous (Al_2O3) in its chemical composition. It might have little or no cementitious value(CaO). In presence of water, it reacts with calcium hydroxide $Ca(OH)_2$ at everyday temperature to form new compounds (CSH) that possess cementitious properties.

Pozzolanic Materials can be obtain from different sources: mineral and industrial by-products. The discovered mineral pozzolanic materials are calcined clay and Metakaolin whereas the revealed pozzolanic by-product materials are fly ash, silica fume, and slag.

The pozzolanic activity of a material can be tested by many tests such as: the Frattini test, the saturated lime test, and the strength activity index test.

A wide range exists to assess the pozzolanic activity of a material. Assessment is classified by direct methods and indirect methods. The direct methods target the presence and the consumption of $Ca(OH)_2$ with time. The existing direct methods are Frattini test, the Saturated Lime test, X-ray diffraction (XRD), and Thermal gravimetric analysis (TGA).

On the other hand, the objective of the indirect methods is to measure a physical property of sample that can indicate the extent of pozzolanic activity. Such tests includes Strength index, electrical conductivity, and heat evolution by conduction calorimetry.

5.2 Micro structure of hydrated cement paste

The chemical composition of the clinker consists of $C_3S,\ C_2S,\ C_3A, and\ C_4AF$. The percentages of the four compounds range as such: (45- 60), (15-30), (6-12), and (6-8), respectively. When cement reacts with water, the high temperature compounds become driven to the solution that gets saturated rapidly with various ions. Within minutes, interaction occurs between the calcium, sulfate, hydroxyl, and the aluminous compounds called cement hydration. In addition, ettringite (Trysulfoaluminate hydrate) starts to appeal in needle shape that can be observed through SEM at magnification of 70 microns level. Etteringite is later transformed to calcium sulfoaluminates hydrates that have hexagonal plate shape. Hours later after mixing, the calcium hydroxide (CH) and calcium silicate hydrate (CSH) start to appeal by dissolving the cement particle and filling the water space. The CH has a prismatic shape while CSH is needle like. The hydrated cement paste is formed from CSH, CH, calcium sulfoaluminates hydrates, and unhydrated clinker grains. The volume of the CSH makes up to 60% of the paste whereas CH and calcium sulfoaluminates hydrates constitutes 25% and 20% respectively. The hydration starts by dissolving the cement particles. The small particles disappear first while large particles become smaller at first prior to total dissolving with time from the system. The CH and CSH phases can be seen through SEM at 1 to 10 microns levels. It is important to note that the hydration products are the principal strength source of the paste. These products tend to adhere strongly to each other.

The addition of a new pozzolanic material rich with Silicates can modify the structure of the paste which changes the behavior of the paste. The silicate from the pozzolan will react with the CH particles from the cement hydration creating more CSH particles as shown in the following equation:

C3S + H → CSH + CH (Fast reaction)

Pozzolan + H + CH → CSH (Slow pozzolanic reaction)

5.3 Testing plan

In this section, the test procedures for the entire experimental plan of assessing a pozzolanic material is discussed briefly. The powders selected for the study are cement, slag cement, and porcelain. The direct methods used to evaluate the selected pozzolans of this study are: Frattini test, lime saturated test, in addition to XRD, TGA, and SEM. As for the indirect methods, the tests performed are strength index and electrical conductivity. The samples preparation of the selected test are discussed below.

5.4 Direct Methods Analysis and Results

The direct methods aim to study the consumption of $Ca(OH)_2$ with time due to the proposed pozzolans

5.4.1 Frattini test

The Frattini test is performed according to BS standard EN 196-5. The test involves mixing 20 grams of the cementious material that consists of 80% cement and 20%

of the tested pozzolan with 100 ml of distilled water in a bottle. After preparing the paste, the specimens are sealed and placed in the oven at a temperature of 40 degrees. At the testing day, the bottles are removed and cooled to room temperature. Then, Whatman no. 542 filter paper is used for the vacuum filtration process. Using the filtrate, evaluate the alkalinity and the hardness of the solution by performing two classical titrations.

For the alkalinity titration:

- Dilute the filtrate with a ratio of 1 to 100
- Place 50 ml of the sample in a flask
- Add 6 drops of the phenolphthalein indicator
- In case color changed to pinkish titrate the solution with HCL of 0.02 N concentration and mark the volume as P in ml. In case the color has not change, skip this step of titration and record P as zero.
- Add 2 ml of the mixed indicator.
- Titrate with 0.02 N HCL while mixing with magnetic stirrer until an orange color is observed, and record the value as T in ml (total alkalinity).

The hydroxide alkalinity is T multiplied by 20 and 100 the dilution factor and divided by 17 for unit conversion to mmol/L.

For the Hardness titration:

- Dilute the filtrate with a ratio of 1 to 10
- Place 10 ml of the diluted sample in a flask
- Add 0.15 grams of Murexide indicator to the sample
- Add 6 drops of NaOH

- Titrate with 0.1 N EDTA while mixing with magnetic stirrer until light purple color is observed and record the value as C in ml (Figure 5.1).

The Calcium concentration is calculated by multiplying the C by 0.4008 and the dilution factor of 10 measured in mmol/L.

Plot the [CaO] concentration versus the [OH$^-$] concentration for the all powders (Figures 5.2 & 5.3).

The line presented in the Frattini graph is considered as a limit for the theoretical maximum concentration of [CaO] for each [OH$^-$] given by the EN 196-05.

Where max [CaO] and each [OH-] relation can be drawn from the following equation:

$$[CaO] = \frac{350}{[OH^-]-15} \qquad \text{Eq. 5.1}$$

Any results below the line indicated that the tested pozzolan attributes in a pozzolanic reactivity. Since the powder is contributing in removing Ca^{++} ions which means that it is able to consume the ions in forming cementious properties. It should be noted that this method applies assuming that no other calcium source is presented in the solution such as leaching. Further, any point on the line reflects that the powder has zero pozzolanic reactivity, as well as, any point above the line indicates that powder has no pozzolanic activity.

Figure 5.1 Hardness test

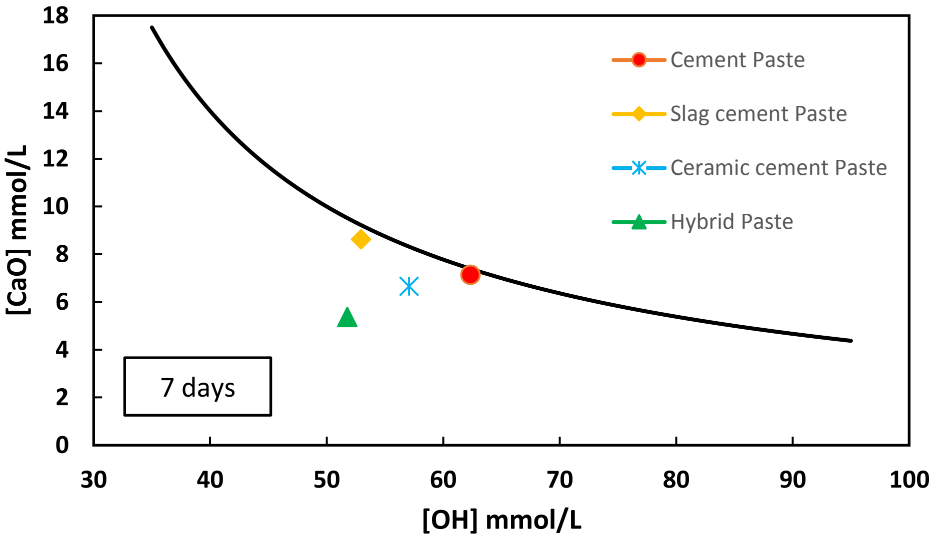


Figure 5.2 Frattini test for the studied pastes at 7 Days

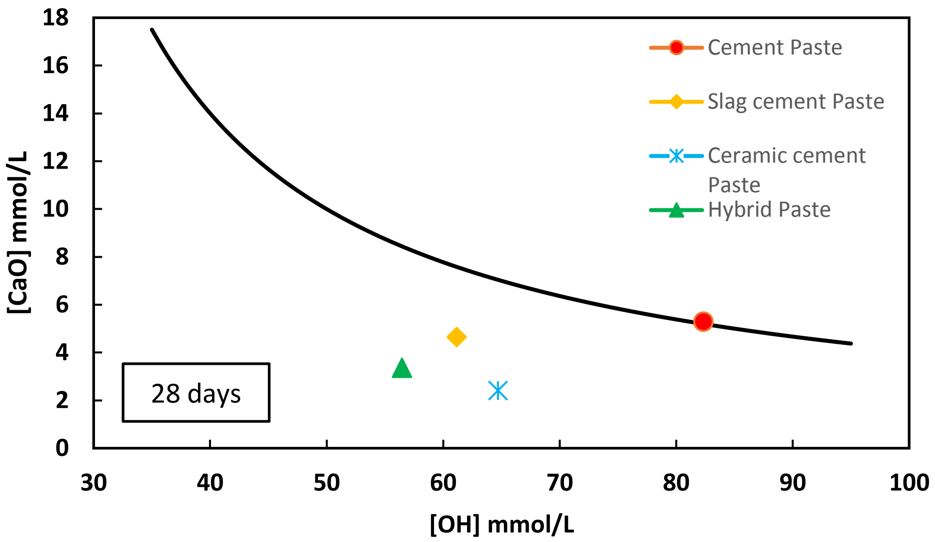


Figure 5.3 Frattini test for the studied pastes at 28 Days

Table 5.1 CaO consumptions for the studied pastes

[CaO] consumption		
Age	7 Days	28 Days
SP	7%	39%
CP	20%	66%
HP	44%	60%

Where P is cement paste, SP is slag cement paste, CP is ceramic cement paste, and HP is hybrid paste made of slag cement and ceramics.

The results of the Frattini test shown in Figures 5.2 and 5.3 reveal that the [CaO] concentration falls below the maximum theoretical CaO concentration for the slag cement paste, ceramic cement paste and hybrid paste. This is due to the fact that the pozzolan reaction leads to consuming the CaO in making new microstructures. In addition, it is noted that the slag cement paste and ceramic paste have low rate in consuming CaO where resulted only 7% and 20% respectively at 7 days. In contrast, the hybrid paste made of ceramic and slag cement resulted in a better consumption of CaO at early days estimated by

44%. At 28 days, the ceramic paste had the highest CaO consumption and that can be explained by pozzolanic activity of the three other pastes.

5.4.2 Saturated Lime test

The saturated Lime test is also called the modified Frattini test since the same procedure of titrations applies in this test ; the only difference is the sample preparation. The lime saturated test contains lime and no cement and thus the (CaO) source is higher and is attributed by lime.

The preparation of solutions involves the following steps:

- Prepare a lime saturated solution by adding 2g of lime to a 1 liter of distilled water.
- Place 75 ml of the saturated solution in a bottle
- Add 1g of the test pozzolan to the bottle.
- Seal the samples and place it in the oven till testing date.
- One measurement can be taken from each sample. So select the number of samples according to the selective days at which you need to test.
- Filtrate and continue the procedure of the test as mentioned in the frattini test.

The zero-activity baseline is the control specimen itself in this test. In addition, CO_2 and temperature highly affect the results of the tests which makes it important to seal the material and make sure that the temperature is kept at 40 degrees. It is very important to perform the lime test at early age since some materials are too reactive and can react with lime in the first days and show minimal [CaO] removal at 7 and 28 days whereas other materials can have a slow reaction that can start at 7 days and keep increasing in removing CaO till late age.

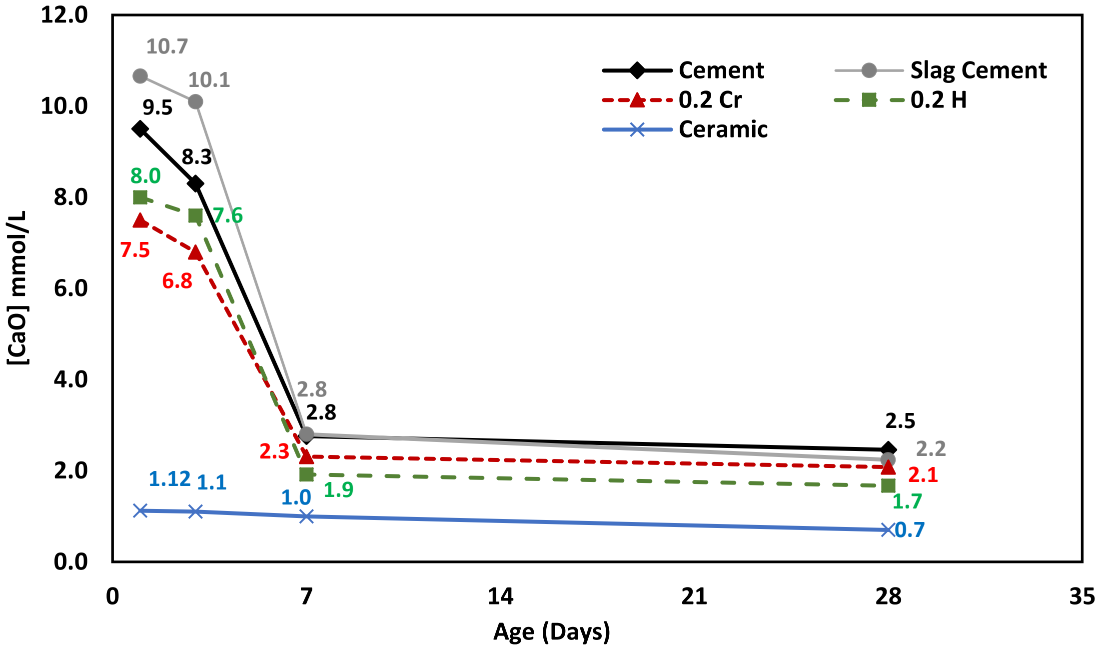


Figure 5.4 Concentration of CaO in saturated lime test for different pastes

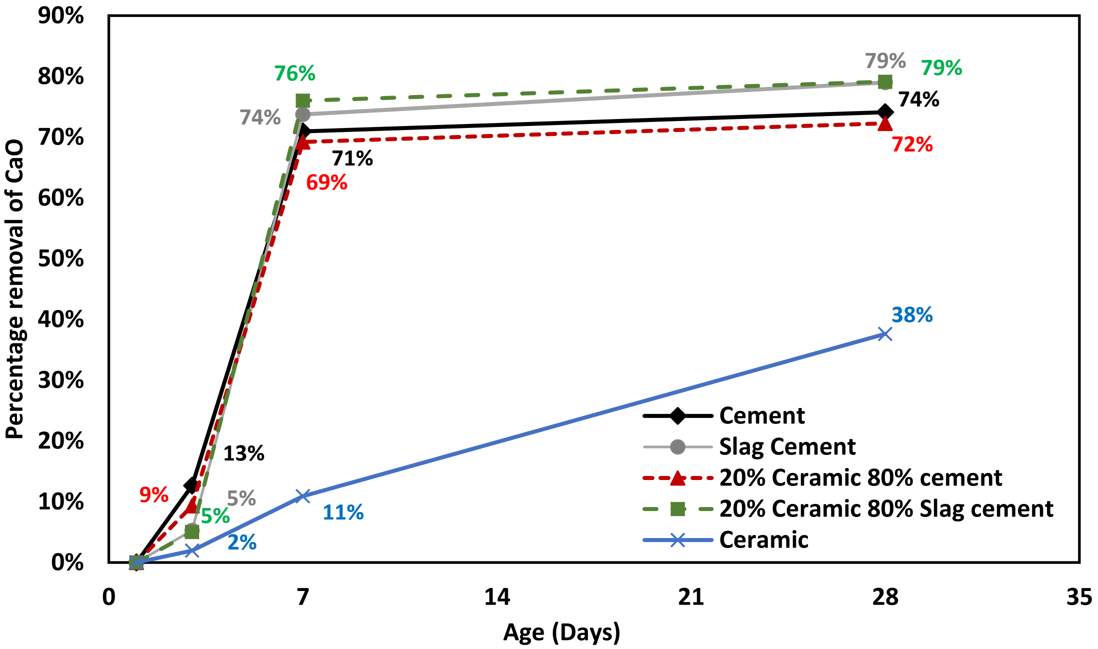


Figure 5.5 Percentage removal of CaO in saturated lime test for different pastes

Five paste mixes were selected for the saturated lime test: (cement, slag cement, ceramic, blended mixture of ceramic and cement of a ratio 1:4, and lastly blended slag cement and ceramic with the same ratio 1:4). The results on Figure 5.4 of the lime tests revealed that the CaO concentration is reduced with time for all mixtures which indicates that a reaction is occurred between the pozzolan tested and the lime available in the solution. It can be observed that the ceramic has the lowest rate of consumption. At 3 days, the ceramic consumed only 3% of the [CaO] content whereas slag and slag-ceramic mixture resulted a reduction of 5%. The consumption increased for the cement and cement-ceramic mixtures that recorded 13% and 9% respectively. Further, the reduction of [CaO] increases for all mixtures where the percentage of removal ranged between 69% and 75% except for the ceramic mixture that recorded 11%. Similarly, the consumption at 28 days reached 72% to 79% for all materials except for ceramic which indicates that the most evident consumption occurred in the age range of 3 to 7 days. The loss in [CaO] reached 38% at 28 days.

5.4.3 XRD

Burker X-ray D8 advance machine was used to observe any change in the Silicate and CH compounds with time. The test gives a good indication of how ceramic is contributing in the paste. Four pastes were made for this test: cement paste, slag cement paste, 20% porcelain paste, 20% hybrid paste. The same paste specimens were also used for the SEM and TGA tests.

Figure 5.6 presents the change of the XRD patterns with time. Two pastes were selected and tested at 1 and 28 days after mixing: slag cement paste and hybrid paste. Both pastes showed high peaks of C_2S-β and C_3S, CH and CSH. With time it was noticed that the C_2S and C_3S are being consumed producing higher peaks of CH and CSH gels. It is worth noting that the paste containing ceramic had higher peaks of CSH and that the XRD shows that some quartz that initially comes from the ceramic still did not fully react with cement.

In Figure 5.7, the XRD patterns of the four paste types at 28 days are presented. The results of the test indicate that the four-pastes had close composition with minor differences. The ceramic paste showed the highest CSH peak whereas the highest CH peaks was more evident for the slag mixes (slag paste and hybrid paste) and this can be explained by the fact that ceramic contains the highest quartz content among the pozzolan material used in the test as well as slag contain high reactive CaO content. Further, the Ceramic paste showed peaks of C2S, C3S and SiO2. Such phenomena can be explained by that the reaction of ceramic is the lowest among the powders.

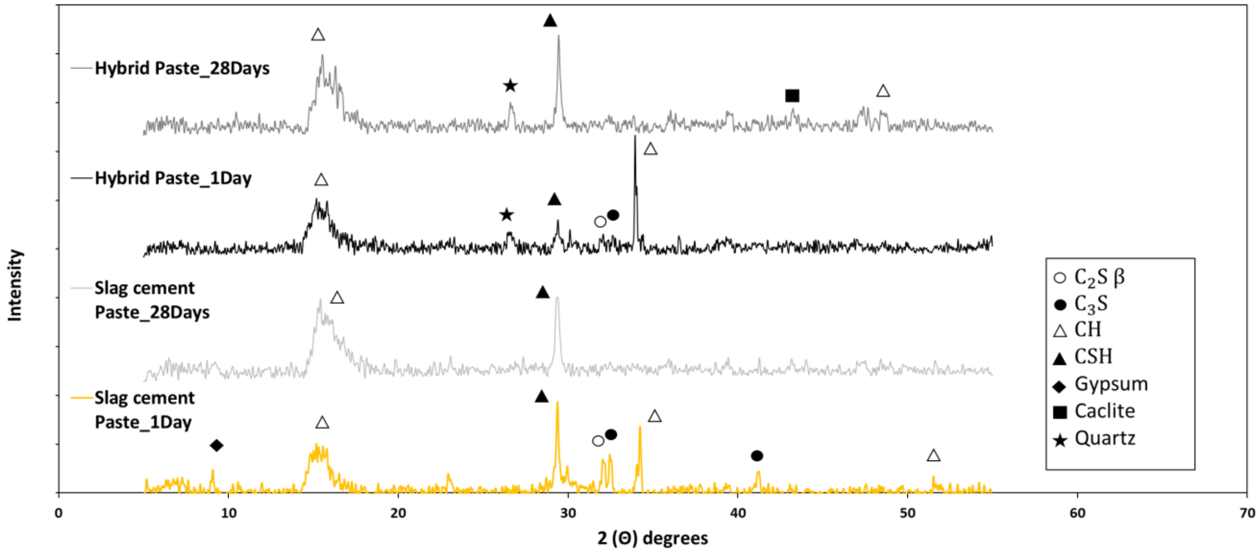


Figure 5.6 XRD patterns for two pastes (Slag cement, Hybrid) tested at 1st day and 28 days of mixing

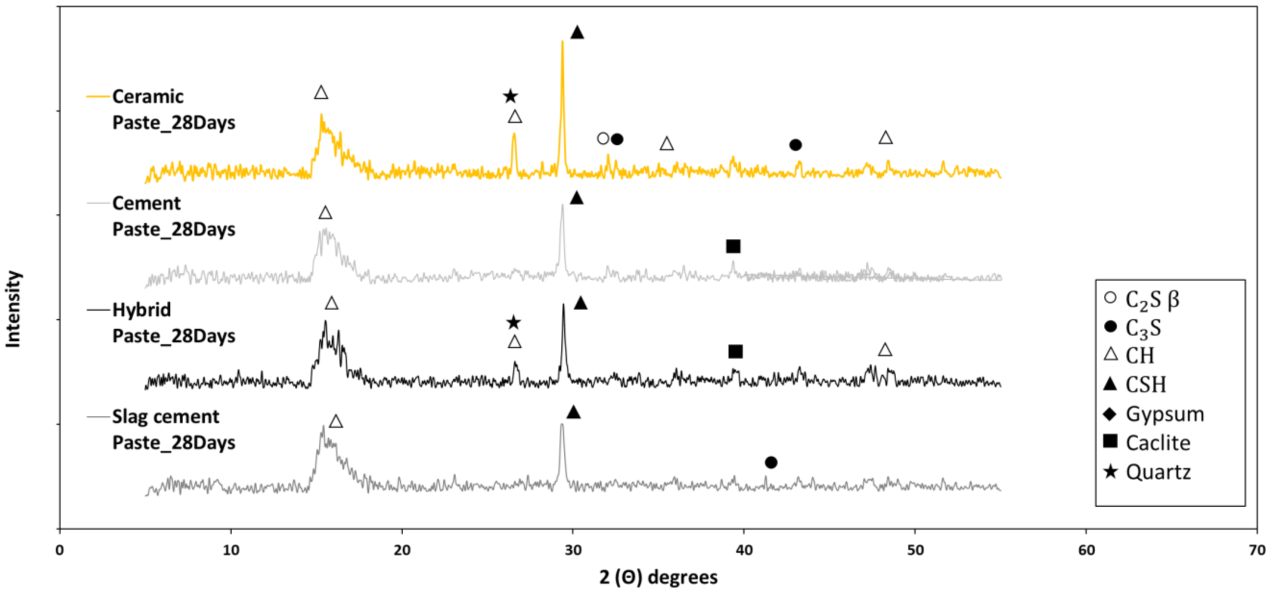


Figure 5.7 XRD patterns of the four paste types at 28 days

5.4.4 TGA

The thermal gravity test was performed to assure the mass stability of the paste with time. It should be noted that CSH compounds are more stable than the CH. Therefore the consumption of the CH with time will make the paste matrix more stable against heat.

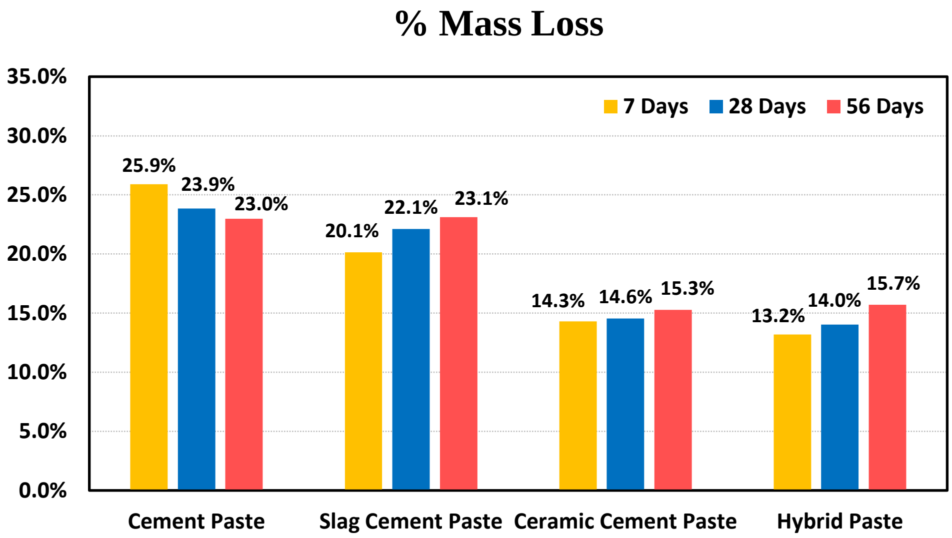


Figure 5.8 Mass loss percentage for the different studied pastes

The results of the TGA test are shown in Figure 5.8. The mass loss of slag and cement pastes fall between 20 and 25% whereas the inclusion of ceramic reduced the mass loss by around 10% and the mass loss of hybrid paste fall between 13 and 16% and this shows how ceramic increases the mass stability. Moreover, the change in mass for all pastes changed insignificantly with time.

5.4.5 SEM

TESCAN, VEGA 3 LMU, Scan Electronic Microscope machine was utilized to scan the CH and CSH compounds for the four pastes.

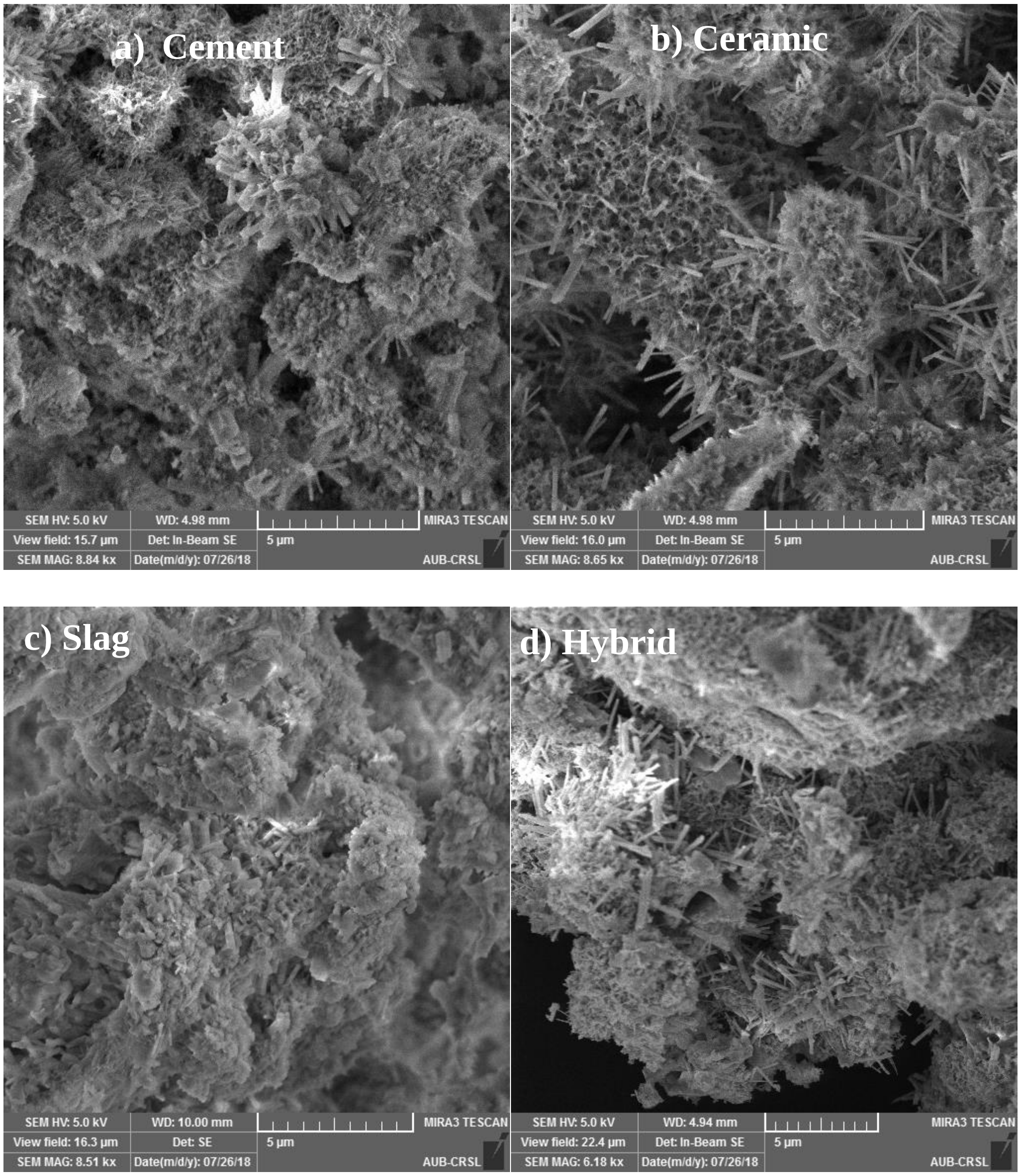


Figure 5.9 CH and CSH morphology of four paste types a) Cement b) Ceramic c) Slag d) Hybrid

The CH and CSH morphology are shown in Figure 5.9 for the four paste types. Referring to Figure 5.9, the CH gel has a prismatic shape and the CSH strength gel is needle-like as can be observed in the Figure 5.9. It is important to mention that the cement paste image shows less CSH particles when compared to the other pastes. In addition, the needles observed in the cement paste are too small and thick. However, the image taken for the ceramic paste shows different needle-like shapes which are thinner and longer than the ones for cement paste. Further, the slag-paste and the hybrid-paste images display bigger area covered by CSH.

Figure 5.10 Sample holders

5.5 Indirect Methods Analysis and Results

The Indirect methods are used measure a physical property of sample that can indicate the extent of pozzolanic activity.

5.5.1 Strength Index

The strength activity index of porcelain is in accordance of ASTM C311 and ASTM C618. A preparation of six cubes from the following mix proportions is required: (400g of cement + 100g of pozzolan), 1375 g of graded standard Ottawa sand, and 242 ml of water. In addition, the control cement mortar mix consists of similar mix proportions with cement content being 500 grams. The strength activity index (SAI) is calculated from dividing the compressive strength of the pozzolan mortar over the control cement mortar. ASTM C618 specifies that the SAI must be higher than 75% for both 7 and 28 days.

Table 5.2 Strength activity index comparison between cement and 20% porcelain

	compressive strength		Strength index	
testing day	7 days	28 days	7 days	28 days
cement	18.6	26.6	100%	100%
20% porcelain	13.1	21.2	70%	81%

The results from Table 5.2 indicate that porcelain is considered non-reactive at 7 days since its activity index is low. However, at 28 days, the strength activity index is satisfactory and passes the code requirements.

5.5.2 Electrical Conductivity

Electrical conductivity method is a method adopted by a number of researchers to assess the pozzolanic reactivity of a material. The theory behind the test is that the reaction between the pozzolan material and the calcium hydroxide (available in aqueous solution) can result in loss of the electrical conductivity that will start to decrease due to the absence of suspended CH particles available in the solution with time. One way of making the test is mixing powdered Ca $(OH)_2$ with the pozzolan powder by a ratio of 4 to 1 , followed by water addition. The water to solid ratio can ranges between 0.45 and 1.2. Further, the Pozzolanic activity is calculated as a ratio of electrical conductivity of the maximum rate of change of conductivity to the time at which this maximum is reached. Another procedure to measure the electrical conductivity of a solution is by adding 1 gram of the pozzolan to a 200 ml of an OPC solution previously prepared by mixing 350 grams of cement with 1 Liter of distilled water. The solution must be agitated by a stirrer at a temperature of 80 degrees to accelerate the reaction.

5.6 Summary

Based on the assessment of the pozzolanic activity of the paste samples, the following can be concluded:

1. The Frattini test showed that the ceramic paste, slag paste, and hybrid paste are considered reactive since it does consume the calcium content with time.

2. The saturated lime test showed that the ceramic has a very little reactivity since it was the only powder that failed to develop high consumption of lime with time.
3. The thermal growth results showed that the ceramic mixes are more stable against heating.
4. The SEM images showed that the hybrid paste is the one that developed CSH the most needles.
5. The strength index showed also that ceramic has no reactivity at 7 days. But with time it is able to become reactive which makes the ceramic a low reactive material.

Chapter 6

MORTAR TESTING AND RESULTS

6.1 Introduction

This chapter was designed to investigate the effect of slag and ceramic materials on the mortar compressive strength. Additional testing was done for the purpose of testing the durability of mortar specimens exposed to heat. The parameters corresponding to each test together with the results are presented for control samples and for samples of various combinations of slag/ceramic as a cementitious material in Table 9.1 in the Appendix.

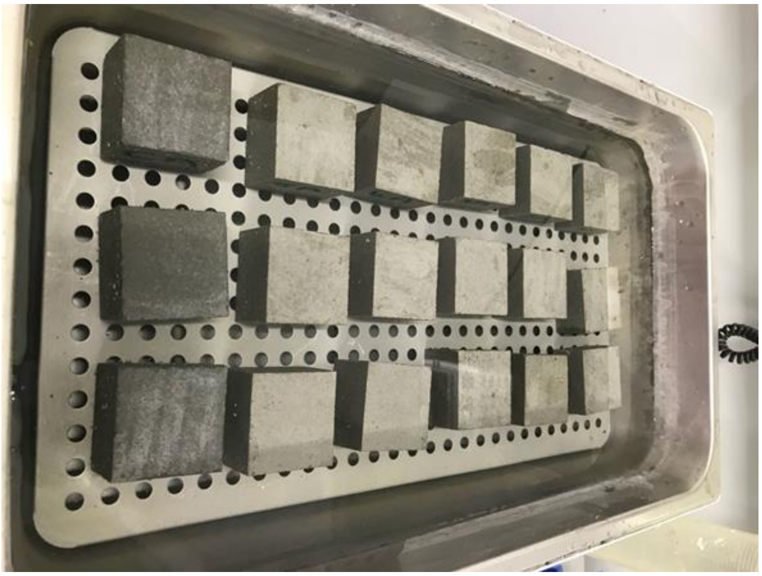


Figure 6.1 Mortar specimens

6.2 Testing Plan

The mortar phase testing consisted of three stages: (1) test the slag activity index of slag, (2) investigate the effect of two types of ceramics (Porcelain and Terracotta) of two particle size (45 and 75 microns) on the compressive strength of mortar specimens and (3) examine the durability of mortar specimens made from several combinations of different cementitious materials through heat refractory tests according with ASTM C865.

6.3 Mortar Preparation

For the mortar scale, testing of phase 3, according to ASTM C109 the mold dimensions should be 5x5cm and shall not have more than three cube compartments (Figure 3.13). The molds shall be made of hard whose interior faces are plane surfaces. For the purpose of leveling the mortar, the flat side of the trowel (with the leading edge slightly raised) should be drawn lightly once along the length of the mold (Figure 6.2).

Figure 6.2 ASTM C109 mortar mold dimensions

Figure 6.3 Mortar samples cast in the molds

The mortar phase testing consists of performing two tests: the compressive strength tests according to ASTM C109 and the Mortar fire refractory tests according to ASTM C865. The mix proportions for the mortar is similar for both tests. The weight proportions shall be one unit of cement to 2.75 units of sand and a water to cement ratio of 0.5 for both tests. However, the method of mixing differs between the tests. The Water used for the mortar experiments is distilled water to ensure that no minerals affect the strength or the mechanical behavior of the mortar cube.

According to ASTM C109, the mixer used to make mortar cubes (5x5x5 cm) must have a planetary motion of two speeds: slow and medium that are estimated to be 62 rounds/min and 125 rounds/min, respectively. In addition, the bowl must have a nominal capacity of 4.73 L as shown in Figure 6.4. The mixing of the materials follows a specific procedure. Start by adding the water into the bowl. Then add the cement to the water and turn on the mixer at the slow speed for 30 seconds. Next, add the sand gradually while the mixer is on at slow speed over 30 seconds. Regulate its speed to medium and complete mixing for an addition 30 seconds. Stop the mixer for one and a half minute. During the first 15 seconds scrape down with a spatula the mortar that are on the side of the bowl, then cover the mortar with a sheet. Finally, finish the mixing procedure by mixing the mortar for 1 min at medium speed.

After mixing, start to mold the specimens within a time not exceeding 2 minutes and a half. Divide the cube into two layers of 2.5 cm each. Tamp each layer of the mortar 32 times in about 10 s in 4 rounds and each round consists of tamping 8 times as shown in the Figure 6.4. A mortar cube shall be completed before start molding the next one. After one day of mixing, demold the cube specimens and store them in water till the testing date specified. Wipe each sample with a towel so that the cubes are in surface-dry conditions prior testing.

As for the fire refractory cube specimens, the test procedure takes several stages prior testing as follows: mixing, curing, drying, and firing. ASTM C865 specifies that mixing must be made according to the ASTM C862. Add sand and cement to the bowl and turn on the mixer at slow speed for 1 minute. Add part of the water and mix at the same speed for an additional 1 minute. Then add the entire water quantity and continue mixing at the slow speed for 3 minutes.

Mold and compact the material as previously mentioned in ASTM C109. Then, seal and cover the samples within their molds with a nylon sheet and place the sample within the molds in an oven at a temperature of 32 degrees. The practiced code allows to cure the sealed samples at a temperature of 15 to 32 degrees for 16 hours. It is preferable to cure the specimens at a higher temperature since it helps in gaining more strength prior firing process. Further, the drying stage starts after completing the curing stage. Remove the cubes from their molds and place them in a furnace. Increase the temperature of the Furnace so that the temperature reaches 110 degrees in three hours (rate not exceeding 28 degrees/hour), then keep the temperature constant at 110 degrees for 21 hours so that the whole drying duration takes one complete day. Heat the cubes at the specified temperature with a rate not exceeding 178 degrees/hour for five constant hours. In the study multi samples were heated at different temperature (200, 400, 600, and 800 degrees).

It can be noticed that the mixing procedure differs for both mortar cube tests. For instance, cement is mixed with water as a first step in the ASTM C109 mixing procedure and such scenario can be explained by the fact that water must bind with cement rather than being absorbed by the sand. The reason is that the paste contributes in gaining strength in the cube and sand works only as a filler in the mix since sand is none reactive and cannot bind with water. As for the fire refractory samples, knowing that loss of water will occur at high temperature, the importance is to have a homogeneous matrix from the dry materials in order to resist fire.

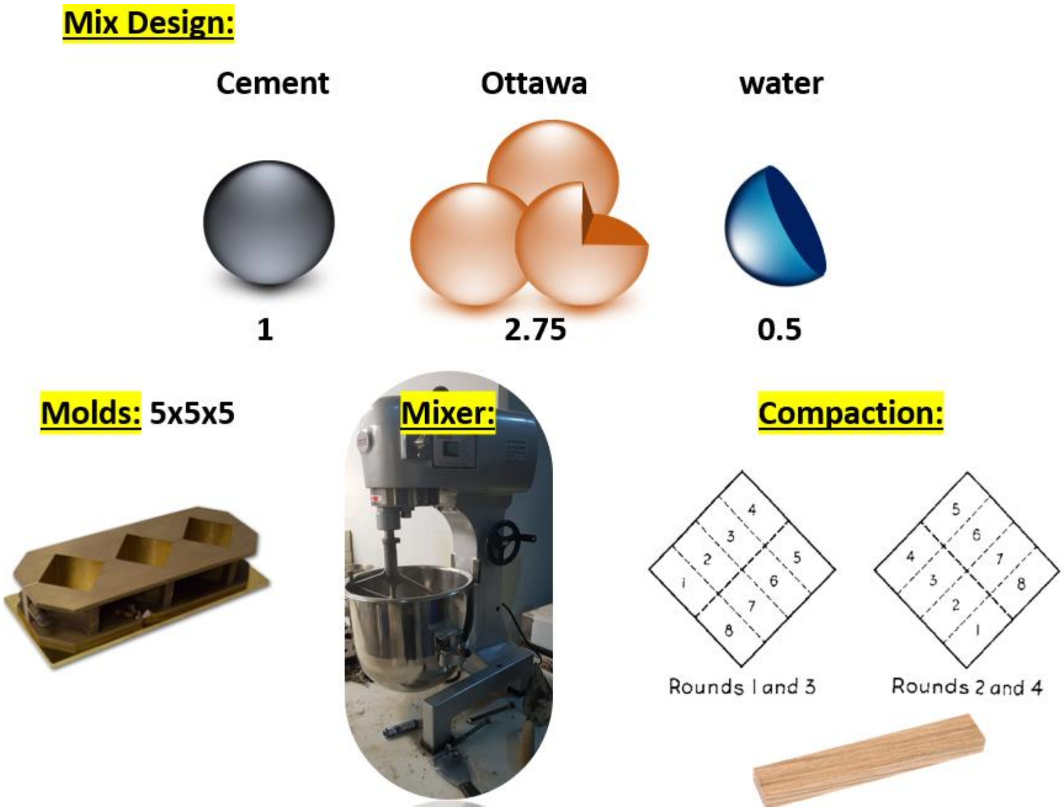


Figure 6.4 Mortar preparation procedure

6.4 Testing Procedure, Analysis and Results

In this section, the test procedures for the entire experimental plan are briefly discussed followed by the test results. The procedure of testing the mortar sample is similar for the three tests. The samples were soaked in water tanks until the testing day except for the fire refractory test. The samples were left to cool to room temperature after the heating operation and then tested at room temperature.

6.4.1 Slag activity index

Slag activity index ASTM C989 classifies the slag into three strength grades: Grade 80, Grade 100, and Grade 120 according to its performance in the slag activity test.

In this section, two types of slag were tested: the blended slag cement from Cimenterie National and the slag from Araco. Four mortar mixes were selected for this experiment: the control cement mortar, mortar made of blended slag cement (60% cement and 40% slag), and two mortar mixes containing 40% and 50% replacement of cement with slag.

Results of the mortar compressive strength tests are listed in Table 6.1 and Figure 6.2 shows the test setup of mortar

Table 6.1 Slag activity index SAI results

	compressive strength		Strength index	
testing day	7 days	28 days	7 days	28 days
cement	18.6	26.6	100%	100%
Blended slag cement (40%slag-60%cement)	15.1	25.6	81%	96%
Slag 50%	15.0	23.8	81%	90%
Slag 40%	14.7	22.6	79%	85%

The results in Table 6.1 revealed that the blended slag has the highest strength index. Therefore, the completely concrete scale experiments were performed using the blended type.

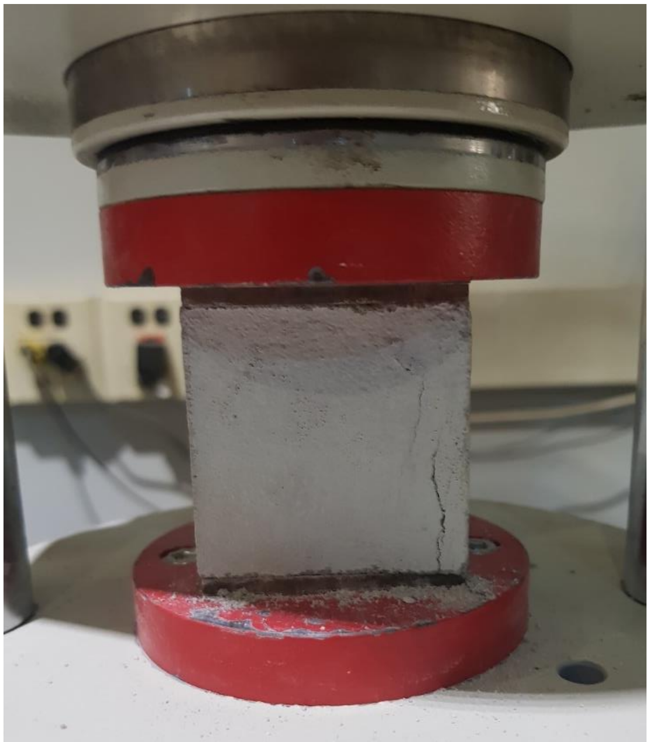


Figure 6.5 Example of a compressive strength test for mortar

6.4.2 Fire refractory test

A durable heat-resistant concrete type can survive for a longer duration under high heat and can be used in multiple applications: Any place subjected to a heat source such as a gas burner, wood fire, electrical heating spiral & other heat producing elements.

The test goes several steps: Sampling → Curing (32°C) for 16 hours → Drying (110°C) for 1 day → Firing (Recommended temperature: 200°C, 400°C, 600°C, and 800°C) while temperature kept constant for 5 hours. → Testing (At room temperature).

Figure 6.6 Fire refractory test

Six mortar mixes were selected for this experiment made of different combination of cementious materials: cement, 10% porcelain, 15% porcelain, 15% Terracotta, slag cement, and 15% Hybrid (15% ceramic, 35% slag and 50% cement). Complete results are presented in Table 6.2.

Table 6.2 Compressive strength results MPa for the fire refractory tests

Heat	Cement	10% Porcelain	15% Porcelain	15% Terracotta	Slag cement	Hybrid 15%
100	15.9	13	14.5	12.1	20.4	20
200	13.6	10.6	10.9	9.7	18.6	17.2
400	6.4	5.1	4.3	4.1	14.4	11.5
600	3.9	4.5	4.2	4.1	12.38	10.72
800	2	2.2	2.4	2.3	4.2	3.7

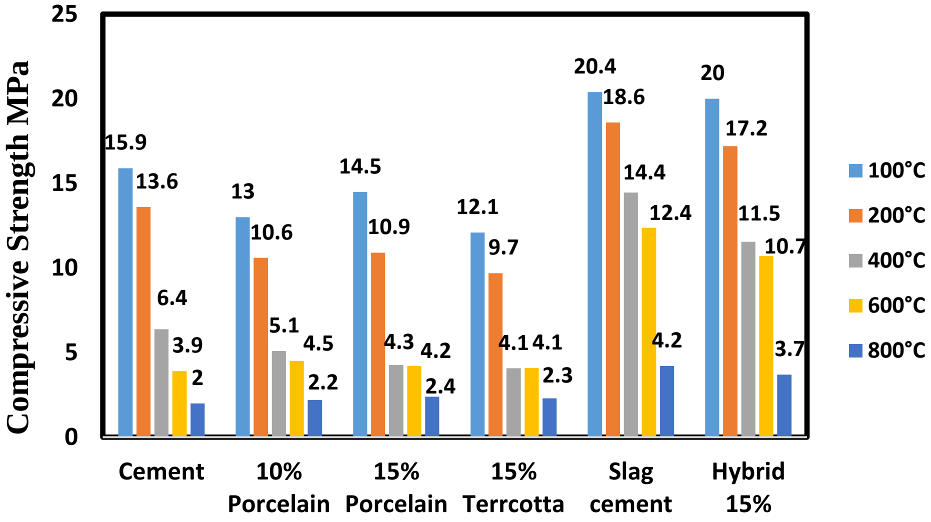


Figure 6.7 The effect of increasing temperatures (100→ 800 degrees) on compressive strength for the various materials studied

The results shown in Figure 6.7 indicate that the ceramic and cement mortars lost their compressive strength excessively above 200 degrees. Actually at 400 degrees, the mortars lost more than 50% of the compressive strength. In contrast, all mortar mixes made with slag (slag cement and hybrid) performed better and it survived the 400 and 600 heating temperature such that the compressive strength reached the 50% at 600 degrees. Further, the Slag mixes (slag cement and hybrid cement) led to highest compressive strength among all mixes where slag cement improved the compressive strength of the conventional cement by 33% at 100 degrees and 120% at 600 degrees. It is important also to mention that the ceramic mixes were weaker than the control at a temperature lower than 600 degrees. It can be shown that above 600 degrees the ceramic cement mortar resulted an improvement of 15%. However, such improvement is still negligible since the compressive strength of 600 and 800 degrees ranges between 4 and 2 MPa which is considered very low (10 to 15%) of the compressive strength of a mortar.

6.5 Summary

Based on the results of the mortar testing that covers the strength index of ceramic and slag in addition to the heat refractory test performed at 5 different temperatures: 100, 200, 400, 600, and 800 degrees, the following can be concluded:

1. The ceramic had low activity at early days, however at 28 days the ceramic is considered to have a pozzolanic activity.
2. The slag used in this study has a grade 100.
3. Slag is the most pozzolanic material that can resist heat so that slag mixes lost less than half of its compressive strength at 600 degrees whereas cement mixes lost more than half of its strength at 400 degrees.
4. The ceramic replacing cement showed a less compressive strength compared to the control cement till 400 degrees. Above this temperature, the ceramic showed an improvement in compressive strength.

Chapter 7

CONCRETE TESTING AND RESULTS

7.1 Introduction

The effect of various combinations of different cementitious materials on the mechanical properties (Compressive, Tensile, flexure, Modulus of elasticity) of concrete specimens. Additional testing was done for the purpose of targeting the durability of specimens exposed to freezing and thawing cycles and thermal conductivity. The parameters corresponding to each test together with the results are presented in details in Tables 9.3, 9.4 and 9.5 of the appendix for control samples and for samples of various combinations of slag/ceramic as cementitious materials.

Figure 7.1 Concrete scale samples

7.2 Testing Plan

The testing plan for the concrete phase included the following tests: slump test, mechanical tests (compressive, split tensile, flexure, and modulus of elasticity tests), and durability tests (thermal conductivity and freezing and thawing). The tested specimens were divided into three series of tests as shown in Table 7.1. In Series 1, the percentage of ceramic replacing cement was chosen to be 10, 15, or 20%. The choice of these ceramic percentage of replacement was based on the results of the published literature that showed that the acceptable ceramic-range scheme lies between 10% and 20%. Series 2 testing plan is similar to Series 1 however in Series 2 the cement type used was slag cement instead of Portland cement. In Series 3, a high strength concrete of 60 MPa compressive strength was made with a blended slag cement while varying the percentage of ceramic substituting slag cement. Number of replicates were done for the purpose of increasing credibility for each type of test as shown in Table 7.2 and Figure 7.2. Samples were tested at different time intervals (7 , 28 and 56 days) to assess the effect of time on the mechanical properties of the cementitious material. It is important to mention that samples were cured prior to testing in water tanks (Figure 7.3).

Table 7.1 Testing plan

	F'c	Mixes	Ceramic	Slag	Cement
Series 1	30 MPa	Mix1	0%	-	100%
		Mix2	10%	-	90%
		Mix3	15%	-	85%
		Mix4	20%	-	80%
Series 2	30 MPa	Mix5	0%	40%	60%
		Mix6	10%	36%	56%
		Mix7	15%	34%	51%
		Mix8	20%	32%	48%
Series 3	60 MPa	Mix9	0%	40%	60%
		Mix10	15%	34%	51%
		Mix11	20%	32%	48%

Table 7.2 Number of replicates selected for each test

Hardened concrete Testing	Dimensions (cm)	Replicates		
		7 days	28 days	56 days
compressive Strength	Cylinder 10x20	2	3	2
split tensile strength	Cylinder 10x20	-	2	2
Modulus of Elasticity	Cylinder 15x30	-	2	2
Flexure Capacity	Beam 10x10x35	-	2	2
Freeze and Thaw	Beam 7.5x10x40.5	-	2	-
Thermal conductivity	Slab 30x30x3	-	1	-

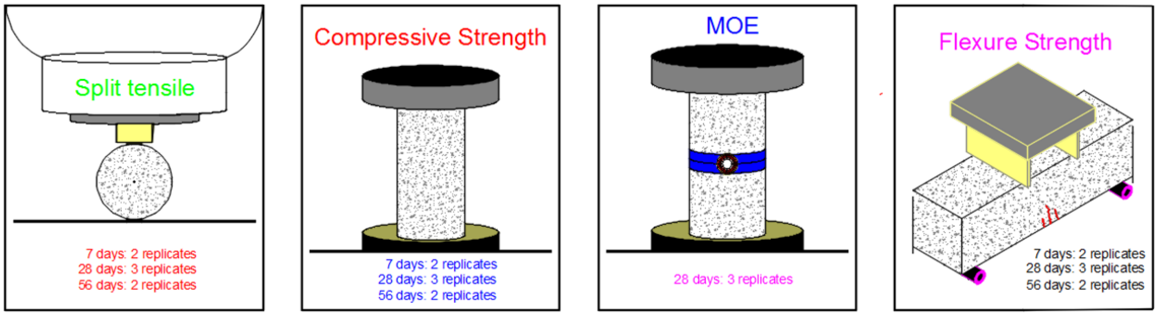


Figure 7.2 Schematic diagram for the testing done

Figure 7.3 Samples cured in the water tank

Figure 7.4 Concrete scale specimens after demolding

7.3 Concrete Preparation

Formwork preparation plays an important role in the final appearance of the concrete surface. It molds the placed fresh concrete, which in this stage normally is viscous, to the shape specified in the drawing.

For the concrete scale testing of phase 4, the specimens formwork dimensions are presented in the Table 7.4 according to ASTM C39 “Compressive strength of cylindrical concrete specimens’’and ASTM C78 “Flexural strength of concrete (using simple beam with third point loading)”

Table 7.3 Mold dimensions for the various conducted hardened concrete tests

Hardened concrete testing	Dimensions (cm)
compressive Strength	Cylinder 10x20
split tensile strength	Cylinder 10x20
Modulus of Elasticity	Cylinder 15x30
Flexure Capacity	Beam 10x10x35
Freeze and Thaw	Beam 7.5x10x40.5
Thermal conductivity	Slab 30x30x3

Figure 7.5 Cylinder 10x20 cm

Figure 7.6 Cylindrical molds 15*30 cm

Figure 7.7 Beam 10x10x35 cm

Figure 7.8 Beams 7.5x10x40.5 cm

Figure 7.9 shows whole concrete test lab setup.

Figure 7.9 Concrete test setup

The concrete phase tests include the following: workability testing (slump test), mechanical properties testing (compressive, split tensile, flexure, and modulus of elasticity tests), and durability testing (thermal conductivity and freezing and thawing). This section includes the material preparation and concrete mixing.

Prior mixing, the materials used to make the concrete mix must be well prepared. The coarse aggregate must be washed one day prior mixing to clean the aggregates from dust particles and impurities. In addition, sieve the fine aggregate through #8 to ensure no large sand particles exist in the mix. Then, the washed coarse aggregates and sieved fine aggregates are placed in the oven for 24 hours to make sure that all aggregate particles are fully dried (refer to Figure 7.10). Aggregates used in the concrete mix must be in the saturated surface dry conditions. In the mixing day, remove the aggregates from the oven and allow it to cool to room temperature. Avoid using hot aggregates in the mix since the water of the mix may evaporate if the aggregates used in the mix were at temperature higher than 100 degrees.

After material preparation and weighing, start the batching according to ASTM C192. The code specifies two kinds of mixing: manual and machine mixing.

Figure 7.10 Oven dried fine and coarse aggregates

The batching operations consists of the following steps:

- Add the coarse aggregates to the mixer
- Turn on the mixer and add some of the mixing water and allow it to rotate couple of rotations.
- Mix the remaining water with the superplasticizer.
- Add the fine aggregate, then cement, and then lubricant (water and superplasticizer).
- Mix all the concrete ingredients for 3 minutes in the mixer, then allow it to rest for 2 minutes followed by a 2 minutes final mixing.

- Cover the mixer when adding cement so to prevent the evaporation of any material inside the mixer and that the proportions are correctly mixed
- Try to eliminate segregation when damping the mixture in a pan.
- Remix the material with shovel until uniformity is acquired.

7.3.1 Concrete Mix Design

The procedure of defining required characteristics and features of a concrete mixture is named mix design. Characteristics can include the fresh concrete properties, specific hardened concrete properties (strength and durability), in addition to specific measurement taken such as maximum aggregate size. Design tables are used to design the mix according to the specifications requested. A proper mix design must be followed in order to achieve a durable concrete with an acceptable workability and specific strength with least cost.

The concrete testing program that was adopted includes three series. The first series of tests investigates the effect of ceramics as cement replacement on concrete of 30 MPa compressive strength. Next, the second series of tests studies the effect of hybrid concrete made of ceramic and slag cement of 30 MPa compressive strength. Lastly, the series of tests targets a high-strength concrete (60 MPa) made of the hybrid material. Therefore, two mix designs are required: 30 and 60 MPa.

The following criteria and assumptions were adopted while designing the 30MPa mix:

1. Intended concrete compressive strength of 30 MPa
2. Slump of 150 to 175 mm
3. Maximum aggregate size of 19 mm
4. Minimum cement content of 320 Kg/m^3

5. Non-air entrained concrete.
6. Superplasticizer used was 0.6% by weight of cement

Additional parameters are required in order to complete the mix design:

1. Dry bulk specific gravity of coarse aggregates: 2.680
2. Dry bulk specific gravity of fine aggregates: 2.640
3. Fineness Modulus of sand: 3.0
4. Dry-rodded unit weight of coarse aggregates: 1600 Kg/m^3

Table 7.4 Concrete mixing proportions for 30 MPa strength

30 MPa							
Mix Proportions	Water (Kg)	W/C	Cement (Kg)	CA (Kg)	FA (Kg)	NN (kg)	Density (Kg/m^3)
Dry weights	200	0.54	370	991	807	2.2	2368
Weights Corrected	222.1	-	370	991	807	2.2	2391

The proportions were calculated in dry conditions so that water required to change the sand and coarse aggregates to the SSD condition must be added to the mix. The saturated surface dry conditions (SSD) batching weights are listed in Table 7.4

As for the 60 MPa concrete, the following assumptions were taken while designing:

1. Intended concrete compressive strength of 60 MPa
2. Slump of 25 to 50 mm
3. Maximum aggregate size of 19 mm

4. Water content was 150 rather than 168 Kg/m^3 for the fact that the usage of superplasticizer allows the decrease in water content up to 30%
5. Non-air entrained concrete
6. Superplasticizer used was 1.2% by weight of cement.

The additional parameters used to complete the mix design of the 60 MPa concrete mix are the same as the 30 MPa since same source of sand and coarse aggregates were used in the mix design (Table 7.5).

Table 7.5 Concrete mixing proportions for 60 MPa strength

60 MPa							
Mix Proportions	Water (Kg)	W/C	Cement (Kg)	CA (Kg)	FA (Kg)	NN (kg)	Density (Kg/m^3)
Dry weights	150	0.27	560	960	772	6.7	2368
Weights Corrected	222.1	-	370	991	772	6.7	2391

All mixes were designed following these two guidelines according to the compressive strength of concrete desired. The only variable is the inclusion of sustainable materials as a cement substitute where the percentage of replacement of cement by sustainable materials is by weight. All other parameters were kept the same to insure a proper evaluation of the effect of the ceramics and slag on the concrete properties.

7.4 Testing Procedure, Analysis and Results

In this section, the test procedures for the entire experimental plan are discussed briefly followed by the analysis of the test results.

7.4.1 Slump Test

To test the fresh concrete properties, the consistency of concrete was measured through a Slump test according to ASTM C143, which covers the determination of hydraulic concrete slump in the field and the laboratory.

The slump test measures the consistency of fresh concrete or the ease with which concrete flows. It can also be used as an indicator of an improperly mixed batch.

Abram cone was used for the slump test (Figure 7.11). A view of slump measurement is shown in Figure 7.12.

Figure 7.11 Abram cone used for slump test

Figure 7.12 Slump test

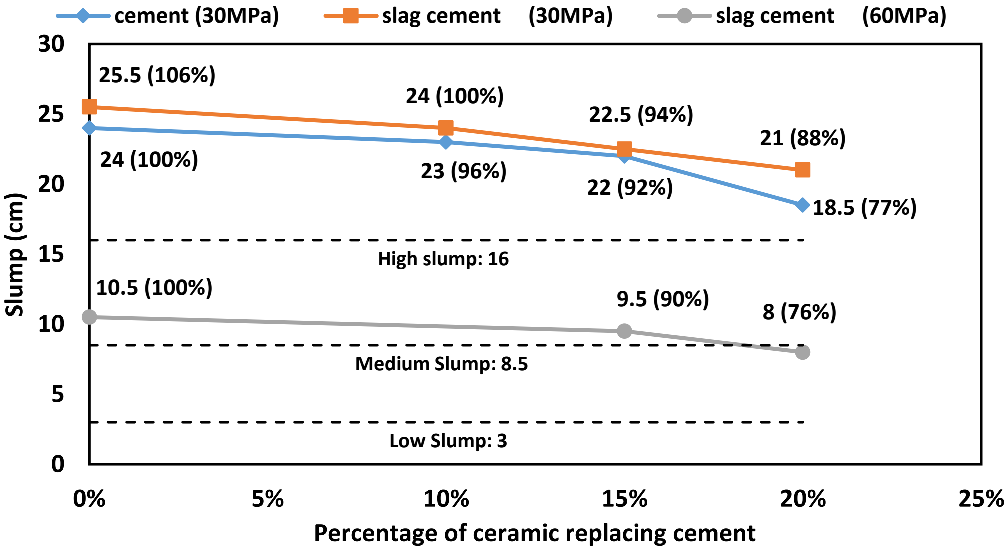


Figure 7.13 The variation of slump due to the incorporation of ceramic; the percentage between parenthesis is the ratio of the measured slump to that of the mix with 0% ceramic replacement.

Results shown in Figure 7.13 indicate the variation of slump due to the incorporation of ceramic as cement replacement in the concrete batch for the following three series of tests: Series 1 conventional concrete (30 MPa), Series 2 slag cement concrete (30 MPa), and Series 3 slag cement concrete (60 MPa).

Test results of Series 1 tests revealed that the consistency of the concrete dropped with the increase in percentage of the cement replacement with ceramic powder in the mix, where a drop of 5.5 cm (23%) in the slump was noticed when replacing 20% of cement by ceramic powder. As for Series 2, the usage of slag cement instead of cement improved the consistency slightly where the slump of the concrete increased by 1.5 cm (6%) as compared to conventional concrete. However, the addition of ceramics to the slag cement concrete reduced the slump. It was observed that the slump decreased from 25.5 to 21 cm when replacing 20% of slag cement. It is important also to mention that the hybrid concrete made of slag cement and 10% ceramic indicated the same slump of the conventional concrete (24 cm) and that the substitution of 15% by ceramics lead to same slump (22 cm) for both conventional and slag cement concretes. Knowing that ceramic led to a decrease in the consistency of the concrete, it can be observed that the concrete still has a high slump where all the slumps of the Series 1 and Series 2 tests were found to be above the 16 cm specified by the ASTM C143.

As for the third series, the consistency of slag cement fell in the medium slump range. Similarly, the addition of ceramics led to a drop-in slump where slump dropped from 10.5 to 8 cm with 20% of cement replacement.

7.4.2 Compressive Strength Test

The compressive strength of the cylindrical concrete specimens was estimated in accordance with ASTM C39. In this test method, a compressive axial load is applied to the specimen at a rate of 1.25mm/min until failure occurs (Figure 7.14). The compressive strength of the specimens is calculated by dividing the maximum load reached by the cross-sectional area of the cylinder. Capping the samples prior to testing is essential to ensure a uniform distribution of the load along the surface. Cylinders were capped with Sulphur as specified per ASTM C617 (Figure 7.16).

Figure 7.14 Failed Specimen after compressive strength test

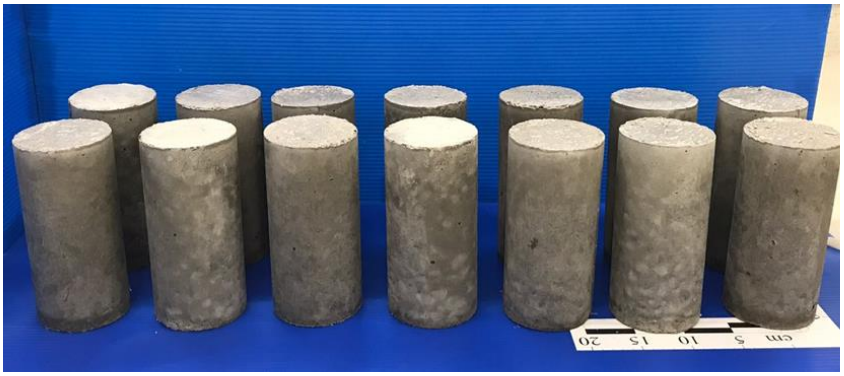


Figure 7.15 Cylindrical specimens prepared for compressive test

Figure 7.16 Capped cylinders before testing

Figure 7.17 Failure modes for specimens after testing

The average compressive strength for the Series 1 specimens tested at 7, 28, and 56 days are shown in Figure 7.12. The compressive strength of the control sample recorded 21.3 MPa at 7days, 30.6 MPa at 28 days, and 33.4 MPa at 56 days. The addition of the ceramic contributed in lowering the compressive strength of the concrete. The compressive strength for the ceramic mixes (10% Cr,15% Cr, 20% Cr) varied between 14 and 17 MPa at 7 days. The results are close to each other showing an only difference of 3 MPa for the three ceramic mixes, However compared to the control compressive strength (21.3 MPa) a drop in the ranges of 15% to 30% approximatly was noticed depending on the percentage of ceramic added to the mixes as shown in Figure 7.13. As for the 28 days results, the gap among the ceramic mixes increased reaching 7 MPa such that the compressive strength for the 20%Cr is 19.5 MPa whereas the 10% Cr it is 26 MPa. Further, at 28 days, the ratio of the compressive strength of the ceramics mixes to the control compressive strength was found to be improving with time compared to the 7 days results where the 10% Cr has gained 76% of control strength at 7 days and kept improving with time reaching 88% at 28 days and 91% at 56 days (Figure 7.13).

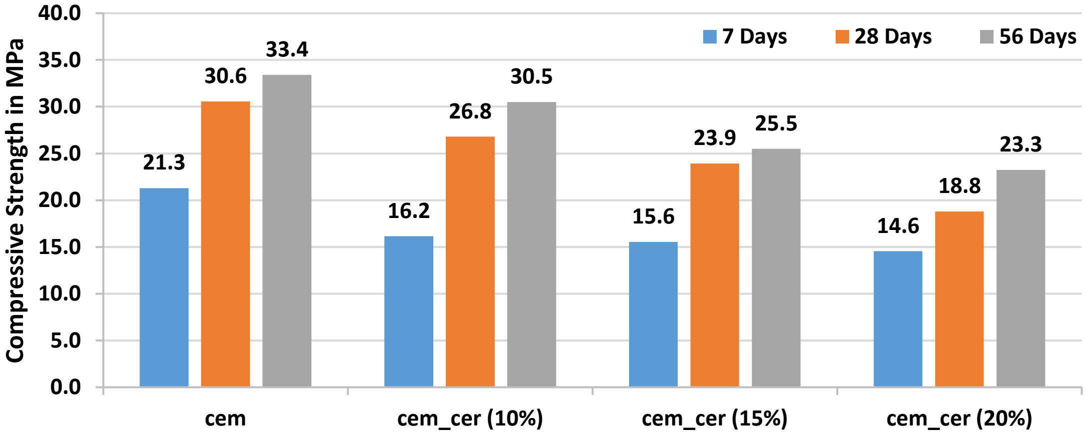


Figure 7.18 Average compressive strength for series 1 specimens tested at 7, 28, and 56 days

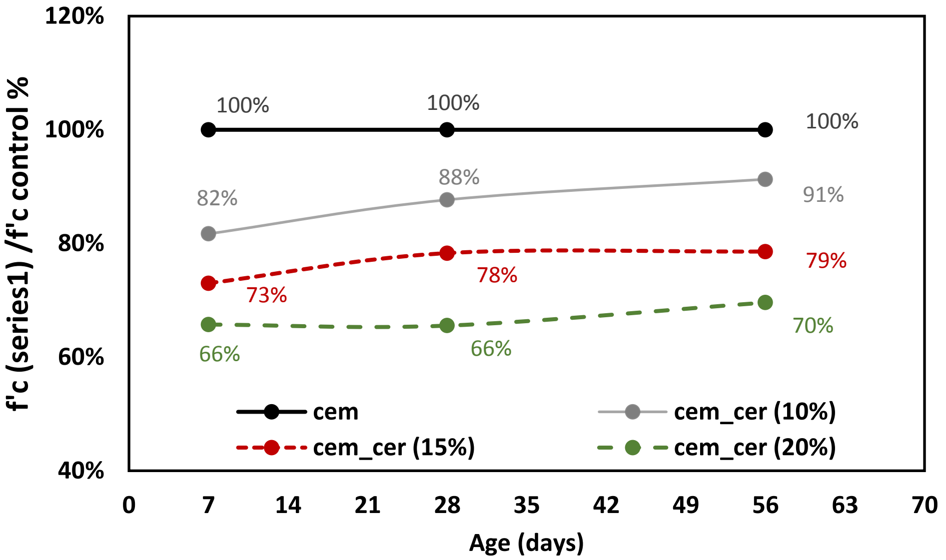


Figure 7.19 The variation of the ceramic mixes (series 1) compressive strength ratios to the control compressive strength with time

Figure 7.14 shows the compressive strength gain with time of the series (2) specimens which covers 4 mixes made with slag cement and several percentages of replacement of slag cement by ceramic (0%, 10% 15%, and 20%) as well as the control concrete which is made only of cement. It can be observed that the slag cement attributed in lowering the compressive strenth at 7 days from 21.3 to 19.3MPa (a drop of 2 MPa), however this diffficency is turned to gain in strength at 28 and 56 days recording 31.2 and 39.4 MPa (an improvement of 0.6 and 4.1 MPa respectively). As for the hybrid mixes made of slag cement and ceramic, the addition of ceramic attributed in lowering the strength compared to the slag cement mix. However, compared to the control sample, the hybrid mixes led to a major improvement in compressive strength where 10% of ceramic hybrid concrete recorded 30.6 MPa (95% of control f'c) at 28 days and 34.9 MPa (104% of control f'c) at 56 days as shown in Figure 7.14. Further, the addition of 15%H with respect to the control sample resulted a compressive strength ratio of 88% at 28 days and 92% at 56 days (Figure 7.15) . The results of 15%H are close to the results of the 10%Cr replacing cement. So that the usage of slag cement allows using more ceramic in the mix without losing strength. As for the 20%H, a huge diffency in strength resulted (77% at 28 days and 80% at 56 days) which is close to what happened for 20%Cr.

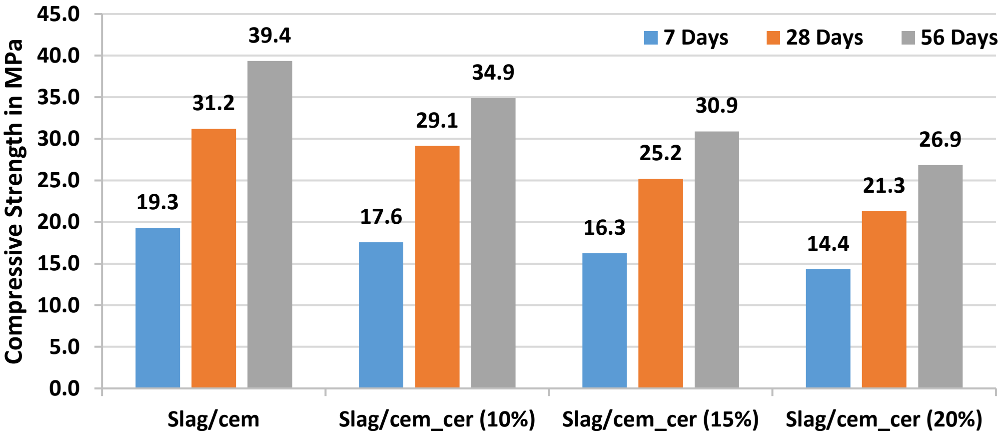


Figure 7.20 Average compressive strength for series 2 specimens tested at 7, 28, and 56 days

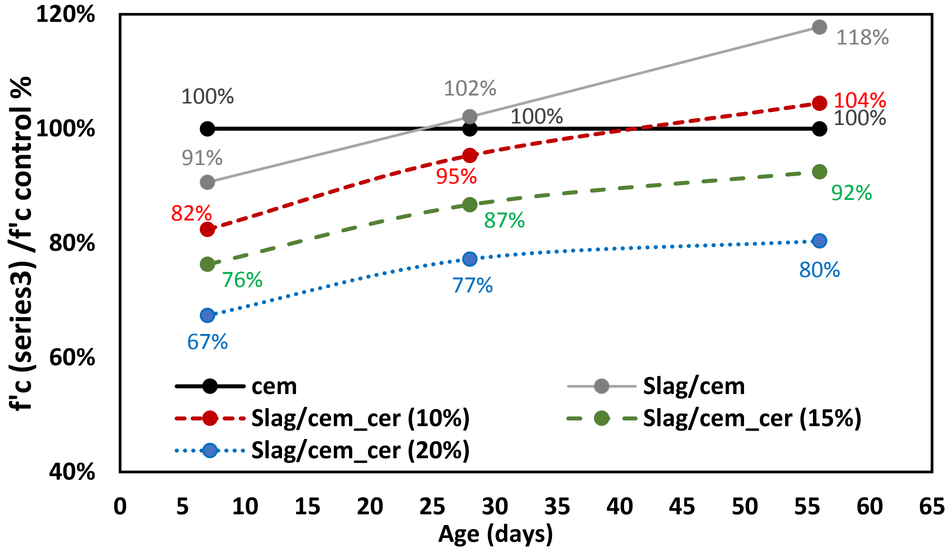


Figure 7.21 The variation of the ceramic's mixes (series 2) compressive strength ratios to the control compressive strength with time

The average compressive strength for the series (3) tested at 7, 28, and 56 days are shown in the Figure 7.16. The series consist of three high strength concrete made of the hybrid binders slag cement and ceramic. The results of the compressive strength test indicated that the control (60MPa) hybrid concrete resulted in a compressive strength of 40.3, 56, and 61.5 MPa at 7, 28, and 56 days respectively. The addition of ceramic reduced the compressive strength such that 15% ceramic replacement resulted in a decrease in the order of 11, 6, and 8% at 7, 28, and 56 days whereas the addition of 20% caused a drop-in strength of about 20, 17, and 18% at 7, 28, and 56 days. It can be noticed that ceramic has low gain in strength since at 7 days the strength drop was the most significant, however at 28 days the ceramic starts to contribute in gaining strength so that the ratio of composite to hybrid control compressive strength percentages have improved at 28 days as shown in Figure 7.17. Nevertheless, the slag is a well-known material for its late strength gain in strength (gain strength continues after 28 days), the percentages drops due to the addition of ceramics to the mix.

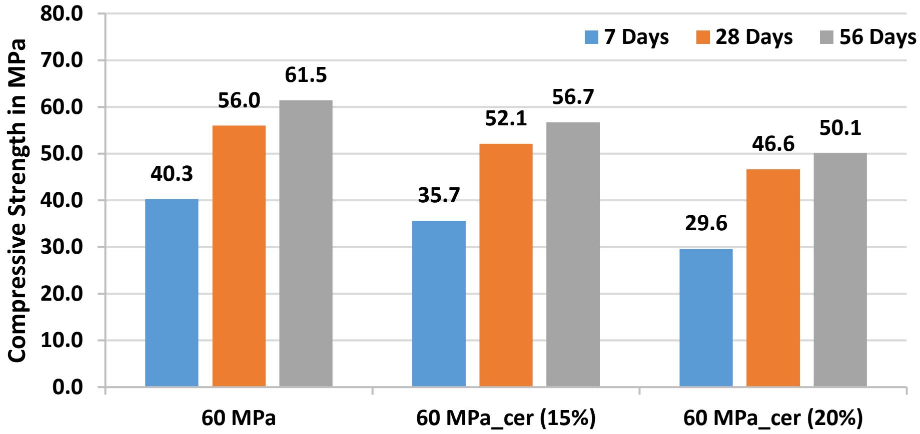


Figure 7.22 Average compressive strength for series 3 specimens tested at 7, 28, and 56 days

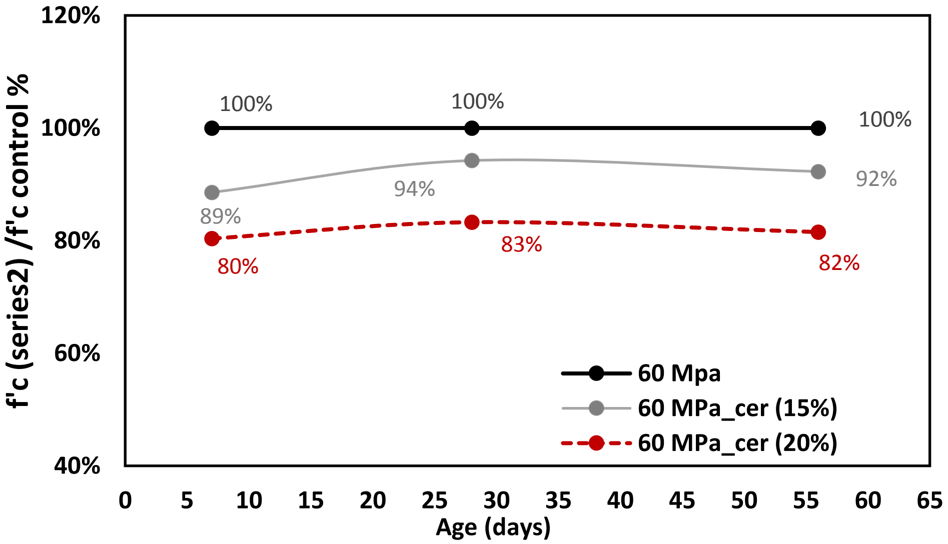


Figure 7.23 The variation of the ceramic’s mixes (series 3) compressive strength ratios to the control compressive strength with time

7.4.3 Split Tensile Test

The splitting tensile strength of 10 × 20 cm cylinders for the three series was determined, according to ASTM C496 using the YLS testing machine with a capacity of 50 Tons. Before starting the test. The specimens were placed between 2 metal plates of 4 mm thickness so that the specimens were constrained by the two bottom and top plates as shown in the Figure 7.18. The loading rate was set to 2 mm/min.

The splitting tensile strength f_{ct} (MPa) was calculated from the following equation:

$$f_{ct} = \frac{2P}{\pi l_c d}$$

Where P is the peak load (N), lc is the length of the specimen (mm), and D is the diameter (mm) of the cylinder specimen.

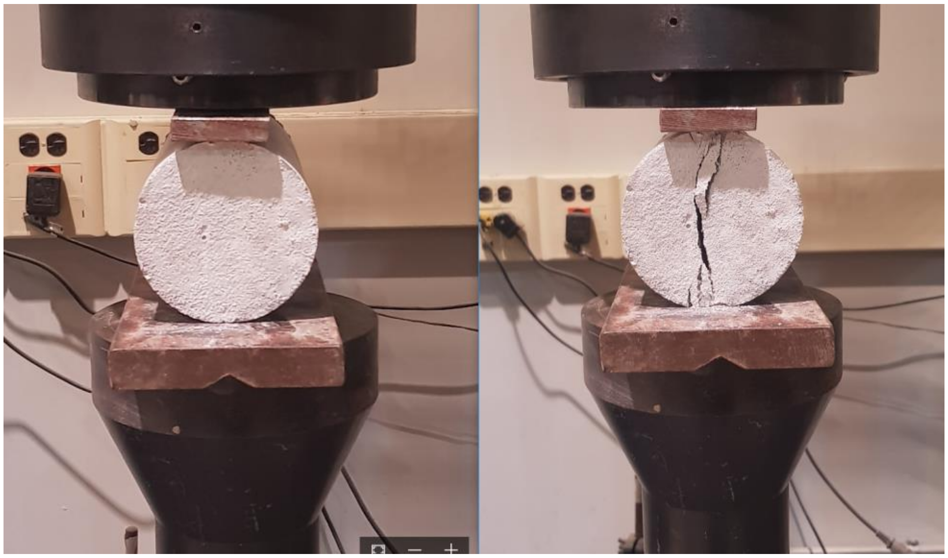


Figure 7.24 Split tensile test

The splitting tensile strength results of Series 1 specimens at 28 and 56 days are presented in Figure 7.19. The results indicated that the ceramic attributed to a slight reduction in the indirect tensile strength of the concrete at 28 and 56 days. It can be observed that 10% ceramic led to almost 3% reduction at both testing days. In addition, the 15% and 20% replacement led to a decrease in the splitting tensile of 9 and 10% at 28 days, as well as 7 and 14% at 56 days. Further, the split tensile strength of the 15% ceramic inclusion at 56 days was found to be more prominent compared to the 28 days result.

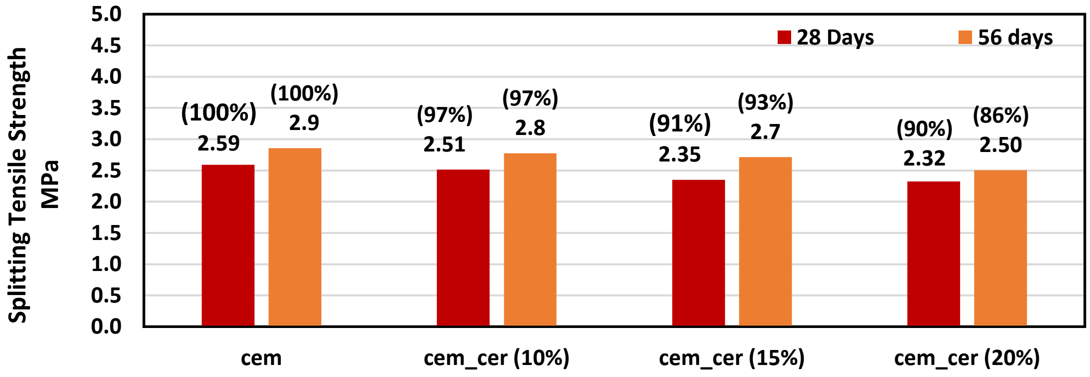


Figure 7.25 Splitting tensile strength results of Series 1 specimens at 28 and 56 days

As for the Series 2 specimens the splitting tensile strength results at 28 and 56 days are presented in Figure 7.20. The slag cement slightly improved the splitting tensile strength of the concrete at 28 days where the splitting tensile strength increased from 2.59 to 2.79 MPa at 28 days and from 2.86 to 3.18 at 56 days (an improvement of 8% and 11%

as shown in Figure 7.20). In addition, the ceramics addition up to 20% contributed in decreasing the splitting tensile strength of the slag cement concrete. However, compared to the conventional concrete's split tensile strength, the hybrid concrete with 15% replacement had almost the same strength of 2.59 MPa at 28 days and almost 6% improvement at 56 days.

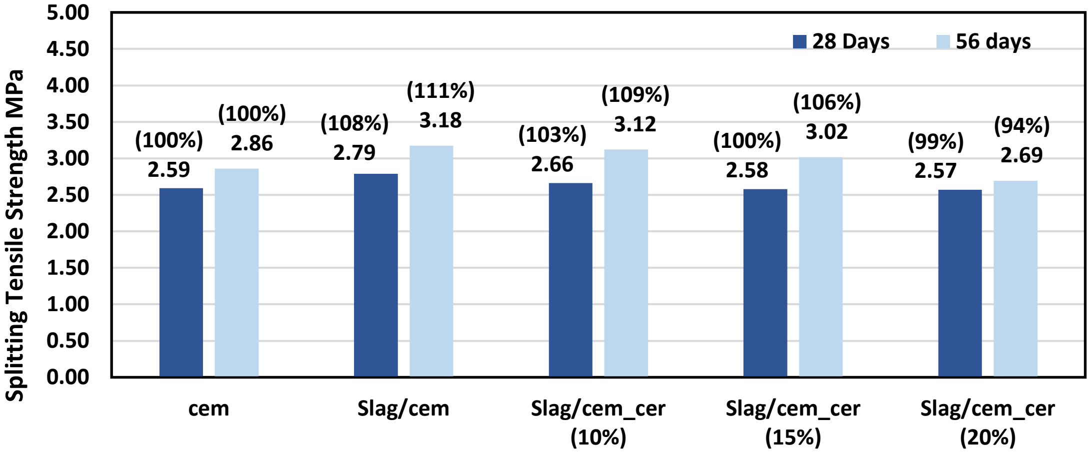


Figure 7.26 Splitting tensile strength results of Series 2 specimens at 28 and 56 days

The splitting tensile strength results of Series 3 specimens at 28 and 56 days are presented in Figure 7.21. The indirect tensile strength results of the hybrid concrete of series (3) indicated that the ceramics had a minor effect on the split tensile strength at 28 days since a drop was noticed from 4.3 (60 MPa) to 4 (60 MPa 15%) reaching 4.1 MPa (60% 20%). As for the 56 days results, the slag had a better effect than ceramic in gaining strength in a way that the split tensile of the 60 MPa mix recorded was 5MPa at 56 days while the split tensile strength for the ceramic mixes recorded were 4.55 and 4.18 MPa for the 60MPa 15% and 60MPa 20% respectively.

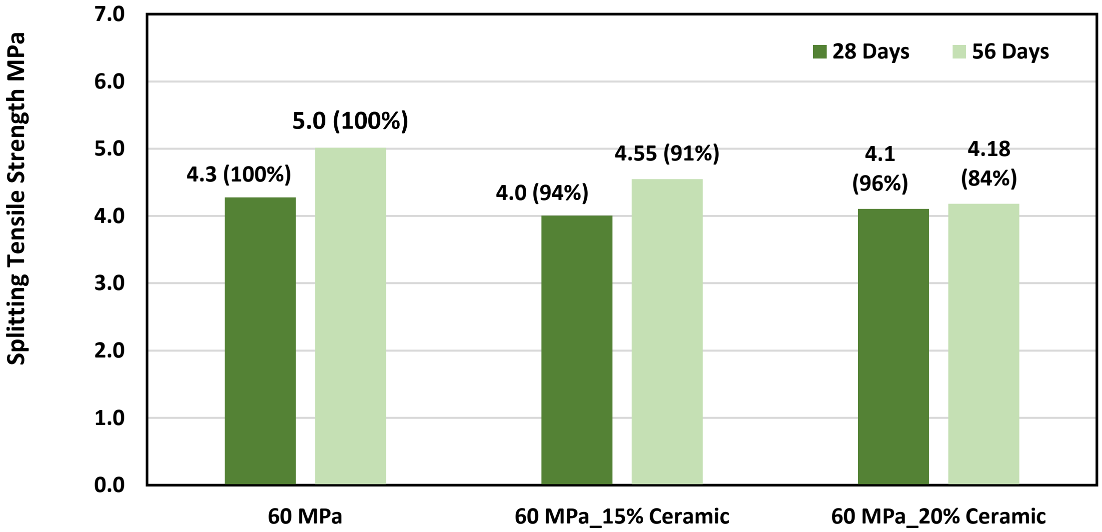


Figure 7.27 Splitting tensile strength results of Series 3 specimens at 28 and 56 days

7.4.4 Flexural Capacity and First crack Toughness Test

The modulus of rupture R (MPa) was calculated from the following equation:

$$R = \frac{PL}{bd^2}$$

Where P is the max applied load (N), l is the clear length of the specimen (mm), b is the average width of the beam (mm), and d is the average depth of the beam specimen (mm).

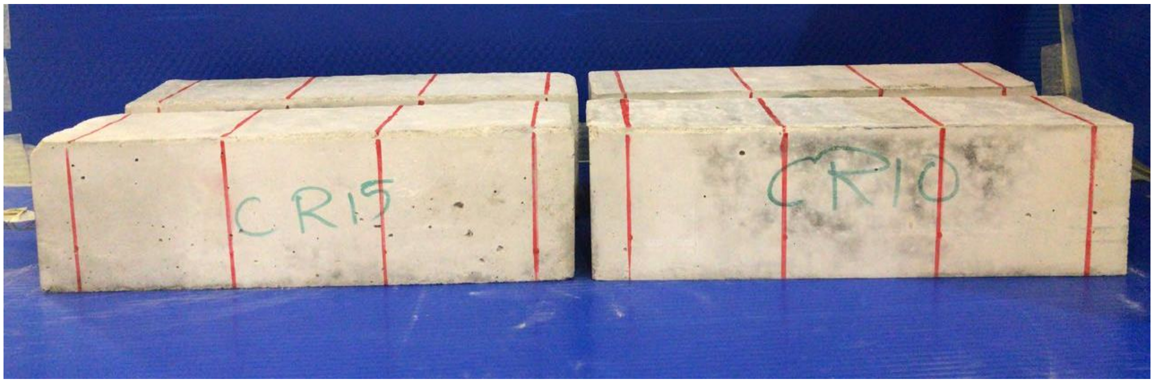


Figure 7.28 Beams (100 x 100 x 350 mm) prepared for flexural capacity test

Further, the toughness is determined by the area under the load deflection curve as an indication of energy absorption capacity of a specimen. Different ratios that reflect toughness indices can be calculated. In this study, since the specimens are unreinforced and contain no fibers, the focus will be on the first crack toughness calculated as the area under the load defection curve calculated at P, the load at first crack.

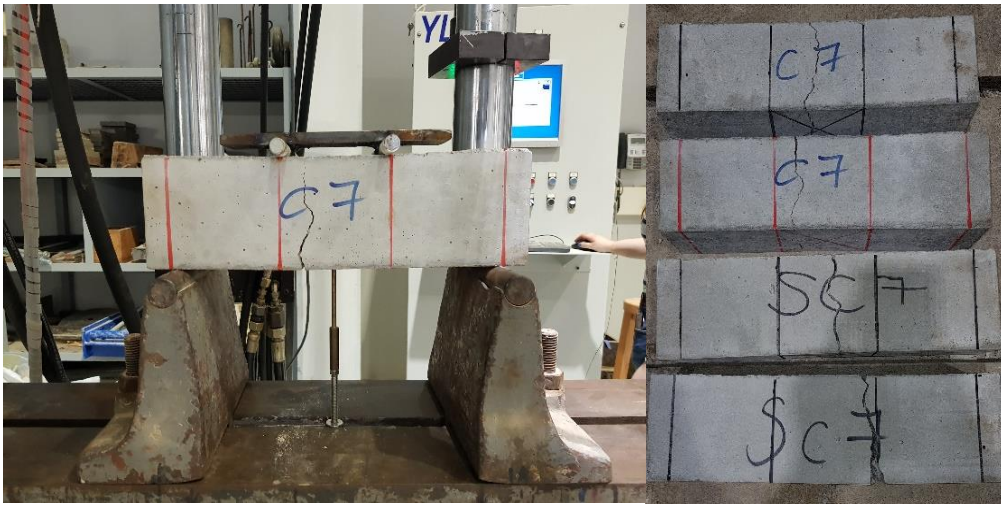


Figure 7.29 Flexural capacity test Setup

Figure 7.24 shows the flexure capacity of Series 1 tested at 28 and 56 days. The results indicate that the control concrete had a capacity of 4.76 MPa at 28 days and 5.2 MPa at 56 days. Further, when ceramic is added to the mix, the capacity of the concrete is reduced. At 28 days the results of the flexure capacity are very close ranging between 4.15 and 4.31 MPa (for 10 15 20% ceramic replacing cement). However, at 56 days the flexural capacity for the 10% Cr and 15% Cr was found to be satisfactory of about 5 MPa and 4.9 MPa respectively. Lastly, the inclusion of 20% Cr resulted in a reduction of 17% in flexural strength reaching 4.3 MPa.

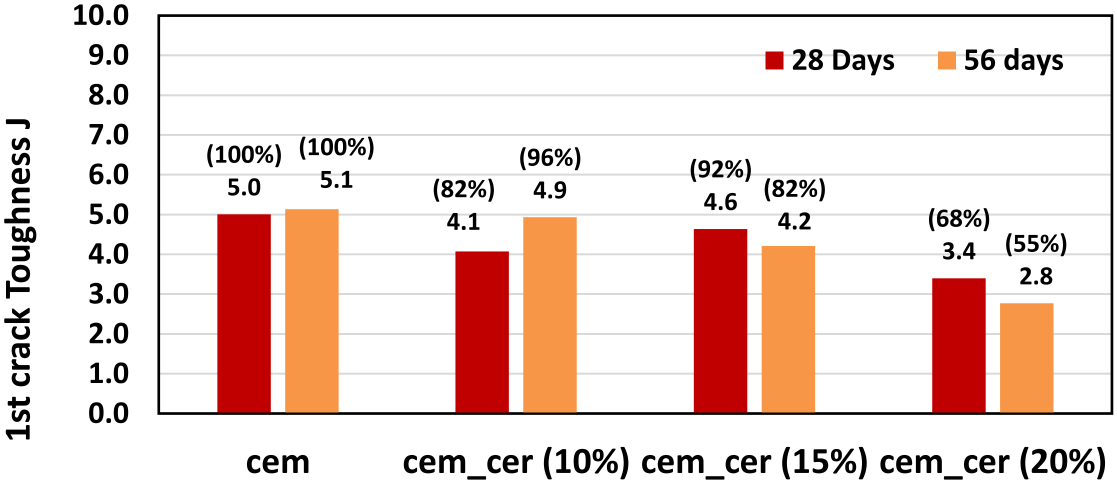


Figure 7.30 Flexural capacity results of Series 1 specimens at 28 and 56 days

Figure 7.25 shows the first crack toughness of Series 1 tested at 28 and 56 days. The difference in the toughness results for the control specimen at 7 and 56 days was found to be negligible (0.1 MPa). However, this difference for the 10 % replacement ceramic mixes was found to be significant of about 0.8 Joules (from 4.1 to 4.9 joules at 28 and 56 days respectively). As for the rest of the ceramic mixes (15% and 20%) an opposite behavior was noticed, the toughness of the concrete has decreased, and this decrease was more evident at 20% ceramic replacement of about 13% (from 3.4 to 2.8 joules at 28 and 56 days respectively).

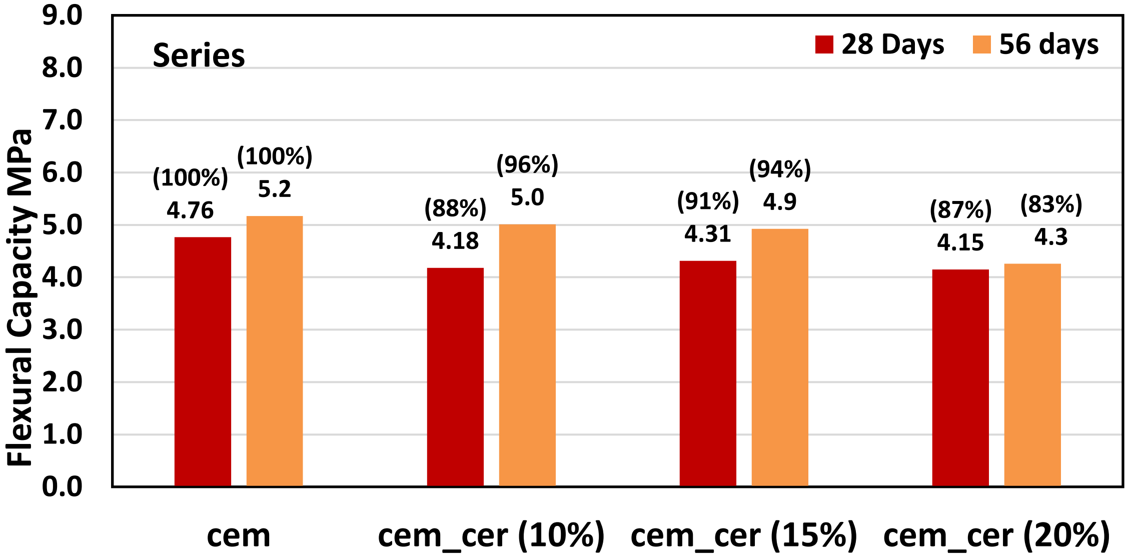


Figure 7.31 First crack toughness of Series 1 tested at 28 and 56 days

The results of the flexural capacity for Series 2S are presented in Figure 7.26. It can be observed that the usage of slag cement improved the flexural capacity of the concrete where at 28 days the slag cement concrete showed an improvement levels of 19% at 28 days and 22% at 56 days. As for the hybrid mixes made of ceramic substituting slag cement, the flexural capacity of concrete is reduced compared to the slag cement capacity. It is worth noting that 15% replacement level led to the highest capacity among hybrid mixes achieving a capacity of 4.67 MPa at 28 days and 6 MPa at 56 days. The 15 % hybrid flexural capacity was found to be comparable to the control concrete flexural capacity at 28 days, while at 56 days the flexural capacity of the 15% hybrid is higher compared to the control showing an improvement level above 100% (116%).

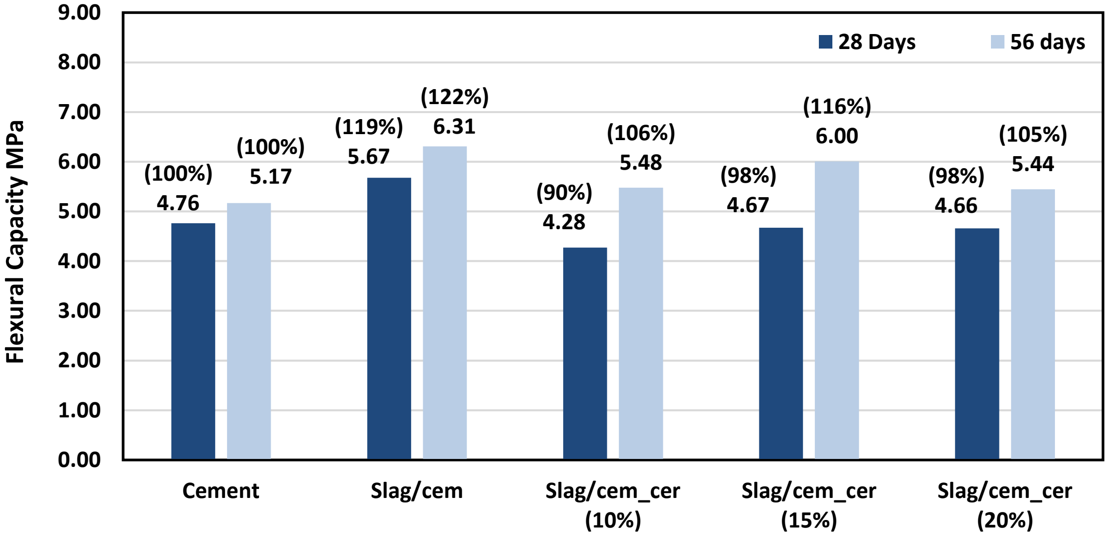


Figure 7.32 Flexural capacity results of Series 2 specimens at 28 and 56 days

Figure 7.27 shows the 1st crack toughness of Series 2 specimens tested at 28 and 56 days. It can be perceived from Figure 7.27 that the slag cement had the most evident toughness compared to the control sample with an improvement levels in the order of 10% for both 28 and 56 days. As for the three hybrid mixes (10% 15% 20%), the inclusion of ceramics led to a substantial reduction in the 1st crack toughness. However this reduction was less prominent for the 15% hybrid mix showing a better toughness level compared to the other hybrid mixes.

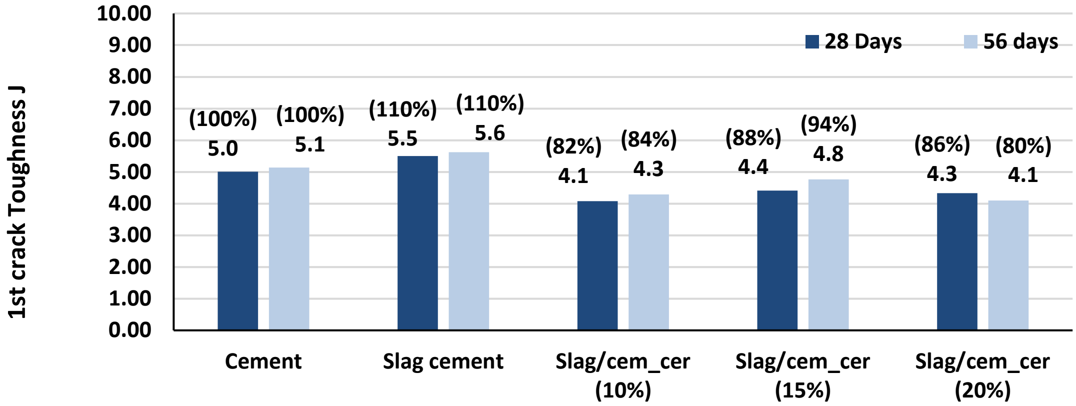


Figure 7.33 First crack toughness of Series 2 tested at 28 and 56 days

Figure 7.28 presents the flexural capacity of the Series 3 high strength concrete specimens. The results of the flexural capacity tests indicated that the addition of 15% ceramic is satisfactory since this mix achieved 94% and 98% of the conventional 60 MPa capacity at 28 days and 56 days respectively. As for the 20% replacement level, the capacity achieved is 83% (7.1 MPa) which is considered the lowest capacity among others. However, at 56 days, the strength increases up to 90% of the conventional control capacity.

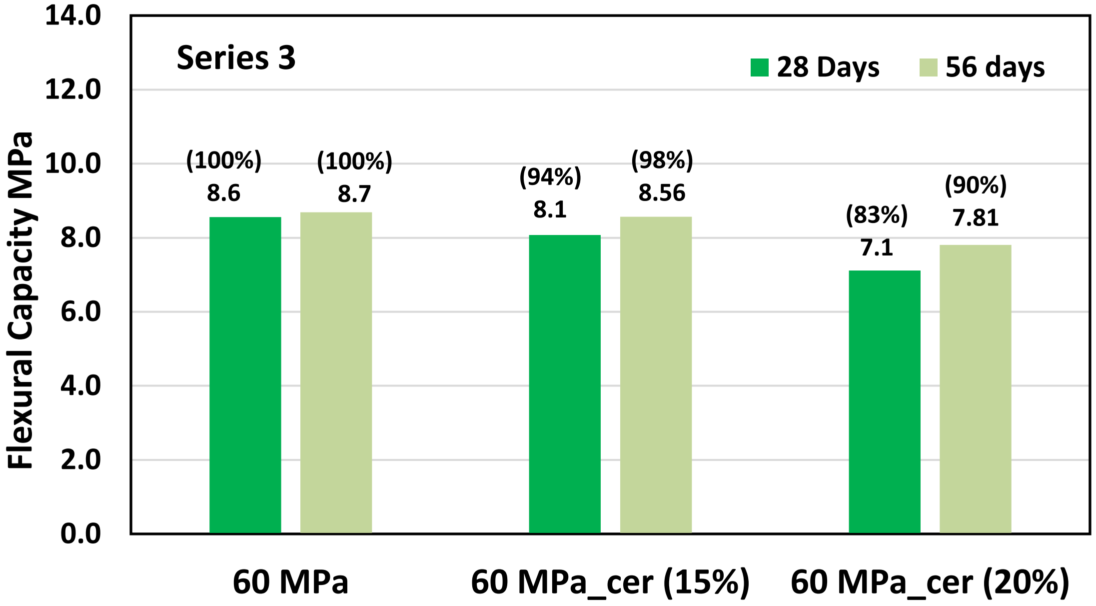


Figure 7.34 Flexural capacity results of Series 3 specimens at 28 and 56 days

The results of the 1st crack toughness of the Series 3 are shown in Figure 7.29. The results also indicated that the 60 MPa concrete had a toughness of 7.1 Joules at 28 days and 8.9 Joules at 56 days. In fact, the addition of ceramic reduced the toughness of the concrete. The toughness for the 15% ceramic replacing cement was found to be equal to 6.8 MPa at 28 days and 7.4 MPa at 56 days whereas the 20% level of replacement the toughness recorded was 6 Joules at 28 days and 6.6 joules at 56 days.

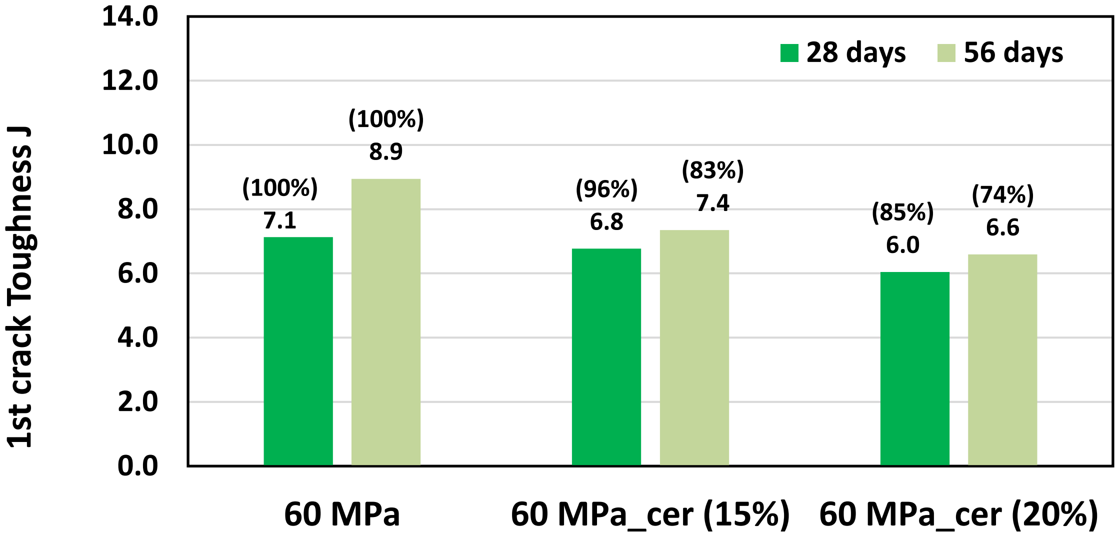


Figure 7.35 First crack toughness of Series 3 tested at 28 and 56 days

7.4.5 Modulus of Elasticity

The Modulus of Elasticity of the concrete was determined in accordance to ASTM C469. The cylindrical concrete samples have the following dimension 15x30 cm^2. The test was conducted in the MTS machine of 300 Tons capacity and was controlled by displacement with a rate of 1.5 mm/min. The axial deformation was measured through a dial gauge. 24 hours prior testing the samples were removed from the water and capped with Sulphur in accordance to ASTM C617.

The cylinders were loaded until 40% of its ultimate load capacity. Measurement for deformation must be taken at 10% increments of the maximum load capacity of the cylinder until reaching the 40%.

The Modulus of elasticity (Young's modulus) is calculated from the following equation:

$$E = \frac{S_2 - S_1}{\epsilon_2 - 0.00005}$$

Where S_2 is the stress corresponding to 40% of the ultimate load. S_1 is the stress assessed at a strain of 0.00005. ϵ_2 is the strain measured in correspondence with the Stress S_2.

Figure 7.36 Modulus of elasticity test setup

The modulus of elasticity test results of the Series 1 are shown in Figure 7.31. The results indicated that the addition of ceramic decreased the young's modulus of the concrete. It can be observed that the control specimen had a modulus of 16.7 MPa at 28 days and 19.9 MPa at 56 days. However, the addition of ceramics reduced the modulus at 28 days to 15.6, 13.2, and 13.3 MPa for the percentages 10% Cr, 15% Cr, and 20% Cr respectively. At 56 days, the young's modulus of the ceramic mixes improved reaching recorded values of 19.5, 18.2, and 16.7 MPa for the 10% Cr, 15% Cr, and 20% Cr mixes. It is worth noting that at 28 days only 10%Cr is considered satisfactory (above 90%). Further, the 56 days results for the 10%Cr and 15% Cr were found to be evident compared to the control results of about 98% and 91% of the control modulus of elasticity respectively.

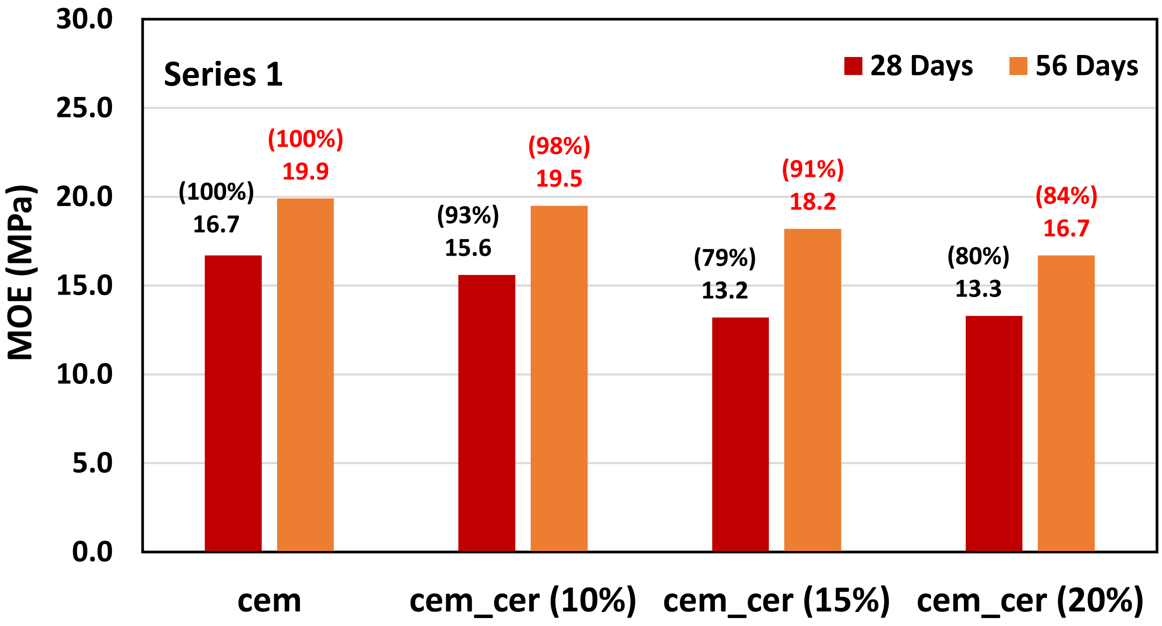


Figure 7.37 Modulus of elasticity test results of Series 1

Figure 7.32 demonstrates the modulus of elasticity measured at 28 and 56 days of the series (2) that covers 4 mixes made with several percentages of ceramics substituting slag cement (0%, 10% 15%, and 20%) as well as the control mix. The results of the test indicated that the usage of slag cement improved the modulus of elasticity of the concrete for both 28 and 56 testing days. The slag cement’s young modulus achieved 18.8 MPa (113%) at 28 days and 23.6 MPa (119%) at

56 days. Further, the addition of ceramic resulted in lowering the compressive strength. It can be noticed that the addition of ceramics up to 15% is satisfactory at 28 days where concrete lost only 10% of its modulus of elasticity. However, at 28 days, the addition of ceramic up to 20% is considered satisfactory since the modulus is only reduced by 6%.

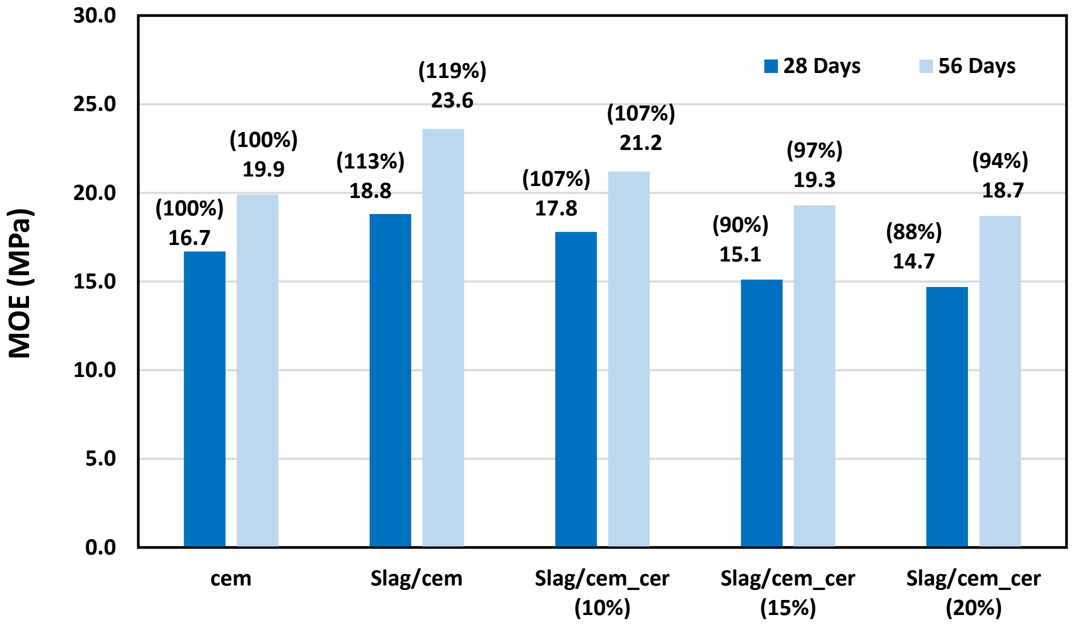


Figure 7.38 Modulus of elasticity test results of Series 2

The modulus of elasticity test results of the series (3) are shown in Figure 7.33. The modulus of elasticity of the 60 MPa resulted 26.4 MPa at 28 days and 31.8 MPa at 56 days. The addition of ceramic reduced the modulus of elasticity of concrete. As shown in Figure 7.33, the addition of 15% ceramics reduced the modulus by 11% at 28 days and 10% at 56 days. Further, the inclusion of 20% ceramics led to a decrease in the modulus of elasticity in the order of 19% at 28 days and 16% at 56 days.

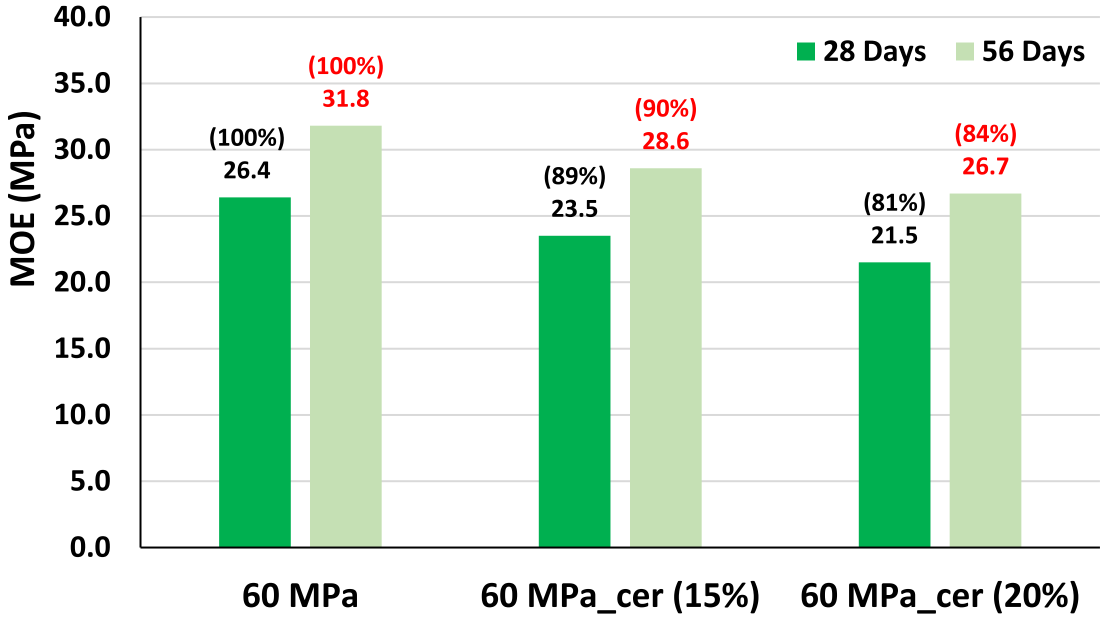


Figure 7.39 Modulus of elasticity test results of Series 3

7.4.6 Freezing and Thawing test

Freezing of water results in volumetric expansion estimated to be 9 percent. When moist concrete freezes the water filled in the pores expands and develop internal pressure inside the concrete. When the forces resulted exceeds the tensile capacity of concrete, the cavity will become larger under the consecutive freeze thaw cycles which will end up by scaling of concrete, paste deterioration, and eventually abrasion leading to an aggregate pop out of the concrete.

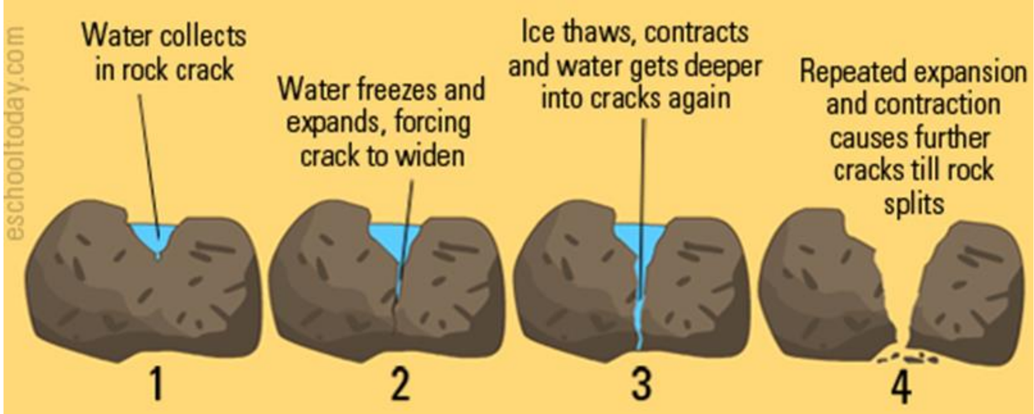


Figure 7.40 Freezing and thawing concept

The freezing and thawing test requires to make beam samples of specific dimension. In this experiment, beams of dimension 7.5x10x40.5 were made so it can be transferred to the stainless-steel sample tray of the freezing and thawing machine manufactured by Humboldt.

The samples were cured in water for 14 days prior inserting the beams in the freeze and thaw machine. The ASTM C666 specifies two procedures for the freezing and thawing A and B. The former consists of thawing the samples in water and the latter consists of thawing the sample in air. The freezing for both procedures is made under water. The freeze-thaw cycle consists of lowering the temperature from 4 to -18 degrees (freezing) and then rising the temperature back to 4 degrees (thawing). The duration of the cycle selected for the experiment is 2 hours which means that each day the sample is subjected to 12 cycles. The Samples were left then in the freezing and thawing cabinet for 1 month (360 cycles).

Figure 7.41 Samples inserted in the freezing and thawing machine

Freezing-and-Thawing Cycle: one cycle consists of lowering the temperature from 4.4C to -18C (Freezing) and then levitation it from -18C to 4.4C. Such operation must be done in not less than 2 nor more than 5 hours. Literature limit the cycle to 3 hours which allows 8 cycles per day.

Figure 7.42 Samples after freezing and thawing cycles

Due to the lack of the ability of making the frequency resonance test, the available data concerning the freezing and thawing machine are qualitative through observations. At first all samples shown in Figure 7.36 are inverted in a way that the bottom is showed up on top since the freezing start from bottom where aggregate pop out and paste deterioration start to appeal down. From Figure 7.36 it can observed that ceramic had an effect of harming the concrete where the addition of 20% ceramic led to huge crack that started from the bottom and reached the top of the beam. As for the slag cement and hybrid mixes the slag contributed in improving the resistivity of the concrete due to the freeze and thaw where even the hybrid mixes had almost same deterioration effect as the control concrete made of cement. Lastly shifting the concrete to a higher compressive strength helped in arresting the deterioration where the 3rd series is almost not affected by the freeze and thaw cycles.

7.4.7 Thermal Conductivity

The thermal conductivity is the ability of a material to conduct and allow heat to pass from the heated side to the other cold side. The thermal conductivity of the concrete was determined in accordance to ASTM C518 for the three series. One block (300 x 300 x 25 mm) was tested through the steady state conductivity tester. Samples must be in dry conditions for the test. ASTM C518 specifies conditioning at 22°C and 50 % Relative Humidity for a period of time until no more than a 1 % of mass loss is observed over a 24-h period.

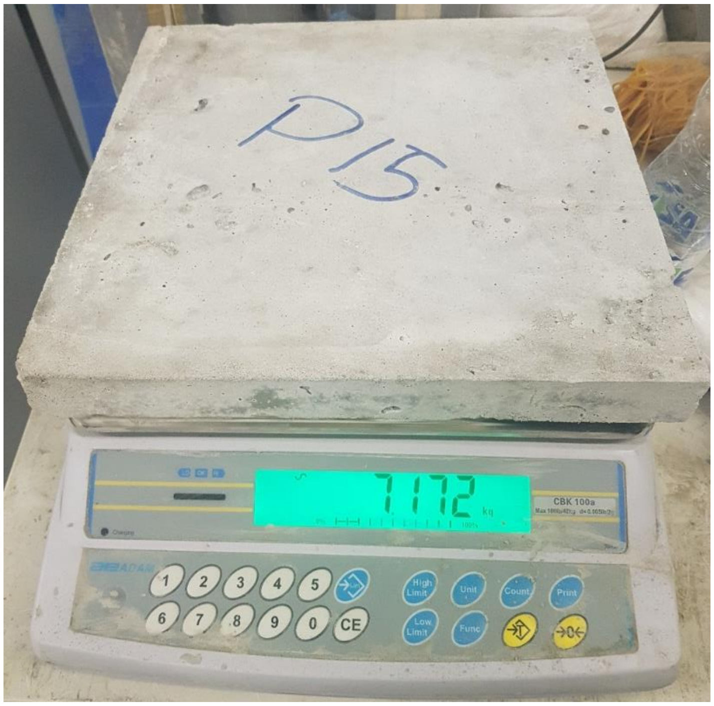


Figure 7.43 Concrete block (300 x 300 x 25 mm) prepared for the thermal conductivity test

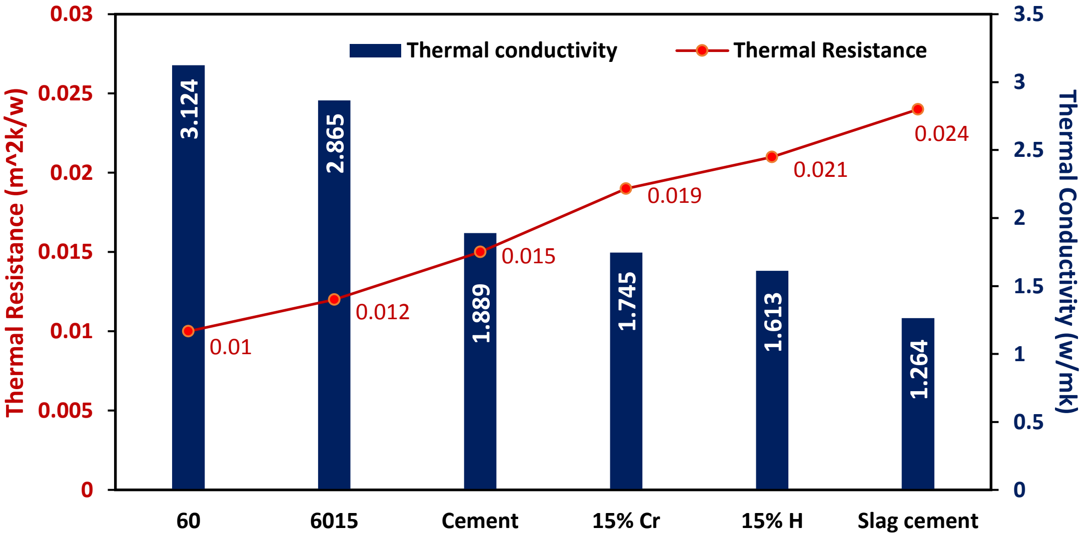


Figure 7.44 Thermal conductivity and thermal resistivity of six mixes

Figure 7.38 represents the thermal conductivity and thermal resistivity of six mixes selected from the three series previously discussed: cement and 15%cr from series (1), slag cement and 15%H from series (2), 60MPa and 60MPa 15% from series (3).

The results of the tests indicate that the thermal conductivity and thermal resistivity are negatively proportioned. It is worth noting that the higher the compressive strength the higher the conductivity and the lower the resistance. As for the 30 MPa mixes, the Slag cement had the lowest thermal conductivity (1.264 w/mk) and the highest thermal resistivity (0.024 m^2k/w) whereas cement had the highest among the 30MPa mixes resulting a conductivity of 1.889 w/mk and resistivity of 0.015 m^2k/w. Moreover, the concrete mixes can be ranked from highest conductivity to the lowest as follows: 60MPa, 60MPa 15, cement, 15% Cr, 15%H, and lastly slag cement. The thermal resistivity is graded the same ranking with opposite sorting from lowest to highest.

7.5 Summary

Based on the results of the concrete testing that covers: slump, compressive strength, split tensile, flexural capacity, first crack toughness, modulus of elasticity, freeze and thawing, thermal conductivity, and thermal resistivity tests made on the three series of testing: ceramic replacing cement (30MPa), ceramic replacing slag cement (30MPa), and ceramic inclusion in high strength concrete of 60 MPa, the following conclusion can be drawn:

1. Ceramic contributed in reducing the compressive strength of the concrete however 10% level of replacement is still considered satisfactory.
2. The usage of slag cement improved the concrete compressive strength at 28 and 56 days which contributed in improving the hybrid concrete mixes made of slag cement and ceramic.
3. The split tensile test results revealed that the ceramic inclusion up to 15% led to a satisfactory tensile strength recording almost 90% of the control strength. Further, all hybrid concrete mixes (10, 15, and 20%) are considered satisfactory.
4. The flexure and 1st crack toughness results were in line with the split tensile results.
5. The modulus of elasticity test showed that inclusion of 10% ceramic led to a modulus above 90% of the control modulus. However, all the hybrid mixes are considered acceptable and showed higher strength than 90% at 56 days.
6. The freezing and thawing test revealed that the ceramic has accelerated the deterioration of concrete due to the freeze-thaw cycles whereas slag improved the resistivity of the concrete.
7. The thermal resistivity and thermal conductivity negatively proportioned.
8. The slag had the highest thermal resistivity among the cementitious material then the ceramic followed by the cement that has the lowest resistivity. As for the effect of the compressive strength, a higher strength led to a higher thermal conductivity.

Chapter 8

CONCLUSION AND RECOMMENDATION

8.1 Introduction

In this Chapter, the conclusions and recommendations that resulted from this research are presented. The work presented in this thesis aimed at assessing the pozzolanic activity of the ceramic and slag and investigate the effect of such materials as cement substitute in concrete. The objective was to produce a green concrete reducing the cement quantity in the concrete mix that has a negative impact on the environment as well as recycling the ceramic wastes generated from the construction demolition waste. It is critical to note here, that the works presented in this dissertation and the associated findings have potential impact and applications, which extend well beyond the local context into regional and international realms.

8.2 Summary of the findings

Based on the results of the chapters 4 to 7 titled powder characterization, assessment of the pozzolanic activity, mortar testing, and concrete testing, the following findings, conclusions can be drawn:

1. The ceramic powder contains siliceous in its chemical composition which means that it has the potential of being a pozzolanic material.
2. The assessing of the pozzolanic reactivity of ceramic and slag revealed that these powders contributed in consuming the CH with time, which is explained

by the fact that the Siliceous is reacting with CH making CSH structures in the paste matrix.

3. The ceramic and slag can perform better under heat compared to the cement as it showed mass stability under heat and led to a higher compressive strength at high temperatures.
4. The addition of 10% ceramic is considered satisfactory for compressive strength and modulus of elasticity whereas 15% ceramic is satisfactory for beam and split tensile tests. It can be concluded that different percentages can be used depend on the application itself where 10% suits columns and 15% for slabs and beams.
5. The usage of slag cement led to overcome the deficiency caused by the ceramic
6. Ceramic accelerates the deterioration of the concrete under freeze and thaw cycles.
7. Ceramic and slag are considered having low thermal conductivity.

8.3 Future work

This section includes the future work that can be done on ceramic and slag in concrete. As this thesis is divided to chemical and mechanical analysis. On one hand, a study can be conducted on the alkali activation of hybrid binder concrete. On the other hand, applying the theory on a structural big scale elements can prove the possibility of implementing the study in the local industries.

8.3.1 Alkali Activated Cement

Alkali activated cement (AAC) has been a hot topic lately. The concept of the AAC is to use two pozzolan non-cement materials, one with high calcium content and the other with low calcium content, in presence of alkali solution (sodium hydroxide, sodium silicate, sodium carbonate, or combinations made of these element). Such mix is beneficial in removing cement from the concrete mix that is causing harm to the environment. Many studies involved the usage of slag and silica fume in the alkali activated system. A new study can be established using ceramic (a high siliceous and low calcium material) and slag (high calcium material).

Figure 8.1 Alkali activated cement (AAC)

8.3.2 Structural Elements

Applying the results of concrete testing on structural full-scale reinforced concrete is essential in order to implement the modified concrete in the industrial companies. The idea consists of making beams that will be prepared using two optimum concrete mixes: one with ceramic and cement and the other using ceramic and slag cement. Then testing will include a full detailed beam which are designed to fail in shear, flexure, and bond. Evaluation will be based on mode of failure, ultimate load capacity, Load-deflection history, and crack width.

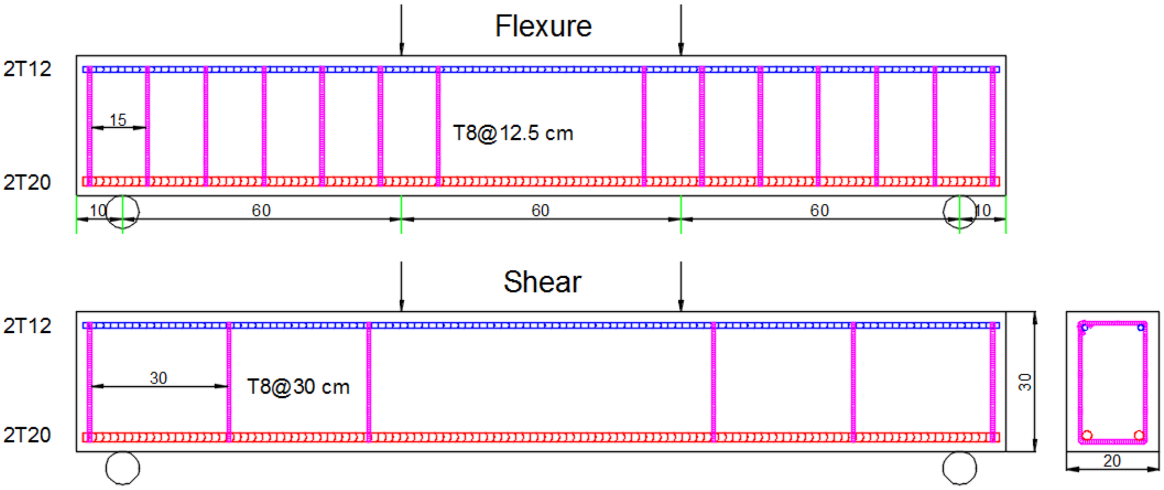


Figure 8.2 Big scale structural elements

APPENDIX

Table 9.1 Compressive strength results for all series of tests

f’c	R	7 days	AV	%	28 days	AV	%	56 days	AV	%
control	1	20.5	21.3	100%	28.6	30.6	100%	33.62	33.4	100%
	2	22.1			31.4			33.19		
	3	x			31.7			x		
Slag control	1	18.13	19.3	91%	31.5	31.2	102%	40.2	39.4	118%
	2	20.48			30.4			38.5		
	3	x			31.7			x		
10%Cr	1	17.2	17.4	82%	26.4	26.8	88%	31.2	30.5	91%
	2	17.6			27.1			29.8		
	3	x			26.9			x		
15%Cr	1	15.8	15.6	73%	24.2	23.9	78%	26.6	26.3	79%
	2	15.3			23.6			25.9		
	3	x			24			x		
20% Cr	1	14.3	14.0	66%	19.4	20.0	66%	22.2	23.3	70%
	2	13.7			20.9			24.3		
	3	x			19.8			x		
10%H	1	18.8	17.6	82%	29.3	29.1	95%	35.5	34.9	104%
	2	16.3			29.5			34.3		
	3	x			28.6			x		
15%H	1	14.7	16.3	76%	27.0	26.5	87%	32.2	30.9	92%
	2	17.8			26.9			29.6		
	3	x			25.6			x		
20%H	1	16.7	14.4	67%	23.2	23.6	77%	27.2	26.9	80%
	2	12.0			23.6			26.5		
	3	x			24.0			x		
60H	1	38.2	40.3	100%	55.2	56.0	100%	62.1	61.5	100%
	2	42.3			56.7			60.8		
	3	x			56.1			x		
60H15	1	35.9	35.7	89%	52.1	52.8	94%	57.2	56.7	92%
	2	35.4			52.8			56.2		
	3	x			53.4			x		
60H20	1	33.4	32.4	80%	47.7	46.6	83%	49.7	50.1	82%
	2	31.3			45.7			50.5		
	3	x			46.5			x		

Table 9.2 Split tensile results for all series of tests

Days	28 days				56 days				
Mix	**R**	**Load (KN)**	**T (Mpa)**	**AV**	**%**	**Load (KN)**	**T (Mpa)**	**AV**	**%**
control	1	82.6	2.6	2.59	100%	86.878	2.86	2.86	100%
	2	78.3	2.6			86.47	2.85		
Slag control	1	85.9	2.8	2.79	108%	94.403	3.11	3.18	111%
	2	83.2	2.7			98.24	3.24		
10%Cr	1	75.5	2.5	2.51	97%	83.017	2.74	2.78	97%
	2	77.0	2.5			85.45	2.82		
15%Cr	1	72.0	2.4	2.35	91%	84.221	2.78	2.71	95%
	2	70.5	2.3			80.32	2.65		
20% Cr	1	68.4	2.3	2.32	90%	73.8	2.43	2.50	88%
	2	72.5	2.4			78	2.57		
10%H	1	83.1	2.7	2.66	103%	91.8	3.03	3.12	109%
	2	78.5	2.6			97.5	3.21		
15%H	1	75.5	2.5	2.58	100%	88.112	2.90	3.02	106%
	2	81.0	2.7			95.008	3.13		
20%H	1	77.2	2.5	2.57	99%	82.1	2.71	2.69	94%
	2	78.8	2.6			81.336	2.68		
60	1	127.4	4.2	4.28	100%	154.4	5.09	5.01	100%
	2	132.2	4.4			149.64	4.93		
6015	1	120.4	4.0	4.00	94%	136.5	4.50	4.55	91%
	2	122.5	4.0			139.4	4.60		
6020	1	127.5	4.2	4.11	96%	125.4	4.13	4.18	83%
	2	121.6	4.0			128.4	4.23		

Table 9.3 Flexure capacity and 1st crack toughness results for all series of tests at 28 days

Mixes	**R**	**P (KN)**	**δ (mm)**	**R (Mpa)**	**R av**	**%R**	**Tougness (J)**	**Tav (J)**	**%T**
control	1	14.44	0.60	4.33	4.76	100%	4.34	5.0	100%
	2	17.32	0.66	5.20			5.67		
Slag cement	1	18.6	0.51	5.58	5.67	119%	4.74	5.5	110%
	2	19.23	0.65	5.77			6.27		
10%Cr	1	13.71	0.63	4.11	4.18	88%	4.32	4.1	81%
	2	14.15	0.54	4.25			3.83		
15%Cr	1	14.36	0.69	4.31	4.31	91%	4.95	4.6	93%
	2	14.4	0.60	4.32			4.32		
20% Cr	1	13.71	0.48	4.11	4.15	87%	3.29	3.4	68%
	2	13.95	0.50	4.19			3.51		
10%H	1	12.57	0.56	3.77	4.28	90%	3.54	4.1	81%
	2	15.93	0.58	4.78			4.60		
15%H	1	14.81	0.56	4.44	4.67	98%	4.14	4.4	88%
	2	16.34	0.57	4.90			4.69		
20%H	1	15.22	0.56	4.57	4.66	98%	4.24	4.3	86%
	2	15.83	0.56	4.75			4.42		
60	1	30.7	0.51	9.20	8.56	100%	7.82	7.1	143%
	2	26.4	0.49	7.91			6.45		
6015	1	26.1	0.57	7.84	8.07	94%	7.44	6.8	135%
	2	27.7	0.44	8.30			6.09		
6020	1	24.1	0.46	7.22	7.11	83%	5.56	6.0	121%
	2	23.3	0.56	7.00			6.54		

Table 9.4 Flexure capacity and 1st crack toughness results for all series of tests at 56 days

Mixes	P (KN)	δ (mm)	R (Mpa)	Rav (Mpa)	%R	Tougness (J)	T av	%T
control	17.32	0.548	5.20	5.17	100%	4.7	5.1	100%
	17.15	0.644	5.15			5.5		
Slag cement	20.43	0.53	6.13	6.31	122%	5.4	5.6	110%
	21.63	0.54	6.49			5.8		
10%Cr	17.71	0.608	5.31	5.01	97%	5.4	4.9	96%
	15.71	0.57	4.71			4.5		
15%Cr	15.517	0.55	4.66	4.92	95%	4.3	4.2	82%
	17.31	0.48	5.19			4.2		
20% Cr	14.14	0.394	4.24	4.26	82%	2.8	2.8	54%
	14.34	0.384	4.27			2.8		
10%H	17.2	0.46	5.16	5.48	106%	4.0	4.3	84%
	19.3	0.48	5.79			4.6		
15%H	18.92	0.48	5.68	6.00	116%	4.5	4.8	93%
	21.11	0.472	6.33			5.0		
20%H	17.73	0.497	5.32	5.44	105%	4.4	4.1	80%
	18.56	0.408	5.57			3.8		
60	28.49	0.608	8.55	8.69	100%	8.7	8.9	100%
	29.45	0.627	8.84			9.2		
6015	26.42	0.492	7.93	8.56	99%	6.5	7.4	82%
	30.67	0.535	9.20			8.2		
6020	24.27	0.437	7.28	7.81	90%	5.3	6.6	74%
	27.79	0.567	8.34			7.9		

Table 9.5 Gradation of Coarse aggregate from ASTM C33

Sieve Number	Nominal Size	4" 100 mm	3.5" 90 mm	3" 75 mm	2.5" 63 mm	2" 50 mm	1.5" 37.5 mm	1" 25 mm	3/4" 19 mm	1/2" 12.5 mm	3/8" 9.5 mm	No 4 4.75 mm	No 8 2.36 mm	No 16 1.18 mm	No 50 300 Microns
1	90 to 37.5 mm	100	90 to 100		25 to 60		0 to 15		0 to 5						
2	63 to 37.5 mm			100	90 to 100	35 to 70	0 to 15		0 to 5						
3	50 to 25 mm				100	90 to 100	35 to 70	0 to 15		0 to 5					
357	50 to 4.75 mm				100	95 to 100		35 to 70		10 to 30		0 to 5			
4	37.5 to 19 mm					100	90 to 100	20 to 55	0 to 15		0 to 5				
467	37.5 to 4.75 mm					100	95 to 100	40 to 85	35 to 70		10 to 30	0 to 5			
5	25 to 12.5 mm						100		20 to 55	0 to 10	0 to 5				
56	25 to 9.5 mm						100	90 to100	40 to 85	10 to 40	0 to 15	0 to 5			
57	25 to 4.75 mm						100	90 to 100		25 to 60		0 to 10	0 to 5		
6	19 to 9.5 mm							100	90 to 100	20 to 55	0 to 15	0 to 5			
67	19 to 4.75 mm								90 to 100		20 to 55	0 to 10	0 to 5		
7	12.5 to4.75 mm								100	90 to 100	40 to 70	0 to 15	0 to 5		
8	9.5 to 2.36 mm									100	85 to 100	10 to 30	0 to 10	0 to 5	
89	9.5 to 1.18 mm									100	90 to 100	20 to 55	5 to 30	0 to 10	0 to 5
9	4.75 to 1.18 mm										100	85 to 100	10 to 40	0 to 10	0 to 5

SUMMARY OF ANNOTATIONS USED IN THE WHOLE THESIS

Pozzolanic performance: P is cement paste, SP is slag cement paste, CP is ceramic cement paste, and HP is hybrid paste made of slag cement and ceramics.

Mortar Testing: 10% porcelain, 15% porcelain, 15% Terracotta, slag cement, and 15% Hybrid (15% porcelain as a substitute of slag cement).

Concrete Testing:

Series 1: 10% Cr (10% ceramic replacing cement), 15% Cr, 20% Cr

Series 2: 10% H (10% ceramic replacing slag cement), 15% H, 20% H

Series 3: 60 (high strength concrete made of slag cement) **/** 60 15%H (High strength concrete made of slag cement and 15% ceramic as a replacement), 60 20% H

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