AMERICAN UNIVERSITY OF BEIRUT

BEHAVIOR OF HIGH STRENGTH REINFORCED CONCRETE STRUCTURES INCORPORATING SLAG/CERAMIC BINDERS

by
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ABSTRACT
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A recent research was conducted at AUB to evaluate the structural properties of a sustainable concrete material produced by replacing a suitable percentage of Portland cement with a hybrid ceramic/slag binder. The research was triggered by different objectives including the need to mitigate the negative environmental impact of cement production and the need to recycle the waste of the ceramic industry. Research reported in the literature indicated that the replacement of different percentages of cement with ground ceramic powder decreased the compressive strength of concrete. A recent research was conducted at the American University of Beirut to test the hypothesis whether the negative impact of ceramic powder on concrete properties would be reduced when supplementary pozzolanic materials such as slag were also incorporated in the concrete mix. Different combinations of cement, ceramic, and slag were tested in the different phases. The results validated that the inclusion of the ceramic/slag binder in the concrete mix with an optimum percentage replacement of cement overcame the negative impact of ceramic powder on the mechanical properties of concrete. It is important to evaluate the effect of the new sustainable material on the structural behavior of high strength concrete beams designed to fail in flexure or shear or bond-splitting modes. Evaluation will be based on crack patterns, ultimate load capacity, and Load-deflection history.

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CHAPTER 1

INTRODUCTION AND BACKGROUND

1.1 Introduction

Conventional concrete, a widely used construction material worldwide, has been imposing a negative environmental impact due its production process. Portland cement production involves substantial quarrying of raw materials (sand, clay, limestone, etc.). More than 1.7 Tons of these materials are needed to produce each Ton of Portland cement clinker, leading to the exhaustion of natural resources. As the raw materials are burned at very high temperatures, clinker production consumes large amounts of energy causing significant emissions of carbon dioxide. As for the ceramic industry, 3 to 7% of the daily production is discarded and cannot be directly treated in plants. For countries that lack proper waste management regulations, such as Lebanon, these amounts contribute to a major environmental dilemma.

Developing new efficient methods to integrate waste materials, from other industries, into the concrete mix can transform the current concrete industry into a green practice. In line with that, several studies were previously conducted to target construction demolition wastes. These materials include 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). A previous study was conducted at the American University of Beirut to investigate a sustainable concrete material incorporating a hybrid binder composed of ground ceramic powder, processed from production wastes, and slag as replacement of a certain percentage of Portland cement. The results proved to yield acceptable mechanical performance of small-scale specimens, as compared to the ordinary Portland cement concrete material. 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 pozzolanic material used as a partial replacement of cement. This research, based on the study mentioned previously, aims to investigate the behavior of full-scale reinforced concrete members cast using this new sustainable material.

1.2 Ceramic raw material and production

Ceramic production can be tracked back to early 24,000 BC (Figure 1.1), making it one of the most ancient fabricated products on earth. According to the American ceramic Society, Eileen (2014) stated that ceramic production started initially by firing slurry, a semiliquid clayey material. The first manufactured ceramic tile was established in India 14,000 BC and the glazing material was discovered 5000 BC in Egypt. In 1550, furnaces were integrated into the production process to increase the resistance of ceramics to high temperature. Ceramic production continued developing until several forms, usages, and properties were achieved.

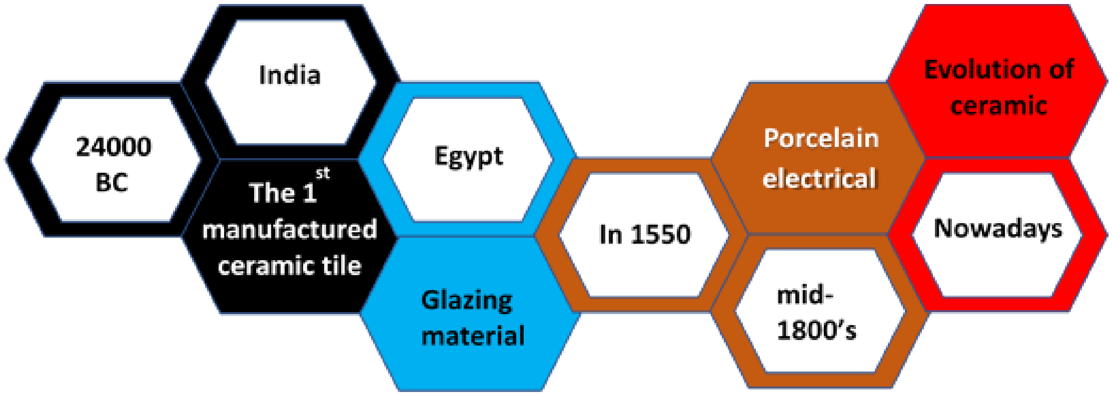


Figure 1.1 Ceramics evolution timeline

Composed of the same raw materials, ceramic tiles differ as the used proportions are almost unique for each manufacturer. These raw materials are all natural resources and they include:

- 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 major constituents of ceramics. Feldspar, however, is a critical flux in the mix, as it accelerates the melting of quartz. The type and amount of the feldspar contribute directly to the drop in the melting point of the quartz. While low temperatures contribute to weakening the structure of ceramics, hardening at very high temperatures strengthen the ceramic tiles.

The proportions of ceramic mixtures differ, depending on manufacturing companies. In general, high clay content facilitates shaping ceramics while high feldspar content makes the ceramic glasslike. The potash feldspar has a white color, whereas the sodium feldspar has a brownish color. The selection of raw materials affects the fired final product coloration. Clay and kaolin govern the strength, composition, and plasticity of ceramics. The chemical and physical properties of ceramics' raw materials are listed in Tables 1.1 and 1.2. It is important to notice that feldspar has almost the same chemical composition of ceramics, which is why it can be considered as a ceramic raw powder.

Table 1. 1 Chemical composition of ceramics raw materials

	Molecule	**Chemical composition (%)**							
		SiO_2	Al_2O_3	Fe_2O_3	K_2O	Na_2O	MgO	CaO	LOI
Potash Feldspar	$KAlSi_3O_8$	68.0	18.0	0.08	11.5	2.0	0.0	0.0	0.4
Sodium Feldspar	$NaAlSi_3O_8$	68.0	18.0	0.08	1.5	9.0	0.0	0.5	0.4
Quartz (sand)	SiO_2	99.8	0.0	0.0	0.0	0.0	0.0	0.0	0.1
Ball Clay	Al_2O_3-$2SiO_2$-$2H_2O$	53.8	28.5	0.83	0.7	0.06	0.12	0.41	10.0
Kaolin (china clay)	$Al_2O_3·2SiO_2·2H_2O$	45.3	33.4	0.30	0.44	0.27	0.25	0.05	0.14
Talc powder	$3MgO.4SiO_2.H_2O$	63.7	0.0	0.0	0.0	0.0	31.9	0.0	3.0

Table 1.2 Physical properties of feldspar and clay

Material	Physical properties	
	SG	Melting range
Feldspar	2.60	1100-1150
Clay	2.65	1650

Several studies tackled 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 void filler in concrete since the coarse aggregate and the paste are responsible for concrete strength capacity. Ceramic production is a multi-staged process (Figure 1.2). First, raw materials are selected and proportioned according to the criteria followed by the manufacturer. After that, mixing takes place and special molds are used to obtain a green ceramic. The green material term describes the raw unfired materials, which are soft and precede the hardening and calcination that occur after firing. Ceramics are heated twice, once after forming and second after glazing.

Figure 1.2 Ceramics manufacturing process

Ceramics can take different forms and have many types. In the reported literature, two types of ceramics were investigated: Terracotta and Porcelain. The first is mainly a brownish red earthenware, which consists of fired clay, glazed with a porcelain layer. The second is a full body of low porous ceramic that is heated at a temperature of 1400° C.

1.3 Ceramic Quantification

Cement manufacturing generates large amounts of ceramic waste, estimated to around 19 kg/m^2 of tiling products (Singh and Srivastava 2018). A recent study showed that the global generation of ceramic waste in 2012 was about 22 billion tons, causing serious disposal and environmental complications (El-Dieb et al. 2018). In 2018, India produced 650 million m^2 of tiles, generating around 12 billion tons of ceramic waste.

Furthermore, landfilling ceramic wastes could degrade groundwater and soil fertility, especially with the toxic metals like cadmium, copper, and barium (Silva et al. 2016).

According to a privately funded study, the estimated number of the destroyed houses due to the Syrian Civil War was more than half a million (535,000) , costing around \$68 billion. Abdullah Dardari, the Director of the Economic Development and Globalization Division (EDGD), stated 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 into 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. Based on a conservative building area of 1,000 m^2, the amount of ceramic wastes due to the Syrian Civil War is estimated to be around 26 million Tons. Such huge quantities are extremely difficult to recycle and the convenient method for solving such issues is to dump the accumulated waste in the sea and coastal areas, which is what the Lebanese government did after the war in 2006.

This research provides a sustainable solution of consuming such waste quantities by integrating them into the concrete industry. Furthermore, wars result in destroyed areas that need to be reconstructed. Construction of such areas requires large quantities of cement and partially replacing these quantities by ceramics and slag powders will help further consume the excess waste material.

1.4 Slag

Ground granulated blast furnace (GGBS) is a byproduct of iron production. Iron 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 are produced depending on the method used to cool the molten slag:

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

Slag was first established in Germany in 1853 (Malhotra 1996). Using slag as a pozzolanic material in concrete started in the beginning of the 1900s (Abrams 1925). The granulated slag size is similar to the cement particle size according to ACI standards while European standards require a finer slag particle size than that of the cement. The specific gravity of slag is typically between 2.85 and 2.95.

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 consist of 500 g of cement, 1,375 g of sand, and 250 g of water. The slag mix is made similarly, however in this mix slag replaces 50% of cement by weight. Compressive cubes must be test at 7 and 28 days. The strength activity index is determined by dividing the compressive strength of the slag cement cube to control cube. Then slag can be classified according to the results. While Grade 120 is the most effective type of slag, Grade 100 is closer to cement at 28 days, and grade 80 is the weakest. Slag typically plays a role in lowering the heat of hydration of cement, which will result a drop in the compressive strength at early days and an increase in the compressive strength at late stages.

1.5 Research Objectives and Scope of Work

This study builds upon the results of a previous research that was conducted at the American University of Beirut. Ceramic is a well-known material for its high heat resistance, a reason to be investigating ceramic concrete and comparing it to slag and conventional concrete. The previous AUB research compared different types of ceramics and studied the microstructure of ceramic and slag pastes. The pozzolanic reactivity of blast furnace slag (BFS) and ceramic waste powder (CWP) was assessed to ensure the efficiency of such hybrid materials as cement substitutes. Through 11 mixes, the experimental plan covered a wide range of small-scale concrete testing for normal and high strength concrete. The results indicated that the inclusion of BFS to the concrete mix helps in overcoming the concrete strength deficiency caused by CWP.

The objective of this study is to evaluate the structural behavior of high strength reinforced concrete structures, incorporating a sustainable concrete material made by replacing a suitable percentage of Portland cement with slag/ceramic hybrid binder. The binder is composed of processed CWP from the ceramic industry combined with BFS. The previous research yielded promising results, as the proposed BFS inclusion successfully neutralized the negative impact of CWP on the strength of normal and high strength concrete. However, large-scale structural testing is a critical step in assessing the feasibility of introducing this new sustainable concrete material to local and global industries.

1.6 Research Significance and Local Context

This study explores the use of recycled ceramic tiles and BFS in the concrete mix as a partial replacement for cement. Composed of 95% clinker and 5% gypsum, cement is a worldwide used material that imposes a negative environmental impact through its production. Clinker production consumes enormous amounts of energy since it is burnt at a very high temperature exceeding 1,400˚C. Such energy releases significant amounts of CO_2, contributing to around 7% of global anthropogenic CO_2 emissions. In addition, each million Tons of clinker requires 1.7 million Tons of raw materials, which are all-natural resources such as limestone, clay shale and quartz sand. Hence, the cement production process is not only contributing to air pollution, but also leading to the exhaustion of natural resources.

As for the ceramic industry, disposing waste materials, which cannot be recycled, has raised environmental concerns for countries that lack proper waste management regulations. Furthermore, demolition wastes from destroyed buildings in wars include significant quantities of ceramic wastes that are dumped, instead of passing through any treatment process.

CWP and BFS can be used as sustainable building materials that are expected to reduce energy and resources depletion from cement production. By replacing an acceptable percentage of cement in the concrete mix by BFS and CWP, these materials can potentially contribute to creating a new sustainable concrete that satisfies strength and durability requirements. Furthermore, integrating these materials into the concrete mix provides a solution for the ceramics wastes that are not subjected to proper recycling. As mentioned earlier, the ceramic industry yields significant quantities of wastes in countries that lack proper waste management regulations. This research aims to test whether replacing a certain percentage of Portland cement with BFS would overcome the reduction in the mechanical properties of concrete incorporating CWP.

1.7 Research Methodology

This study aims to evaluate the behavior of reinforced high strength concrete beams incorporating hybrid binders. The study is composed of three phases: material acquisition and processing cement/BFS/CWP, experimental testing, and structural evaluation of the hybrid concrete. Blended slag, acting as a pozzolanic component in the mix, was ordered from Lebanese suppliers and consisted of 40% slag and 60% cement. While cement and aggregates were obtained from local suppliers, the ceramic powder was processed through several phases starting with ceramic tiles.

In addition to that, formworks and reinforcement steel cages were prepared based on the designated beam dimensions. Four concrete mixes, including a control batch, with different cement replacement percentages were cast. For each mix, three modes of failure were tested: flexure, shear, and bond splitting modes. The beams were tested 28 days after casting to assess the corresponding modes. Furthermore, concrete cylinders were cast and tested at 7, 28, and 54 days to evaluate the compressive strength of the corresponding mixes at several stages. The assessment of hybrid material combinations was based on ultimate load capacities, load deflection behaviors, and crack patterns.

1.8 Thesis Outline

This study is composed of five chapters. Chapter 1 introduces the topic of hybrid concrete incorporating BFS and CWP and summarizes the research objectives, significance and methodology. Chapter 2 presents some of the relevant conducted literature review including the previous research conducted at the American University of Beirut, which this study is based on. Chapter 3 discusses the required testing materials and the processing of ceramic powder in full details. Chapter 4 highlights the experimental program including mix designs, structural detailing and structural beam testing. In chapter 5, the testing results are presented and analyzed before assessing the efficiency of the replacement in the mixes based on ultimate load capacities, crack patterns, and load deflection histories. Chapter 6 concludes the research and provides recommendations and next steps based on the obtained results.

CHAPTER 2

LITERATURE REVIEW

2.1 Relevant Literature - General Context

In an attempt to transform the current concrete industry into a green practice, the potential use of ceramic in concrete as a cement substitute is garnering more interest in the material and structure community. This interest in ceramics has generated a number of research initiatives and experimental testing programs aimed at investigating the mechanical properties of concrete incorporating new materials. Ceramic usage in concrete is still a theoretical concept, where a successful application in concrete industries requires more investigations and experimental studies to assess the structural, economic and environmental feasibility of integrating this material into the concrete mix.

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. Furthermore, some of the environmental benefits expected to take place due to recycling the ceramic wastes include diminishing landfilling and providing a sustainable solution for countries that lack proper waste management regulations where ceramic wastes are generated on a daily basis.

2.2 Studies involving material characterization and mortar level

Ay et al. (2000) investigated blending cement with processed CWP. Ceramic wastes were initially crushed in a jaw crusher before grinding the particles in a ball mill for 55 minutes. The obtained powder was then blended with cement in a ball mill (by weight ratios of 25%, 30%, 35%, and 40%) for 30 minutes. In order to test the pozzolanic reactivity of the blended mixes, four batches were prepared according to the Rilem cembureau method. Mortar prisms were tested at 1, 2, 7, and 28 days. The results indicated an acceptable range of compressive strength with a cement replacement up to 30% (Table 2.1). At 7 days, the compressive strength of the mix with 40% ceramic content was around 19% less than the average compressive strength of the rest of the mixes. The mixes with 25% and 30 % ceramic content yielded similar acceptable results at 28 days, while the obtained compressive strength decreased as higher ceramic content was used in the mixes. Furthermore, the study concluded that CWP can be considered as a pozzolanic material and that its usage in cement production contributes to 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)

Tile (%)	1-day	2-day	7-day	28-day
	Compressive strength (N/mm^2)	Compressive strength (N/mm^2)	Compressive strength (N/mm^2)	Compressive strength (N/mm^2)
25	8.6	14.7	27.8	38.4
30	10.2	15.7	27.8	38.0
35	7.2	12.0	26.8	33.7
40	6.9	11.6	22.2	32.2

Zhang et al. (2017) studied the effect of BFS, activated by 4% of lime, on the freeze-thaw and carbonation resistances of mortars. The experimental investigation indicated that the frost resistance and carbonation resistance decreased as the slag ratio increased by weight in the concrete. BFS plays a role in lowering the heat of hydration, which consumes the CH content in concrete and encourages the carbonation progress. Although the inclusion of lime enhanced the compressive strength, the frost resistance was negatively affected by this addition.

Jannie S.J van Deventer et al. (2014) discussed a new blended system that aims to achieve a full cement replacement. The hybrid system contained equal amounts of blended slag and fly ash. These binders were mixed with an activator solution dose of 8 g Na_2SiO_3 per 100 g of anhydrous binders. Ordinary cement paste was also produced for comparison purposes. The hybrid system yielded positive results, where the achieved strength was comparable to that of the ordinary concrete.

Steiner et al. (2015) studied the integration of CWP, produced from polishing ceramic, into the concrete mix as a cement substitute. Using two polishing residues from different types of tiles, CWP was processed to obtain a final average particle size of 9 microns. The scope of the study covered the chemical and physical properties of the powder as well as the compressive strength, pozzolanic reactivity and thermal behavior due to the integration of the powder. Furthermore, an XRD analysis was conducted to indicate the presence of SiO_2 in the ceramic. The mortar compressive strength test indicated that replacing 20% of the cement by the polishing residue reduced the compressive strength by 10% at 28 days. The pozzolanic activity index was determined to be 85%, 101% and 104% at 28, 100 and 120 days, respectively, indicating an extremely low rate of strength enhancement in ceramic. The differential thermal analysis concluded that the CH content of the cement paste was estimated to be 4.7% by mass at 120 days. Integrating ceramic into the mix lowered the CH content to 2.18%, possibly due to the reaction between SiO_2 and CH and the formation of calcium silicate hydrate (CSH).

2.3 Studies involving CWP and BFS in concrete

Asiwaju-bello et al. (2012) studied the effect of using salty water to cure concrete. CWP was used to replace 5 to 30% of the cement content. The compressive strength of concrete specimens was tested at 7, 28, 56 and 90 days. Although no effect on the compressive strength was recorded after 28 days, using salty water led to an enhancement at early days. It was also noted that hydration was retarded due to the addition of CWP, while the salty water accelerated the curing rate ensuring a higher gain for both early and late strengths.

Heidari and Tavakoli (2013) investigated the usage of CWP incorporating nano-silica as a replacement of Type II cement, 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 compressive strength of concrete with CWP, as a partial replacement of cement, was studied. The percentage of replacement in the mixes varied from 10 to 40%. In the second phase, mixes with 10 to 25% replacement were studied. The objective was to enhance the compressive strength of the ceramic concrete by the further addition of nano silica particles. The proposed nano-silica addition in this phase replaced 0.5% and 1% of the cement content. Concrete cubes (150 x 150 x 150 mm) were prepared for both phases and were tested at 7, 28, 56 and 90 days. The results indicated that ceramic concrete yielded a similar compressive strength to that of the control batch at 90 days, whereas at early age a higher reduction in strength was recorded. In the second phase, nano silica-was used as an additive to concrete in an attempt to enhance the mechanical performance at early age. Furthermore, nano silica was very effective in improving strength that 10% ceramic with 1% nano-silica concrete achieved 110% of the strength of the control concrete.

In 2012, Vejmelkova et al. investigated the basic physical and mechanical characteristics, fracture-mechanics properties, durability characteristics and hydric and thermal properties of high-performance concrete with fine-ground ceramics replacing Portland cement of ratios up to 60%. The durability tests were conducted to assess frost resistance, thermal conductivity and water absorption of high strength concrete incorporating different percentages of fine-round ceramics. The addition of ceramics, up to 40% of the cement content, improved the frost resistance of concrete. Furthermore, a reduction in the thermal conductivity of the concrete was recorded due to this addition. Water absorption tests indicated a negligible effect when CWP was incorporated into the concrete mix. As for the mechanical testing, mixes with 10% cement replacement did not experience any drop in the compressive strength relative to the control mix. As for mixes with 20% replacement, 97% of the control strength was achieved at 28 days while a 24% drop in the 7-day strength was recorded. On the other hand, mixes with higher percentages of replacement recorded a significant reduction in strength at early and late stages. Lastly, CWP decreased the fracture energy and fracture toughness with respect to the control samples.

In 2013, Raval et al. studied the use of CWP, generated as a waste during the process of dressing and polishing ceramic tiles in the Indian ceramic industry, to replace part of the cement in the concrete industry. The study tackled the financial aspect of utilizing ceramics in the concrete mix as well as the mechanical behavior of the ceramic concrete. The ceramic content in the mixes varied between 10 and 50%. The addition of CWP had a negative impact on the compressive strength when it replaced 20% of the cement content. A 50% replacement of cement lead to a drop of 40% in concrete strength. On the contrary, replacing 20% and 50% of cement by CWP could save up to 8.45% and 21% of concrete cost per each cubic meter respectively.

Serkan et al. (2017) conducted a comprehensive testing of self-consolidating concrete including ceramic powders. Using a CWP fineness of 125 microns, which is more than two times larger than cement particles (45 microns), the fresh properties of ceramic concrete were studied by conducting slump flow, L-box, and J-ring tests. Furthermore, the mechanical properties of ceramic concrete were assessed through testing the compressive strength, splitting tensile strength, flexural strength and bond strength. The results indicated that with up to 15% replacement, an insignificant loss in both compressive and flexural strengths was recorded. However, concrete bond strength was negatively impacted by the inclusion of CWP into the concrete mix.

Samad et al. (2017) investigated the effect of partial replacement of cement with BFS on strength development of concrete. 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. In the second regime, winter curing was conducted and samples were sealed and stored at a temperature of 7°C. In the third regime, samples were immersed in a controlled water chamber at a temperature of 20°C. At early stages (1 to 5 days), slag concrete, with a partial cement replacement of 30%, yielded the highest compressive strength among the slag concrete mixes when summer and winter curing regimes were used. In addition, a 40% slag replacement of cement resulted in the highest compressive strength values at 7, 28 and 56 days. BFS plays a role in lowering the heat of hydration, delaying early day strength development. Furthermore, the aluminous and siliceous content in slag reacts with calcium hydroxide, in the presence of water, to form more calcium silicate hydrate (CSH), which is responsible for enhancing strength and other concrete properties. Although winter curing resulted in a higher drop in strength when compared to summer curing, the control concrete achieved the same compressive strength in both curing regimes at 56 days. Furthermore, BFS was more affected by the curing regime. At 56 days, BFS 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, BFS mixes at 28 days achieved 85% to 97% of the control strengths in winter regime and 98% to 104% in summer curing.

2.4 Recent study at AUB: Sustainable concrete incorporating ceramic hybrid binders

This study was conducted at the American University of Beirut in order to assess the pozzolanic activity of CWP and BFS and, more importantly, to investigate the effect of incorporating these materials into the concrete mix as cement substitutes. The study tackled several mechanical properties by testing the compressive strength, tensile strength, flexural capacity and modulus of elasticity of normal and high strength concrete mixes made with different replacement contents. Moreover, further testing was conducted to assess the thermal conductivity and durability of specimens exposed to freezing and thawing cycles.

The small-scale testing was divided into three phases. In the first phase, the percentage of CWP replacing cement was chosen to be 10, 15, or 20%. The choice of these percentage replacements was based on the results of the published literature that showed that the acceptable ceramic-range scheme lies between 10% and 20%. The testing plan in the second phase introduced the usage of BFS along with CWP in the concrete mix. The percentages of CWP replacement were similar to the ones used in the first phase. In the third phase, high strength concrete was made with a blended slag cement while varying the percentage of CWP replacement. Samples were generally tested at different time intervals (7, 28 and 56 days) to assess the effect of time on the mechanical properties of concrete. When assessing the pozzolanic activity of the powder, the tests indicated that CWP contains sufficient siliceous content to be considered a pozzolanic material. Reactions between the siliceous content and the available CH contributed in forming more CSH structures in the paste matrix. The results of the mechanical tests suggested that CWP contributed in reducing the compressive strength of the concrete, however a 10% level of replacement was still considered satisfactory with a reduction of around 12%. 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 cement/BFS/CWP. The split tensile test results revealed that the ceramic inclusion, up to 15%, yielded acceptable strength recording almost 90% of the control strength. Further, all hybrid cement/BFS/CWP concrete mixes with 10, 15, and 20% CWP replacements were considered satisfactory. The flexural strength results were in line with the split tensile strength results. As for the modulus of elasticity, all hybrid mixes recorded at least 90% of the control batch values at 56 days. On the other hand, durability tests indicated that CWP accelerates the deterioration of the concrete under freeze and thaw cycles, while the addition of BFS improves the resistivity of concrete. Finally, both CWP and BFS indicated low levels of thermal conductivity.

Overall, the obtained results suggested that the negative impact of CWP on the mechanical properties of concrete could be neutralized by the further addition of BFS. The research was triggered by the need to mitigate the negative environmental impact of cement production, as well as the need to recycle the waste of the ceramic industry. In other words, using less cement and more specified ceramic and slag contents in the concrete mix does not only achieve an acceptable performance, but also creates a new sustainable concrete material that has the potential of transforming the current concrete industry into a green practice. In order to assess the feasibility of using this new sustainable material in real life construction projects, it is essential to further test the behavior of normal and high strength full-scale reinforced concrete beams incorporating BFS and CWP.

2.5 Limitations addressed in Literature

Most of the studies that tackled the inclusion of ceramics in the concrete investigated the residue produced from the polishing process instead of grinding the entire tile material. This study aims to integrate the waste of the ceramic production process into the concrete mix. The used powder was processed by crushing ceramic tiles manually before sieving and using two machines to obtain a final fineness that is comparable to that of the cement particles. Recent worldwide awareness led to an unprecedented interest in sustainability concepts; hence, if the concrete industry is to develop new efficient methods to recycle wastes of other industries, several environmental benefits are expected to take place such as the preservation of natural resources and reducing air pollution.

Most of the studies that discussed the inclusion of ceramic to the concrete mix indicated an expected loss in the compressive strength of concrete, with the ceramic content being directly correlated to the reduction in strength in most cases. Only one of the studies in the reported literature suggested the further inclusion of a pozzolanic material in addition to ceramic. Nano-silica was introduced in order to amend the deficiency caused by ceramic on the concrete strength. As for this study, the further addition of a new pozzolanic material, such as BFS, was tested in an attempt to neutralize the expected loss in strength due to the ceramic inclusion.

Several ceramic sizes were used in the reported literature, where some studies tackled the using a powder of a finer size than cement (9 microns). However, most practical studies aimed to use a powder that passes N200 (75 microns) due to the high processing cost and energy required to obtain a finer particle size. A finer ceramic particle size allows more surface area to be available for hydration, which potentially contributes to a higher compressive strength. Since this study aims to test if BFS has the ability to neutralize the drop in strength caused by the inclusion of CWP, a final powder fineness less than 75 microns was considered satisfactory.

CHAPTER 3

TEST MATERIALS

3.1 Introduction

The experimental program in this study aims to extend the previous research conducted at the American University of Beirut. Although small-scale testing proved the efficiency of BFS in neutralizing the negative impact of CWP on the strength of concrete, it is essential to conduct further testing on large-scale high strength reinforced concrete beams to assess the feasibility of this replacement in real life construction projects. In compliance with sustainability criteria, CWP and BFS were used based on the optimal replacement percentages concluded in the previous research.

This chapter tackles the materials used in the testing program, including ceramics, cement and slag, as well as the mix design that was used for the high strength control concrete.

3.2 Test Materials

3.2.1 Ceramic

Ceramics are generally made by taking mixtures of clay, earthen elements, powders and water and shaping them into desired forms. Once the ceramic has been shaped, it is fired in a high temperature oven referred to as the kiln. Ceramics are usually covered decorative, waterproof, paint-like substances known as glazes. Ceramics are used in tiling, sanitary, and refractory works requiring specific properties, such as increased hardness and strong resistance against scratches, chemical attacks, and high temperatures. The most common two types are the porcelain ceramic, which is fully made from ceramics, and the Terracotta ceramic that contains clay with a thin layer of ceramic on top. The tiles used in this study were brought from a local source in Lebanon, where they were initially imported from Spain. Each ceramic box contained 1.215 m^3 of ceramics (Figure 3.1).

This study tackled the integration of ceramic wastes, with further supplements, into the concrete mix as a partial cement replacement. An acceptable concrete performance will encourage the recycling of ceramic wastes produced from construction and demolition. Furthermore, this new sustainable concrete material will contribute to mitigating the negative environmental impact of the cement production process. To achieve an effective replacement, where the drop in strength due to using ceramics is minimized, the powder must be of a comparable particle size to that of the cement. Hence, the ceramic tiles were processed through several stages in order to obtain the final powder. As shown in Figure 3.2, the tiles were first crushed manually using hammers before feeding them into the crushing machine shown in Figure 3.3. This crushing machine outputs particles that are smaller than ½ inch (12.5 mm), as shown in Figure 3.4. The resulting output is then sieved through sieve #4 before feeding it into the bico pulverizer (Figure 3.5). Precautious measurements must be taken when dealing with the pulverizer. The gap between the two grinding disks should be minimal to ensure a finer powder output. It is also recommended to use a maximum input size of 3/8 inches for the bico pulverizer machine in order to avoid harming the discs due to the stiff nature of the ceramic particles. Finally, the output of the bico pulverizer machine is sieved using sieve #200 in order to obtain a final powder of a comparable size to cement (Figure 3.6). Processing ceramic to lesser sizes requires significant amounts of energy and expensive sophisticated machines that are not available in the lab. Furthermore, the feasibility of using sieve #325 is a major concern since the processing output to input ratio is reduced significantly as compared to sieve #200. The physical and chemical properties of the processed CWP are shown in Table 3.1.

Table 3.1 Chemical and physical properties of CWP

CaO (%)	2.3
SiO_2 (%)	67.3
Al_2O_3 (%)	19.8
Fe_2O_3 (%)	2.5
MgO (%)	2.0
SO_3 (%)	0.1
Bulk specific gravity	2.65
Specific surface area (m^2/kg)	365
Porosity (%)	22.4

Figure 3.1 Ceramic box

Figure 3.2 Broken ceramic by hammer

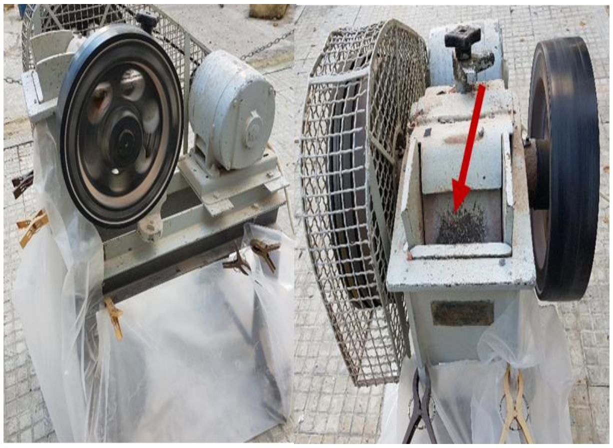


Figure 3.3 Crushing machine

Figure 3.4 Product of the crushing machine

Figure 3.5 Bico pulverizer machine

Figure 3.6 Pulverized ceramic powder

3.2.2 Slag

Slag is a pozzolanic material, typically composed of metal oxides and silicon dioxide, produced by cooling the molten by-product in the iron production process. The pozzolanic activity of a material indicates the presence of sufficient amounts of aluminous and siliceous, which, in the presence of water, react with calcium hydroxide to produce calcium silicate hydrate (CSH). Although the reaction is time consuming, the expected benefits at later stages include an enhancement in strength and reducing the permeability of concrete.

Since Lebanon imports iron and steel from other countries, slag is not easily available. Furthermore, slag is considered a waste by-product and importing it to Lebanon is banned due to the current waste management crisis in the country. Some cement manufacturing companies, however, have a permission to use this material. The slag material used in this study was obtained from Cimenterie Nationale, also referred to as Al Sabeh Cement, for research purposes. The used material was a blended slag/cement that composed of 40% slag and 60% cement. The purchased material was stored in the Civil Engineering Materials Laboratory at the American University of Beirut (Figure 3.7).

Different forms of slag can be produced depending on the method used to cool the molten slag. In general, the role of slag is to lower the heat of hydration of cement, causing a drop in the early stage compressive strength and an enhancement at later stages. While ACI standards require a granulated slag size similar to that of the cement, European standards require a finer particle size for slag. The physical and chemical properties of the used BFS are shown in Table 3.2.

Table 3.2 Chemical and physical properties of BFS

CaO (%)	42.1
SiO_2 (%)	32.6
Al_2O_3 (%)	12.2
Fe_2O_3 (%)	0.55
MgO (%)	5.45
SO_3 (%)	4.0
Bulk specific gravity	2.60

Specific surface area (m^2/kg)	770
Porosity (%)	18.3
Loss on ignition (%)	2

Figure 3.7 Blended slag bags

3.2.3 Cement

Type I cement (P-AL 42.5) was brought from Holcim plant, located in Chekka, and used by Nakhle Zgheib & Co, where the concrete mixing took place. The used cement conforms to EN 197 European norms (CEM II /A-L) and to Lebanese standards (LIBNOR). The physical and chemical properties of the used cement are shown in Table 3.3.

Table 3.3 Chemical and physical properties of cement

CaO (%)	66.6
SiO_2 (%)	21.5
Al_2O_3 (%)	4.6
Fe_2O_3 (%)	2.8
MgO (%)	1.2
SO_3 (%)	2.7
Bulk specific gravity	3.15
Specific surface area (m^2/kg)	515
Porosity (%)	4.3
Loss on ignition (%)	3

3.3 Concrete Mix Design

The requested mix design specified that high strength concrete be used. It was also requested to avoid using any pozzolanic supplements, such as silica fume, since slag will be used in some of the mixes. Since the study aims to understand the structural effect of slag on ceramic concrete, the further addition of another pozzolanic material to the mix will complicate understanding the individual effect of each material on the strength.

In general, following an appropriate mix design is essential for achieving the desired concrete properties. The mix design of the control mix at saturated surface dry (SSD) conditions is shown in Table 3.4. With the exception of cement, all other constituents were maintained in the mixes incorporating CWP and BFS. Further details regarding the mixes and replacement contents will be discussed in Chapter 4. The following criteria and assumptions were implemented while designing the high strength concrete mix:

1. Intended concrete compressive strength of 70 MPa
2. Slump of 150 to 175 mm
3. Maximum aggregate size of 20 mm
4. Minimum cement content of 450 kg/m^3
5. Dry bulk specific gravity of course aggregates: 2.68
6. Dry bulk specific gravity of fine aggregates: 2.68
7. Fineness Modulus of sand: 2.45

Table 3.4 Mix proportions of the control batch at SSD

Material	SSD Weight	% of total aggregates	SSD S.G.	Volume (m^3/1000)
Cement (kg/m^3)	480		3.20	150
Free water (kg/m^3)	129		1.00	129
Admixture (kg/m^3) 1.5%	15.4		1.20	12.8
Natural sand (kg/m^3)	521	28.93%	2.59	201
Crushed sand (kg/m^3)	280	15.58%	2.56	109.5
Aggregates (4.75 – 9.5 mm) (kg/m^3)	400	22.20%	2.68	149.1
Aggregates (9.5 – 19 mm) (kg/m^3)	599	33.30%	2.68	223.7
Air content				25
Total	2424	100.00%		1000.1

CHAPTER 4

EXPERIMENTAL PROGRAM

4.1 Program Scope

Full-scale testing is an essential step in order to assess the structural feasibility of using the new sustainable concrete material in real life construction projects. Four high strength concrete mixes, including a control batch, were tested in the laboratory. For each mix, three reinforced concrete beams were tested in addition to several concrete cylinders. Beams were tested to fail in flexure, shear or bond splitting modes using an MTS machine. Furthermore, the compressive strength of each mix was recorded at 7, 28 and 56 days through testing standard 150x300 mm (6x12 in.) cylinders.

4.2 Concrete Mix Variables

In order to evaluate the effect of BFS on ceramic concrete, four mixes of high strength concrete were tested while varying cement, ceramic powder, and slag contents. Material contents of the mixes are listed in Table 4.1. Mix 1, the control mix, was designed as specified in Table 3.4 of Chapter 3 to attain an intended 28-days concrete compressive strength of 55 MPa. In Mix 2, 10% by weight of the cement content was replaced by the processed CWP. The second mix aimed to check whether the inclusion of CWP into the concrete mix, which reduces the concrete strength, would also contribute negatively to the behavior of reinforced concrete beams. As for Mix 3, blended slag cement, consisting of 40% slag and 60% cement, was used with no CWP content. This mix should typically yield relatively higher ultimate concrete strength, since the pozzolanic material is present in high contents. Finally, 10% of the blended slag cement content was replaced in Mix 4 with CWP, resulting in the contents identified in Table 4.1. This last mix aimed to test whether the expected negative impact of CWP on concrete strength and reinforced concrete behavior could be neutralized by adding BFS. Although the concrete strength of Mix 4 is not supposed to be as high as that of Mix 3, achieving the control's strength is considered satisfactory, as the negative effect of ceramic would be then completely neutralized.

Table 4.1 Identification and content of the mixes

Mix	Mix ID*	C (%)	CWP (%)	BFS (%)
Mix 1 (Control Mix)	H-C	100	0	0
Mix 2	H-C/CWP	90	10	0
Mix 3	H-C/BFS	60	0	40
Mix 4	H-C/BFS/CWP	54	10	36

*N: High strength concrete; C: Cement; CWP: Ceramic waste powder; BFS: Blast furnace slag

4.3 Testing Plan

4.3.1. Concrete Compressive Strength Test

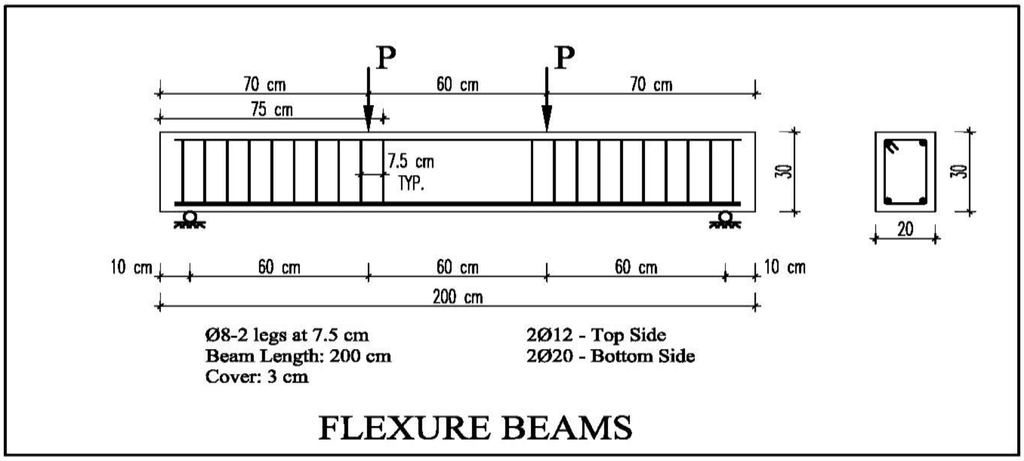
The concrete compressive strength of each mix was determined through testing 150x300 mm (6x12 in.) standard cylindrical specimens in accordance with ASTM C39 (reference year). In the test, a compressive axial load is applied to the specimen at a rate of 1.25 mm/min until failure occurs. It is essential that the cylinders be capped with sulfur, as specified per ASTM C617 (reference year), before testing to allow uniform load distribution along the surface. The compressive strength is then determined by dividing the maximum sustained load by the cross-sectional area of the cylinder. Four replicates were tested at 28 days while three replicates were tested at 7 and 56 days each. The final values were then determined based on the averages of the tested specimen. The cylindrical molds used for concrete casting are shown in Figure 4.1, while the cast cylinders are shown in Figure 4.2.

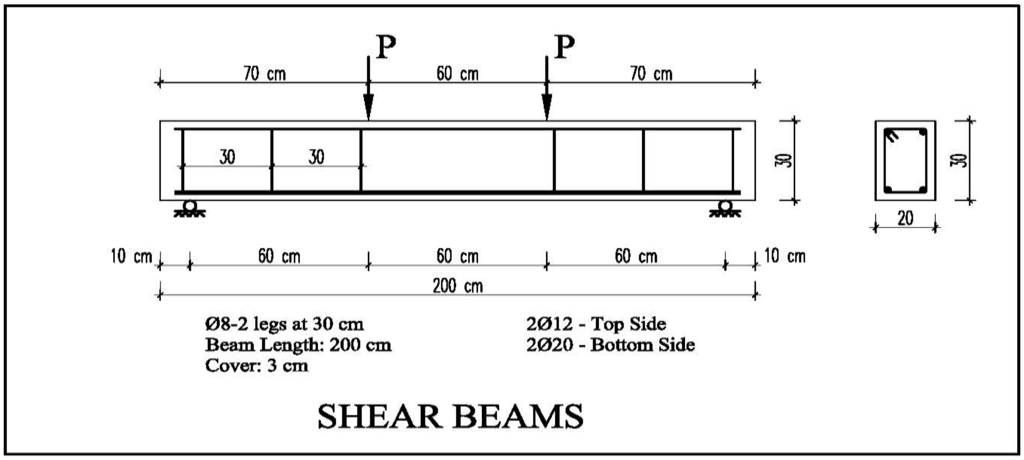
Figure 4.1 Cylindrical molds prior to concrete casting

Figure 4.2 Cast concrete cylinders

4.3.2 Full-Scale Beams

Twelve reinforced concrete beams were fabricated and tested to fail in flexure, shear, or bond splitting modes using the MTS machine. Each set of four beams was designed to fail in one mode, with each of the four batched with one of the four mixes identified in Table 4.1 above. The beams failing in flexure mode are referred to as Flexure beams, those failing in shear are called Shear beams, and those failing in bond splitting of the concrete cover are called Bond beams. As shown in Figure 4.3, the reinforced beams are 200x20x30 cm. The longitudinal reinforcement for the Flexure and Shear beams consisted of two 20 mm reinforcing bars on the bottom side and two 12 mm reinforcing bars on the top. The top side of the Bond beams was similarly reinforced with two 12 mm reinforcing bars, while the bottom 20 mm bars were spliced 305 mm at mid span. The splice length was shorter than what is required by the ACI Building Code (ACI 318-14) to ensure bond-splitting failure. Vertical stirrups, 8 mm in diameter, were applied at a spacing of 7.5 cm in the Flexure and Bond beams in order to avoid shear failure in these modes. As for the Shear beams, stirrups of the same diameter were applied insufficiently, at a spacing of 30 cm, to allow shear failure to occur. All bars were Grade 60 satisfying ASTM A615M. Coupons of each bar size were tested in the lab. The test results for yield strength, ultimate strength, and percentage elongation at rupture are listed in Table 4.2. Steel cages were prepared accordingly as shown in Figure 4.4. Prior to batching, the steel cages were placed in the wood forms. The forms were manufactured to have an inner length of 200 cm and an inner cross section of 20x30 cm. Furthermore, plastic spacers were installed between the steel cages and the form sides in order to guarantee side and bottom covers of 3 cm.





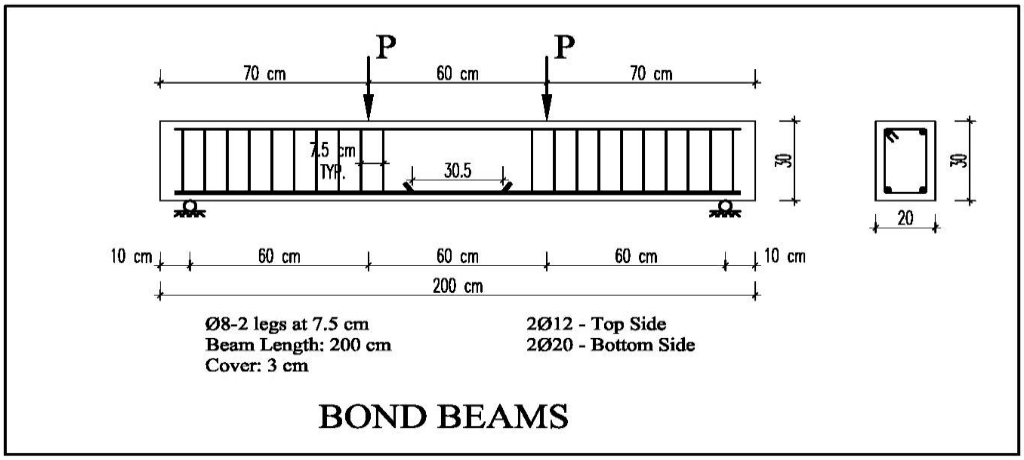


Figure 4.3 Structural detailing of the tested reinforced concrete beams

Table 4.2 Steel bar properties

Bar size (mm)	Yield strength (MPa)	Ultimate strength (MPa)	Elongation at rupture (%)
20	585	715	12.75

Figure 4.4 Steel cages preparation

The materials were mixed in the batching machine used in the ready-mix plant and then transported, using mixing trucks, to the Civil Engineering Materials Laboratory at the American University of Beirut. After casting the beams and accompanying cylinders, a vibrator was used to proper consolidation of concrete inside the forms. The final view of the fresh cast beams is shown in Figure 4.5. The sides of the wooden forms were stripped off the beams three days after casting and wet burlaps were then used to cover the beams. The burlaps were sprayed with water on a daily basis until the age of 28 days, when testing took place. A comprehensive view of the concrete beams prior to testing is shown in Figure

4.6.

Figure 4.5 Concrete beams post casting

Figure 4.6 Concrete samples prior to testing

An MTS machine was used to test the reinforced concrete beams. The centerlines of the supports were 1800 mm apart. Two concentrated loads, each one being 600 mm away from the adjacent support, were applied continuously while crack propagations were monitored and recorded until failure. The vertical deflection at mid-span was monitored at each load increment using an LVDT sensor. A schematic view for the test setup is shown in Figure 4.7 and the actual test setup is shown in Figure 4.8.

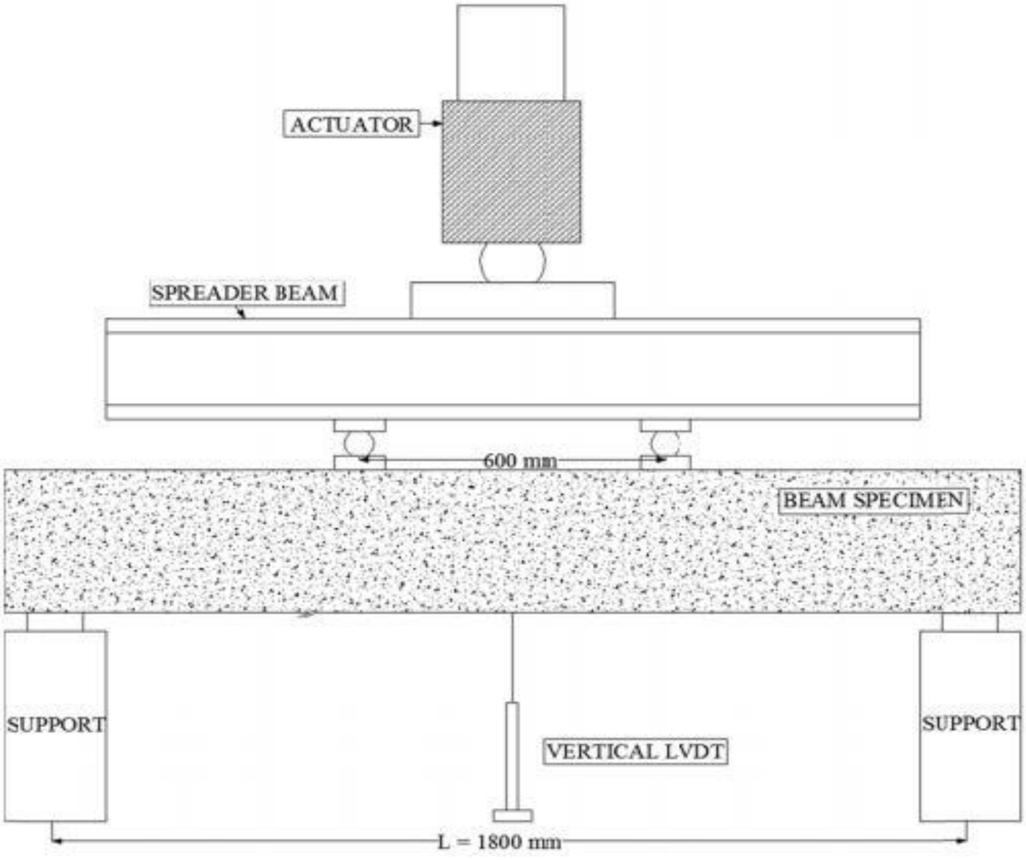


Figure 4.7 Schematic diagram of the test setup

Figure 4.8 Actual beam test setup

CHAPTER 5

CONCRETE TESTING RESULTS

5.1 Introduction

This chapter tackles the structural behavior of reinforced concrete beams prepared by replacing different percentages of cement with BFS and/or CWP. The compressive strength values of the different mixes at 7, 28, and 56 days are studied. It is essential to understand the individual and combined effect of BFS and CWP on the cylinder compressive strength at different stages. The following sections summarize the experimental results of the reinforced concrete beams, which were designed to fail in flexure, shear, or bond splitting modes. Furthermore, the obtained results are compared to the theoretical values computed values using the ACI Building Code. The effect of the proposed cement replacement is assessed by comparing crack patterns, ultimate load capacities, and load deflection behaviors.

For each set of beams with a given mode of failure, test results are displayed in a separate Table (refer to Tables 5.2, 5.3, and 5.4). The data includes the values of the ultimate load reached P_{max}, load ratio or the ratio of ultimate load of the beam relative to the control beam N-C, beam mid-span deflection Δ_{max} at P_{max}, ultimate load as per the ACI code P_{ACI}, P_{max}/P_{ACI}, deflection ductility index, fracture energy, and energy ductility index. The deflection ductility index is defined as the ratio of the beam mid-span deflection $\Delta_{0.9}$ at $0.9P_{max}$ or $P_{0.9}$ to the mid-span deflection Δ_{max} at P_{max}. The fracture energy is defined as the area under the load-deflection curve for a mid-span deflection ranging between 0 and $\Delta_{0.9}$

for the Flexure and Shear beams, and between 0 and Δ_{max} for the Bond beams. Figure 5.1 is a schematic load-deflection diagram used to define $\Delta_{0.9}$, Δ_{max}, and the fracture energy. The energy ductility index is defined as the ratio of the beam fracture energy to the fracture energy of the control beam.

This schematic diagram is only applicable for shear and flexure beams where Δ0.9 is much easier to be located. Unlike bond beams where sharp drop in beam capacity due to brittle failure prevented us from locating Δ0.9.

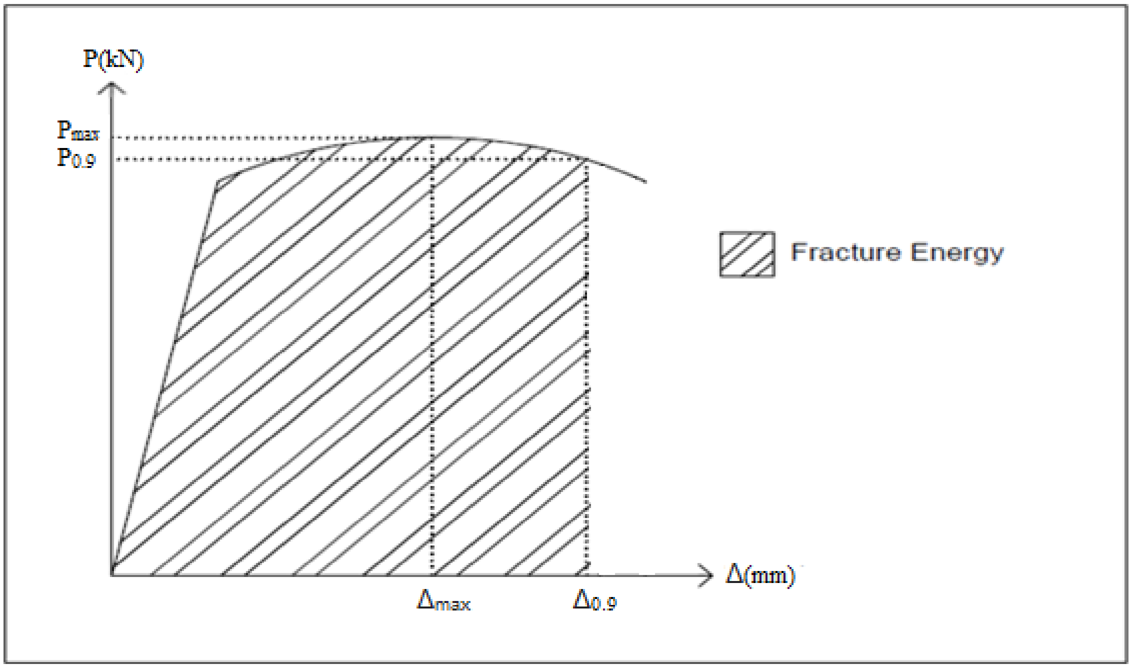


Figure 5.1 Schematic load-deflection diagram for flexure and shear beams

5.2 Compressive Strength Results

Concrete cylinder samples were tested at 7, 28 and 56 days in accordance with ASTM C39. Several samples were tested at each phase, summing up to six samples per mix, to avoid any testing errors. Table 5.1 presents the compressive strength values of the various mixes at specified stages. The final values were obtained by averaging the results of the replicates of each conducted test. The extended results of all the tested cylinders are available in the appendix. On the other hand, the variation of the compressive strength of the different mixes from the corresponding control's compressive strength values with time is illustrated in Figure 5.2.

Table 5.1 Average cylinder compressive strength at 7, 28 and 56 days

Testing date	H-C (MPa)	H-C/CWP (MPa)	H-C/BFS (MPa)	H-C/BFS/CWP (MPa)
7 days	55.56	52.92	59.55	57.85
28 days	71.25	67.45	73.55	72
56 days	74	70	77	75

*Percentages in parenthesis represent the increase or reduction relative to the control mix at each stage

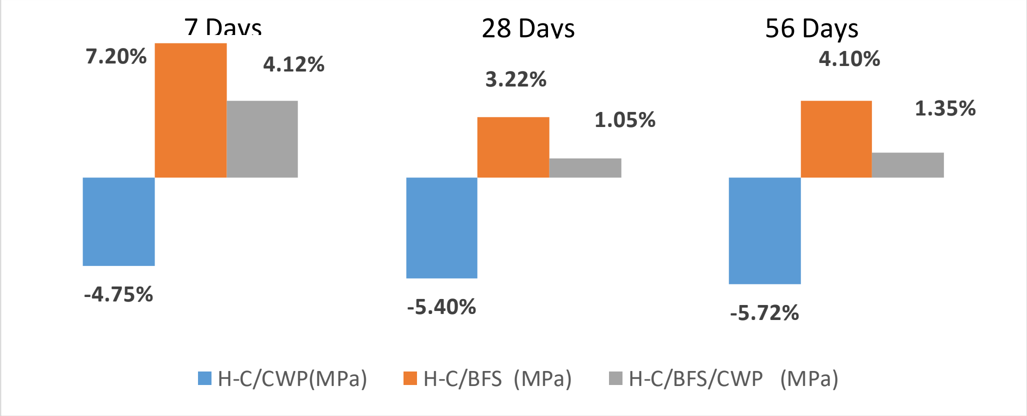


Figure 5.2 Compressive strength variation relative to the control mix

The H-C/CWP cylinders were batched by replacing 10% of the cement content by CWP. As shown in Figure 5.2, this replacement resulted in a slight drop in strength at all stages. While the 7-days strength was reduced by 4.75%, the 28-day and 56-day compressive strengths were respectively 5.4% and 5.72% less than the control's strength. The consistent reduction in strength recorded in H-C/CWP, as compared to the control batch, at all stages confirms the negative impact of CWP on the concrete strength. It is essential to mention that the processed powder fineness was less than 75 microns, as compared to cement where 95% of the particles are less than 45 microns in size. In H-C/BFS, the cement content was fully replaced with blended slag, composed of 40% BFS and 60% Portland cement, without any addition of CWP. As shown in Figure 5.2, the 7-day strength was increased by 7.2% while a 3.22% and 4.1% increase in compressive strengths was recorded at 28 and 56 days respectively. Enhancement at 7, 28, and 56 days can be explained by the significant presence of BFS in the mix. Silica, available in slag, reacts with calcium hydroxide in the presence of water while consuming CH and producing CSH structures in the paste matrix. The newly formed CSH contributes to the enhancement in strength as well as other properties. In H-C/BFS/CWP, the objective was to test whether the negative impact of CWP on concrete strength can be neutralized by the further addition of BFS. The 7-day strength of the hybrid mix was increased by 4.12% as compared to the control mix. On the other hand, the slag addition resulted in an almost complete neutralization of the strength drop at 28 days. While the compressive strength of H-C/CWP was reduced by 5.4% as compared to the control mix, the hybrid mix was able to achieve a compressive strength that is only 1.05% more than the control mix. Furthermore, the integration of BFS into ceramic concrete successfully enhanced the strength by 1.35% at 56 days. Since the reaction between BFS and calcium hydroxide is time consuming, the strength enhancement is typically expected at later stages while the drop of the 7-day strength is also expected.

When comparing the obtained compressive strength results to the recent study previously by Al Arab (2018); Al Arab et al. (2020); Al Arab et al. (2022), a similar pattern can be recognized. The compatibility of the concrete performance in both scales confirms the validity of the main hypothesis through the obtained results; the further addition of BFS to ceramic concrete successfully neutralized the negative impact of CWP on the compressive strength. While the full-scale compressive strength results support the main hypothesis, the structural feasibility of this new sustainable material should be further assessed through testing concrete beams to fail in several modes.

As mentioned earlier, the recent study conducted Al Arab (2018) only tackled small-scale concrete testing. Several mixes were tested while varying the ceramic content between 10 and 20%. At 28 days, the mix with 10% CWP and no BFS contents yielded a 12.41% reduction in the compressive strength as compared to the control mix. On the other hand, a 1.96% enhancement in the compressive strength was recorded when blended slag, composed of 40% BFS and 60% cement, was used. As for the hybrid mix, the achieved compressive strength was reduced by 4.9%, indicating that the further addition of BFS to ceramic concrete partially neutralized the negative impact of CWP. Figure 5.3 highlights the compatibility of the compressive strength testing results in both testing scales. Although a similar behavior can be noticed, the efficiency of BFS is more evident in full-scale testing as a better enhancement was recorded when using blended slag H-C/BFS. Furthermore, the hybrid mix, referred to as H-C/BFS/CWP, in full-scale testing recorded a better neutralization of the negative impact of CWP on the compressive strength. While only a slight increase of 1.05% was recorded in full-scale testing, the small-scale testing yielded a

4.9% reduction in the compressive strength.

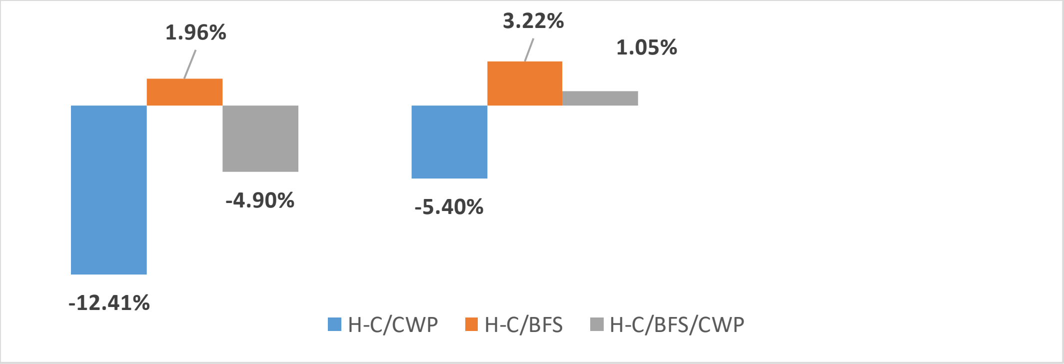


Figure 5. 3 Compressive strength scale variation relative to the control mix at 28days.

5.3 Flexure Beams

In the Flexure beams, cracks originated from the tension zone when the subjected loading exceeds the concrete tensile capacity. As the loading increases, cracks propagate throughout the beam until the ultimate failure occurs at mid-span.

5.3.1 Crack Pattern

A view of the cracked flexural beams is shown in Figure 5.5. The figure displays the recorded cracks for the flexural beams corresponding to the different mixes. Two types of cracks were monitored throughout the beams: Flexure and shear cracks. Flexure cracks typically originate from the tensile zone and propagate vertically until failure is reached, assuming the shear reinforcement is sufficient. On the other hand, shear cracks originate nearer to the supports, where the maximum shear stresses are present, and propagate diagonally due to combined effects of bending and shearing. It is essential to mention that the loads studied in this section represent the individual values for each applied concentrated load.

The first crack in all beams initiated in the tension zone at loads approximately between 30 and 40kN. Due to the overdesigned shear reinforcement, with stirrups at a spacing of 7.5 cm, no major shear cracks were detected in the beams. Furthermore, minor shear cracks occurred near the supports at loads around 115, 125, and 135 reaching 145kN are shown in Figure 5.5.

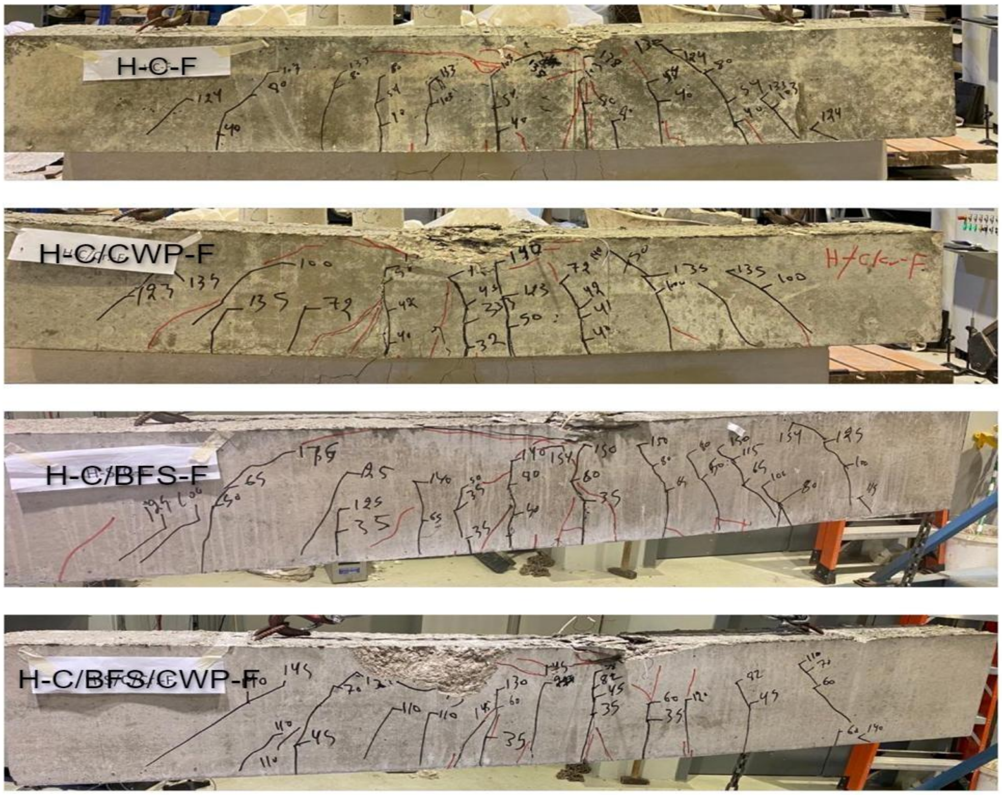


Figure 5.3 Cracked Flexure beams

5.3.2 Test Results and Load-Deflection Behavior

Test results of the Flexure beams are shown in Table 5.2 and the load deflection curves are shown in Figure 5.4. While the control beam was able to sustain a total ultimate load of 140kN, an expected strength reduction was recorded in H-C/CWP-F due to the inclusion of CWP. H-C/CWP-F achieved a total ultimate load of 137.8kN, recording a 1.7% reduction in strength when compared to the control's capacity. Due to the integration of BFS into concrete, H-C/BFS recorded the highest capacity among the tested mixes. The tested beam sustained a total ultimate load of 153.7kN, recording a 12% enhancement in strength as compared to the control's capacity. The hybrid mix, H-C/BFS/CWP-F, sustained a total ultimate load of 145.5kN, recording an improvement of 6% as compared to the control's capacity. The obtained results indicated that the further addition of BFS to ceramic concrete not only neutralized the negative impact of CWP, but also resulted in a better flexural performance when compared to the conventional control concrete. In other words, the strength enhancement in H-C/BFS/CWP-F, the hybrid mix, successfully overcame the initial negative impact, resembled by the drop in strength from the control mix to H-C/CWP-F, of CWP on the concrete. The curves corresponding to the flexure beams (Figure 5.4) indicate a strongly similar load-deflection behavior among the mixes, with variations in the achieved ultimate load for each mix. Furthermore, Table 5.2 displays the ultimate loads and their ratios to the control's ultimate load in addition to the corresponding mid-span deflection as well as different energy and ductility indices.

The experimental values of Pmax were compared to the theoretical flexure strength values calculated according to the ACI Building Code (ACI 318-14) using Equation 1 and 2:

$M_n = (\frac{As}{fy})(d - \frac{a}{2})$ Equation 1

$P_{ACI} = Mn/0.6$ Equation 2

Where Mn is the nominal capacity of the flexure beam in (kN.m), As is the area of longitudinal reinforcement in mm, fy is the yielding stress of rebar taken as 575MPa, d is the effective depth in mm, and a is based on section properties of the beam in mm. PACI is the load capacity of the beam referring to ACI 318-14 in kN.

The ratio of the experimental to theoretical value (Pmax/PACI) decreased from 0.89 in control beam to 0.88 in specimen including 10% CWP. Inclusion of BFS increases the ratio to 0.98 and 0.93 in the hybrid mix. This validates the hypothesis on the effect of BFS to neutralize the drop on load capacity caused by adding 10% CWP.

Deflection ductility index relative to control beam H-C-F shows 1.11, 1.07, 1.2, and 1.17 for H-C-F, H-C/CWP-F, H-C/BFS-F, and H-C/BFS/CWP-F respectively.

Fracture energy, which is defined as the area under load-deflection curve corresponding to 0.9Pmax and its corresponding indices relative to control beam, shown in table 5.2, shows the highest value of 2350kN.mm in H-C/BFS-F , 2250kN.mm, 2100kN.mm, and 2150kN.mm for H-C/BFS/CWP-F, H-C/CWP-F, and H-C-F respectively.

Table 5.2 Test results of the flexure beams

Specimen notation	**f'c (MPa)**	**Pmax (kN)**	**Load Ratio**	**Δmax (mm)**	**Paci (KN)**	**Pmax/PACI**	**Deflection Ductility index (DI)**	**Fracture Energy (kN.mm)**	**Energy Ductility Index (EDI)**
H-C-F	71.25	140	……	15.54	156.03	0.89	1.11	2150	--
H-C/CWP-F	67.45	137.8	0.983	16.63	155.5	0.88	1.07	2100	0.98
H-C/BFS-F	73.55	153.7	1.09	18.19	156.3	0.98	1.2	2350	1.10
H-C/BFS/CWP-F	72	145.5	1.03	23.45	156.1	0.93	1.17	2250	1.04

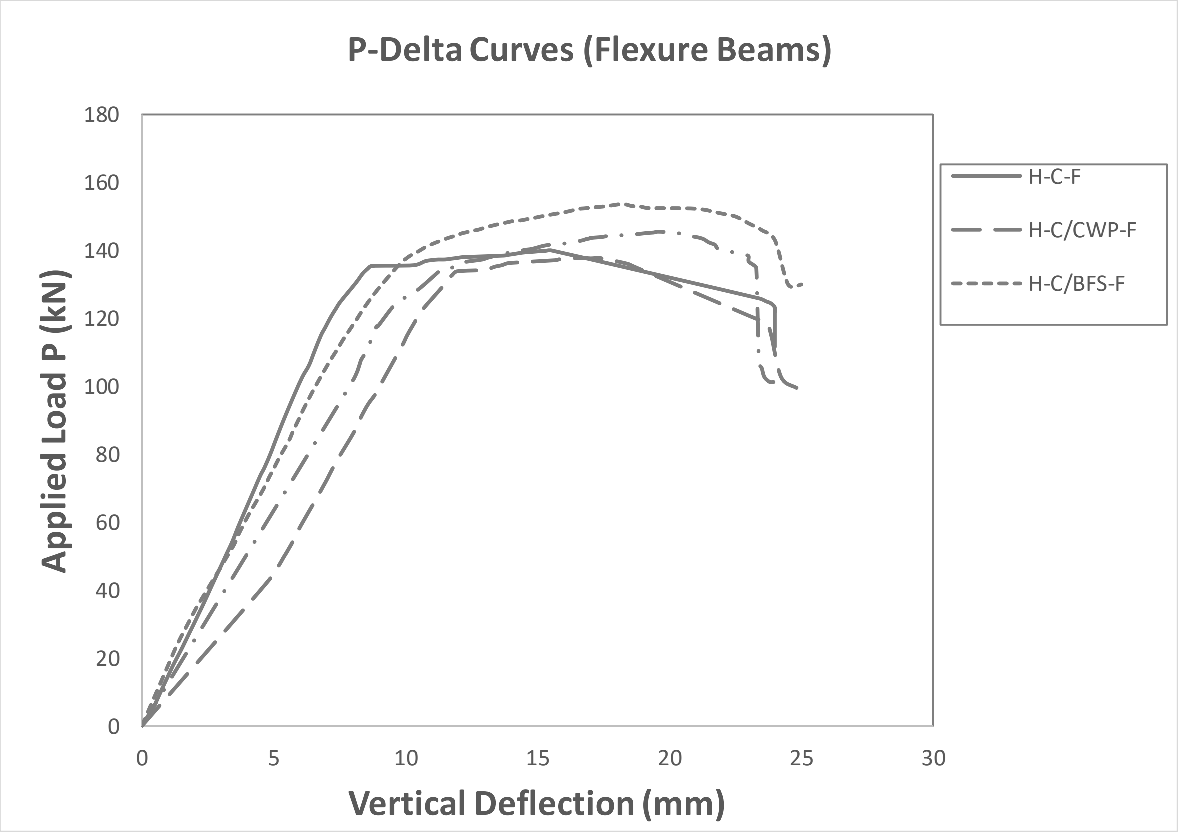


Figure 5.4 Load deflection curves for the Flexure beams

Load-deflection curves shown in Figure 5.4 indicate that whereas the incorporation of CWP in the concrete mix resulted in lower stiffness as compared with the control beam, substituting 40% of cement with BFS led to increase in the load-deflection stiffness. The beam with CWP and BFS (H-C/BFS/CWP) had similar stiffness to the control beam but reached higher ultimate load. The inclusion of BFS in the beam with CWP helped reducing the negative effect of CWP on the load-deflection behavior.

5.4 Shear Beams

Shear cracks typically originate near the supports due to the increased shear stresses. The shear reinforcement of the tested beams was designed inadequately, allowing this mode of failure to prevail.

5.4.1 Crack Pattern

A view of the cracked Shear beams is shown in Figure 5.7. Flexural and shear cracks were recorded in the beams. As mentioned earlier, these beams were intentionally under-designed with stirrups, using a spacing of 30 cm, in order to allow shear failure to prevail. As expected, much less flexural cracks developed in these beams in comparison to the previously investigated Flexure beams.

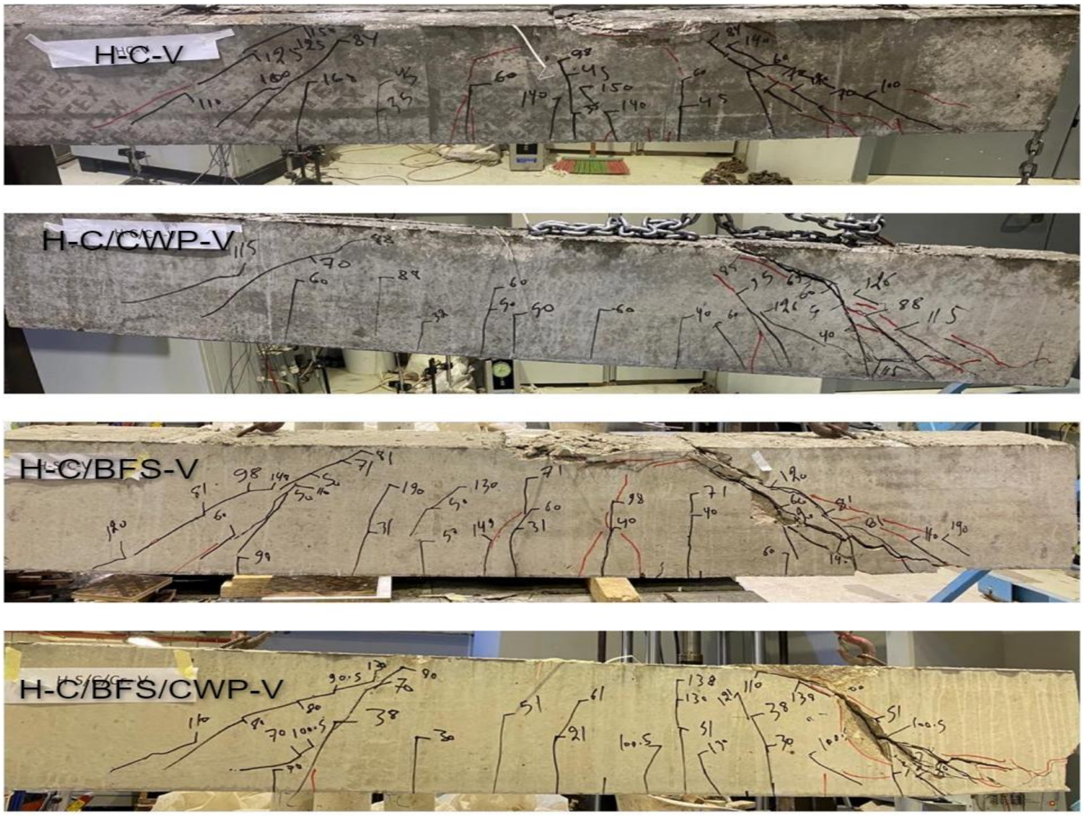


Figure 5.5 Cracked Shear beams

As shown in Figure 24, the first cracks occurred in the flexure zone at loads between 20 and 80kN. As the load increased, shear cracks started to appear close to the support and propagate diagonally. The major shear cracks originated at loads of approximately 100, 115, 110, and 100kN for the control, the 10% CWP replacement, the 100% blended slag replacement, and the hybrid replacement beams, respectively. The propagation of the diagonal shear cracks was similar for all shear beams in terms of starting point and angle of propagation.

5.4.2 Test Results and Load-Deflection Behavior

Test results are listed in table 5.3 and load deflection behavior are shown in figure 5.6.While the conventional concrete sustained a total ultimate load of 150kN, replacing 10% of the cement with CWP reduced the capacity by 14.7% and recorded a total ultimate load of 128.05kN. While this reduction is expected due to the addition of the CWP, the objective is to neutralize this drop in strength when both BFS and CWP are integrated in H-C/BFS/CWP-V. H-C/BFS-V recorded an ultimate load 155.5kN, marking a capacity greater than the control mix by 3.6%. Finally, H-C/BFS/CWP-V recorded a total ultimate load of 150.05kN, with a value similar to the control mix. Inclusion of hybrid material consisting of BFS and CWP perfectly overcame the reduction in ultimate capacity recorded by H-C/CWP-V.

The corresponding load-deflection curves are displayed in Figure 5.6. While a similar load-deflection behavior is noticed among three of the mixes, the significant ultimate load enhancement in H-C/BFS is also evident. Furthermore, Table 5.3 presents the ultimate loads and their ratios to the control's ultimate load as well as the corresponding mid-span deflections and different ductility indices as well as fracture energy in kN.mm.

Table 5.3 Test results of the shear beams

Specimen notation	**f'c (MPa)**	**Pmax (kN)**	**Load Ratio**	**Δmax (mm)**	**Paci (Kn)**	**Pmax/Paci**	**Deflection Ductility index (DI)**	**Fracture Energy (kN.mm)**	**Energy Ductility Index (EDI)**
H-C-V	71.25	150	--	19.02	72.02	2.08	1.11	1938.87	--
H-C/CWP-V	67.45	128.1	0.853	13.74	70.1	1.83	1.02	1400	0.72
H-C/BFS-V	73.55	155.5	1.036	18.5	73.2	2.12	1.2	2300	1.18
H-C/BFS/CWP-V	72	150.1	1	16.7	72.4	2.07	1.10	1941.25	1.00

Furthermore, the experimental values of P_{max} were compared to the theoretical shear strength values calculated according to the ACI Building Code (ACI 318-14) using Equation 3:

$$V_{ACI} = \left[0.17 \times \sqrt{f_c'} \times b_w \times d\right], \text{ and } V_{ACI} = P_{ACI} \quad \text{Equation 3}$$

Where f'_c is the concrete compressive strength in MPa, b_w is the beam width in mm, and d is the effective depth in mm.

To know the effect of BFS and CWP on the behavior of shear beams, (Pmax/Paci) was computed for different replicates, H-C-V, which is the control mix, recorded a value of 2.08. As expected, the ratio dropped in H-C/CWP-V to 1.83, increased to 2.12 in H-C/BFS-V, and recorded a similar value in H-C/BFS/CWP-V compared to control mix, which is 2.07. DI, which is the deflection ductility index relative to H-C-V, indicates 1.11, 1.02, 1.2, and 1.1 for different replicates shown in table 5.3. As expected, integration of BFS improves the ability of reinforced concrete beams to undergo considerable deflection prior to failure under maximum applied load whereas; addition of CWP decreases the yield plateau, in other words, CWP shows inability and weakness to provide a ductile behavior in reinforced concrete beams. A better ductility was expected in hybrid mix H-C/BFS/CWP-F, this proves the hypothesis of the ability of BFS to overcome the negative effect resulting from CWP on different characteristics studied in this project.

Fracture energy and its corresponding indices listed in table mentioned before varies between 1400kN.mm and 2300kN.mm, as well as EDI, which recorded the highest value of 1.18 in H-C/BFS-V, decreases to 1 in H-C/BFS/CWP-V, and 0.72 in H-C/CWP-V.

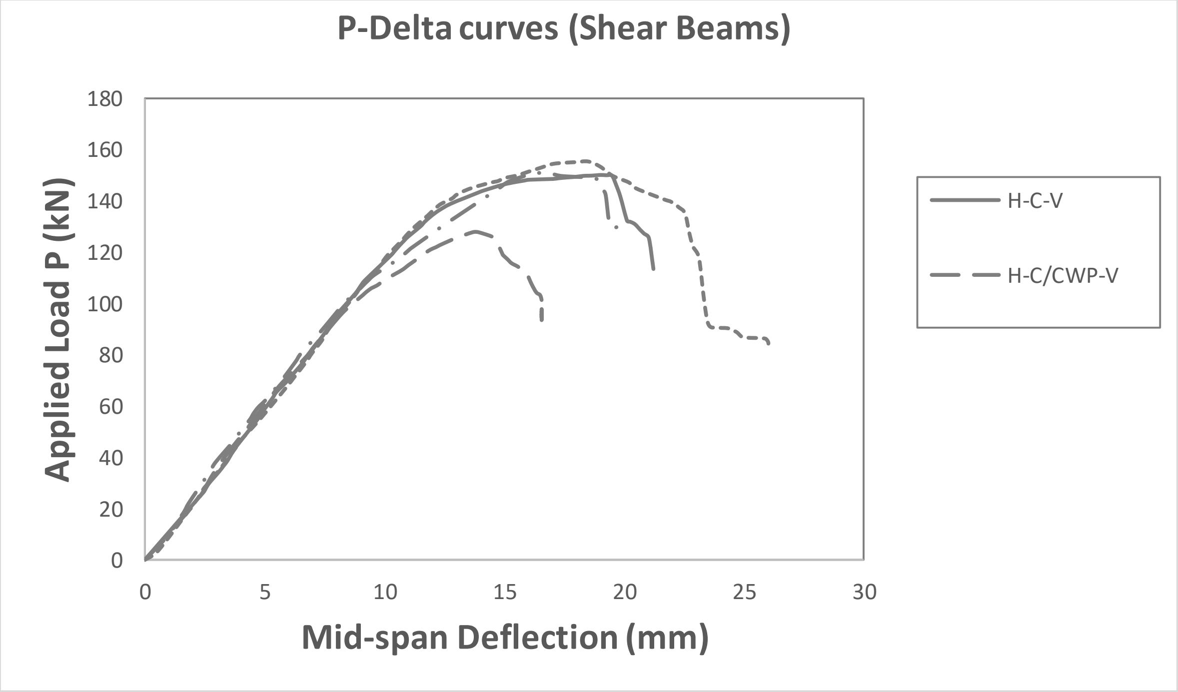


Figure 5.6 Load deflection curves for shear beams

5.5 Bond Beams

Bond beams were designed to fail in bond splitting modes in the splice region at mid-span by having a splice length less than what is required by the ACI Building Code.

5.5.1 Crack Pattern

A view of the cracked bond beams is shown in Figure 5.9. The first cracks occurred at loads approximately between 25 and 55kN. On the other hand, two minor diagonal cracks occurred at a loads of 75 and 87kN H-C/BFS-B, but the propagation of this shear crack did not continue beyond this value. In all beams, failure occurred when splitting of the side and bottom face concrete covers spread along the entire splice length of the tensile bars. Figure 6 provides a closer view of the bottom side of the cracked splice region H-C/BFS-B showing complete spalling of the concrete cover in the splice region.Moreover, the view of the bottom side of the splice regions is available in the appendix.

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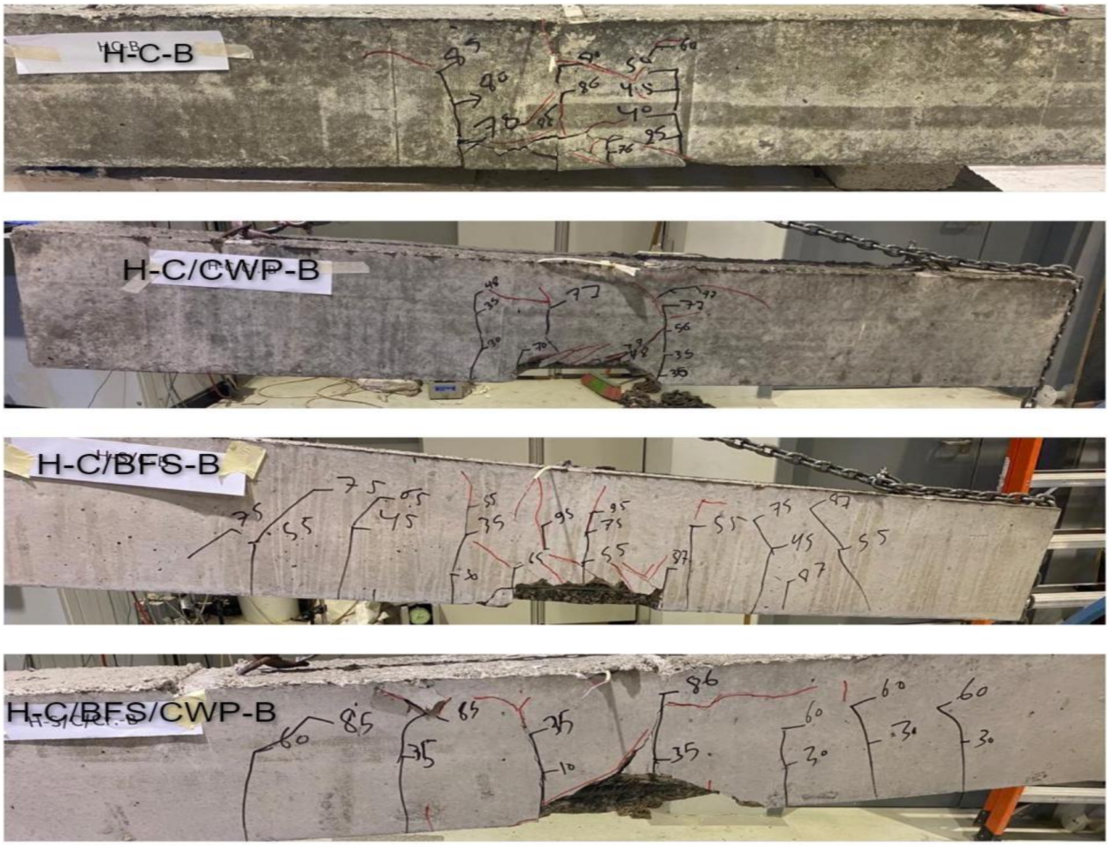

Figure 5.7 Cracked bond beams

Figure 5.8 Failed splice region for beam N-C/BFS

5.5.2 Test Results and Load-Deflection Behavior

Test results for the Bond beams are listed in table 5.4 and the load-deflection curves are shown in figure 5.8.The control mix with conventional concrete sustained a maximum total load of 86.5kN. Replacing 10% of the cement by CWP resulted in a 10.8% drop in the ultimate load recording 77.2kN. The beam corresponding to H-C/BFS-B, with full blended slag replacement, sustained a total ultimate load of 95.1 kN, which is 9.9% more than the control's ultimate load. Finally, the hybrid mix recorded a relatively similar total ultimate load, when compared to control mix, of 86.75kN. Furthermore, the sharp drop in loading shown in Figure 5.8 suggests a brittle behavior for the failure of bond beams, unlike the evident ductile failure recorded for flexural and shear beams. Table 5.4 displays the recorded ultimate loads in addition to the corresponding mid-span deflections for the bond beams. The mid-span deflections at ultimate loads ranged from 6.73 to 11.06 mm. The small deflection values are correlated to the brittle failure in bond beams as compared to the ductile failure in both flexure and shear beams.

Among the listed results is the average bond strength u_t (MPa), which was calculated by dividing the total force developed in the bar by the surface area of the bar over the splice length:

$$u_t = \frac{A_b * f_s}{\pi * d_b * l_s} \quad \text{Equation 4}$$

Where A_b is the cross-sectional area of the bar (mm^2), f_s is the ultimate steel stress (MPa), d_b is the diameter of the bar (mm), and l_s is the splice length (mm). f_s was calculated based on the cracked section analysis of each beam when subjected to P_{max}.

BFS and CWP highly affects the splitting bond strength of the beams as shown in table 5.4. A highest value of 6.58MPa was recorded in H-C/BFS-B, while the lowest value was 5.35MPa for H-C/CWP-B. Control and hybrid mix recorded a similar value of around 6MPa.

Bond ratios, which are defined as (Ut specimen / Ut control), are listed in table 13 and recorded a highest value of 1.1 for H-C/BFS-B, decreases to 1 in hybrid mix, and 0.89 for H-C/CWP-F.

The low values of the fracture energy were expected, and they reflect the brittle nature of the failure for the bond beams. These values are listed in table 5.4.

Table 5.4 Test results for bond beams

Specimen Notation	f'c (Mpa)	Pmax (kN)	Δmax (mm)	fs (MPa)	Ut (MPa)	Bond Ratio	Fracture Energy (kN.mm)	Energy Ductility Index (EDI)
H-C-B	71.25	86.5	6.73	365.2	5.99	--	237.65	--
H-C/CWP-B	67.45	77.2	11.06	326.2	5.345	0.89	368.4	1.55
H-C/BFS-B	73.55	95.1	6.66	401.8	6.585	1.1	236.35	0.99
H-C/BFS/CWP-B	72	86.75	7.46	365.9	6	1	238.57	1

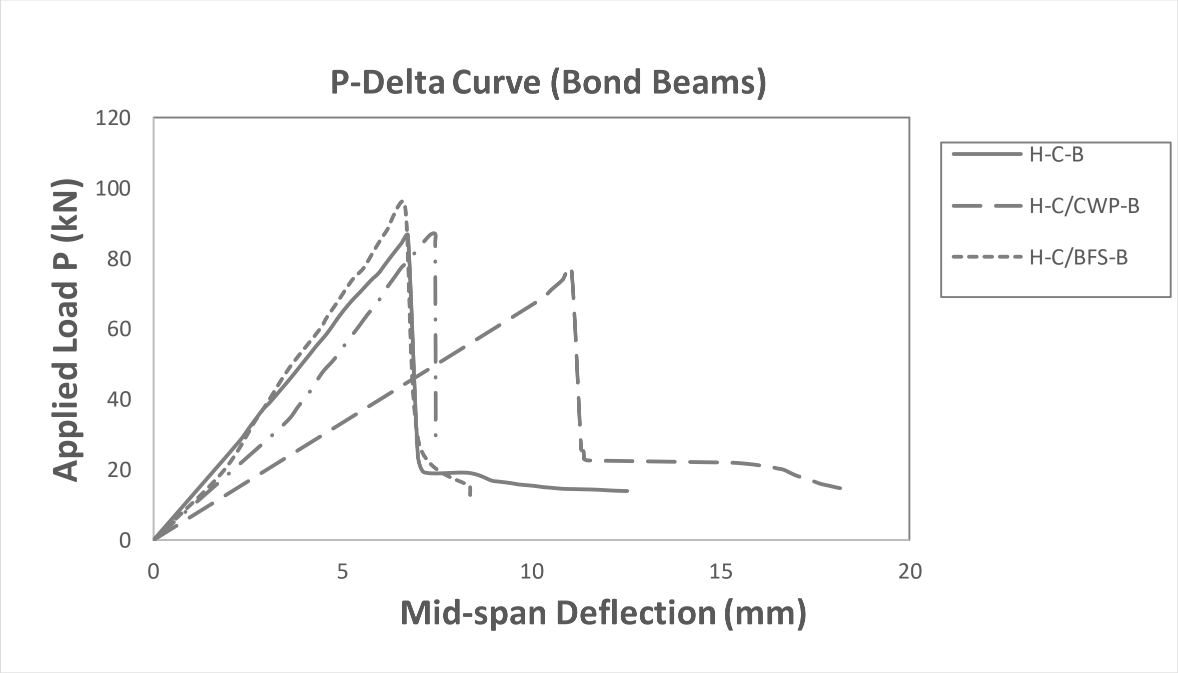

Figure 5.9 Load deflection curves for bond beams

CHAPTER 6

CONCLUSION AND RECOMMENDATION

6.1 Introduction

This chapter presents the conclusions and recommendations of the conducted research, including further steps to be tackled before implementing the integration of CWP and BFS into real life construction projects. Aiming to transform the current concrete industry into a green practice, the structural behavior of a new sustainable concrete material was investigated. The proposed mix reduces the required cement quantities in concrete, hence mitigating the negative environmental impact of cement production and reducing the depletion of natural resources. Furthermore, the mix integrates ceramics into the concrete, which are typically recycled from the wastes of daily ceramic production or construction demolition wastes. The final inclusion of slag, a waste by-product of iron, is the main contributor to the strength enhancement. The findings presented in this dissertation, along with the previous conducted study at the American University of Beirut and the future feasibility studies, can potentially impact the concrete industry on a global scale.

6.2 Summary and future work

Based on the conducted tests on concrete cylinders and beams, presented in Chapter 5, the following conclusions can be drawn:

1. The processed CWP yielded a negative impact on the structural behavior of high strength concrete; this was resembled by a 5.3% reduction in the 28-day compressive

strength and a consistent reduction in ultimate flexural, shear, and bond strengths of around 1.6%, 14.6%, and 10.8% respectively.

2. A significant strength enhancement was recorded when cement was replaced with fully blended slag, composed of 40% BFS and 60% cement. While the 28-day compressive strength improved by 3.22%, flexural, shear, and bond strengths were enhanced by 9%, 3.6%, and 9.94%, respectively.

3. The hybrid mix, composing of 10% CWP and 90% blended slag, was considered satisfactory for compressive strength as a slight enhancement of 1.04% was recorded on the 28-day compressive strength. Furthermore, the recorded flexural, shear, and bond strengths were comparable to the control mix, proving the positive effect of BFS integration into the conventional concrete.

4. The addition of BFS to ceramic concrete almost completely neutralized the negative effect of the CWP on the compressive strength. While the 7-day strength was increased by 4.12%, the 28-day strength was only 1.05% more than the control's strength while the 56-day strength improved by 2.08%.

5. The obtained testing results did not indicate any significant effect on the maximum centerline deflections due to the integration of BFS and CWP into the concrete mix.

6. The results of (Pmax/PACI) increased in mixes including BFS validating the hypothesis of the effect of such pozzolanic material on concrete by increasing its load capacity, and neutralizing the negative impact of CWP addition.

7. BFS and CWP highly affect the splitting bond strength of the beams. The highest value of 6.58MPa was recorded for the blended slag/cement beam, while the lowest value was recorded for CWP/cement beam. Control and hybrid mixes recorded similar values.

8. Low values of fracture energy were recorded for the bond beams, reflecting the brittle nature of the failure.

9. Similar fracture energy values were recorded for the different shear and flexure beams. The highest fracture energy was recorded in both the flexure and the shear beams with 100% slag-cement.

As mentioned earlier, this research is based on a previous study conducted by Alarab at the American University of Beirut which aimed to achieve a green concrete mix reducing the cement quantity in the concrete mix as well as recycling the ceramic wastes generated from the construction demolition waste. The study tackled two types of ceramics (Terracotta and Porcelain). Binders integrating different proportions of cement, ceramic waste powder, and blast furnace slag were checked. The testing procedures included powder characterization, assessment of the pozzolanic activity, mortar specimens, and small-scale concrete specimens. Based on the test results, a mix with 10% CWP and 90% blended cement/slag powder (55% cement and 35% slag) was recommended.

On the other hand, this research aimed to assess the structural feasibility of the previously established concrete material. Large-scale testing is critical step before implementing this new sustainable concrete material in real-life construction projects. The further integration of BFS into ceramic concrete successfully neutralized the negative impact of the CWP on the compressive strength and resulted in an improvement in flexural and shear capacities of the conventional concrete.

It is important to note that the results of research are limited to the local ceramic wastes generated in Lebanon. These wastes were processed in the lab and their chemical composition was presented in Chapter 3. Moreover, a comprehensive economic and environmental feasibility analysis is an essential final step in order to evaluate the net benefits associated with this new sustainable material and, possibly, start implementing it in local and global industries. Also, it is recommended to study the structural behavior of large-scale structural elements incorporating this material under the effect of cyclic loading.

APPENDIX

SUMMARY OF ANNOTATIONS

Materials: H is high strength concrete, C is cement, CWP is ceramic waste powder, and BFS is blast furnace slag.

Concrete Testing:

H-C: Control mix

H-C/CWP: 10% ceramic (10% ceramic replacement of cement)

H-C/BFS: 100% Blended slag (40% slag, 60% cement)

H-C/BFS/CWP: 10% ceramic and 90% blended slag (10% ceramic, 36% slag, 54% cement)

SAMPLE ACI CALCULATION

Flexure Beam H-C

$$a = \frac{As \times fy}{0.85 \times f'c \times b} = \frac{0.000628 \times 585}{0.85 \times 71.25 \times 0.2} = 0.0303\ m$$

$$Mn = As \times fy \times \left(d - \frac{a}{2}\right) = 0.000628 \times 585 \times 1000 \times \left(0.27 - \frac{0.0303}{2}\right)$$

$$= 93.626\ kN.m$$

$$PACI = \frac{Mn}{0.6} = \frac{93.626}{0.6} = 156.04\ kN$$

Shear Beam H-C

$$VACI = b \times d \times \left(\left(0.158 \times \sqrt{f'c} \right) + \left(17.6 \times \frac{Vf}{Mf} \times \frac{As}{b} \right) \right)$$

$$= 0.2 \times 0.27$$

$$\times \left(\left(0.158 \times \sqrt{71.25 \times 1000000} \right) + \left(17.6 \times 1.67 \times \frac{0.000628 \text{ x } 2}{0.2} \right) \right)$$

$$= 72.02\ kN$$

$$VACI\ limit = 0.29 \times b \times d \times \sqrt{f'c} = 0.29 \times 0.2 \times 0.27 \times \sqrt{71.25 \times 1000000}$$

$$= 132.1\ kN$$

$VACI < VACI\ limit$

$PACI = VACI = 72.02\ kN$

Another formula can be used as per the following:

$$VACI = 0.17 \times \sqrt{f'c} \times b \times d = 0.17 \times \sqrt{71.25 \times 1000000} \times 0.2 \times 0.27 = 53.8\ kN$$

$VACI < VACI\ limit$

$PACI = VACI = 77.48\ kN$

Bond Beam H-C

$$ut = \frac{fs \times db}{4 \times ls} = \frac{365.22 \times 0.02}{4 \times 0.305} = 5.99$$

REFERENCES

1. AlArab, Amir, “Evaluation of sustainable concrete incorporating ceramic hybrid binders”, Unpublished thesis, 2018, American University of Beirut, Beirut, Lebanon.

2. Asiwaju-Bello, I., and Olutoge, F.,“Effect of salt water on the compressive strength of ceramic powder concrete”, Civil Engineering Department, University of Ibadan, Ibadan, Nigeria, 2012.

3. Ay, N., and Ünal, M.,“The use of waste ceramic tile in cement production”,*Cement and Concrete Research*, 2000, 30(3), pp. 497-499.

4. Editors: Provis, J., and Van Deventer, J., “Alkali activated materials: State-of-the-art report, RILEM TC 224-AAM”, 2013, Springer Netherlands.

5. Gartner, E., “Industrially interesting approaches to low-CO_2 cements, *Cement Concrete Research*, 2004, 34(9), pp. 1489-1498.

6. Givi, A. N., Rashid, S. A., Aziz, F. N. A., and Salleh, M. A. M., “Experimental investigation of the size effects of SiO_2 nano-particles on the mechanical properties of binary blended concrete”’ 2010, *Composites Part B: Engineering*, 41(8), pp. 673-677.

7. Hausmann, R., Hidalgo, C., Bustos, S., Coscia, M., Chung, S. Jimenez, J., Simoes, A., and Yildrim, M., “MIT Atlas of economic complexity”, 2014, Massachusetts Institute of Technology, Cambridge, MA

8. Heidari, A., and Tavakoli, D., “A study of the mechanical properties of ground ceramic powder concrete incorporating nano-SiO_2 particles”, 2013, Construction and Building Materials, 38, pp. 255-264
9. Lavat, A.E., Trezza, M. A., and Poggi, M., “Characterization of ceramic roof tile wastes as pozzolanic admixture”, 2009, *Waste management*, 29(5), pp. 1666-1674.

10. Meyer, C.,“The greening of the concrete industry”,*Cement Concrete Composites*, 2009, 31(8), pp. 601-605

11. Patel, H., Arora, N. K., Vaniya, S. R., Patel, H., Arora, N. K., and Vaniya, S. R., “Use of ceramic waste powder in cement concrete”, *International Journal for Innovative Research in Science & Technology*, 2015, 2(1), pp. 91-97.

12. Raval, A. D., Patel, I. N., & Pitroda, J., “Ceramic waste: Effective replacement of cement for establishing sustainable concrete”, *International Journal of Engineering Trends and Technology (IJETT),* 2013, 4(6), pp. 2324, 2329.

13. Van Deventer, J. S., San Nicolas, R., Ismail, I., Bernal, S. A., Brice, D. G., and Provis, J. L. “Microstructure and durability of alkali-activated materials as key parameters for standardization”, 2015, *Journal of Sustainable Cement-Based Materials*, 4(2), pp. 116-128.

14. Vejmelkova, E., Keppert, M., Rovnanikova, P, Ondracek, M., and Kersner, Z., “Properties of high performance concrete containing fine-ground ceramics as supplementary cementitious material”, Cement and Concrete Composites, 2012, Vol. 34(1), pp. 44-61.