Effects of Waste Glass as a Partial Replacement of Coarse Aggregate on Concrete Performance

Mohammed Ahmed Alaraj

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Assoc. Prof. Dr. Ali Hakan Ulusoy
Acting Director

I certify that this thesis satisfies all the requirements as a thesis for the degree of Master of Science in Civil Engineering.

Assoc. Prof. Dr. Serhan Şensoy
Chair, Department of Civil Engineering

We certify that we have read this thesis and that in our opinion it is fully adequate in scope and quality as a thesis for the degree of Master of Science in Civil Engineering.

Asst. Prof. Dr. Tülin Akçaoğlu
Supervisor

Examining Committee

1. Prof. Dr. Özgür Eren
2. Asst. Prof. Dr. Tülin Akçaoğlu
3. Asst. Prof. Dr. Ayşe Pekrioğlu

ABSTRACT

This thesis explores the effects of using waste glass (WG) as a coarse aggregate on the performance and properties of concrete in relation to its fresh mix properties, mechanical properties, and durability. For this purpose, WG is used to replace coarse aggregates in concrete mixes at three different proportions (10, 15, and 20 %). Furthermore, either silica fume or glass powder was used as an additive in the mixes at 5% of the cement weight. Superplasticizer (Glenium 27) at 1.5 % of the weight of the binder was also added to each mix. After assessing their workability, each of the mixtures was subjected to compressive, splitting tensile, and flexural strength tests, as well as an impact energy test. They were also tested for durability using the Alkali-silica reaction (ASR), accelerated carbonation and water absorption capacity tests. Overall, results show that it is possible to use recycled waste glass particles as aggregates for up to 20 % of the concrete mix. Using waste glass particles as coarse aggregates has positive effects on the properties of concrete, as well as increases its compressive strength, splitting tensile strength and flexural strength. Conversely, it also has negative effects on the outcome of the impact energy test, as well as the durability and workability of concrete. In order to compensate the negative impact on the concrete's durability and workability, pozzolanic materials (such as silica fume and glass powder) and superplasticizers (Glenium 27) can be used.

Keywords: Waste Glass (WG), Silica fume, Glass Powder, Mechanical properties, Workability, Durability, Compressive Strength, Splitting Tensile Strength, Flexural Strength, Impact Test, Alkali-Silica Reaction (ASR), Accelerated Carbonation, Water Absorption Capacity.

ÖZ

Bu deneysel çalışmada; atık camın (AC) kaba bir agrega olarak betonun performansı ve özellikleri üzerine etkileri, işlenebilirliği, mekanik özellikleri ve dayanıklılığı ile ilgilisi incelenmiştir. Bu amaçla, AC kaba agrega ile üç farklı oranda (10, 15 ve % 20) değiştirildi. Ayrıca, silis dumanı veya cam tozu, çimento ağırlığının % 5'i kadar karışımlara bir katkı maddesi olarak kullanılmıştır. Bağlayıcının ağırlığının %1.5'i kadar süper akışkanlaştırıcı (Glenium 27) her bir karışıma ilave edildi. Karışımların işlenebilirliğini hesaplamak için çökme deneyi kullanıldı. İşlenebilirliklerini değerlendirdikten sonra, karışımların her biri, bir çarpma enerjisi deneyinin yanı sıra, basınç mukavemeti, ayrılma gerilimi ve bükülme mukavemeti deneylerine tabii tutuldu. Ayrıca dayanıklılık açısından; alkali-silika reaksiyonu (ASR), hızlandırılmış karbonasyon ve su emme kapasitesi deneyleri yapılmıştır. Genel sonuç olarak, geri dönüştürülmüş atık cam agrega partiküllerini % 20'si beton karışımınında kullanmanın mümkün olduğu gözlemlenmiştir. Atık cam parçacıklarının kaba agregalar olarak kullanılması betonun özellikleri üzerinde olumlu etkilere göstermiştir. Sıkıştırma mukavemeti, kopma mukavemeti ve eğilme mukavemeti değerlerinin iyileştiği deneylerle ortaya çıkmıştır. Ayrıca, olumsuz olarak darbe enerjisi deneyinin sonucunun yanı sıra betonun dayanıklılığı ve işlenebilirliği üzerinde etkileri vardır. Ancak, dayanıklılık ve işlenebilirlik üzerindeki olumsuz etkilerin telafi edilmesi, silis dumanı ve cam tozu gibi puzolanik malzemeler ve super akışkanlaştırıcı (Glenium 27) eklenerek yapılabilir.

Anahtar Kelimeler: Atık Cam (AC), Silis Dumanı, Cam Tozu, Mekanik Özellikleri, İşlenebilirlik, Dayanıklılık, Basınç Dayanımı, Ayrılma Mukavemeti, Eğilme

Dayanımı, Darbe Deneyi, Alkali-Silis Reaksiyonu (ASR), Hızlandırılmış Karbonasyon, Su Emme Kapasitesi.

DEDICATION

To My Family

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LIST OF SYMBOLS AND ABBREVIATIONS

ASR	Alkali-Silica Reaction
C	Cement
CA	Coarse Aggregates
E_I	Impact Energy
FA	Fine Aggregates
GP	Glass Powder
SF	Silica Fume
SCM	Supplementary Cementitious Material
UTM	Universal Testing Machine
WG	Waste Glass
W	Water
W/C	Water-Cement ratio
σ_c	Compressive Strength
σ_f	Flexural Strength
σ_s	Splitting Tensile Strength

Chapter 1

INTRODUCTION

1.1 Study Overview

Innovative materials are provided in line with the requirements of the modern construction industry. Ideas are developed to meet up with the challenging construction markets and environmental development. These creative ideas are mostly from household garbage, municipal waste, or waste glass from buildings that have collapsed due to natural disasters such as earthquakes, man-made disasters such as wars, or man-made products such as bottles.

As the construction industry strives to achieve sustainable buildings, construction materials possess the highest level of positive environmental impact because they affect the building quality both internally and externally. By definition, sustainable buildings are made from construction materials that are produced locally (which in turn reduces CO_2 emissions and transportation cost), including recycled materials. They possess a low environmental impact and are thermally efficient. They are also financially viable and have low toxic emissions (Meyer, 2002).

The use of recycled materials such as broken glass in place of coarse aggregate in concrete has presented itself as an innovative idea with multiple advantages. First, it has economic benefits. This refers to the reduction in the overall construction cost, including the cost of required transport and mix design requirements (Luz & Ribeiro, 2007). Second is its compatibility with other materials; the waste materials used must not have an adverse reaction with other materials in the mixture (Smith & Hashemi, 2011). Third is the concrete properties. The ability of waste glass to take part in the alkali-aggregate reaction (Ganiron Jr, 2014).

According to the United Nations (UN), 7% of the annual disposed solid waste are glass. In addition, glass is imperishable, and therefore has negative effect on the environment. Utilizing it in construction also frees the environment of non-degradable waste which contributes to environmental sanitation (Topcu & Canbaz, 2004).

1.2 Motivation of the Study

The Gaza strip area has experienced serious wars over the past couple of decades. Apart from the obvious loss of life, other engineering problems include limited access to construction materials due to procurement and logistics problems from the blockade, and the inevitable environmental and structural damage.

The amount of waste glass as a result or structural damage raises environmental and public health concerns. The Palestinian Central Bureau of Statistics reported an estimated daily average solid waste of 1,006 tons/day in 2005, of which 17.9% is glass and metal, and is expected to grow significantly in the next couple of decades (Al-Najar, 2005). The large amount of glass waste produced needs an environmental friendly means of disposal, and not the conventional land disposal that is practiced. A practical way is to use the waste glass in construction.

The blockade minimizes the free movement of construction materials including quality coarse aggregate, and the availability of waste glass presents a solution to the environmental problem that needs proper disposal of waste glass. Therefore, to mitigate both problems, we explore the properties of using glass as coarse aggregate in mixture concrete.

1.3 Objectives of the Study

The aim of this research is to evaluate the effects of waste glass on the properties of concrete. In this study, coarse aggregate is replaced with waste glass in the following percentages: 10, 15, and 20%. The use of waste glass will contribute to the environmental benefits of reducing waste glass disposal. Furthermore, some properties of concrete are expected to improve when waste glass is used as a replacement for coarse aggregate.

To test the effects of waste glass, the following test will be performed on the samples:

- Slump test for workability of the concrete
- Compressive strength
- Flexural strength
- Splitting tensile strength
- Impact energy
- Alkali-silica reaction (ASR)
- Accelerated carbonation
- Water absorption capacity

In performing the tests, professional standards for testing specimens will be adhered to, such as ASTM C1260 and ASTM C227.

With the completion of the above mentioned tests, analysis will be performed and conclusion will be drawn on the relationship and effects of adding waste glass as coarse aggregate in mixture concrete.

1.4 Thesis Outline

The remainder of the thesis is organized as follows: Chapter 2 presents a literature review by describing the properties and composition of waste glass, and the behavior of concretes containing waste glass. This is followed by the methodology of the study in chapter 3. Results of the experiments are discussed in chapter 4. Conclusions on the results and findings of the experiments are presented in chapter 5.

Chapter 2

LITERATURE REVIEW

2.1 Introduction

Glass is one of man's most innovative inventions. The unique properties of glass made it applicable in various industries, including windows in buildings and cars, or bottles for beverages. The life of glass is short. Therefore, it needs to be recycled often to prevent environmental disasters from its compilation. The use of glass in construction industry has provided an innovative and environmental friendly avenue for glass disposal. The quantity of waste glass continuous to grow rapidly. Industrialization and improved living standards are some of the contributors to the growing waste glass quantity.

Disposal of waste glass for municipalities around the world or conflict inflicted regions such as the Gaza strip has become a problem for rebuilding. This has encouraged the use of waste glass in construction. Utilizing waste glass in construction industry has gained considerable attention.

2.2 Properties of Glass and General Application

Glass is manufactured by mixing components of metal oxides such as limestone, soda ash and sand (silicon dioxide or silica). At certain proportions, the components are mixed and heated then cooled at controlled process according to the desired glass type. Figure 2.1 shows the schematic diagram of glass production (float glass) (Achintha, 2016).

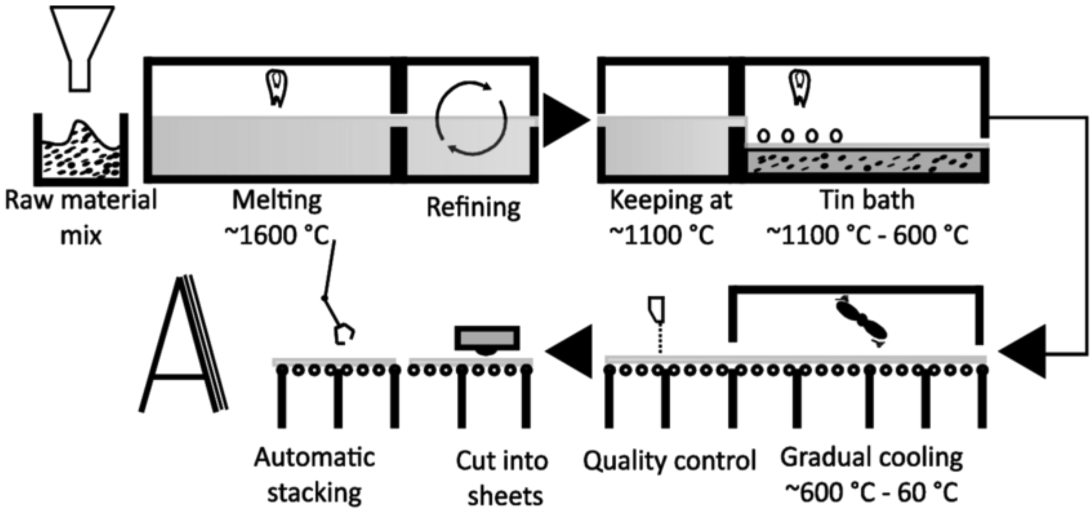

Figure 2.1: Schematic of Glass Production
Source: (Achintha, 2016)

The production process of glass presents it with various properties such as mechanical, thermal, optical and technical properties. The primary characteristics of glass are heat resistance, chemical resistance, transparent, breakage and pressure resistant. Below are some of the common properties of glass (Saint-Gobain, 2018):

Mechanical properties

Density: 2,500 kg/m^3

Modulus of elasticity: 700 GPa

Hardness: 470 K

Bending strength: 45 MPa

Surface reflectance (visible): 4% (each surface)

Compression resistance: 800-1000 MPa

Poisons ratio: 0.23

Specific heat: 840 J/kg.K

Technical properties

The following are the chemical resistance of glass to some materials:

Alkaline: class 2 (DIN 52322 and ISO 695)

Water: class 3 (DIN 52296)

Acid: class 1 (DIN 12116)

2.2.1 General Applications

There are different types of waste glass. Glass cullet is recycled glass prior to processing from jars, bottles and other similar products collected around using collections schemes or bottle banks. The main aim of glass cullet is to process it for the purpose of reusing in glass making for manufacturing new products made of glass. The term "cullet" represents waste glass products as a result of rejection from quality control or beverage in manufacturing process. Applications of the glass cullet in both the construction and non-construction industries have been carried out in the past (Meyer, Egosi, & Andela, 2001).

According to Reindl (2003), waste glass has been used in a variety of construction reasons including asphalt paving, road construction, building materials (glass tiles, wallpaper, bricks etc.), glass fiber, abrasive, fiber glass for insulation, land scraping, art glass, hydraulic, cement and concrete aggregate. For a successful application of waste glass, the physical properties and characteristics must be understood.

The focus of this study is on the application of waste glass as concrete aggregate. Studies have explored the potential of using waste glass in construction in the early 1960's, 1970's and 1980's (see Johnston, 1974; Phillips, 1972; Schmidt & Santucci, 1966). It was later reported that these studies lack accuracy. However, the use of waste glass recently re-emerged due to the growing environmental concern of high waste glass disposal and its environmental problems. The implementation of new environmental regulations around the world (eg. European Union Directive 2008/98/EC) also contribute to the growing research in sustainable glass disposal.

Many studies concluded that the use of crushed waste glass creates a good abrasion resistance and lower shrinkage in dry conditions in comparison to plain concrete. In addition, concrete with waste glass has lower water absorption compared to plain concrete (Anna, 2013).

A study by Jin et al. (Jin, Meyer & Baxter, 2000) used colored glass coarse aggregate as a partial substitute for fine and coarse aggregate in mixture concrete. Their results concluded that the non-colored waste glass exhibited a high expansion as a result of ASR compared to concrete with colored waste glass.

The study of Meyer et al. (2001) stated that the use of glass as aggregate affects the mechanical properties of concrete. Explaining further that the low adhesion and bond strength between the cement paste and glass aggregate in combination with the relatively smooth glass surfaces alters the mechanical properties.

The experimental work of Topcu et al. (Topcu & Canbaz, 2004) stated that concrete mechanical properties are reduced when glass wastes are used.

The study Topcu et al. (Topcu & Canbaz, 2004) was supported by Park et al. (Park, Lee & Kim, 2004) also concluding that using waste glass as fine aggregate replacement in concrete mixture reduces the slump value. Indicating that as the replacement level increases, the mechanical properties decreases.

Using waste glass as partial replacement of fine aggregate was reported by Shehata et al. (Shehata, Varzavand, Elsawy & Fahmy, 1996). The mechanical properties of concrete showed an increase in modulus of rupture for all samples compared to other mixes. The primary findings show that using waste glass improves the interfacial bonding between cement paste and aggregate. The glass aggregate also plays the role of cracks arrestors, stopping cracks from advancing.

Shayan (2002) reported that the maximum percentage by weight of normal aggregate that could be replaced by glass for both coarse and fine aggregate is 50%. In both structural and non-structural applications. Precaution must be made to minimize the negative effect of alkali-silica reaction such as utilizing the suitable pozzolanic material at the right amount.

Serniabat et al. (Serniabat, Khan, & Zain, 2014) used waste glass as coarse aggregate in concrete at different 9 proportions. The glass is crushed at 5 mm-20 mm size, using ordinary Portland cement type 1 with fine sand less than 0.5 mm, coarse aggregate was replaced at 0, 10, 20, 30, 40, 50, 60, 70, and 80%. They observed a maximum compressive strength of 3889 psi (26.813 MPa) at a balance ratio of glass beads.

Ganiron Jr. (2014) used wasted glass bottles as a substitute for coarse aggregate in concrete for mass housing projects. Using the specified ASTM requirement as the standard for the experiment, they utilized Portland pozzolanic cement (Type IP) for the specimen due to the low hardening properties. Using UTM on the 7th and 28th day curing, data was collected. The experiment was conducted at 0% and 10% coarse aggregate replacement.

The study of Otunyo et al. (Otunyo & Tornwini, 2016) used waste glass as partial replacement for coarse aggregate in concrete. The partial aggregate was tested at 5, 10, 15, 20, and 25%. A concrete mix ratio of 1:2:4 with a water/cement ratio of 0.4 was utilized, and was cured and tested after 7, 14, and 28 days.

Gerges et al. (2018) used recycled green waste bottles to replace coarse aggregate at 33, 50, 66 and 100% replacement ratios. Their experiment concluded that 33% was the appropriate percentage replacement to maintain concrete properties. They concluded that the use of glass in concrete has significant influence on both fresh and hardened properties of concrete.

Kereyou et al. (Kereyou & Ibrahim, 2014) used windows waste glass as substitute in concrete coarse aggregate. The replacement of coarse aggregate was at 0, 20, 25, and 30% replacement ratios. They studied the fresh and hardened properties of the specimen at 28 days. They concluded that there are optimal economic effects at 25% coarse aggregate replacement.

The study of Al-Bawi et al. (Al-Bawi, Kadhim & Al-Kerttani, 2017) used recycled waste glass as a partial replacement of aggregate in self compacting concrete (SCC). The specimen was tested at different weight percentages of 0, 20, 40, 60, 80 and 100%. Water to binder ratio of 0.35, total binder content of 570 kg/m^3, and constant slump flow of 700±30 was used. The specimens were tested at age 28 days. They concluded that the waste glass content decreased the brittle nature of the concrete compare to the reference concrete.

2.3 Constituents of Concrete

The basic elements in concrete are air, water, cement, fine aggregate, and coarse aggregate. Fly ash and silica fume are sometimes used to improve certain properties of concrete.

Air is the main part of cement paste matrix. It is the isolated part trapped in cement paste during mixing of concrete (Mindess, Young, & Darwin, 2003). Air trapped in admixtures allows expansion during freezing the thawing, and improves cement workability. However, entrapped air can also cause reduction in the strength of concrete. Therefore the mixture must be created to maintain the appropriate amount of air in the mixture concrete (Du & Folliard, 2005).

Cements are compounds that consist of calcium silicate, calcium aluminofarrite and calcium aluminates. The hydration of cement powder, aggregates and water forms concrete. There are different standards of cements such as the ASTM C 150 Type I Portland cement.

Fly ash are materials added to concrete to improve properties of hardened concrete through pozzolanic activity. The fly ash of class F from (ASTM C 1567) standard is used to mitigate ASR in glass concrete (Shafaatian, Akhavan, Maraghechi, & Rajabipour, 2013).

Silica fume is a byproduct of ferrosilicon alloy or silicon metal. It is a very significant SCM due to its physical and chemical properties. The pozzolanic reactive nature of silica fume contributes to the properties of concrete by increasing the strength and durability of concrete. Other properties of concrete that are improved by silica fume include reduced permeability, increase in abrasion strength, improving corrosion resistance minimizing expansion from ASR phenomenon (Karein, Ramezanianpour, Ebadi, Isapour, & Karakouzian, 2017). The standard specification of silica fume to be added in Portland cement is defined in ASTM C1240.

2.4 Alkali-Silica Reaction (ASR)

ASR is an adverse reaction that occurs in concrete between silica that is found in some aggregate and alkali in cement. It is a degradation process that produces internal cracks in concrete material due to volumetric expansion. Stanton discovered ASR in 1940 when he found that silica gel is produced from the reaction between silica and alkali, which expands the moisture that is present in concrete (Abdelrahman et al., 2015). Figure 2.2 illustrates the ASR reaction in concrete.

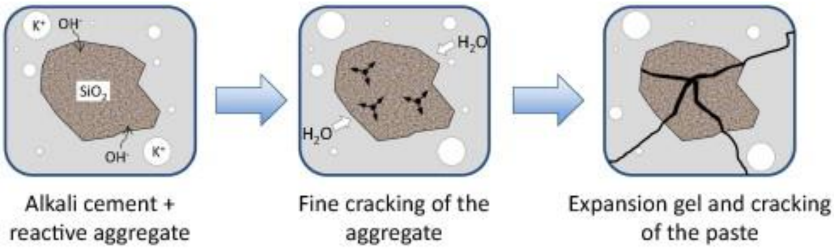

Figure 2. 2: Alkali- Silica Reaction in Concrete
Source: (Abdelrahman et al., 2015)

Although, ASR is detrimental to the stability of concrete, the reaction can also increase the concrete strength. This is as a result of cementitious reaction materials filling in the bond-area. It is similar to pozzolanic reaction in concrete (Hadlington, 2002).

To test ASR, specimens are usually tested according to standards to ensure valuable results. The American Section of the International Association for Testing Materials is an international organization known for publishing technical test standards in a wide range of application founded in 1898. It predates all other test standards.

To classify ASR in concrete, Abdelrahman et al. (2015) applied the ASTM C1293 specification for all specimens. The data extracted were reliable and within standards.

2.4.1 Alkali-Silica Reaction in Waste Glass Concrete

Aggregates in concrete were assumed to unaffected by cement paste, thus they were selected based on physical properties. It was later observed that chemical reactions occur between cement and aggregates. Glass is assumed to be unstable in alkali environment (Hadlington, 2002).

Glass and sand are concentrated with silica, but behave very differently. This is due to the properties of silica in sand because the structure is regular crystalline, which makes it stable and resistant to chemical influence. Glass on the other hand is in amorphous form which is not stable. This observation has been the topic of intensive research.

The use of glass power in concrete has shown promising results in mitigating ASR in concrete. A study by Afshinnia & Rangaraju (2015) stated that the use of glass in concrete as 20% and 30% replacement of aggregate showed effective results in mitigating ASR. Zheng (Zheng, 2016) also reported that the use fine glass grain in concrete mitigates ASR. The result of a research Ammash, Muhammed, & Nahhab (2017) using glass waste as replacement for fine and coarse aggregate at 10, 20, 30, and 40% showed reduction in ASR in specimens.

2.5 Effects of Waste Glass on Properties of Concrete

The use of waste glass to replace the aggregate in concrete affects the properties of concrete. The physical properties of waste glass are approximately the same with sand, hence it is used as an aggregate. Table 2.1 shows the comparison between waste glass and sand.

Table 2.1: Comparison of Physical Properties between Sand and Waste Glass

Physical property	Sand	Waste glass
Absorption %	0.36	2.71
Density kg/m^3	1672	1688
Specific gravity %	2.19	2.57
Pozzolanic index %	80	-

Below are some tests performed on concrete containing waste glass as aggregate, and details on how they affect the concrete properties. The tests are usually performed on fresh mortar and hardened mortar.

2.5.1 Slump Test

Slump test is a method for measuring concrete workability. It is the most widely used and oldest test for concrete workability. It is performed on concrete that is freshly mixed. A standard for slump test is ASTM C 143.

The study of Topcu et al. (Topcu & Canbaz, 2004) revealed that increase in waste glass in concrete mixture decreased the slump value by about 0.2%. They attributed this decrease to waste glass poor geometry.

The experimental work of Andrić et al. (2017) used a 0.45 water cement ratio with waste glass as aggregate in concrete. They observed a reduction on workability of concrete mixture by about 1.5%.

2.5.2 Compressive Strength Test

Compressive strength represents the maximum resistance of a concrete to an exerted axial loading which is applied by compression. Its unit is pound per inch square (psi) or Kilo-newton per millimeter square (MPa).

Compressive strength test is considered one of the most important mechanical test of concrete. It shows the effects of the constituent concrete material, and can easily illustrate the effect of materials added to improve the properties of concrete. The effects of added wasted glass can easily be illustrated by compressive strength test, as it has been performed previously. Most studies stated that compressive strength decreases as the amount of waste glass increases (de Castro & de Brito, 2013).

The study of Topcu et al. (Topcu & Canbaz, 2004) used waste glass at different percentages in concrete and samples cured for 28days. The compressive strength for concrete without waste glass was 2.04-23.50 MPa. A decrease in compressive strength was identified as waste glass increased. 8% reduction in compressive strength was seen for 15% waste glass, and 15% decrease for 30% waste glass. It reached to the value of 31% decrease for 45% waste glass. This is as a result of incomplete adhesion between waste glass and cement paste.

The study of Serniabat et al. (2014) on 9 different mixtures of waste glass in concrete crushed at 5mm-20mm shows a maximum compressive strength of 38891 psi (268.14 MPa).

The work of Ganiron Jr. (2014) at 10% glass replacement showed increase in compressive strength of about 28.7% after 7days. No increase in compressive strength was observed after 28days. They used the ASTMC-39-86 for testing.

Al-Zubaid, Shabeeb, & Ali (2017) tested how waste glass affect concrete at 11%, 13%, and 15%. The results show 13% replacement to have the highest compressive strength after 7, 14, and 28 days.

Some studies observed that the compressive strength of concrete is similarly influenced by the size of waste glass aggregate. This is attributed to the pozzolanic properties of waste glass used. The compressive strength of concrete was found to have increased from 30-35 MPa by Ildir et al. (Ildir, Cyr & Tgnit-Hamou, 2010) when the size of the aggregate is at 80 *u*m.

2.5.3 Flexural Strength Test

Flexural strength is a measure of concrete tensile strength. It measures a concrete slab or beam ability to resist failure in bending. Modulus of rupture (MR) expresses concrete flexural strength (Jamal, 2018). The standard for flexural strength test is ASTM C 78 (third-point loading) or ASTM C 293 (Center point loading). Figure 3 illustrates flexural strength test.

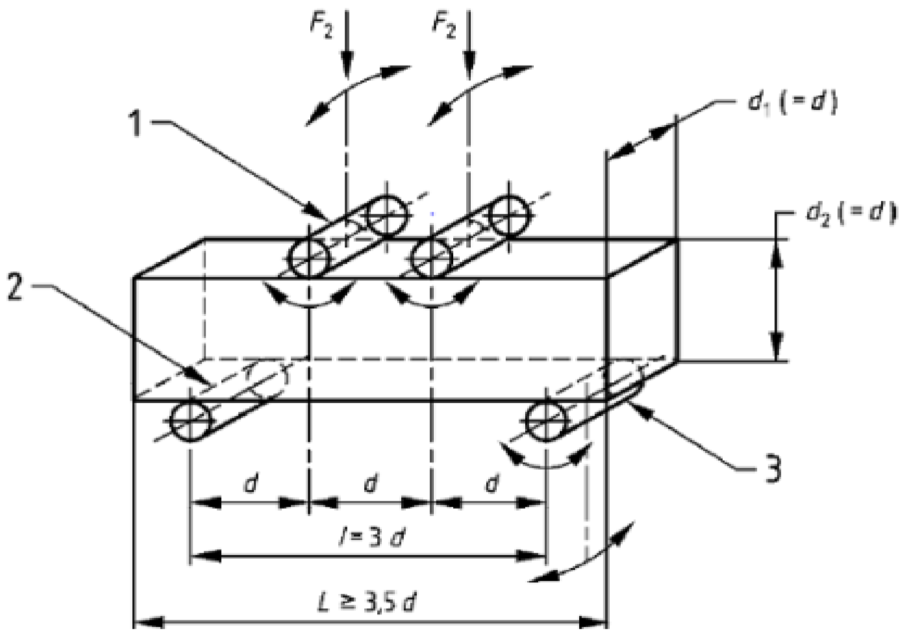

Figure 2.3: Flexural Strength Test for Concrete
Source: (Jamal, 2018)

Results from several studies shows that as waste glass quantity increases, the flexural strength of concrete decreases (Jani & Hogland, 2014). This is a result of the reduction in adhesive strength of glass particles (Khmiri, Chaabouni, & Samet, 2013).

The experimental result of Topcu et al. (Topcu & Canbaz, 2004) showed inconsistent flexural strength, ranging between 3.00 and 5.27 MPa. The increase in waste glass decreases the flexural strength by up to 2%.

The results from the study of Al-Zubaid et al. (2017) shows that the flexural strength of concrete containing waste glass increased compared to the conventional concrete. A 13% percent partial replacement proved to have the highest flexural strength at 7, 14, and 18 days. This is due to the increase in the amount of ($CaCo_3$) in the concrete.

Contrary to most studies, the work of Batayneh et al. (Batayneh, Marie & Asi, 2007) observed a rise in flexural strength when waste glass is used as fine aggregate. An increment in flexural strength of about 20% was recorded. Similarly, others (Mageswari & Vidivelli, 2010) used sheet glass powder in concrete. The result also showed a rise in flexural strength of about 20%.

2.5.4 Splitting Tensile Strength Test

Split tensile strength test measures the tensile strength of a concrete specimen. The brittle nature of concrete makes it crack when subjected to tensile forces. The tensile strength test determines the load required for the concrete to crack.

The use of waste glass as aggregate in concrete produces variation in results with regards to its effects on tensile strength. Some studies recorded a decrease in tensile strength, while some studies recorded increase in tensile strength.

The tensile strength of concrete decreased by about 10% in the study of Topcu et al. (Topcu & Canbaz, 2004). A 37% decrease is observed for 60% waste glass replacement. This is due to the amorphous structure of waste glass. Similar result was also observed by others (Park et al., 2004). They recorded a reduction in tensile strength of their specimen when the waste glass percentage increases.

The study of Mageswari et al. (Mageswari & Vidivelli, 2010) showed an increase in tensile strength of concrete containing waste glass of about 20%. The work of Tan et al. (Tan & Du, 2013) also showed an increase in tensile strength of 25%. Furthermore, they concluded that, as the percentage of waste glass increases, the tensile strength of the specimen increases.

The splitting tensile strength from the study of Al-Zubaid et al. (2017) shows that concrete with waste glass exhibit increase in splitting strength. The splitting tensile strength however decrease at 15% partial replacement compared to its gradual increase at 11 and 13%.

2.5.5 Impact Energy Test

Impact test shows the ability of concrete to absorb energy in an event of collision. Factors such as toughness, fracture resistance and impact strength can be determined from impact test (Rehacek, Hunka, Citek, Kolisko, & Simunek, 2015).

Impact tests are mostly performed on specimen that have fiber as an addition to the concrete or conventional concrete. Studies that use waste glass as aggregate in concrete do not perform the impact tests. In this thesis, to add another dimension to the mechanical properties of concrete, the impact test will be performed.

2.5.6 Accelerated Carbonation Test

Carbonation in concrete occurs because the calcium bearing phases present react with air. An advantage of carbonation is the rise in the tensile strength and compressive strength of concrete (Gharpedia, 2018). Fresh concrete reacts with CO_2 from the air, it gradually penetrates deep into the concrete

To test for concrete carbonization, phenolphthalein indicator solution can be used. It is a white or pale yellow crystalline material. The procedure of RILEM CPC-18 can also be used to test concrete carbonation rate (DE LA RILEM, 1988). The study of Matos et al. (Matos & Sousa-Coutinho, 2012) showed that carbonization magnified when waste glass content increases in the concrete.

2.5.7 Water Absorption Capacity Test

Water absorption capacity is an important concrete characteristics used to test durability of concrete. It can be used to predict certain properties, including permeability and sulfate attack resistance (Zhang & Zong, 2014).

ASTM C 642-13 describes water absorption as the increase in the weight of oven dry concrete after it has been immersed in water for a specific time period. Using waste glass as aggregate in concrete is expected to affect the absorption capacity of concrete. The impermeable nature of glass is expected to affect the permeability of concrete

The work of taha et al. (Taha & Nounu, 2008) stated that, using waste glass reduced the water absorption capacity of concrete and restrict the movement of micro-cracks and moisture migration.

2.5.8 Alkali-Silica Reaction Test

According to ASTM C1293-08, expansion greater than 0.04% in a year is indicative of degradation from alkali-silica activity. The work of Almesfer (2013) states that samples with waste glass has greater expansion due to the formation of expansion gel.

They observed an expansion of 0.802% for 12 % waste glass, 0.777% for 24% waste glass, and 0.583% for 0% waste glass.

The study of Shayan (2003) reported improved alkali-silica reactivity when recycled waste glass aggregate is added to concrete. In addition, the use of fly ash can improve alkali-silica reactivity.

Chapter 3

EXPERIMENTAL WORKS

3.1 Introduction

This chapter contains information on the materials and experimental methods utilized throughout the study as they relate to the objectives sketched out in Chapter 1. This research is essentially focused on exploring the potential benefits of utilizing waste glass in concrete mixtures. At present, the waste glass created in the Gaza Strip is subjected to the same treatment as several other solid waste materials and is tossed in dump sites. Waste glass is usually the product of empty glass containers, construction, reconstruction remains, and other glass waste materials. This glass can alternatively be crushed into many pieces and used as a replacement for coarse aggregate. In this study, crushed waste glass is mixed into concrete with the goal of observing the effects of crushed waste glass on the performance and properties of concrete.

In accordance with the objectives of this thesis, eight different mixes were produced by supplanting four different percentages (0%, 10%, 15%, and 20%) of waste glass for each of the two different additives: silica fume or glass powder. The following experiments were performed to determine the effects of waste glass on the concrete:

1. Workability (slump test)
2. Compressive strength
3. Splitting tensile strength
4. Flexural strength

5. Alkali-silica reaction (ASR)
6. Accelerated carbonation
7. Impact energy
8. Water absorption capacity

Finally, this chapter outlines the materials used for the experiments outlined above, explains the ASTM standard codes and any other measures that were used for the experiments, and describes the methods used for the relevant machines, apparatuses and test techniques in detail.

3.2 Materials Utilized

3.2.1 Cement Type

Cement is usually utilized as a binder material in concrete. The most important role of cement within the concrete mix design is developing the σ_c during the curing period. CEM II 42.5 N Slag Portland cement from Boğaz Endüstri ve Madencilik Ltd. in North Cyprus was used for this study.

3.2.2 Mixing Water

Tap water that is safe to drink and clear of acids, oils, alkalis and natural elements was used to mix the concrete blends and for the curing processes.

3.2.3 Fine Aggregate

Crushed limestone from the Beşparmak Mountains with an average diameter of 5 mm was utilized as the fine aggregate in this study. The gradation was analyzed by using ASTM standard C136M-14 to perform a sieve analysis controlled by C33/C33M-16 of the ASTM standard (see Figure 3.1).

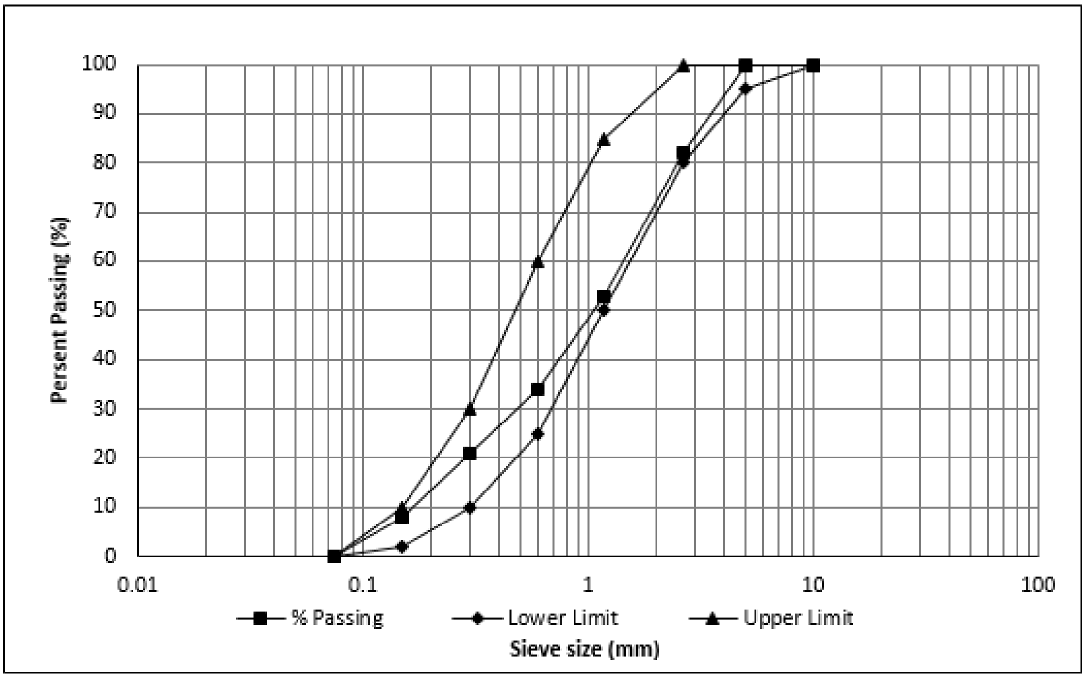

Figure 3.1: Sieve Analysis of Fine Aggregates

3.2.4 Coarse Aggregates

The crushed coarse aggregate utilized in the tests was crushed limestone from the Beşparmak Mountains at different sizes: 10, 14, and 20 mm in diameter. Sieve analysis was used to find out the gradation of the coarse aggregates based on the ASTM C136M-14 standard, and controlled by ASTM C33M-16 (Figure 3.2).

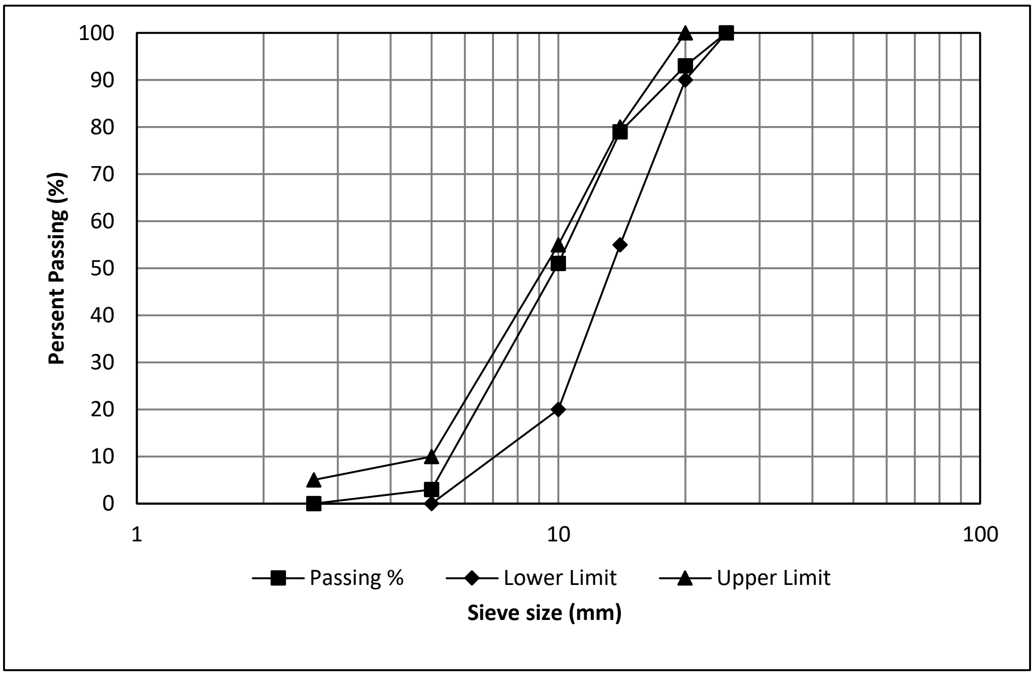

Figure 3.2: Sieve Analysis of Coarse Aggregates

3.2.5 Waste Glass

The waste glass used in this study was obtained from the disposals at reconstruction sites, streets and beaches in Gazimağusa, North Cyprus. These materials were essentially from just pure glass windows and green bottles. The whole sample was cleaned to remove dirt materials and impurities, and then smashed in crushing machines (Los Angeles Abrasion Machine) into different particle sizes, as shown in Figures 3.3 and 3.4.

The same standard strategy was then applied to conduct another sieve analysis for representative samples of waste glass adhering to the ASTM C33M-16 specifications as shown in Figures 3.5 and with a nominal maximum particle size 14 mm in diameter.


Figure 3.3: Waste Glass Materials as Collected before Crushing and Sieving


Figure 3.4: Crushing of Waste Glass to Coarse and Fine Aggregate Sizes

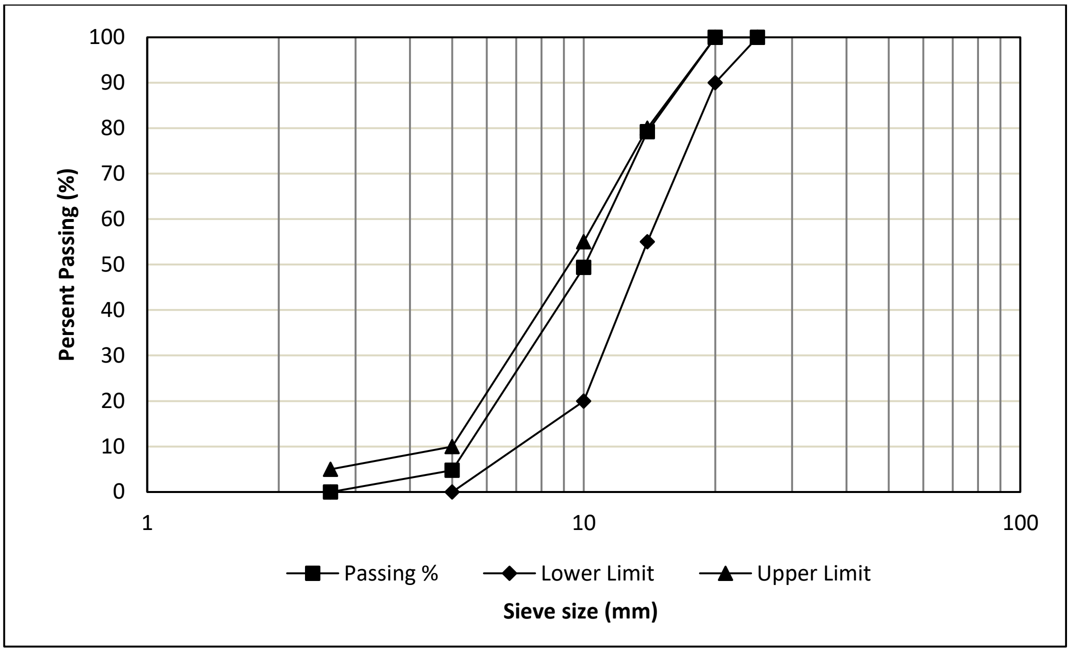

Figure 3.5: Sieve Analysis of Waste Glass Aggregates

3.2.6 Silica fume

Silica fume, also known as microsilica (CAS number 69012-64-2, EINECS number 273-761-1), is a shapeless (non-crystalline) silicon dioxide polymorph. An ultrafine powder, it is produced as a by-product of the ferrosilicon and silicon amalgamtion, and contains round particles with a diameter averaging 150 µm. It is a pozzolanic material that is added to cement to upgrade the concrete properties. The percentage of silica fume added to the concrete mixes in this study was 5 % of the weight of cement. The chemical composition and physical properties of SF are outlined in Table 3.1 and the particle shape is shown in Figure 3.6.

Figure 3.6: Silica Fume

Table 3.1: Physical and Chemical Properties of Silica Fume Used

Property	Amount
SiO_2	82.2
Al_2O_3	0.5
Fe_2O_3	0.42
CaO	1.55
MgO	0.0
SO_3	3.03
K_2O	1.01
Na_2O	0.31
Specific surface (m^2/kg)	15,000–30,000
Specific gravity (kg/m^3)	2.2
Fineness (m^2/kg)	29,000

3.2.7 Glass Powder

Waste glass powder with a maximum diameter of 90 µm diameter was utilized. It was created from brown colored bottles, most of which were formerly wine bottles. The bottles were sourced from shops and shorelines in Gazimağusa. After collection, the bottles were scrubbed to remove paper labels, dust, and any other unwanted materials. After allowing them to dry, they were smashed manually by hammer and then ground using a rotary grinder machine. The percentage of glass powder added was 5 % of the weight of cement. The chemical composition and physical properties of glass powder are outlined in Table 3.2 and the particle shape is shown in Figure 3.7.

Figure 3.7: Grinded Glass Powder

Table 3.2: Physical and Chemical Properties of Glass Powder Used

Property	**Amount**
SiO_2	89.85%
SO_3	0.25%
MgO	0.0%
Fe_2O_3	0.05%
CaO	0.0%
Al_2O_3	0.0%
Specific gravity	2.64
Specific surface area(cm^2/g)	5670

3.2.8 Superplasticizer

The high-range water-reducing admixture Master Glenium 27 was utilized in all the blends to achieve the desired workability and to enhance the durability and strength of the concrete.

3.3 Mix Design

Mix design is a procedure used to ensure that the appropriate material proportions are used to produce economical concrete, which has a strength, durability, and workability as high as possible. Tables 3.3 and 3.4 outline this thesis' mix designs according to the standard (BRE 331, 1988).

Table 3.3: Proportions & Quantities of Mixing Materials for 0.52W/C ratio & 5% SF

Concrete Type	WG (%)	W (kg/m^3)	C (kg/m^3)	SF (kg/m^3)	FA (kg/m^3)	CA (kg/m^3)	WG (kg/m^3)	SP (kg/m^3)
Control	0	190	365	18.25	950	950	0	5.75
WG (10%)	10	190	365	18.25	950	855	95	5.75
WG (15%)	15	190	365	18.25	950	807.5	142.5	5.75
WG (20%)	20	190	365	18.25	950	760	190	5.75

WG: Waste Glass W: Water C: Cement SF: Silica fume FA: Fine Aggregate CA: Coarse Aggregate SP: Superplasticiser

Table 3.4: Proportions & Quantities of Mixing Materials for 0.52W/C ratio & 5% GP

Concrete Type	WG (%)	W (kg/m3)	C (kg/m^3)	GP (kg/m^3)	FA (kg/m^3)	CA (kg/m^3)	WG (kg/m^3)	SP (kg/m^3)
Control	0	190	365	18.25	950	950	0	5.75
WG (10%)	10	190	365	18.25	950	855	95	5.75
WG (15%)	15	190	365	18.25	950	807.5	142.5	5.75
WG (20%)	20	190	365	18.25	950	760	190	5.75

WG: Waste Glass W: Water C: Cement GP: Glass Powder FA: Fine Aggregate CA: Coarse Aggregate SP:Superplasticiser

3.4 Experimental Program

Four different substitution percentages of WG as a coarse aggregate: 0, 10, 15 and 20 % with 5% of two different additives (silica fume or glass powder) and 0.52 W/C ratio were created to investigate the influences of WG on the performance and properties of concrete. To realize this objective, eight batches were prepared to be tested using the aforementioned experiments. In this study, each waste glass replacement percentage was compared to the others, and also to the control samples in order to determine the effects of WG in different additives.

3.4.1 Concrete Mixing Procedure

A mixer of 0.25 m^3 capacity was utilized to mix the eight concrete mixes (see Figure 3.8). The mixer drum surfaces were initially dampened with water to avoid any loss of the mixtures' moisture. Half of the coarse and fine aggregates, waste glass and mixed cement with GP or SF were added, followed by the other half. They were mixed for approximately 45 seconds after which water and superplasticizer (Glenium 27) were added. Finally, they were mixed for another two minutes in order to create a uniform concrete blend.

Figure 3.8: Concrete Mixer of 0.25 m^3 Capacity

3.4.2 Fresh Concrete Test, Workability

In an effort to identify the effects of four unique percentages of waste glass: 0, 10, 15 and 20%, as a coarse aggregate substitution material on the workability of fresh concrete with 5% of two different additives (SF or GP), the slump test was applied (see Figure 3.9). The slump test was performed in line with the ASTM C143/C143M 15a.

Figure 3.9: Slump Test

3.4.3 Specimen Preparation and Curing

After the fresh concrete tests, the concrete was then poured into the mixer once more and mixed for 40 additional seconds. To prevent any chemical reaction between the concrete and the molds, and to make the remolding process of the concrete samples easier, oil was used to lubricate and clean the molds right before casting. Afterwards, they were put on a vibration machine to make them compact, as shown in Figure 3.10. The specimens were subsequently placed inside the curing room with a relative humidity of 99%. The concrete specimens were demolded twenty-four hours later and transferred to a curing water tank where they remained for 28 days at 20±2°C as shown in Figure 3.11.

Four different kinds of specimens were created for each of the replacement percentages: three beams 100×100×500 mm, six cubes 150×150×150 mm, six cubes 100×100×100 mm, and three cylinders 100×200 mm.

Figure 3.10: Standard Compaction of Specimens

Figure 3.11: Curing Tank

3.5 Testing of Hardened Concrete

To determine the impact of WG on the properties of hardened concrete, the following experiments were performed on specimens molded in several shapes and sizes.

3.5.1 Compressive Strength

In line with the BS EN 12390-3:2009, the compressive strength test was done after curing for 28 days. Cubic specimens with the dimensions 150x150x150 mm were selected for this test, as can be seen in Figure 3.12. The test was performed on three cubes for each substitution percentage of WG containing 5% additives of either SF or GP. The σ_c loading speed was 0.4 MPa/s, while the maximum capacity of the compression testing machine is 3000 Kn.

Figure 3.12: Compression Testing Machine

3.5.2 Splitting Tensile Strength

Cylindrical samples measuring 100x200 mm were chosen and tested after 28 days of curing to investigate the impact of replacing coarse aggregate with WG and 5% additives of either SF or GP on σ_s. The experiment process was performed based on ASTM C496/C496M – 17. Three cylindrical samples were tested for each substitution level of WG in order to arrive at more exact results.

3.5.3 Flexural Strength

The impact of waste glass as a coarse aggregate substitute on flexural strength was examined using beam samples measuring 100x100x500 mm. The beam samples were prepared and tested at the age of 28 days (Figure 3.14). The test procedure was done in accordance with ASTM C78/C78M – 16. Three specimens were utilized for testing flexural strength: one for each proportion of waste glass, with 5% of either SF or GP as additives. The maximum capacity of the flexural testing apparatus is 200 kN.

Figure 3.13: Flexural Strength Testing

3.5.4 Impact Energy

The impact energy test was carried out using a drop-weight hammer weighing 13.5 kg and at a 1.808 m/s velocity for the cylindrical disc; the testing arrangement can be seen in Figure 3.15. In the drop-weight hammer test, cylindrical discs measuring 100x60 mm are arranged and tested at ages of 28 days. The discs were positioned on the base plate of the impact testing machine and struck repeatedly. The impact load was dropped from a height of 300 mm onto the discs. The number of blows needed to reach complete failure in each of the specimens was taken to be the impact failure strength. The cylinders that were used contained 0%, 10%, 15% and 20% WG replacement, with 5% additives of either SF or GP. The eight specimens were taken to be placed in the drop-weight impact-testing machine after which they were then set firmly in the interior of the machine. A hammer was then dropped physically for a repeated number of blows until the specimen reached complete failure. The number of blows was recorded for each specimen in order to calculate the energy impact load and impact resistance. This instrument is a combination of the aggregate impact test device and the drop-weight test device prescribed by the ACI 544 standards.

Figure 3.14: Drop-Weight Impact Test Machine

3.5.5 Accelerated Carbonation

A chamber that was to be able to carry the sum of the cubes (16 samples measuring 100x100 mm each) was prepared. Figure 3.16 shows a wrapped carbonation chamber containing cube samples with waste glass as a coarse aggregate substitution at 0%, 10%,15% and 20% of WG and 5% of either silica fume or glass powder as additives in it. The chamber was created in a way that allowed it to be sealed shut at the top to avoid any leakage of the gas and was connected to the carbon dioxide cylinder with pipes for 20 days. A fan was set facing the insides of the chamber to form an environment that was aggressive and through which the gas could keep circulating nonstop inside the chamber.

Figure 3.15: The Carbonation Chamber

3.5.6 Alkali-Silica Reaction (ASR)

The alkali silica reaction (ASR) could present a major durability issue for concrete with waste glass. The accelerated test utilized in this study was the mortar bar test outlined in ASTM C1260. The test had to be modified since a sample of the concrete 100x100 mm cubes was tested rather than making mortar bars. The cubes that were tested contained waste glass as a coarse aggregate replacement at 0%, 10%, 15% and 20% with 5% of either SF or GP as additives. The cubes were set in a 1N NaOH solution in an 80 ± 2°C water bath. Readings were taken periodically over a 14 days period to decide whether any expansion occurred using a DEMEC gage, shown in Figure 3.17. According to ASTM C 1260, a specimen is considered nonreactive if after 14 days the expansion is less than 0.1%; a specimen is reactive if after 14 days the expansion is higher than 0.2%. If the expansion is between these two limits, the result of the test is uncertain and the test ought to be continued beyond 14 days.

Figure 3.16: Water Bath & DEMEC Gauge

3.5.7 Water Absorption Capacity

To determine the capacity for water absorption of concrete specimens containing four different percentages of WG mixed with 5% of either SF or GP additives, cube specimens measuring 150×150×150 mm were subjected to testing in accordance with the ASTM C642 –13. Three specimens were tested for each waste glass percentage and the two kinds of additives.

Chapter 4

RESULTS AND DISCUSSIONS

4.1 Introduction

The main goal of this chapter is to show the experimental outcomes and results of eight different concrete mixtures to determine the usefulness and effects of waste glass on the performance and properties of concrete. For every test, the samples modified using waste glass were compared to those made using the control mixes. The following tests, including: slump test of fresh concrete, compressive strength, flexural strength, splitting tensile strength, impact energy, water absorption capacity, accelerated carbonation, and ASR, were performed for each of the samples. Lastly, the results are illustrated using different tables and graphs for better understanding.

4.2 Properties of Fresh Concrete

4.2.1 Slump Test

The workability of the fresh mixes was determined using the slump test, which was performed for every specimen containing the replacement of waste glass as a coarse aggregate (0%,10%,15 and 20%) with 5% of either silica fume or glass powder and constant W/C ratio (0.52). The results are shown in Table 4.1 and Figure 4.1.

It is obvious that the workability of the concrete decreased with each increase in the waste glass percentage. Due to the poor geometry of waste glass, coupled with the very fine particles and greater water demand of silica fume and glass powders, concrete containing finer particles will have a lower slump value. The slump value is also lower for samples using silica fume when compared to those using glass powder as an additive. As a result, it is evident that slump value has a direct relation to the size of particles in the mix.

Table 4.1: Influence of WG on Workability

Mixture type	Slump (mm)
SF0WG	165
SF10WG	150
SF15WG	145
SF20WG	140
GP0WG	180
GP10WG	170
GP15WG	165
GP20WG	150

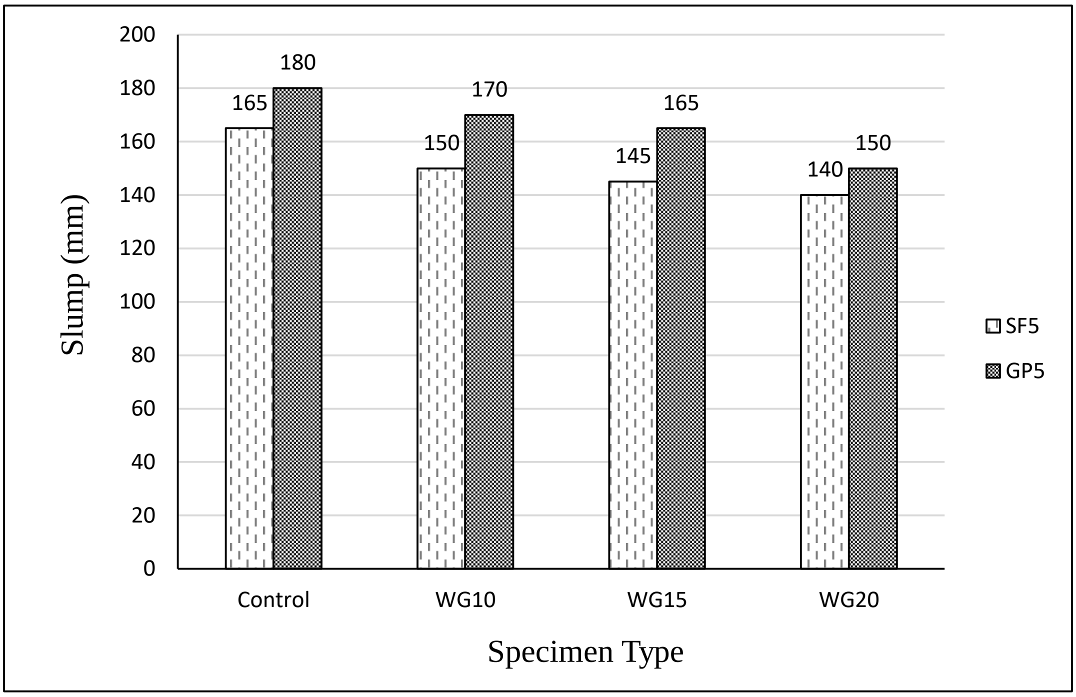

Figure 4.1: Effect of WG as Partial Replacement of Coarse Aggregate on Slump

4.3 Hardened Concrete Tests

4.3.1 Compressive Strength (σ_c)

Three cube 150×150×150 mm specimens' test results were recorded at 28 days for the compressive strength of eight different concrete mixes: four different percentages 0, 10, 15 and 20% of replacement waste glass as a coarse aggregate with 5% of either glass powder or silica fume, seen in Table 4.2 and Figures 4.2.

In relation to the results of the test, concrete mixes with results of over 50 MPa will be considered high strength concrete. It can be seen from Table 4.2 and Figure 4.2 that the σ_c of WG10, WG15 and WG20 specimens in the 5% silica fume group increased by 3.89, 6.74 and 7.62 %, respectively. When compared to the control specimens, while the σ_c of the WG10, WG15 and WG20 specimens in the 5% glass powder group increased by 9.66, 12.86 and 18.12 %, respectively. As it is also shown in Figure 4.2 and Table 4.2, the highest compressive strength value of all of the substitution percentages is from the group of specimens containing 5% silica fume. This could be due to the silica fume itself, which is related to strength development and packing the spaces between cement particles with its finer particles, making the mix denser and also causing a pozzolanic reaction between the silica fume particles. On the other hand, the specimens containing glass powder increase less in terms of compressive strength for all coarse aggregate substitution percentages. This is because of the increase in the amount of non-pozzolanic glass powder particles as glass powder is an inert material, which needs an external heat source to stimulate it to act as a pozzolanic material, meaning that less heat was produced. Consequently, the heat that was produced was not enough to encourage the pozzolanic reaction of all the GP particles.

Table 4.2: Compressive Strength Test Results (MPa) at 28 days

Specimen Type		**σ_c** (MPa)	**Increase in σ_c** (%)
SF5	Control	60.83	-
	WG10	63.20	3.89
	WG15	64.93	6.74
	WG20	65.47	7.62
GP5	Control	50.03	-
	WG10	54.87	9.66
	WG15	56.47	12.86
	WG20	59.10	18.12

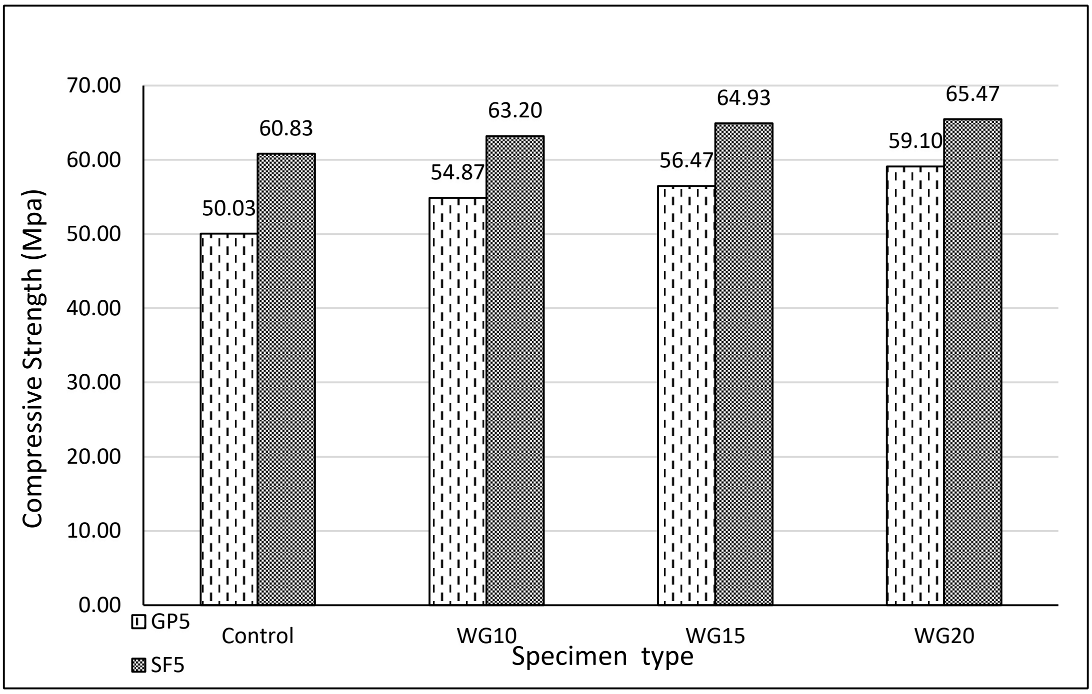

Figure 4.2: Compressive Strength Test Results

4.3.2 Splitting Tensile Strength (σ_S)

The average splitting tensile strength test results for three cylindrical samples (100 mm × 200 mm) of eight different concrete mixes at 28 days: four different percentages of WG replacement as a coarse aggregate (0, 10, 15 and 20%) with 5% silica fume or 5% glass powder as an additive, are shown in Table 4.3 and Figure 4.3.

As expected, the σ_S of the samples was slightly increased once waste glass aggregates were incorporated in mixtures. The σ_S of the WG10, WG15, and WG20 mixes increased by about 9.65, 11.40, and 12.62 %, respectively, when compared to the control mixture for mixes containing 5% silica fume additive. For mixes containing the 5% glass powder additive, the increase was 8.21, 14.42 and 20.76%, respectively, compared to the control mixture.

This σ_s increase is caused by the positive performance of WG particles due to the small percentage of WG use in this study. In addition, Mageswari & Vidivelli (2010) showed an increase in the tensile strength of concrete containing waste glass of about 20%. The σ_s of the concrete samples with WG as a coarse aggregate could decrease however, for higher percentages of waste glass due to the brittleness of the concrete specimens which containing such high percentages. This brittleness also increased with increases in the WG replacement level depending on the interfacial transition zone between aggregates and cement paste.

The splitting tensile strength of concrete containing glass powder as an additive was less affected than concrete containing silica fume (see Figure 4.2), which suffers from poor bonding among its particles. As a result, concrete with silica fume will have a higher splitting tensile strength than concrete with glass powder.

Table 4.3: Splitting Tensile Strength Test Results (MPa) at 28 days

Specimen Type		**σ_s** (MPa)	**Change in σ_s** (%)
SF5	Control	5.195	-
	WG10	5.696	9.65
	WG15	5.787	11.40
	WG20	5.850	12.62
GP5	Control	4.027	-
	WG10	4.358	8.21
	WG15	4.608	14.42
	WG20	4.863	20.76

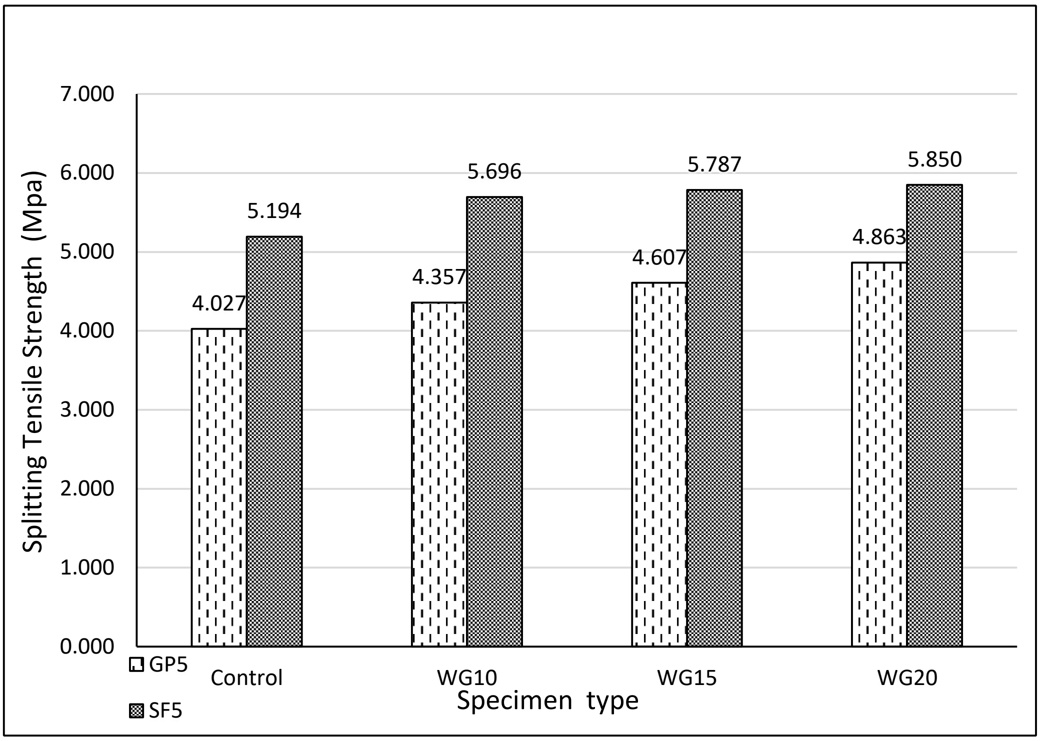

Figure 4.3: Splitting Tensile Strength Test Results

In order to determine the best relationship between σ_s and σ_c, the regression coefficient R^2 was calculated for different regression types (Exponential, Linear, Logarithmic, Polynomial, and Power). The closer the value of R^2 is to one, the less its the dispersion. The highest value of R^2 was recorded for the polynomial regression with an R^2 of 0.99 and 0.99 for mixes with SF and GP, respectively, as is shown in Table 4.4.

Figure 4.4 illustrates the linear relationship between σ_s and σ_c for coarse aggregate replacement with waste WG at 28 days. This figure reveals that the increment of the waste glass percentage increases both σ_c and σ_s.

Table 4.4: Different Relationships between Splitting Tensile Strength and Compressive Strength

Concrete Type	**Regression Type**	**Equation**	**R^2**
SF5	Exponential	$y = 1.1508e^{0.0249x}$	0.92
	Linear	$y = 0.1375x - 3.1132$	0.92
	Logarithmic	$y = 8.6962\ln(x) - 30.478$	0.93
	Polynomial	$y = 0.0304x^2 + 3.9766x - 124.18$	0.99
	Power	$y = 0.008x^{1.5782}$	0.93
GP5	Exponential	$y = 1.403e^{0.021x}$	0.98
	Linear	$y = 0.0925x - 0.6331$	0.97
	Logarithmic	$y = 4.9971\ln(x) - 15.563$	0.97
	Polynomial	$y = 0.004x^2 - 0.338x + 11.023$	0.99
	Power	$y = 0.0475x^{1.1332}$	0.98

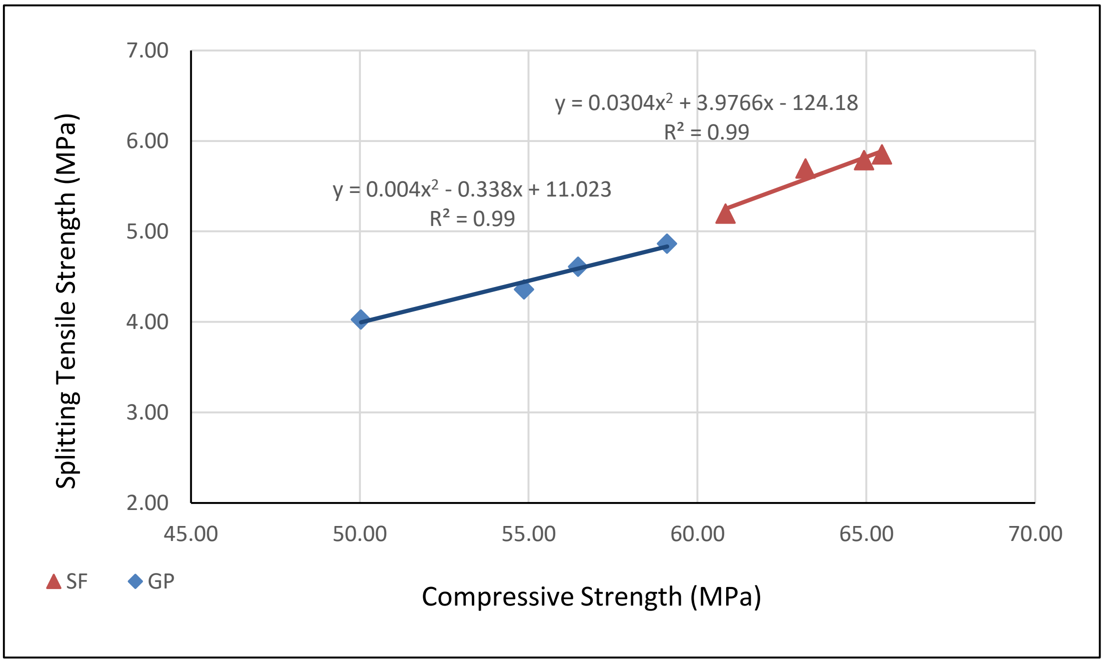

Figure 4.4: Relationship between Splitting Tensile Strength and Compressive Strength

4.3.3 Flexural Strength (σ_f)

To determine the impact of waste glass coarse aggregates on flexural strength, the average flexural strength test of three sample beams measuring 100 mm × 100 mm × 500 mm at 28 days were calculated for eight different concrete mixes. The results for four different percentages of waste glass replacement as a coarse aggregate at 0, 10, 15 and 20%, with 5% silica fume or 5% glass powder as an additive are shown in Table 4.5 and Figure 4.5.

It can be observed that WG has a good impact on concrete's flexural strength and concrete samples with 20% WG coarse aggregate replacement and 5% silica fume achieved the highest flexural strength of all the concrete mixes. The observed increases for concretes with waste glass replacement percentages (10 ,15 and 20%) and 5% SF additive were about 2.76, 6.79 and 21.12%, respectively, while the increases for the 5% GP additive group were 3.52, 7.19 and 10.77 %, only slighting higher than in the 5% SF group.

The increases in flexural strength was realized by using WG as a coarse aggregate replacement in various percentages and with the two additives is due to the good bonding between the aggregates and cementitious materials, in addition to the reasons already mentioned in Section 4.3.1 in relation to compressive strength.

Table 4.5: Flexural Strength Test Results (MPa) at 28 days

Specimen Type		**σf** (MPa)	**Change in σf** (%)
SF5	Control	6.77	-
	WG10	6.96	2.76
	WG15	7.23	6.79
	WG20	8.20	21.12
GP5	Control	6.53	-
	WG10	6.76	3.52
	WG15	7.00	7.19
	WG20	7.24	10.77

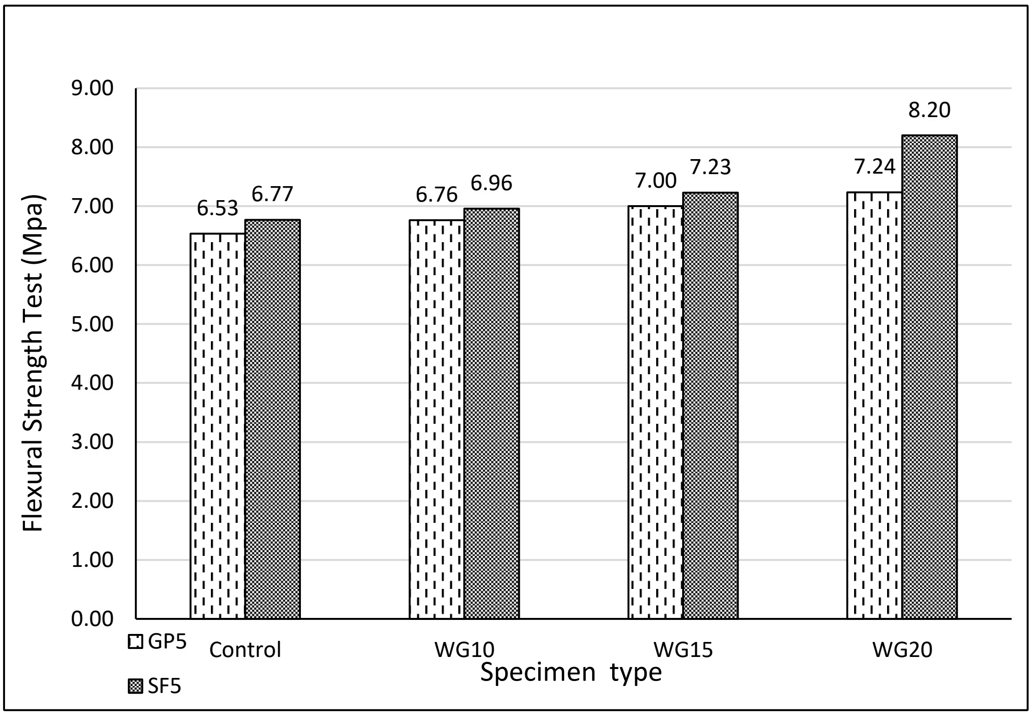

Figure 4.5: Flexural Strength Test Results

Furthermore, to specify the differences in the flexural strength of concrete as a function of the compressive strength of each concrete mixture after 28 days, various regression models were applied using different relation factors R^2 as shown in Table 4.6. It can be observed from the table, with respect to regression R^2, that the best relation for each concrete mixture at 28 days is the polynomial type: 0.83 and 0.98 for the SF & GP mixture groups, respectively. The polynomial relationship was chosen.

Figure 4.6 outlines the relationship between flexural strength and compressive strength for all the concrete mixtures. It confirms that when the compressive strength increased, flexural strength also increased as well.

Table 4.6: Different Relationships Between Flexural Strength and Compressive Strength

Concrete Type	**Regression Type**	**Equation**	**R^2**
SF5	Exponential	$y = 0.8894e^{0.033x}$	0.66
	Linear	$y = 0.2439x - 8.2241$	0.64
	Logarithmic	$y = 15.309\ln(x) - 56.279$	0.64
	Polynomial	$y = 0.1076x^2 - 13.346x + 420.31$	0.83
	Power	$y = 0.0013x^{2.0737}$	0.66
GP5	Exponential	$y = 3.6719e^{0.0114x}$	0.95
	Linear	$y = 0.0781x + 2.5771$	0.95
	Logarithmic	$y = 4.2128\ln(x) - 10.001$	0.94
	Polynomial	$y = 0.0055x^2 - 0.5152x + 18.642$	0.98
	Power	$y = 0.5865x^{0.6143}$	0.94

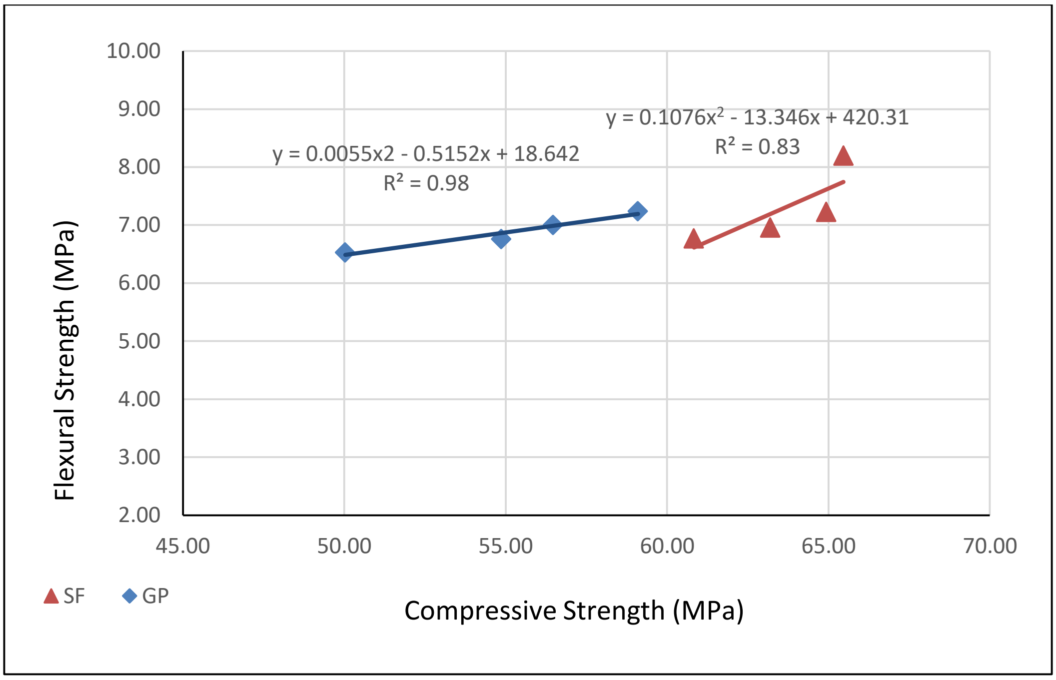

Figure 4.6: Relationship Between Flexural Strength and Compressive Strength

4.3.4 Impact Energy

The averages of three cylinders measuring 100×60 mm and cut by a cutting machine were taken to determine the impact of WG on the impact energy and impact resistance of concrete at 28 days. A hammer was dropped physically for multiple blows until each of the specimens achieved complete failure. Then, the number of blows was recorded for each specimen in order to calculate the energy impact load and impact resistance. Eight different concrete mixes were tested: four different percentages of waste glass replacement as a coarse aggregate at 0, 10, 15 and 20% with 5% silica fume or 5% glass powder as an additive. The impact energy test results for the mixes are shown in Table 4.7 and Figure 4.7, while Table 4.8 and Figure 4.8 contain the impact resistance results.

In relation to the effects of the impact test on WG, it was found that waste glass has a negative impact on concrete mixes with 15% and 20% replaced WG coarse aggregate containing either 5% SF or 5% GP. On the other hand, however, there appears to be no clear effect on the concrete when the WG replacement level was 10%. The declination results for concretes with waste glass replacement at 10 ,15 and 20% with 5% SF additive were about -25, -25 and -37.5% less than the control mix, while those for the 5% GP additive group were 0, -16.67 and -33.33% less than the control, respectively. The reason for this could lie in the properties of waste-glass-based cement composite and the crack control features of the glass, which is determined by properties associated with cracking, including resistance to impact and the brittleness of waste glass. From Figure 4.7, the maximum value in impact energy was for the control mix containing 5% silica fume with 0% replacement level of waste glass when compared to the impact energy of the other control mix containing 5% glass powder without waste glass due to the absence of glass in the concrete mix.

According to Figure 4.8 and Table 4.8, the maximum number of average blows was reached in the SF control mix containing 0% replacement of WG for the same reasons mentioned above. However, for mixed with a higher WG content, the number of blows decreased and reached a minimum value of three blows for the specimen containing 20% WG replacement in the GP group.

Table 4.7: Impact Energy Test Results (N.m) at 28 days

Specimen Type		E_I at failure (N.m)	Change in E_I (%)
SF5	Control	58.84	-
	WG10	44.13	-25.00
	WG15	44.13	-25.00
	WG20	36.77	-37.50
GP5	Control	44.13	-
	WG10	44.13	0.00
	WG15	36.77	-16.67
	WG20	29.42	-33.33

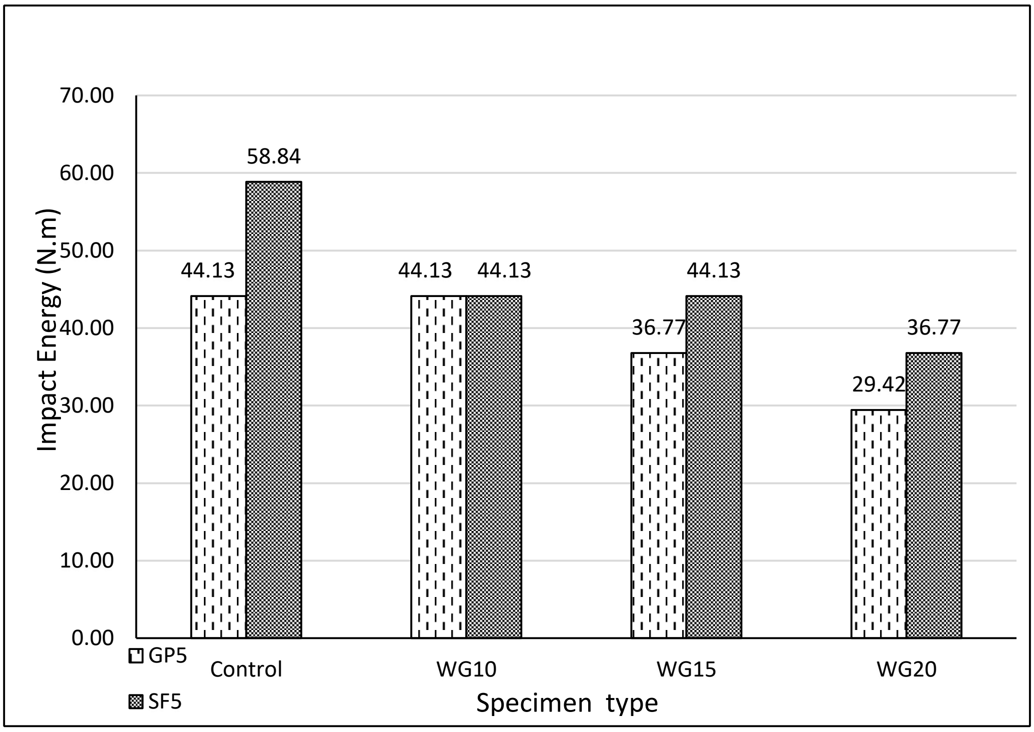

Figure 4.7: Impact Energy Test Results

Table 4.8: The Numbers of Blows on Impact Resistance Results

Specimen Type		#Blows (I)	#Blows (II)	#Blows (III)	Average Of #Blows
SF5	Control	3	3	2	2.67
	WG10	2	2	2	2.00
	WG15	2	2	2	2.00
	WG20	2	2	1	1.67
GP5	Control	2	2	2	2.00
	WG10	2	2	2	2.00
	WG15	1	2	2	1.67
	WG20	2	1	1	1.33

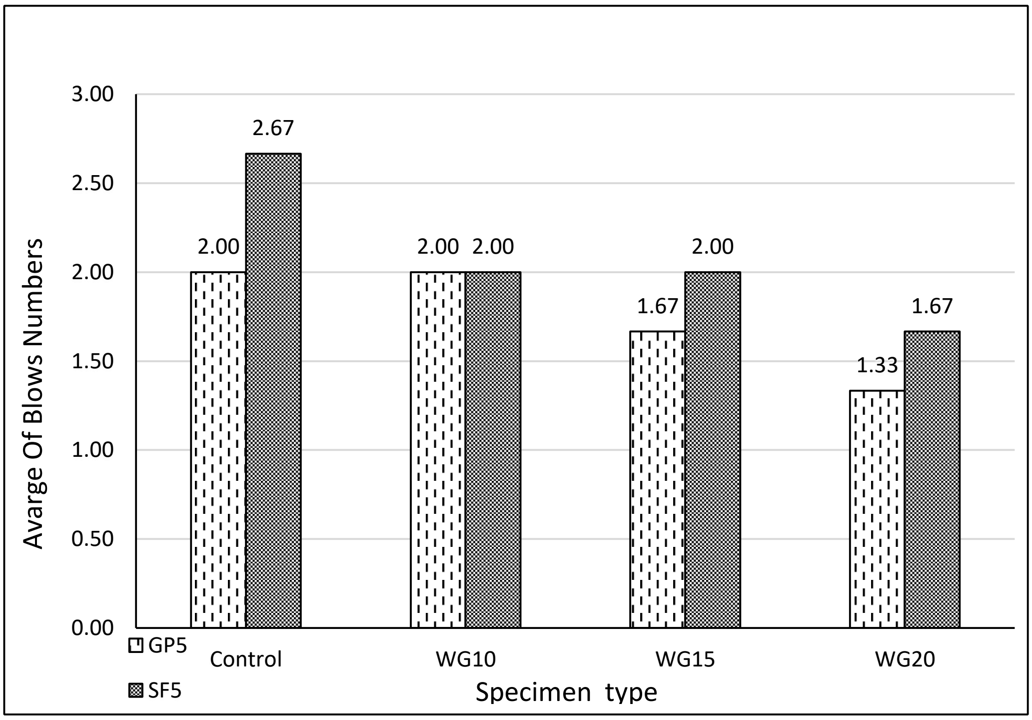

Figure 4.7: The Impact Resistance Results

4.3.5 Accelerated Carbonation

The average results of two cubes measuring 100 mm, which were cured for 28 days followed by 20 days in the chamber for eight different concrete mixes were tested to determine the impact of WG on the durability of concrete through a carbonation test. Four different percentages of WG replacement as a coarse aggregate were used at 0, 10, 15 and 20% with either 5% silica fume or 5% glass powder as an additive. After the specimens were split, the surfaces were cleaned and sprayed with a phenolphthalein pH indicator. On the highly alkaline, noncarbonated part of the specimen, a purple-red color was observed, while no coloration occurred on the carbonated part of the specimen where the mortar was less alkaline (Figure 4.9). Each value matches the average of eight measurements taken for the four sides of each test specimen after their surfaces had been freshly split and sprayed. The results can be seen in Figure 4.10 and Table 4.9.

The carbonation depth for waste glass replacement at 0, 10, 15 and 20 % of the coarse aggregate and 5% silica fume was greater than that using 5% glass powder. Carbonation appears to increase in conjunction with the increase in WG content, consistent with the general trend seen in concrete for different pozzolanic materials that is caused by the lower levels of Calcium Hydroxide (CH). This can perhaps be attributed to the higher reactivity of SF and the resulting CH reduction relative to GP.

Figure 4.8: GP5 Control Samples After Carbonation

Table 4.9: Carbonation Depth Results after 20 Days in The Chamber

Specimen Type		**Carbonation Mean Depth** (mm)
SF5	**Control**	2.8
	WG10	3.1
	WG15	3.3
	WG20	3.5
GP5	**Control**	2.7
	WG10	3.0
	WG15	3.0
	WG20	3.1

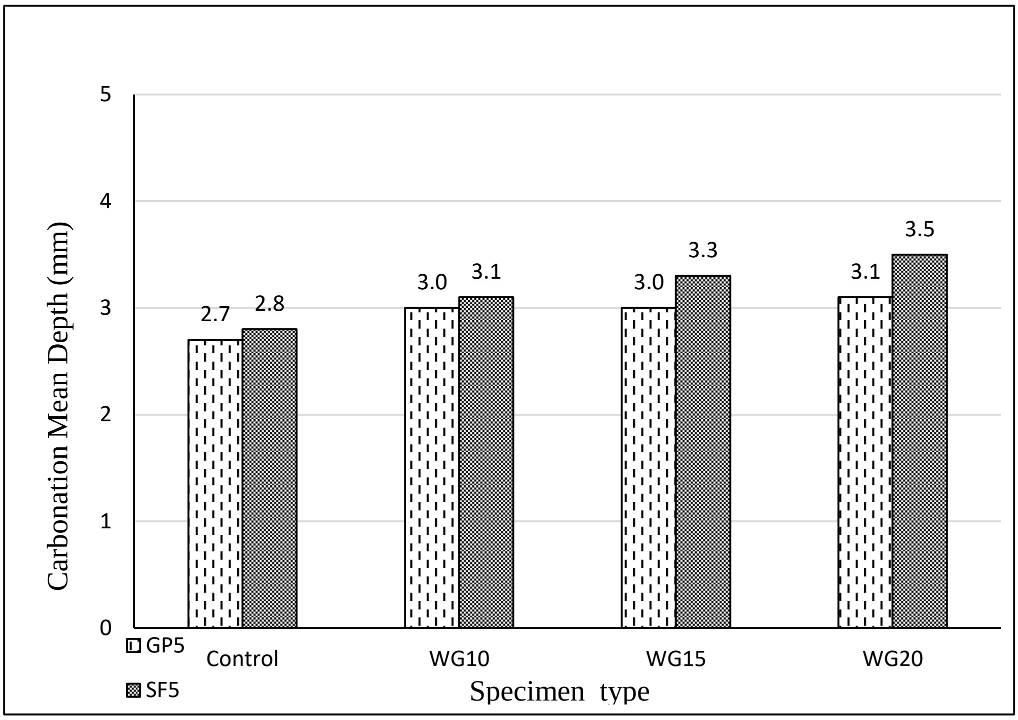

Figure 4.9: Carbonation Depth Results

4.3.6 Alkali-Silica Reaction (ASR)

The average test results for two cube specimens measuring 100mm were taken at 14 days to determine the alkali-silica reaction of eight different concrete mixes: four different percentages (0, 10, 15 and 20%) of replacement waste glass as a coarse aggregate with either 5% glass powder or 5% silica fume. The results are illustrated in Table 4.10, Figure 4.11 and Figure 4.12.

Table 4.10: Results of Final Expansion After 14 Days in 1 N NaOH

Specimen Type		Expansion (%)
SF5	**Control**	0.0344
	WG10	0.0391
	WG15	0.0410
	WG20	0.0434
GP5	**Control**	0.0385
	WG10	0.0417
	WG15	0.0470
	WG20	0.0520

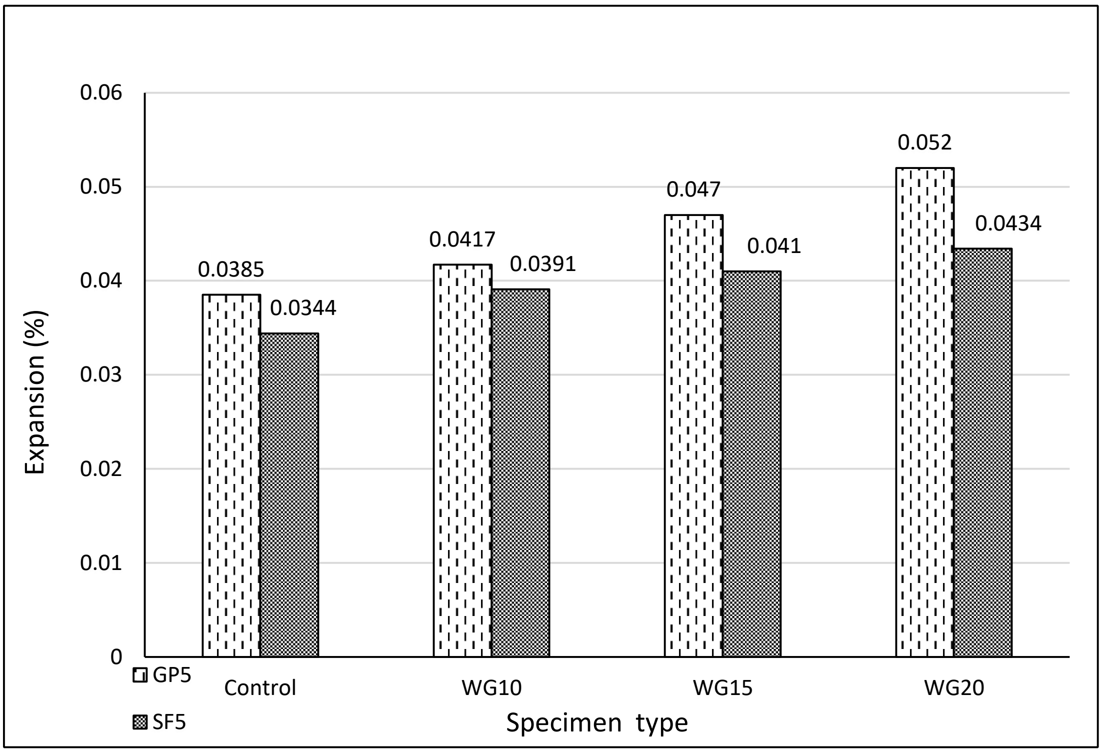

Figure 4.10: Final Expansion after 14 Days in 1 N NaOH

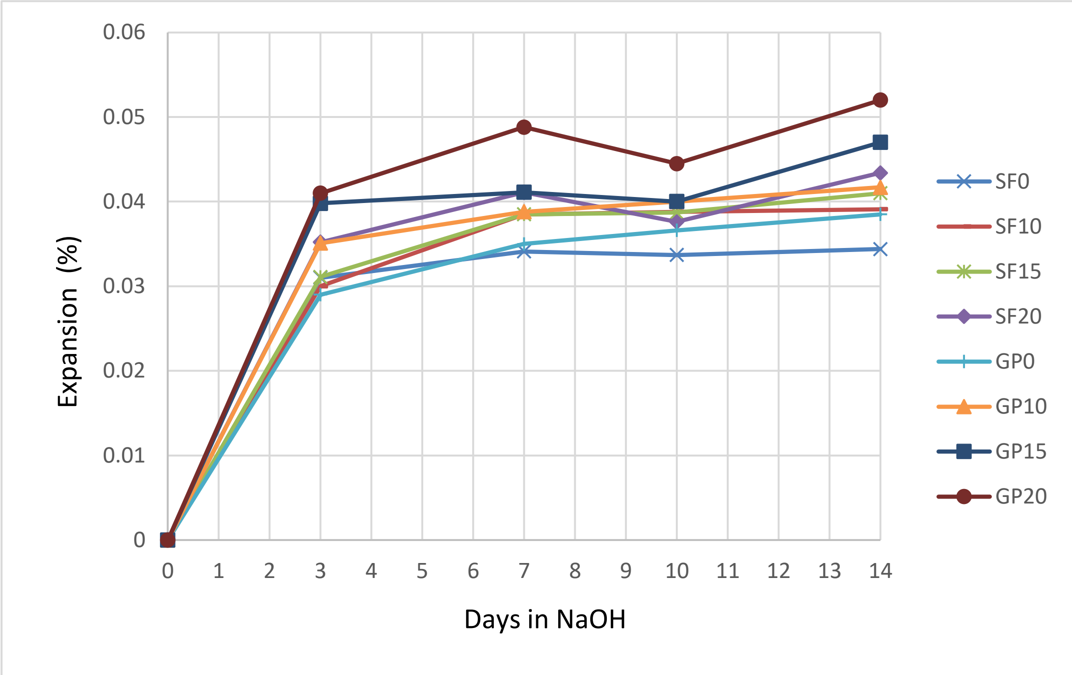

Figure 4.11: Expansion vs. Time Due to ASR

It was observed from the ASR expansion that all specimens were nonreactive after 14 days in NaOH; the resulting expansion is less than 0.1% according to ASTM C 1260. Results for both SF and GP mixture groups show a decline in ASR expansion. Increasing the percentage of WG as a coarse replacement with 5% glass powder content reduced the level of expansion in spite of the higher alkali content. ASR results showed that the expansion for 5% GP as an additive was slightly higher than mixtures using 5% SF as an additive. Moreover, increases in the percentage of WG to 10, 15, and 20%, slightly increased the expansion perhaps due to the use of coarser glass particles. As Table 4.10 shows, the expansion for the SF5 group at 0, 10, 15, and 20% replacement levels of WG as a coarse aggregate were 0.0344, 0.0391, 0.0410 and 0.0434%, respectively. For the GP5 group, the expansion results for the 0, 10, 15, and 20% replacement levels of WG as a coarse aggregate were 0.0385, 0.0417, 0.0470 and 0.0520%, respectively. Therefore, ASR testing confirmed that silica fume performed better at hindering expansion compared to glass powder specimens. Figure 4.12 shows the results for expansion over time at 3, 7 ,10 and 14 days, for which it can be seen that the there is a fluctuating increase in the rate of expansion.

4.3.7 Water Absorption Capacity

The water absorption capacity results for the hardened specimens of eight different mixtures: four percentages of WG replacement at 0%, 10%, 15% and 20% with either 5% GP or 5% SF as additives, are shown in Figure 4.13.

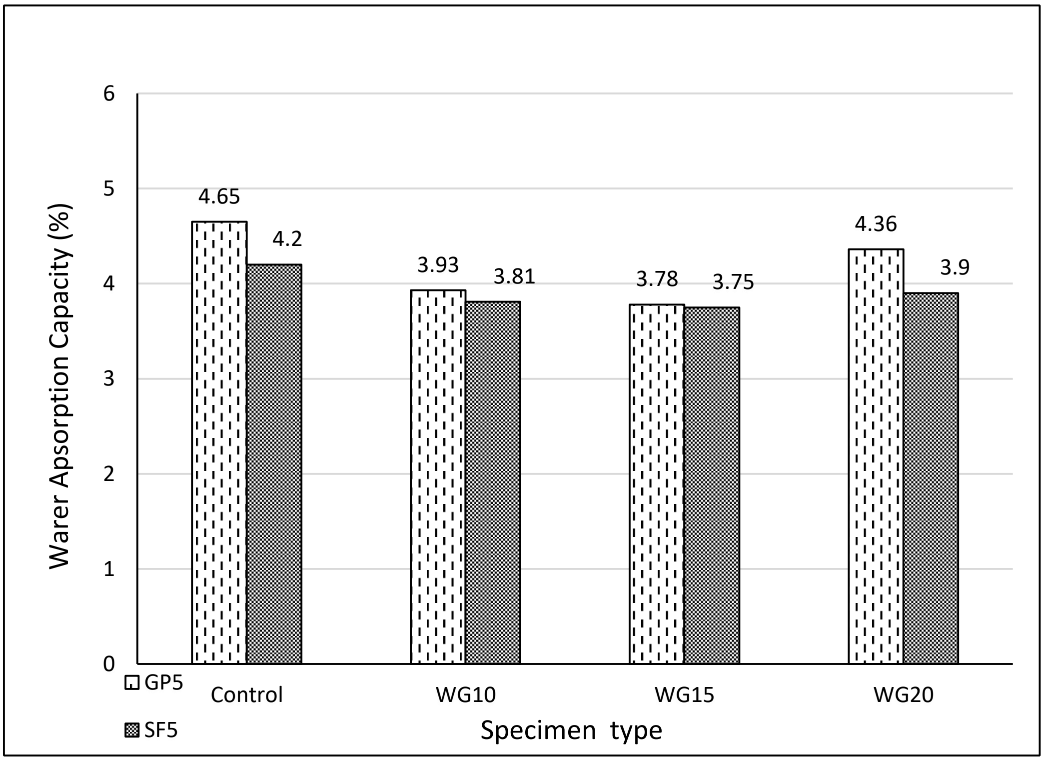

Figure 4.12: Water Absorption Capacity Test Result

As can be seen from Figure 4.13, the GP5 mixture group showed a greater influence on its water absorption capacity. This decreased for concrete mixes containing up to 15% WG, while the SF5 mixture group showed smaller decreases than the GP5 mixtures. There was a general increase, however, in the water absorption capacity of both GP5 and SF5 concrete mixtures with more than a 15% WG content.

The decrease in the capacity for water absorption is because both the GP and SF acted like a filler material and reduced the number of voids in the concrete. This can be explained by the fact that SF and GP have particles finer than cement particles, which can fill the latter's capillary pores physically. Furthermore, the pozzolanic attribute of the additives was also effective on the gel structure. However, when the quantity of waste glass as a coarse aggregate replacement is raised, the result is a weakened concrete specimen that absorbs extra water. The increase in water absorption results from the formation of voids that tends to occur in concrete with high WG replacement levels.

Chapter 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

In this research, eight different mixes were produced by replacing coarse aggregate with waste glass at 0%, 10%, 15%, and 20% for each of the two additives: silica fume and glass powder. The objective was to determine the effects of WG incorporated with the additives on the mechanical and durability properties of concrete. The mixes containing 0% waste glass replacement with either 5% glass powder or 5% silica fume were used as a control.

The outcomes of the tests conducted on the fresh and hardened concrete mixes led to the following conclusions and some suggestions for future research:

1. The incorporation of waste glass has positive effects on the mechanical properties of concrete and negative effects on the durability of concrete when the replacement level reaches 20 % WG.
2. The replacement of natural coarse aggregate with waste glass particles affects the properties of fresh concrete. The workability tests (Slump test) indicate that the workability in all mixes decreased as the WG content increased. However, the slump value is lower for mixtures containing silica fume instead of glass powder as an additive because slump value has a direct correlation to the size of the particles, where finer particles will have a less slump value.

3. The use of waste glass as a coarse aggregate increased the compressive strength and the splitting tensile strength of the mixtures due to the small percentages used in this study (20%) but could have more negative effects at higher percentages due to the proprieties of waste glass. On other hand, because of silica fume's direct relation to strength development and its filling the voids between cement particles, the pastes are denser and the addition of the pozzolanic reaction between silica fume particles also enhanced the compressive and splitting tensile strength of the cement. This was not the case with mixes containing glass powder because its particles are non-pozzolanic and it is an inert material.
4. Flexural strength also increases as the percentage of WG particles increases due to the good bonding between aggregates and cementitious materials, as well as the reasons already mentioned in point 3 above.
5. As the waste glass content in the concrete increases, the impact energy (resistance) of the specimens was found to decrease. The reason is related to the properties of waste-glass-based cement composite and the crack control mechanism of the glass, which in turn relates to properties that affect cracking, such as resistance to impact and the brittleness of waste glass.
6. It was also found that carbonation was increased by increases in WG content, which conforms to the pattern observed in concrete for several pozzolanic materials and is most likely the result of the reduction in Calcium Hydroxide (CH). This can be attributed to the higher reactivity of SF and thus, the resulting CH decrease relative to GP.
7. The substitution of coarse aggregate with waste glass particles reduces the ASR expansion and all of the specimens were nonreactive after 14 days in NaOH

with expansion rates of less than 0.1% according to ASTM C 1260. The results for both SF and GP mixture groups show that WG replacement is effective in reducing ASR expansion.

8. Both the GP5 and SF5 mixtures showed a significant effect on the water absorption capacity of the concrete. This decreased for concrete mixes containing up to 15 % WG in both groups, although the decreases recorded for the SF5 mixture group were less than the GP5 mixtures. There was, however, a general increase in the water absorption capacity of both GP5 and SP5 concretes with more than 15% WG content.
9. The statistical correlation between the results was also considered and it was found that there is a direct proportional linear regression relationship between compressive strength and splitting tensile strength, and also between compressive strength and flexural strength.

5.2 Recommendations for Future Studies

1. This study was done to measure the mechanical properties of concrete after 28 days. Similar studies could further explore the properties of concrete over longer period of time.
2. Other studies could also research the combined effect of waste glass particles as a partial replacement for fine and coarse aggregate on concrete performance;
3. The influence of using waste glass particles on the mechanical behavior of fiber-reinforced concrete;
4. The effects of high percentages of waste glass up to 60% or more on concrete properties;
5. Investigate the durability properties of WG concrete, such as water permeability, rapid chloride permeability, creep, plastic shrinkage and drying

shrinkage, resistance to freezing and thawing, and degradation test at elevated temperatures; and

6. Study the possibility of increasing the strength of waste glass concrete.

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