CHARACTERISTICS OF CONCRETE BUILDING UNITS CONTAINING CRUSHED WASTE GLASS

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Title

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MASTER OF SCIENCE

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ABSTRACT

"Glascrete" the term used for concrete in which all the aggregates or part of it are substituted by crushed glass. Glass is the only material that can be recycled many times without changing its properties; these properties making it an ideal material in concrete.

The goal of this research was to evaluate the compressive and splitting tensile strength of concrete mixes containing different glass aggregate replacement up to 20 % by volume of sand; with and without admixtures. 144 cubes and 144 cylinders were prepared with different admixtures then tested for compressive and splitting tensile strength.

The results indicate that the addition of glass replacements from 5% to 20% by volume of sand; led to 3.8% - 10.6% decrement in compressive strength and 3.9% - 16.4% decrement in tensile strength comparing with 21-day of control mix. However, the use of mineral admixture improved the mixes properties at all ages.

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LIST OF ABBREVIATIONS

AASHTO…………………..American Association of State Highway and Transportation Official

ASR………………………Alkali-Silica Reaction

C-S-H…………………….Calcium Silica Hydrates

GA………………………..Glass Aggregate

GP………………………...Glass Powder

L.O.I……………………...Loss on Ignition

I.R………………………...Insoluble Residue

HRM………………………Highly Reactive Metakaolin

OPC……………………….Ordinary Portland Cement

SF…………………………Silica Fume

T…………………………..Splitting Tensile Strength

W/C……………………….Water Cement Ratio

W/CM……………………..Water Cementitious Material Ratio

WRA………………………Water Reducing Admixture

CS…………………………Compressive Strength

C…………………………...Control Mix

GA-5 ………………………Mix with cement only and 5% of glass aggregate (GA)

GA-10 ……………………..Mix with cement only and 10% of GA

GA-15 ……………………..Mix with cement only and 15% of GA

GA-20 ……………………..Mix with cement only and 20% of GA

AGA-5 …………………….Mix with cement and 12% of HRM and 5% of GA

AGA-10 …………………...Mix with cement and 12% of HRM and 10% of GA

AGA-15 …………………...Mix with cement and 12% of HRM and 15% of GA

AGA-20 …………………...Mix with cement and 12% of HRM and 20% of GA

WR ……………………….Mix with cement, sand and 12% of WRA by weight of cement

WGA-20 …………………...Mix with cement, 20% by volume of GA and 1.2% of WRA

WAGA-20 …………………Mix with 12% of HRM and 20% of GA and 1.2% of WRA

CHAPTER ONE. INTRODUCTION

1.1. General

The proper and secure disposal of waste materials has been regarded a main interest for the city districts all over the world. Although many researchers tried to study the recycling and with all the regulation and limitations regarding waste disposal and stockpiles, but still the collecting of waste materials without explanation, At this point, the concept of waste recycling into construction materials was created. This new use for waste has advantages in decreasing the quantity of waste materials needing disposal, and also in providing construction materials with important cost saving in raw plants.

Different kinds of waste materials have successfully been reused in the construction industry, for example; old asphalt, recyclable cement, brick, plastic, steel, tires and others. Recent years, significant interest has been given to waste glass. Many models or forms of glass were produced such as container, flat; bulb, and cathode ray tube glass, all of them have short and very limited ages regarding the purposes which are manufactured for. And it is so important to recycle it to get rid from the pollutions problems occurred if sent it to the landfill.

Glass is the only material that can be reprocessed more than one time with keeping its chemical properties; many things stand behind the recycling procedure’s efficiency and they affected this process. Because glass must be sorted by color (clear, green, amber, etc.) in order for it to be suitable for manufacturing new glass containers, the first one is the capability of gathering and ranking methods for glass. Second, the recycling process is affected by the level of contaminates present in glass stockpiles. Finally, because most of the cities don’t have recycling facilities, shipping costs may affect the efficiency of the recycling process as well, that is why it considered the glass could be used into concrete building units, and it would have significant decreasing the need to dispose of waste glass and use it in a cheap and limited purposes such as sub base materials in the road projects. So the material “Glascrete" has been created. Glascrete is a concrete in which the aggregates (sand) wholly or partially substituted by glass, producing charming appearance. The smoothness, the variance colors and reflection property of glass aggregate while substituted with sand in concrete gives it a very attractive and beneficial use in decorative applications such as masonry works, wall partitions, all kinds of tiles , panels, elevator panels, park seats, and curbstones.[1]

1.2. Beneficial Properties of Glass

Regarding the construction material, glass produces many benefits that could be used it in the concrete companies. Some of these benefits properties are :[2, 3]

1. The rigidity of glass gives the glascrete abrasion strength as compared with natural sand while using it in concrete building units.
2. The glass has zero water absorption; so it will improve the workability of fresh concrete due to the reduction of w/c ratio without using WRA.
3. The very small particles of glass has pozzolanic characteristics when it crushed and used as a partial replacement of cement as compared with sand (natural stone), this properties allowing it to use as a partial cement replacement. By considering the high volume of cement consumption, this has the capability to provide an economic advantage.
4. The differences in colors and reflectiveness properties of glass aggregate gives it a good light reflection as compared with the common aggregate, thus it is very important to use it in decoration applications and reflect the lights during night trip.

5. The waste glass always available, so that, the glascrete could be cheap material (economy advantages).

1.3. Research Strategy

Using waste glass as a concrete component has been given a great concern recently. It is considered the best options for solving the related disposal problem; on the other hand, it has the capability to create new possibilities for architectural applications. The main goal of this study is to evaluate the physical properties of mortar mixes that contain different volume replacements of waste glass as fine aggregate substitution, with and without additives. Mineral additives are used to improve the mechanical properties of glascrete mixes and to improve its chemical resistance by absorbing the OH^- ions responsible for the possible alkali-silica reaction (ASR) and to reduce its adverse effects on mix dimensional stability. Water-reducing admixtures are used to reduce the impact of the ASR by minimizing the amount of moisture in concrete, which decreases the possibility of expansion of any produced gel.

1.4. Objective and Scope

This research was conducted to evaluate the compressive and splitting tensile strength of concrete mortar containing waste glass, studying on different substitutions related to this subject. This thesis specifically covers the following objectives:

1. Investigating the effect of adding four different volume replacements up to 20% of crushed waste glass as a partial replacement of fine aggregate on the properties of the glascrete mixes.
2. Studying the impact of cement replacement on mix properties using mineral admixtures from local store.

3. Evaluating the effect of using a water-reducing admixture (WRA) on the fresh and hardened properties of different mixes.

To achieve the above objectives, 12 mixes were used to study workability, fresh density, compressive strength, and splitting tensile strength. Throughout this study, the compressive strength measurement was performed on 144 glascrete cubes. The splitting tensile strength test was conducted on 144 cylinders. The percent of WRA was measured in a trial and error procedure using the slump test. Finally, the percentage of met kaolin was measured throughout 18 cubes. Figure 1.1, shows the detail of the lab work.

1.5. Research Layout

The work presented in this study is covered in six chapters. Chapter one includes an introduction to the subject. Chapter Two covers the review of relevant literature about the use of waste glass in many construction applications, the using of waste glass as an aggregate and as mineral admixture, the possible alkali-silica reaction, and the common ways to avoid its consequences. Chapter three deals with an overview of the materials considered in this study and preparation, mix proportioning, testing methods, and experimental work. In Chapter Four, the results of the experimental tests are presented along with a discussion and interpretation of the results. Chapter Five is concerned with the properties of glascrete products. Finally, the outcome derived from this study and recommendations for future work are presented in Chapter Six.

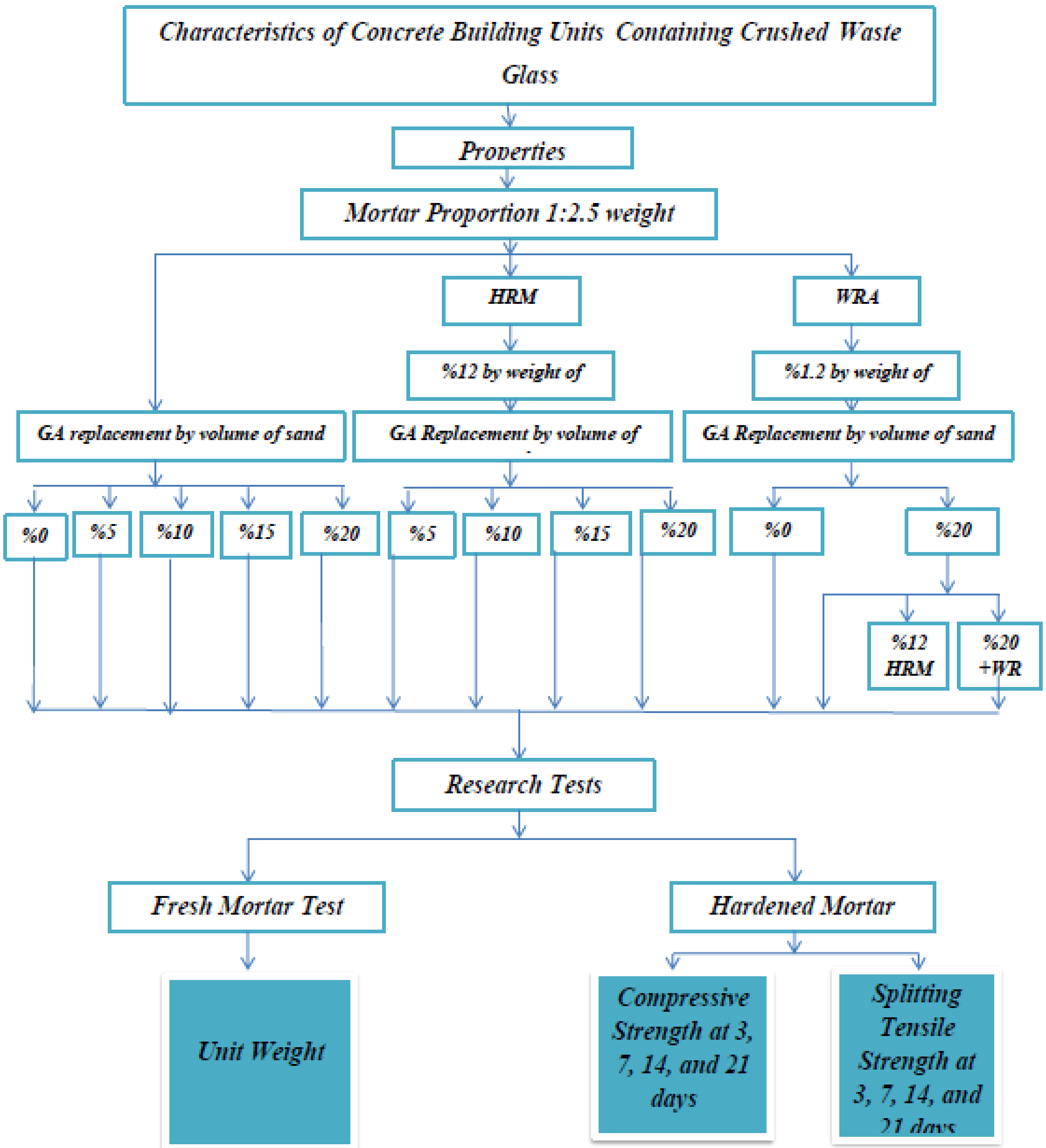

Figure 1.1. Sketch of the lab work

CHAPTER TWO. LITERATURE REVIEW

2.1. General

The using of waste glass as a high value market and quality materials has received a good interest in present time. Waste glass became a main issue for districts all over the world due to the changes in the environmental laws, so it could be a significant encouragement to use the waste glass in different construction applications.

This part of the study presents a review of some of the current literature related to the usage of waste glass in construction and non-construction applications, but it is specifically concentrated on the using of waste glass as a fine aggregate and mineral additives materials in the concrete system. Great interests are also examined the possible alkali-silica reaction and the common ways to avoid its adverse effects.

2.2. General Applications for Glass Cullet

Glass cullet is a material produced from recycling glass (the glass already used in different forms and shapes such as bottles, jars and vessels). The material always collecting from bottle banks, curbside collection schemes, and places have a large amounts of containers. The main goal for collecting cullet is to process it and return it to the manufacturing process again in order to produce new glass products. The term "cullet" also refers to waste glass produced as a result of breakage and refusing from the quality control during production time. [3, 5] Crushed, graded glass cullet has been widely evaluated in several number of construction and non-construction related applications.

Shaopeng et al [13] presented in their research on "glassphalt" that crushed waste glass could be used in asphalt concrete up to the size of (0.19in) and with an optimal replacement ratio of 10% by weight of aggregate. They also studied that performance indicators such as strength index, stable with high temperature, and water stability have been reached.

Hadlington [12] showed a brief of work carried out by other researchers and organizations. For example, he quoted from the Dryden Aqua Company that very fine glass particles can be used as a filtration media for purifying water. Colored glass (green or amber) may be ground into particles of less than a tenth of a millimeter and, during this process; a net negative electrical charge will be left on the particles surfaces, enabling them to attract grays. Filters made from colored glass grains can also split oxygen molecules into single, highly reactive oxygen molecules responsible for drawing microbes to the surface of the grains and killing them.

Smith [15] presented that ground glass can be added to clay during brick manufacturing to save energy costs and produce bricks that are more resistant to the frozen. Glass powder behaves as a “fluxing agent” during the melting process, leading to a reduction in a temperature and time that should be used for melting. Bricks manufactured in this way also have lower water absorption rates and higher compressive strength.

Sagoe, et. al [7] stated in their work that ground glass cullet, due to its high abrasion resistance, has been used as an abrasive material in sandblasting for site cleaning and removal of rust or paint. Glass cullet has the advantage of containing no poisons elements and has less than 1% crystalline silica, so it does not present any risks which appear with natural sand. [7, 14]

Reindl [4] reported that glass cullet can be used through a different uses, including roads aggregate, paving, concrete aggregate, building units such as (tiles, bricks, wall panels, etc.), fiber glass insulation, glass fiber, abrasive, art glass, landscaping, reflective beads, and hydraulic cement. The critical requirement in all of these applications is that the correct engineering properties of the glass cullet must be well understood and defined for the targeted application. [7]

The South Dakota School of Mines and Technology reported that glass cullet in more ways; it is ideally suitable for use as a backfill material with different levels of replacement up to 100%. Due to the zero water absorption makes it suitable for use as a bedding material for pipes and paving stones because the consolidation would be zero as well. Crushed glass cullet is a very stable in moisture places, hence with a good compaction; it does not lead to settlement so it would not cause any rutting when used in streets.

Weitz [9] stated that the American Association of State Highway and Transportation Officials (AASHTO) recently found the use of recycled materials in pavement also produced new properties called "Glass Cullet Use for Soil Aggregate Base Course." The specification clarifies that. In case of a good processed, glass cullet can produce materials with good stability and load support (zero consolidation) while using it as a road or highway bases.

Crushed glass cullet has been used as an aggregate or bituminous concrete pavement has common name as "Glassphalt" [8, 11]. Many field tests of Glassphalt pavements have been carried out in the past [10]. It has been found that Glassphalt keeps heat much more time than the traditional asphalt, which may be beneficial when road work is conducted in cold area or when long drive distances are required. Furthermore, the glass particles increase the reflectivity of road surfaces, therefore improving night-time road visibility. [8]

2.3. Use of Waste Glass in Concrete

Many efforts have been conducted to use glass cullet into concrete applications. In the past, many researches were investigated the glascrete without perfect explanations. In recent years, the scientific development and changes in environmental laws have encouraged the use of glass cullet as one or more elements of concrete. Cullet has been used in concrete in three types:

as a coarse aggregate (gravel), as a fine aggregate (sand), and in a powdered form (mineral admixtures). [16, 17]

2.3.1. Glass Aggregate in Concrete

Recently, many research attempts have been conducted on the use of waste glass as a partial replacement for both fine and coarse aggregates in concrete. Waste glass which has been crushed and checked to be used as a sand replacement behaves the same way to quartz sand, being a hard, crushed material with about the same particle density. It was examined that concrete mixes containing a glass aggregate produce a higher abrasion resistance and lower drying shrinkage as compare with concrete made with quartz sand or similar materials as a fine aggregate. [3]

Sagoe et al [7] showed that the use of a very fine glass aggregate with a particle size < (0.0968in) would not cause important differences in the fresh concrete properties. They indicated that the percent of strength improvement follow a semi-linear relation between a 5% and 30% glass replacement levels. A corresponding 5% reduction in compressive strength was recorded at 5% glass aggregate replacement by weight of sand compared to a 27% reduction at a 30% glass aggregate replacement level. Also, they presented that the reduction in strength is due to the mechanical properties of glass aggregate, rather than its chemical properties. The ideal replacement was recorded to be 20% by weight of the fine aggregate.

Shehata et al [19] studied the impact of incorporating waste glass as a partial volume replacement for the fine aggregate on the physical properties of the concrete composites. Different glass aggregate replacements have been evaluated up to 20%. The important findings of this investigation show the following:

1. The use of a fine glass aggregate did not affect the physical properties of glascrete mixes as compared with control mix. However, the 28-day compressive strength and tensile strength were below the control mix by 15% and 11% respectively, although the compressive strength and tensile strength of the 20% replacement showed values very close to the control mix.
2. Higher modulus of rupture values were investigated for all glascrete mixes relative to the control mix. The main discovering in this research are that good interfacial bonding exists between the cement paste and glass aggregate and that the glass aggregate acts as a crack arrestor, preventing cracks from spread through the concrete structure.

A similar investigation was confirmed by **Siddiqui et al** (18) where the results of a three-support point bending moment test on concrete blocks containing different sizes of glass aggregates indicated that the load carried by these blocks increased gradually with the increasing of particles size of glass aggregates., The research also stated that the route of cracks is skewed due to the resistance produced by the glass aggregate. When the crack keeps spread until reaches the glass slide, the load transfers to the slide and the slope in the load-time graph changes until the crack overcomes the obstacle. This behavior leads to high energy.

Shayan (16) verified that up to 50% by weight of the regular aggregate can be replaced with a mixture of coarse and fine glass aggregate for structural and non-structural applications. However, optimal alternatives, such as using suitable pozzolanic materials in suitable proportions, should be taken to decrease the adverse effects of the ASR.

Naik and Kraus (21) developed a flowable concrete by using recycled glass aggregate and fly ash. Two kinds of flowable concrete were investigated (with and without fly ash). Mixes were proportioned with 30% to 75% replacement by weight of sand with glass aggregate and a flow between 12.25 and 13.5 in. (306-337.5mm). The results indicated a good compressive strength for all mixes. It was also found that lessening the fly ash and increment the amount of glass led to rise bleeding and segregation. The permeability of the flowable glascrete also rises with the increment of glass aggregate replacements. However, the glass cullet is considered to be a suitable aggregate for producing flowable concrete.

Different mixes were investigated at **South Dakota School of Mines and Technology** [6] by Hansen and Nielsen in order to maintain the optimum glass/cement ratio. The results showed that the best mix had a 20/20 ratio, where glass aggregate substituted 20% of the total aggregate and fly ash substituted 20% of the cement. This mix has confirmed to be both economically benefits and durability. The 20/20 mixture has actually been used for pavement patching on city streets in the USA.

Naik and Wu, [20] in the study, they were replaced cement with fly ash up to 45% replacements by weight. For each combination of cement and fly ash, up to 45% by weight of fine aggregate was replaced with glass. The compressive and splitting tensile strengths were calculated for all mixes. The results showed that, for every mixes, the compressive strength decreased with the increment of glass aggregate , however, the same quantity of glass aggregate mixed with 15% of fly ash as cement replacement had the increased compressive strength at all ages. Mixes with high amount of cement replacements (30% and 45%) showed a lower compressive strength at early ages, but at the late ages, the compressive strength increased as compared with control mix without fly ash. But the findings showed that all mixes includes splitting tensile strength test was not that much affected by the glass content. Cement replacement with fly ash had the same effect on compressive and splitting tensile strength.

Polley et al, quoted by Parkinson and Visco, [8] showed that glass aggregate is an acceptable replacement for fine aggregate (sand) at replacement levels up to 20% by weight of the whole aggregate in the mix and at a glass gradation between 75μm and 1.5mm. Those mixes indicated semi constant normalized strength with increment glass content. On the other hand, coarse glass aggregate mixes produced reduction in compressive strength as compare with the control mix, generally the strength decreasing as the amount of glass increases. This results because the shape, and the surface properties of glass, and the flakiness of glass particles is high. Polley et al also added that the freeze-thaw durability of waste glass mixes was confirmed by field trials to be generally promising. .

Meyer [23] indicated that the using of glass aggregate could be affect the physical properties of concrete building units due to the lower adhesion and bond strength between the glass aggregate and cement paste. This behavior due to the relatively smooth surfaces of crushed glass particles which replaced the natural aggregate with relatively rough surfaces.

Grand work has been investigated by **Dhir et al** [22] to use a waste glass as filler aggregate in concrete. Dhir et al found that 20% by weight is the optimum replacement to ensure stability of a fine aggregate. This percentage of glass aggregate indicates the highest amount of glass filler aggregate that has been conducted.

2.3.2. Glass Powder in Concrete

In addition to using fine and coarse aggregates in cement, research has been conducted on the use of glass powder in concrete. There are a number of silica-based waste materials that could be added to cement as pozzolanic additions. A very fine particles of ground glass has non-crystallized silica to react with dissolved calcium hydroxide in a moisture condition, consequently forming hydrated compounds as a pozzolanic materials (mineral additives) such as pulverized-fuel ash (PFA), ground-granulated blast furnace slag (GGBS), and silica fume (SF). (16, 24) the using of glass powder (GP) was studied in 1973, (24) however, the significant works have been carried out in the last 10 years. (17, 25) This published research shows that glass powder will react in a pozzolanic material in the cementitious system and will contribute to the strength development of concrete.

Shayan (16) evaluated the long time strength development of Glass powder concrete as compare with silica fume (SF) concrete. The mixes in this study concluded of a reference mix with a reactive fine aggregate and other mixes that contained 10% SF, 20% GP, or 30% GP as partial replacements by weight of cement. The series also contained another mix proportioned with 30% GP, but as a fine aggregate replacement. The results indicated that the 10% silica fume replacement increased the strength as compared with GP replacements, but they also observed that GP mixes continue to increase the strength with time, indicating its pozzolanic activity. Shayan stated that the observed decrement in compressive strength of GP mixes was because the decreasing of cement content rather than the properties of GP. He also indicated that when 30% of fine aggregate was substituted by GP, the 90-day compressive strength was similar to that of SF replacement.

To verify the significant effect that aggregate replacement by glass powder has on compressive strength, another two tests were investigated on cubes immerse for up to 270 days. 20% of the cement was replaced by GP in set one, 10% of aggregate was replaced by GP in set two. The second set showed higher compressive strength compared to the first set.

Shao et al (27) evaluated the pozzolanic behavior of glass having a very fine particle size (less than 30μm). The strength activity index of these particles was 91, 84, 96, and 108% at 3, 7, 28, and 90 days respectively, exceeding 75% at all ages. A size effect was also investigated where the very fine particle size of glass led to higher compressive strength and lower expansion in their concrete composites. Shao et al also indicated that concrete containing glass powder improves the strength at both early and late ages, as compared with concrete containing fly ash. According to **Wild et al** (43), they concluded that there are factors affecting the contribution that high reactivity met kaolin makes to strength when it partially substitute cement in mortar, the filler effect, the acceleration of Portland cement hydration, and the pozzolanic reaction of met kaolin with CH. The effect of filler is soon, the acceleration of Portland cement hydration has maximum influence with the first day of casting, and the pozzolanic reaction makes the maximum contribution of strength between 7 and 14days of age. Base on the research, met kaolin has greatest potential to improve the mechanical and durability properties of concrete. In general, replacement of 8% of the cement in a system should produce significant strength increases and provide adequate protection against corrosion. Replacement with above 20% results decreases in strength while the replacements 8% to 20% continue increasing in strength.

Byars et al (25) showed that the particle size of glass powder is the key to its pozzolanic reactivity, but the type's glass and the level of pollutions seem to have less impact on strength development. Byars et al mentioned that glass powder with a surface area of >3000cm^2/gm.

(3.23sf/0.03527oz) has pozzolanic activity and could be used as beneficial admixture to cement without hindering its properties. Glass powder effect on water ratio also appears to be minimal. Byars et al recommended replacement levels up to 25% by weight of mineral admixture material. In contrast, a feasibility study carried out by the **Concrete Technology Unit at the University of Dundee** [3] concluded that GP with a particle size of >2000cm^2/gm.(2.15sf/0.0352oz) could be used as a cement replacement with replacement levels between 6-20% by weight of cementitious materials.

Reindl [4] presented a summary of work concluded by Samture on this problem, which indicates that fine particle size of glass powder with <75µm particle size could be used in the relatively quick pozzolanic reaction and thereby decrease the effect of a slower Alkali-Silica Reaction at later stage.

Parkinson and Visco [8] showed that study work recently conducted in Sweden has identified that the fine aggregate consisting mainly of glass. The product, "microfileer," was added to the concrete mix during the mixing process and worked as a mineral. This material improved the properties of concrete in fresh and hardened stages.

As a final conclusion from the above literature in this chapter, it can be summarized that waste glass can be recycled and used to replace amount of the Portland cement in concrete mixes. By regarding the size of cement industry, this is a potentially high volume; hence, the use of waste glass in concrete production could be an economic and environmentally friendly solution to a part of the waste glass problem.

2.4. Alkali-Silica Reaction (ASR)

The first research on the alkali-silica reaction was by **Stanton** [26] who observed a reaction of the alkalis in cement with a California aggregate containing opal. The alkali-silica reaction happens between the hydroxide ions existing with the salts of sodium and potassium and the silica of certain amorphous siliceous rocks. The alkalis do not really attack the reactive silica; but, the most important thing is the amount of alkalis in the solution results in an equally high concentration of OH^- ions to maintain charge balance. The high OH^- concentration and high PH value leads to the initial breakdown of reactive silica components in the aggregates. [17, 28, 29] The alkali-silica reaction produces a silica gel that will expand in the moisture. The gel that is formed at the aggregate surface before hardening has a high concentration of lime. It is very important to note that although the alkali-silica reaction is very detrimental to concrete's stability, this chemical reaction can also increase the strength of the concrete to some extent. This increase in strength is usually due to the filling of bond areas with cementitious reaction products that have not caused any deleterious expansion. This process may be considered similar to the pozzolanic reaction in concrete. [29, 31]

2.5. Alkali –Silica Reaction Due to Glass Aggregate

The duties of aggregates in concrete were completely mechanical. Aggregate particles were thought to be unaffected by the cement paste, and they were selected on the basis of their mechanical properties. Recently, found that there are chemical reactions that can happen between some reactive aggregates and cement paste. [29, 31] It is generally believed that glass is unstable in the alkaline environment of the concrete. Although both sand and glass including silica, they behave differently. This behavior is because the difference is attributed to the nature of the silica in sand, which has a regular crystalline structure and is relatively stable and resistant to chemical influences, whereas the same silica in the amorphous form in glass is not. [23, 31] Therefore, intensive research has been conducted to assess the dimensional stability of glascrete mixes with regard to the alkali-silica reaction.

Meyer [23] showed that the expansion due to the Alkali-Silica Reaction increases with the increasing of a very fine particle size up to the certain point, and then decreases after this point.. Clear glass was found to be the most reactive, followed by amber (brown) glass. On the other hand, green glass did not cause any detrimental expansion; instead, fine particles of green glass can actually reduce expansion. The green color in glass comes from adding Cr_2O_3 (chromium oxide) to the glass through manufacturing process, however, adding chromium oxide directly to the concrete mix has not been found to suppress the ASR. [2, 14, 25]

2.6. Ways to Decrease Alkali-Silica Reaction

Today, numerous research projects are being carried out worldwide to confirm the possibility of incorporating recycled glass into concrete products, and various approaches have been developed to deal with the ASR problem. [2, 28, 29, 34, 35] The most common ways to mitigate the ASR are summarized below:

1. Cleaning the glass aggregate as much as possible. This is very important to decrease the alkalis on the glass, and then decreases the level of contaminants that would change the initial setting and hardening of concrete.
2. Adding minor constituents at the melting stage to create ASR-resistant cement or modified glass. This method has a potential benefit if post-consumer glass is melted and re-colored specifically for the decorative concrete aggregate markets.

3. Increasing the using of very fine particles of glass aggregate. Very small particles size led to accelerate the reaction, then allowing the gel to expand before the concrete hardens.
4. Decreasing the alkali content of the concrete, as mentioned earlier. The use of low alkali cements (cement limited with 0.60 % on the Na_2Oeq in accordance with ASTM-C150 [33] can be effective, as long as alkalis from the environment are kept away.
5. Using an air entrainment system to incorporate same distribution microscopic pockets of air in the cement paste. These air pockets allow additional space for the gel to expand.
6. Using low alkali minerals as partial cement replacement, where mineral admixtures absorb the alkali ions responsible for the reaction.
7. Using a retarder to slow the curing time of the cement paste. This allows more time for the alkali-silica gel to form and expand before concrete hardening, resulting in less internal stress.
8. Decreasing the moisture in the Portland cement concrete mixture, which will decrease the expansion of any gel produced. Water-reducing or high range water-reducing admixtures can be used to achieve this goal.
9. Air drying the poured cement concrete for many weeks to months. Air drying seems to close the alkalis in a solid state, and future re-moist of the concrete by brings a part of the alkali back into the solution.
10. Sealing the concrete to keep it dry. This can minimize or avoid the ASR problem because the reaction needs three factors (alkali, silica, and moisture) to be active. Hence, indoor uses could be one of the most durable applications.

CHAPTER THREE. MATERIALS AND EXPERIMENTAL WORK

3.1. General

The experimental work in this research was carried out in the Laboratory of the Civil Engineering Department at North Dakota State University in Fargo, North Dakota.

In this study, 12 mixes (including different glascrete mixes) were evaluated to study their engineering properties and to find out their behavior. Crushed waste glass was partially replaced for the fine aggregate (sand) in different replacements, with and without mineral admixtures. The materials, work designs, and all tests are explained in this chapter.

3.2. Materials

3.2.1. Cement

The cement used in this research was ordinary Portland cement Type (1), and it was placed in a dry place to decrease the effects of humidity on cement properties. Table 3.1 provides some of the chemical properties of the cement which was used throughout this study. Figure 3.1 shows the weight of cement.

Figure 3.1. Preparing the weight of materials (cement)

Table 3.1. Chemical properties of cement Type (1)

MgO (%)	SO_3 (%)	L.O.I. (%)	I.R. (%)	C_3S (%)	C_3A (%)	Total Alkali (%)
1.7	3.4	1.1	0.32	54	7	0.53

3.2.2. Natural Fine Aggregate

The fine aggregate used in this investigation was bought from a local store in Fargo. Unable to grade and find the specification of the fine aggregate were due to the lack of instruments in our lab, but according to ASTM C136, the absorption is 1.3% for the fine aggregate. Figure 3.2 shows the weight of fine aggregate (sand).

Figure 3.2. Preparing the weight of materials (sand)

3.2.3. Glass Aggregate (GA)

All of the glasses in this research were already crushed by the manufacturer, and the first step is to make sure the glass well crushed; on the other hand, all the glass in this test was clear. Crushed glass has the same feel as regular sand, decreasing the worry that workers could not hurt and get bloody hands when using glass concrete units [7, 13, 14, and 23].The fine clear glass was ground to 0.1in or below [7], it was between 5% and 20% by volume of GA as a partial replacement of sand. The next step was getting the specification of glass from the origin (i.e. the manufacturer). Finally, the glass was washed to limit the effect of constituents that affect the rate of concrete setting and hardening [18, 22]. Table 3.2 shows the mechanical analysis provided through the manufacturer of the glass aggregate (AASHTO T-27) used in this research; the sample used in this study was #30 (600 µm).

Table 3.2. Mechanical analysis of glass aggregate

% Passing #16 (1.18 mm)	100%
20 (850 µm)	99.9%
25 (710 µm)	99.4%
30 (600 µm)	98.5%
35 (500 µm)	90.7%
40 (425 µm)	77.5%
45 (355 µm)	57.1%
50 (300 µm)	39.5%
60 (250 µm)	19.4%
70 (212 µm)	10.0%
100 (150 µm)	1.3%
120 (125 µm)	0.5%
140 (106 µm)	0.3%

3.2.4. Mineral Admixtures

Pozzolans in a very fine particle size form react with $CA(OH)_2$ and water to form calcium silicate hydrates (C-S-H), which are same with those formed by cementitious materials. [42] The pozzolans material produces the binding action in concrete and provide increasing density, lead to reduce porosity and permeability, then improving strength and durability due to the increasing the chemical resistance, Also significantly affect the cost of construction material.

Highly reactive met kaolin (HRM), brought from a store in Chicago, it used as a mineral admixture in this research. HRM is a reactive material produced by burning clay at a temperature of 700-900°C (1290-1650 F) as mentioned in product sheet and specifications. Figure 3.3 shows the glass aggregate and HRM ready for mixing.

Figure 3.3. Preparing the weights of material (glass aggregate and HRM)

3.2.5. Determination of the Optimum Replacement of Mineral Admixtures

To find the suitable replacement of mineral admixtures (HRM) by weight of cement, many trials were investigated. Those were 8, 10, 12, 14, 16, and 18%, as mentioned in literature review; replacement of 8% of the cement in a system produce significant strength increases and provides adequate protection against corrosion. Replacement with above 20% results decreases in strength while the replacements 8% to 20% continue increasing in strength. [43]

All mortars consisted of one part cement or cementitious materials and 2.5 parts of sand by weight. Commonly, 1:2.5:5, 1:1.5:3 or 1:2:4 formulas are used for concrete mixture, but in this study, I have used a 1:2.5 formula in order to concentrate on the use of cement and sand with all additives and without gravels. Further, in my experience, this formula provides good strength results. The water/cement ratios were adjusted to obtain a good flow and workability by using a slump test. The concrete slump test is an empirical test that measures the workability of fresh concrete; more specifically, it measures the consistency of the concrete in a specific batch. It is also used to determine consistency and ensure uniformity among different batches of similar concrete. The slump test is popular due to the simplicity of the procedure and apparatus used. From each replacement in our study, three (6in) cube specimens were molded. After molding, the specimens were placed in a standard moist room maintaining a temperature of 73F±2 and a relative humidity of approximately 95% for 24± 4 hours. The cubes were then de-molded and placed in saturated water. The optimum replacement was found to be 12% by weight of cement, as shown in table 3.3

Table 3.3. Optimum replacement of (HRM) by weight of cement and corresponding w/c ratios for tested mortar mixes

%HRM by weight of cement	w/c or w/cm gives good flow and workability%	Compression strength at 7 days (psi)
0	0.54	3822.11
8	0.56	3481.25
10	0.57	3522.51
12	0.58	3612.10
14	0.60	3455.55
16	0.62	3295.32
18	0.64	3288.89

3.2.6. Water-Reducing Admixture (WRA)

A water-reducing admixture (WRA) can be defined as an additives that reduces the w/c ratio required to produce concrete of a given cohesion. [41] As explained in the literature review, the influence of the Alkali-Silica Reaction can be decreased by decreasing the amount of moisture in the Portland cement concrete mixtures, which will minimize the expansion of any gel produced. The minimizing of w/c ratio in mortar would also increase in viscosity, so that the mixture may be hard in work and cast. If a lower viscosity is needed, WRA can be added. The WRA used in this study was POLYHEED 1020, a mid-range water-reducing admixture. This product is a versatile and economical concrete plasticizer with a wide dosage range suitable for various applications. The properties of this product include improved workability without increased water, reduced water without loss of workability, increased strength, improved surface finish, and reduced shrinkage and creep. POLYHEED 1020 conforms to the requirements given in ASTM C494-99 [41] for type A- water-reducing admixtures.

3.2.7. Optimal Dosage of Water-Reducing Admixture

In set 4 and with all mixes containing the water-reducing admixture, the same optimum dosage was used. The optimum water-reducing admixture was obtained by increasing the dosage of the admixture gradually and adjusting the w/c ratio to obtain the same workability by using the slump test method. The percentage of water reduction at each mix was recorded. Many dosages were evaluated until the optimum dosage of the WRA was reached; at that dosage, the water reduction reached its maximum value and no more water reducing could be obtained.

The recommended dosage of the water-reducing admixture in the product data sheet ranged from 0.5% to 1.1% by weight of cement or cementitious material. The first trial mix started with a dosage 0.6% by weight of cement, and the dose increased at steps of 0.2% by weight of cement at each trial until optimum dosage was obtained. Table 3.4 shows the results of the trial mixes.

Table 3.4. Effect of WRA dosage on the w/c ratio

Dosage of %WRA by weight of cement	w/c Ratio gives perfect flow	Water Reduction %
0.0	0.54	0.0
0.6	0.48	11.1
0.8	0.47	12.9
1.0	0.46	14.8
1.2	0.45	16.6
1.4	0.45	16.6

3.2.8. Water

Ordinary Fargo city water was used for all concrete mixes, as well as for curing.

3.3. Experimental Work

3.3.1. Mix Proportions

In order to achieve the objective of this research, the concrete mixes were classified into four sets; these sets included 12 mixes. The details, mold descriptions, curing periods, tests, and proportion of mixes are shown in the tables 3.5 through 3.18 respectively.

Table 3.5. Description of mixes

Set No.	Designations	Mix Description
1	C	Mix with cement and natural sand only
2	GA-5	Mix with cement only and 5% by volume of GA as partial replacement of sand
	GA-10	Mix with cement only and 10% by volume of GA as partial replacement of sand
	GA-15	Mix with cement only and 15% by volume of GA as partial replacement of sand
	GA-20	Mix with cement only and 20% by volume of GA as partial replacement of sand
3	AGA-5	Mix with 12% by weight of Mineral admixtures(HRM) as partial replacement of cement and 5% by volume of GA as partial replacement of sand
	AGA-10	Mix with 12% by weight of Mineral admixtures (HRM) as partial replacement of cement and 10% by volume of GA as partial replacement of sand
	AGA-15	Mix with 12% by weight of Mineral admixtures(HRM) as partial replacement of cement and 15% by volume of GA as partial replacement of sand
	AGA-20	Mix with 12% by weight of Mineral admixtures (HRM) as partial replacement of cement and 20% by volume of GA as partial replacement of sand
4	WR	Mix with cement, sand and 1.2% of WRA by weight of cement.
	WGA-20	Mix with cement, 20% by volume of GA as partial replacement for the sand and 1.2% of WRA by weight of cement
	WAGA-20	Mix with 12% by weight of Mineral admixture as partial replacement of cement, 20% by volume of GA as partial replacement of sand and 1.2% of WRA by weight of cementitious material

Table 3.6. Control mix(C)

Molds	Size(Inch)	No. of specimens with curing period				Quantity(In^3)	Test Type
		3Days	7Days	14Days	21Days		
Cube	6	3	3	3	3	2592	CT
Cylinder	4*8	3	3	3	3	1206	TS
Total amount of concrete in this set						3798 In^3=0.08 cy	

Table 3.7. Mix with cement only and 5% by volume of glass aggregate as partial replacement of sand (GA-5)

Molds	Size(Inch)	No. of Specimens with curing period				Quantity(In^3)	Test Type
		3Days	7Days	14Days	21Days		
Cube	6	3	3	3	3	2592	CT
Cylinder	4*8	3	3	3	3	1206	TS
Total Amount of Concrete in this set						3798 In^3=0.08 cy	

Table 3.8. Mix with cement only and 10% by volume of glass aggregate as partial replacement of sand (GA-10)

Molds	Size(Inch)	No. of Specimens with curing period				Quantity(In^3)	Test Type
		3Days	7Days	14Days	21Days		
Cube	6	3	3	3	3	2592	CT
Cylinder	4*8	3	3	3	3	1206	TS
Total Amount of Concrete in this set						3798 In^3=0.08 cy	

Table 3.9. Mix with cement only and 15% by volume of glass aggregate as partial replacement of sand (GA-15)

Molds	Size(Inch)	No. of Specimens with curing period				Quantity(In^3)	Test Type
		3Days	7Days	14Days	21Days		
Cube	6	3	3	3	3	2592	CT
Cylinder	4*8	3	3	3	3	1206	TS
Total Amount of Concrete in this set						3798 In^3=0.08 cy	

Table 3.10. Mix with cement only and 20% by volume of glass aggregate as partial replacement of sand (GA-20)

Molds	Size(Inch)	No. of Specimens with curing period				Quantity(In^3)	Test Type
		3Days	7Days	14Days	21Days		
Cube	6	3	3	3	3	2592	CT
Cylinder	4*8	3	3	3	3	1206	TS
Total Amount of Concrete in this set						3798 In^3=0.08 cy	

Table 3.11. Mix with 12% of mineral admixtures as partial replacement of cement and 5% of glass aggregate as partial replacement of sand (AGA-5)

Molds	Size(Inch)	No. of Specimens with curing period				Quantity(In^3)	Test Type
		3Days	7Days	14Days	21Days		
Cube	6	3	3	3	3	2592	CT
Cylinder	4*8	3	3	3	3	1206	TS
Total Amount of Concrete in this set						3798 In^3=0.08 cy	

Table 3.12. Mix with 12% of mineral admixtures as partial replacement of cement and 10% of glass aggregate as partial replacement of sand (AGA-10)

Molds	Size(Inch)	No. of Specimens with curing period				Quantity(In^3)	Test Type
		3Days	7Days	14Days	21Days		
Cube	6	3	3	3	3	2592	CT
Cylinder	4*8	3	3	3	3	1206	TS
Total Amount of Concrete in this set						3798 In^3=0.08 cy	

Table 3.13. Mix with 12% of mineral admixtures as partial replacement of cement and 15% of glass aggregate as partial replacement of sand (AGA-15)

Molds	Size(Inch)	No. of Specimens with curing period				Quantity(In^3)	Test Type
		3Days	7Days	14Days	21Days		
Cube	6	3	3	3	3	2592	CT
Cylinder	4*8	3	3	3	3	1206	TS
Total Amount of Concrete in this set						3798 In^3=0.08 cy	

Table 3.14. Mix with 12% of mineral admixtures as partial replacement of cement and 20% of glass aggregate as partial replacement of sand (AGA-20)

Molds	Size(Inch)	No. of Specimens with curing period				Quantity(In^3)	Test Type
		3Days	7Days	14Days	21Days		
Cube	6	3	3	3	3	2592	CT
Cylinder	4*8	3	3	3	3	1206	TS
Total Amount of Concrete in this set						3798 In^3=0.08 cy	

Table 3.15. Mix with cement, sand and 1.2% of WRA by weight of cement (WR)

Molds	Size(Inch)	No. of Specimens with curing period				Quantity(In^3)	Test Type
		3Days	7Days	14Days	21Days		
Cube	6	3	3	3	3	2592	CT
Cylinder	4*8	3	3	3	3	1206	TS
Total Amount of Concrete in this set						5,094 In^3=0.08 cy	

Table 3.16. Mix with cement, 20% by volume of glass aggregate as partial replacement of sand and 1.2% of WRA by weight of cement (WGA-20)

Molds	Size(Inch)	No. of Specimens with curing period				Quantity(In^3)	Test Type
		3Days	7Days	14Days	21Days		
Cube	6	3	3	3	3	2592	CT
Cylinder	4*8	3	3	3	3	1206	TS
Total Amount of Concrete in this set						3798 In^3=0.08 cy	

Table 3.17. Mix with 12% of mineral admixture, 20% of glass aggregate as partial replacement of sand, and 1.2% of WRA by weight of cement (WAGA-20)

Molds	Size(Inch)	No. of Specimens with curing period				Quantity(In^3)	Test Type
		3Days	7Days	14Days	21Days		
Cube	6	3	3	3	3	2592	CT
Cylinder	4*8	3	3	3	3	1206	TS
Total Amount of Concrete in this set						3798 In^3=0.08 cy	

TOTAL AMOUNT OF CONCRETE IN ALL MIXES	45,576 in^3 = 1.0 cy

Table 3.18. The details of mixes used throughout this investigation

Designation	Cementitious material content(lb./cy)		Fine Aggregate (lb./cy)		Water (lb./cy)	WRA (lb./cy)	W/C or W/CM Ratio %
	Cement	Admixture	Sand	GA			
C	1102.0	--	2755.0	--	600.0	--	0.54
GA-5	1102.0	--	2617.25	137.75	600.0	--	0.54
GA-10	1102.0	--	2479.5	275.5	600.0	--	0.54
GA-15	1102.0	--	2341.75	413.25	600.0	--	0.54
GA-20	1102.0	--	2204.0	551.0	600.0	--	0.54
AGA-5	969.76	132.24	2617.25	137.75	640.0	--	0.58
AGA-10	969.76	132.24	2479.5	275.5	640.0	--	0.58
AGA-15	969.76	132.24	2341.75	413.25	640.0	--	0.58
AGA-20	969.76	132.24	2204.0	551.0	640.0	--	0.58
WR	1102.0	--	2755.0	--	495.9	13.22	0.45
WGA-20	1102.0	--	2341.75	413.25	495.9	13.22	0.45
WAGA-20	969.76	132.24	2341.75	413.25	551.0	13.22	0.50

3.3.2. Procedure of Mixing, Preparation, and Curing

The procedure of the mixing was conducted by using a rotary type mixer for all mixes. The fine aggregate and glass aggregate were used in dry conditions. The dry elements of each mixture were initially mixed for 2 to 3 minutes until a uniform mix was obtained. The required of w/c ratio (with or without water reducing admixtures according to mix's workability) was then added and mixed for additional 3-6 minutes. To obtain a suitable level and fare face of casting and to avoid adhesion between molds and mortar, all of the molds were cleaned and oiled before casting. Specimens were filled in three equal layers and each layer was compacted 25 times with 5/8 inch diameter steel rod with a rounded end.

The top surfaces of the molds were also leveled. After 24±2 hours, each specimen was de-molded from the casting, marked then completely immersed in city water until the time of testing. [39] The materials, mixing procedure, cleaning, oiled molds, and casting, with all steps are show in figures 3.4, 3.5, 3.6, 3.7, 3.8, and 3.9 respectively.

Figure 3.4. The materials ready for mixing

Figure 3.5. Mixing procedure

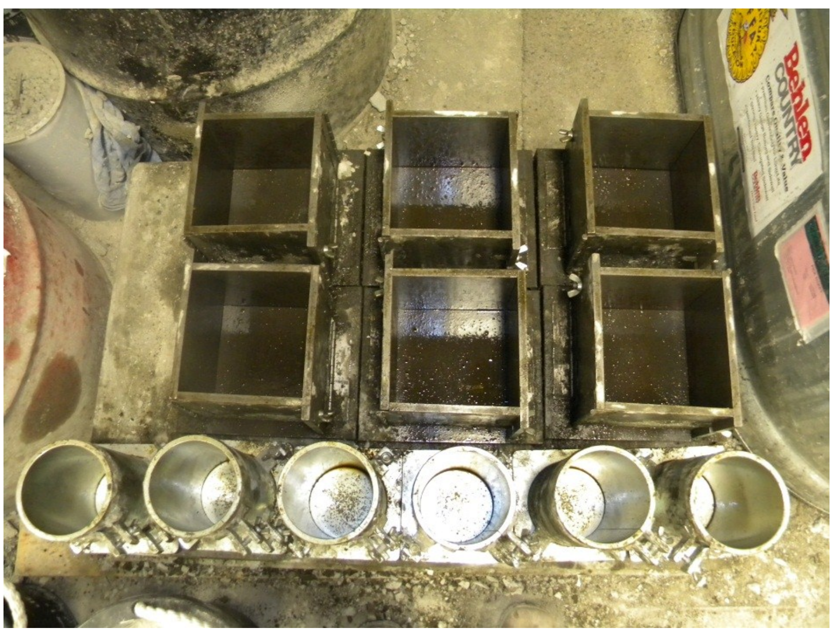

Figure 3.6. Molds already cleaned and oiled

Figure 3.7. Layers of casting

Figure 3.8. The compaction method

Figure 3.9. Leveling the specimens

3.4. Test of Fresh Mortar

3.4.1. Flow Test

The workability test in this research was clarified by terms of a slump test. Slump concrete takes various shapes which are termed as true slump, shear slump, or collapse slump depending on the profile of the slumped concrete. Only a true slump is of any use in the slump test; if a shear or collapse slump results, a fresh sample should be taken and the test repeated. A collapse slump will generally mean that the mix is too wet or that it is a high workability mix, with which a slump test cannot be appropriately used very dry mixes, having a slump of 0 – 1 in., are used in road making and are low workability mixes. Mixes having a 0.4 –1.5 in. slump are used for foundations with light reinforcement; these are termed medium workability mixes. Mixes with a slump of 2 – 3.5 in. are used for normal reinforced concrete placed with vibration. High workability concrete has > 4 in. slump. The slump test is conducted right after mixing.

3.4.2. Unit Weight

The fresh unit weight for all mixes in this study was determined by the following formula:

$D_F = (M_c - M_m) / V_m$

Where:

D_F = Fresh unit weight of concrete (lb. / CY).

M_c= Mass of mold and concrete (lb.).

M_m= Mass of empty mold (lb.).

V_m = Vol. of the mold (CY).

3.5. Test of Hardened Mortar

Two kinds of tests for hardened concrete may be investigated. These are destructive and non-destructive tests. The destructive tests include of compressive strength, splitting tensile strength, and flexural strength. All specimens are taken out of curing tank before testing. While the non-destructive tests include ultrasonic pulse velocity, total absorption, length change, and air dry unit weight. In this study, only compressive and splitting tensile strength tests were carried out due to a lack of time and equipment. The average result of three specimens was regarded for each test.

3.5.1. Compressive Strength

The compressive strength test was taken in the Structural Lab of the Civil Engineering Department on 6in. cube specimens. The cubes were tested by using a compressive machine (available in the structural lab of civil engineering department) with 250 k capacity at loading rate of 250 lb. /sec. The test was conducted at ages of 3, 7, 14, and 21 days. Figures 3.10 and 3.11 show the curing tank and compression machine respectively.

Figure 3.10. The oiled molds with curing tanks

Figure 3.11. The compression machine

3.5.2. Splitting Tensile Strength Test

The splitting tensile strength for all specimens was calculated according to ASTM C496-96 on cylinders of 4x8 in by using the compressive machine in structural lab of civil engineering department with 250k capacity. The loads were gradually increased at the loading rate of about 100lb/sec up to the cubes' failure point. The test was carried out at ages of 3, 7, 14, and 21 days. The splitting tensile strength of the specimens was calculated by the following formula:

$$T = 2P / \pi DL$$

Where:

T = Splitting tensile strength (psi)

P = the maximum applied load indicated by the machine at failure (lb.)

D = Diameter of cylinder (in)

L = Length of cylinder (in)

CHAPTER FOUR. RESULTS AND DISCUSION

4.1. General

The experimental results of this study concerned with fresh and hardened glascrete properties are presented and discussed in this chapter. For the fresh properties, unit weight tests were conducted, while for the hardened properties, tests were classified into two tests: compressive strength and splitting tensile strength.

4.2. Fresh Mortar Properties

4.2.1 Unit Weight

The fresh unit weight for all mixes was determined, listed in table 4.1 and plotted in figure 4.1

Table 4.1. Fresh unit weight for all mixes

Set No.	Details	Designations	Unit Weight (lb./cubic inch)
1	Control Mix	C	0.083
2	Mixes with cement only and glass aggregate (GA) as a partial replacement of sand.	GA-5	0.081
		GA-10	0.076
		GA-15	0.072
		GA-20	0.066
3	Mixes with 12% by weight of the mineral admixture (HRM) as a partial replacement of cement and (GA) as a partial replacement of sand.	AGA-5	0.079
		AGA-10	0.068
		AGA-15	0.065
		AGA-20	0.064
4	Mixes with cement, sand, and 1.1% of WRA by weight of cement, and 20% by volume of GA and 12% of the mineral admixture (HRM).	WR	0.084
		WGA-20	0.068
		WAGA-20	0.067

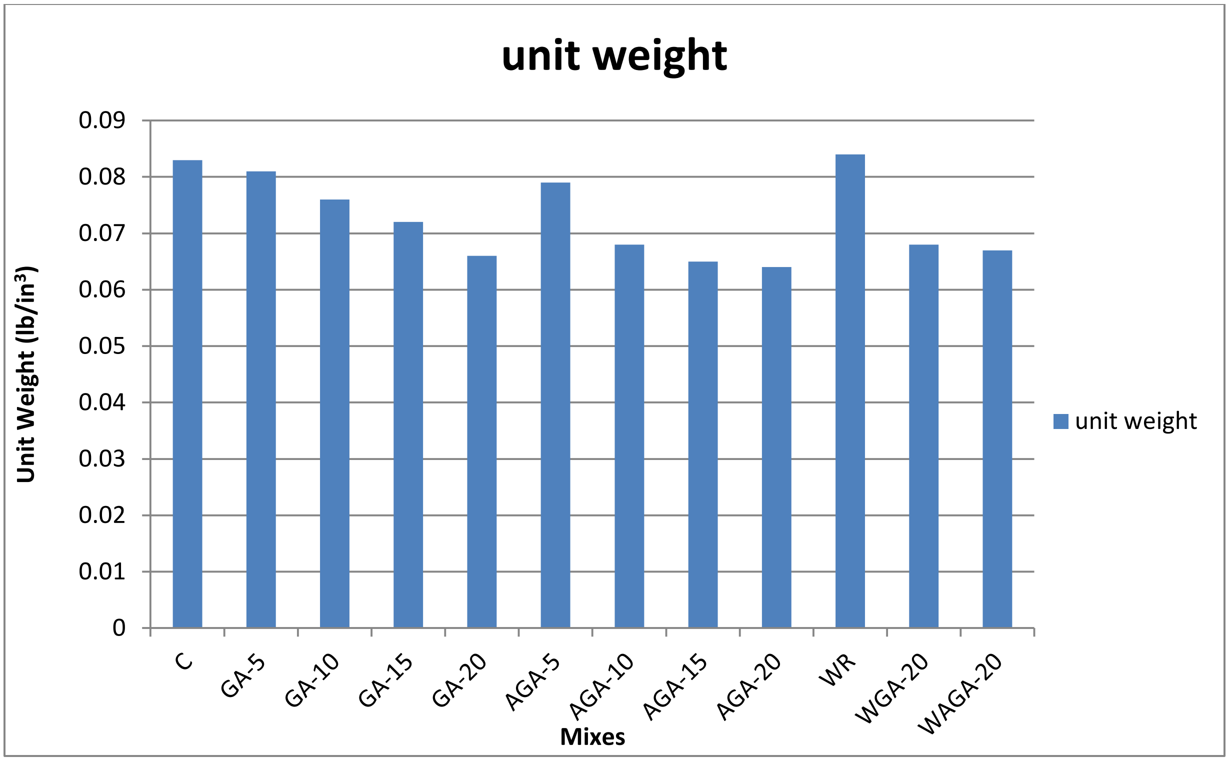

Figure 4.1. Fresh unit weight for all mixes (lb. /in^3)

The results indicate that the using of glass aggregate led to the density of the glascrete mixes decreasing as compared with the control mix. This is because of the lower specific gravity of the glass aggregate as compared with sand. (The specific gravity is the ratio of the weight of a cubic foot of material to the weight of cubic foot of water)

Mineral admixtures mixes indicated lower densities relative to the same mixes without mineral admixtures. This decrease is due to the lower specific gravity of those minerals compared to ordinary Portland cement (O.P.C.)However, mixes containing water reducing admixtures within the set 4 indicated higher fresh densities as compared with control mixes, as shown in figure 4.1. This behavior may be exhibited to the advantage of the reduction of water in concrete mix due to the using of water reducing admixtures.

4.3. Hardened Mortar Properties

4.3.1. Compressive Strength Test

Compressive strength is regarded one of the most important properties of hardened concrete. It is generally the main property value used to investigate the concrete quality in the codes. That is why, it is very important to evaluate whether changes in the mixture composition will affect the early and later compressive strength of concrete. Compressive force results for all mixes at age 3, 7, 14, and 21 days are shown in table 4.2. The compressive strength results for all mixes at ages of 3, 7, 14 and 21days are shown in table 4.3.

Table 4.2. Results of compressive forces (lb.) for all mixes

SET	Details	Designation	w/c Ratio	Compressive Force(lb.) at ages of			
				3 Days	7 Days	14 Days	21 Days
1	Control Mix	C	0.54	138733	141233	178100	195073
2	Mixes with cement only and (GA) as partial replacement of sand	GA-5	0.54	113533	136466	177833	188300
		GA-10	0.54	109359	131126	163177	175392
		GA-15	0.54	105183	124914	152476	166257
		GA-20	0.54	104139	120634	165566	174900
3	Mixes with 12% by weight of HRM as partial replacement of cement and GA	AGA-5	0.58	107271	126480	188800	205700
		AGA-10	0.58	102207	120634	185153	193950
		AGA-15	0.58	90100	120400	168136	177949
		AGA-20	0.58	88113	119224	190800	182250
4	Mixes with cement, sand, WRA and GA, and HRM	WR	0.54	175131	207700	207950	216750
		WGA-20	0.54	156833	186833	188466	209269
		WAGA-20	0.50	154266	174866	216200	219800

Table 4.3. Results of compressive strength (psi) for all mixes

SET	Details	Designation	W/C ratio	Compressive Strength(psi) at ages of			
				3 Days	7 Days	14 Days	21 Days
1	Control Mix	C	0.54	3853.69	3923.13	4947.22	5437.03
2	Mixes with cement only and (GA) as partial replacement of sand	GA-5	0.54	3153.69	3790.70	4939.80	5230.55
		GA-10	0.54	3037.75	3642.40	4532.70	4872.00
		GA-15	0.54	2921.75	3469.85	4235.45	4618.25
		GA-20	0.54	2892.75	3350.95	4599.05	4858.33
3	Mixes with 12% by weight of HRM as partial replacement of cement and GA	AGA-5	0.58	2979.75	3513.35	5244.44	5713.88
		AGA-10	0.58	2839.10	3350.95	5143.15	5387.50
		AGA-15	0.58	2502.77	3344.44	4670.45	4943.05
		AGA-20	0.58	2447.60	3311.80	5300.00	5062.50
4	Mixes with cement, sand, WRA, GA, and HRM	WR	0.45	4864.75	5769.44	5778.38	6020.83
		WGA-20	0.45	4356.47	5189.80	5235.16	5813.05
		WAGA-20	0.50	4285.16	4857.38	6005.55	6083.33

The improvement of compressive strength with age for the control mix and mixes containing 5, 10, 15 and 20% of glass aggregate as partial replacements of sand and the comparison between the values of the compressive strength for the same mixes are plotted and show in figures 4.2, and 4.3 respectively.

1. The using of glass aggregate has a slightly negative effect and reduction on the compressive strength at all ages of the test. This effect increases relatively with the increase of glass aggregate replacement (reduction in strength with GA-20 more than the reduction in GA-5) This behavior is may be because the lower adhesion and bond strength between the glass aggregate and cement paste, mainly attributed to the glass's relatively smooth surfaces as compared with natural sand's rough surfaces. Same results were found by researchers as mentioned in literature review [(23)]. An exception to this trend was recorded at the 21-day GA-20 mix, which shows higher compressive strength than those for mixes GA-10 and GA-15. It may be that this increment is due to the effect of pozzolanic activity (very fine glass particles) prevailing over the adverse effect of glass aggregate texture.

2. All control and glass aggregate mixes show a significant improvement in strength with age. It can be observed that the percentage of compressive strength with age generally increased with the increment of glass aggregate replacements. For example, compared with the 3-day compressive strength, the percentage increase at 21 days for mixes R, GA-5, GA-A0, GA-15, and GA-20 are 41, 65, 60, 58, and 67 % respectively. This behavior refers to the pozzolanic activity of glass aggregate with very fine glass particles, as previously mentioned in the literature section regarding glass powder in concrete.

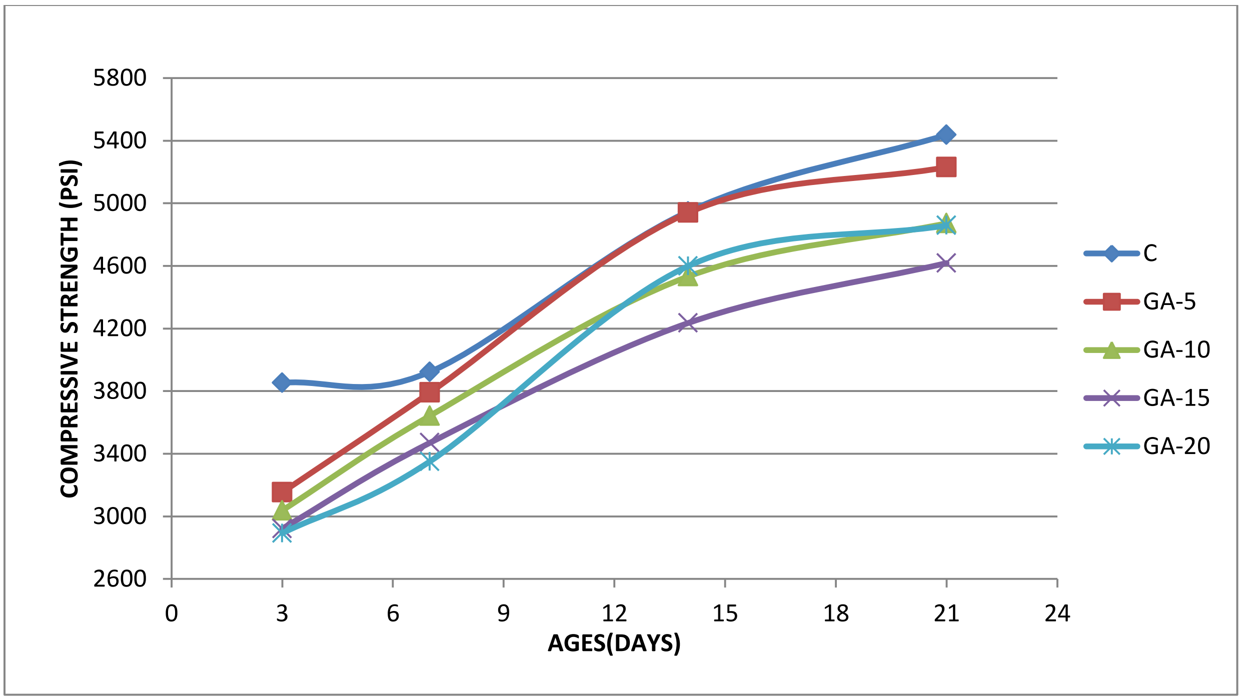

Figure 4.2. Compressive strength developments for the control mix and mix containing different glass aggregate replacements

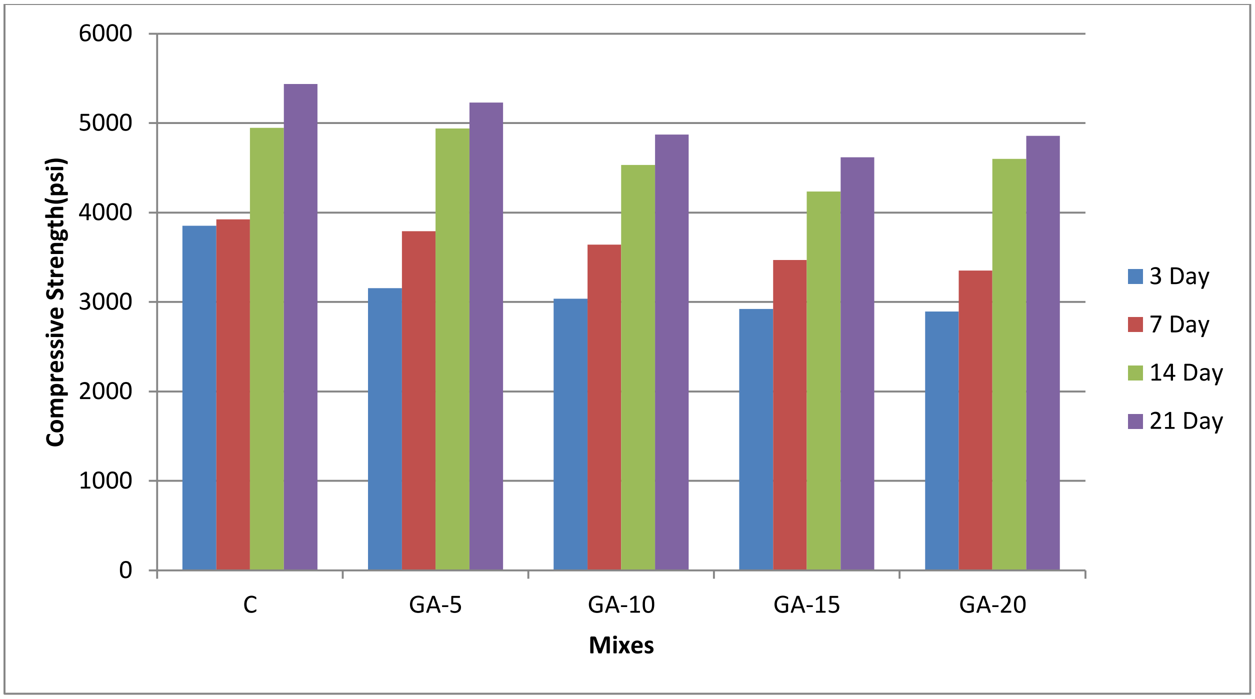

Figure 4.3. The comparison between the values of the compressive strength for the control mix and mixes containing different glass aggregate replacements

The compressive strength improvement for set 3 mixes is plotted in figures 4.4 and 4.5. These mixes contained the same glass aggregate replacement as in set 2, with the addition of 12% by weight of HRM as a partial replacement of cement.

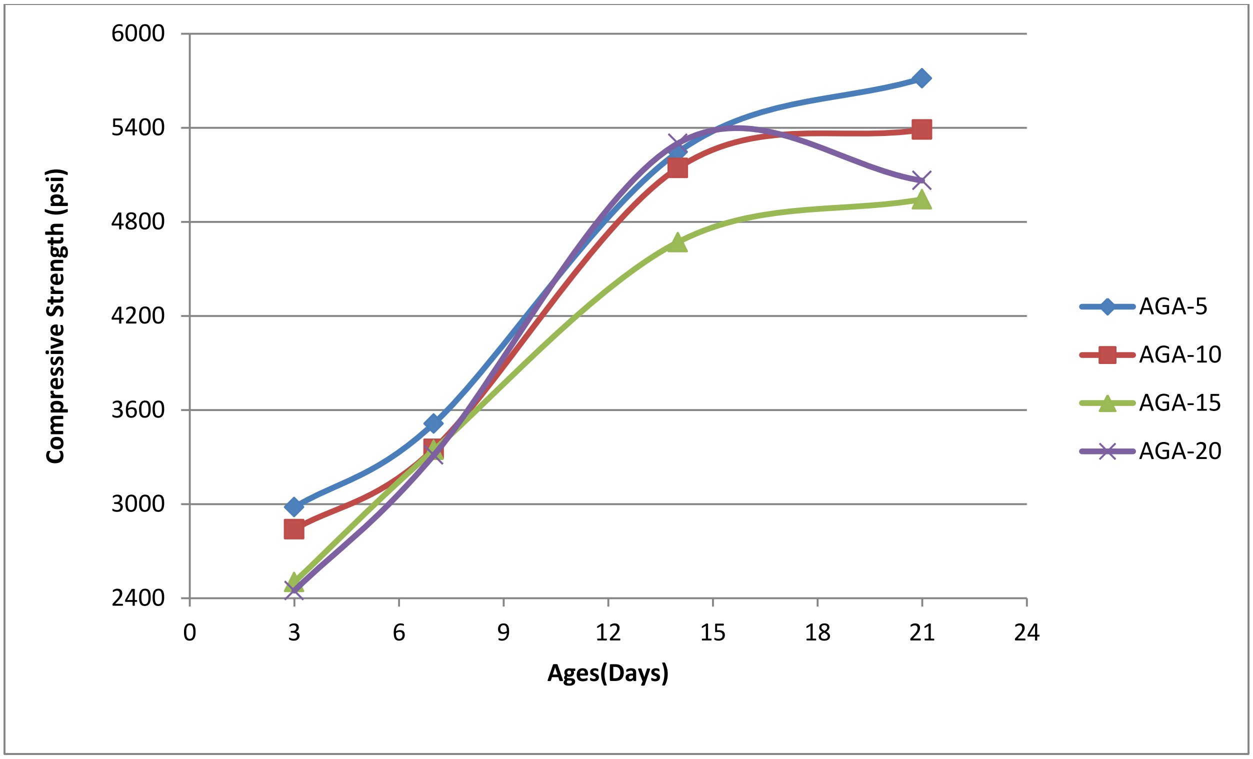

Figure 4.4. Compressive strength development for mixes containing 12% HRM and different glass aggregate replacements

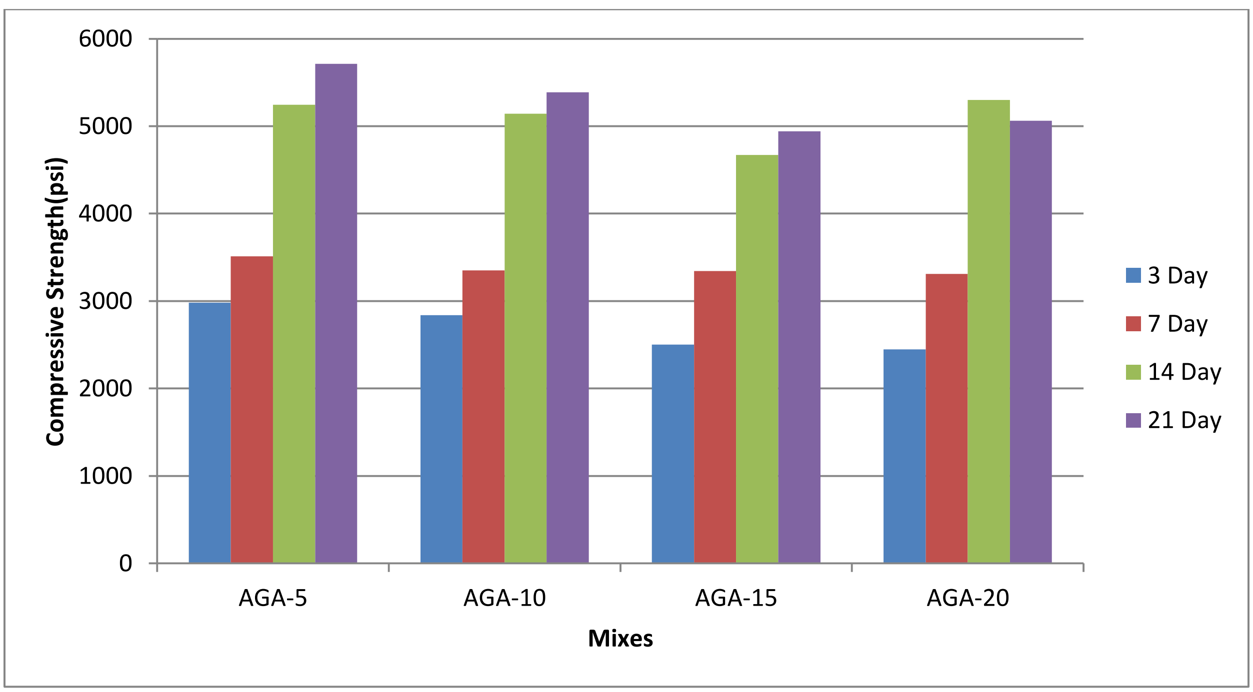

Figure 4.5. The comparison between the values of the compressive strength for mixes containing 12% HRM and different glass aggregate replacements

The following observations can be drawn from these figures:

1. All mixes within sets one and two, mixes show a significant improvement in compressive strength with age. It also shows a weak bond strength and lower adhesion between glass aggregate and cement paste, this reduction increase with the increasing of glass aggregate replacements. This is the reason for the reduction in compressive strength values with the increasing of glass aggregate replacements.
2. Mineral admixture mixes in set number 3, show a reduction in compressive strength at early ages (3 and 7 days) relative to the same mixes in set 2. This behavior as a result of the less cement content and more water content in these mixes; to obtain the same workability, the w/cm ratio increased from 54% in set 2 to 58% in set 3.
3. At ages (14 and 21 days), the compressive strength values for mineral admixtures mixes improved as compared with same compressive strength of set 2 mixes, and of the control mix as well. This behavior is stand for the pozzolanic action of both mineral admixtures and the very fine particles of GA which react with calcium hydroxide, producing additional gel and reducing the amount of voids in the mortar. On the other hand, set 3 showed unexpected reductions in compressive strength at age 21 days as compare with age 14 days mix, this behavior refers to micro fracture was occurred due to different processes in the aspect of the samples in this mix.

The improvement of compressive strength for WRA mixes within set 4 is plotted in figures 4.6 and 4.7. WRA mixes show significant improvements with regards to compressive strength as compared with the same mixes without water reducing admixture at all ages due to reduce the w/c ratio. For example, at 3 days, the percentage increases in compressive strength for

WR, WGA-20, and WAGA-20 relative to C, GA-20, and AGA-20 were 26.2%, 50.5%, and 75% respectively.

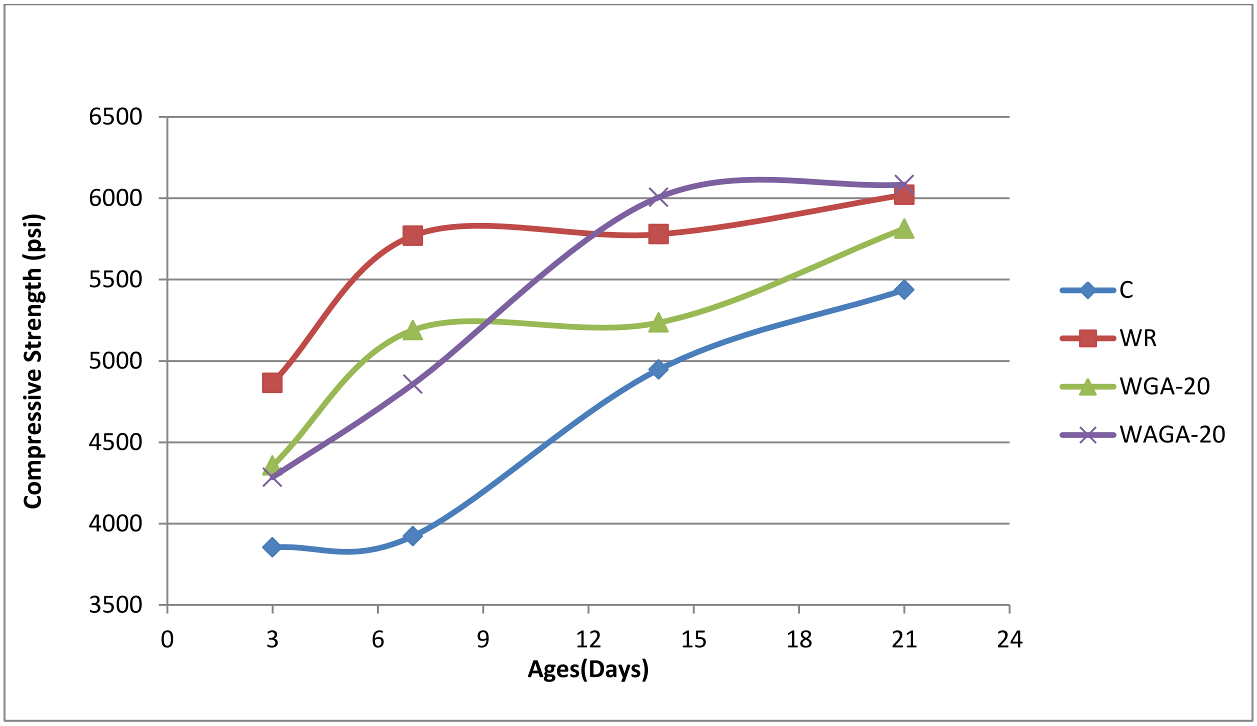

Figure 4.6. Compressive strength development for WRA mixes

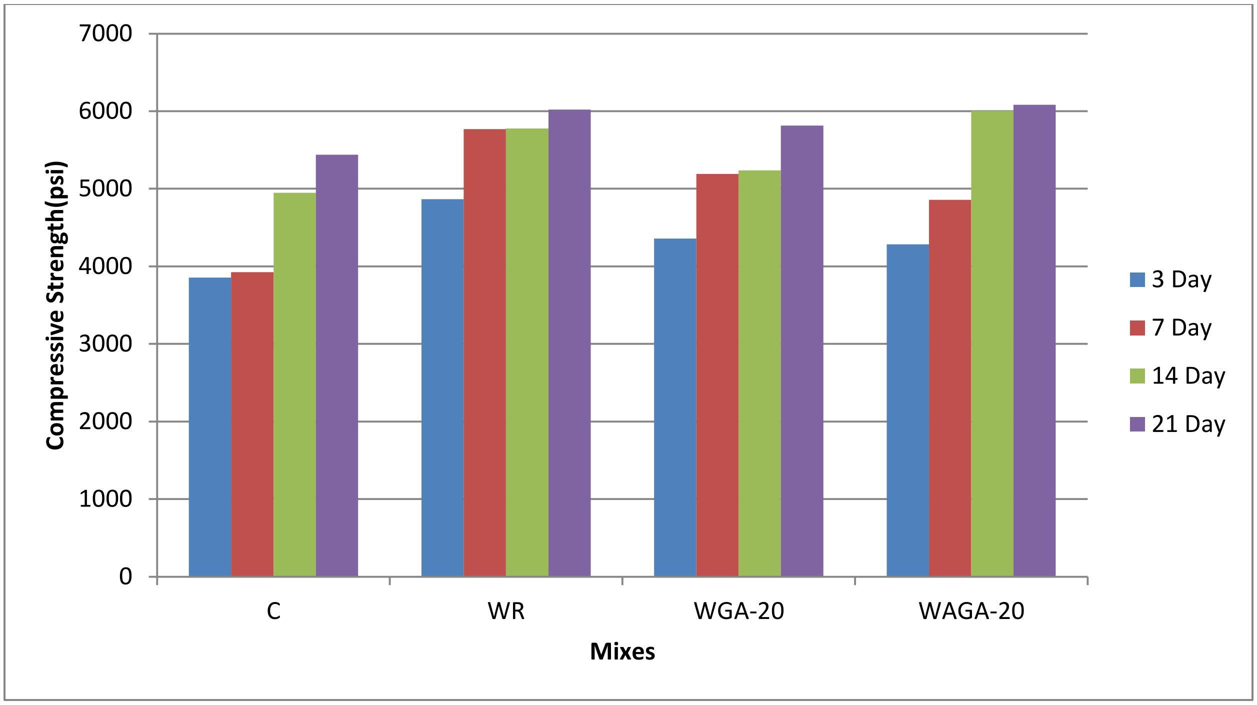

Figure 4.7. The comparison between the values of compressive strength for WRA mixes

Mixes WR and WGA-20 in set number four indicate the significant individual effect of WRA on compressive strength, which is attributed to the lower void content and the more homogenous and consistent structure. Meanwhile, WAGA-20 shows the combined effect of WRA and minerals (HRM) on compressive strength relative to mix GA-20. The combined effect of WRA and minerals produces a strong structure and decrease void content than the individual effect of any one of them.

The figure 4.8 shows the compressive strength development for the control mix and all mixes in set 2, 3, and 4.

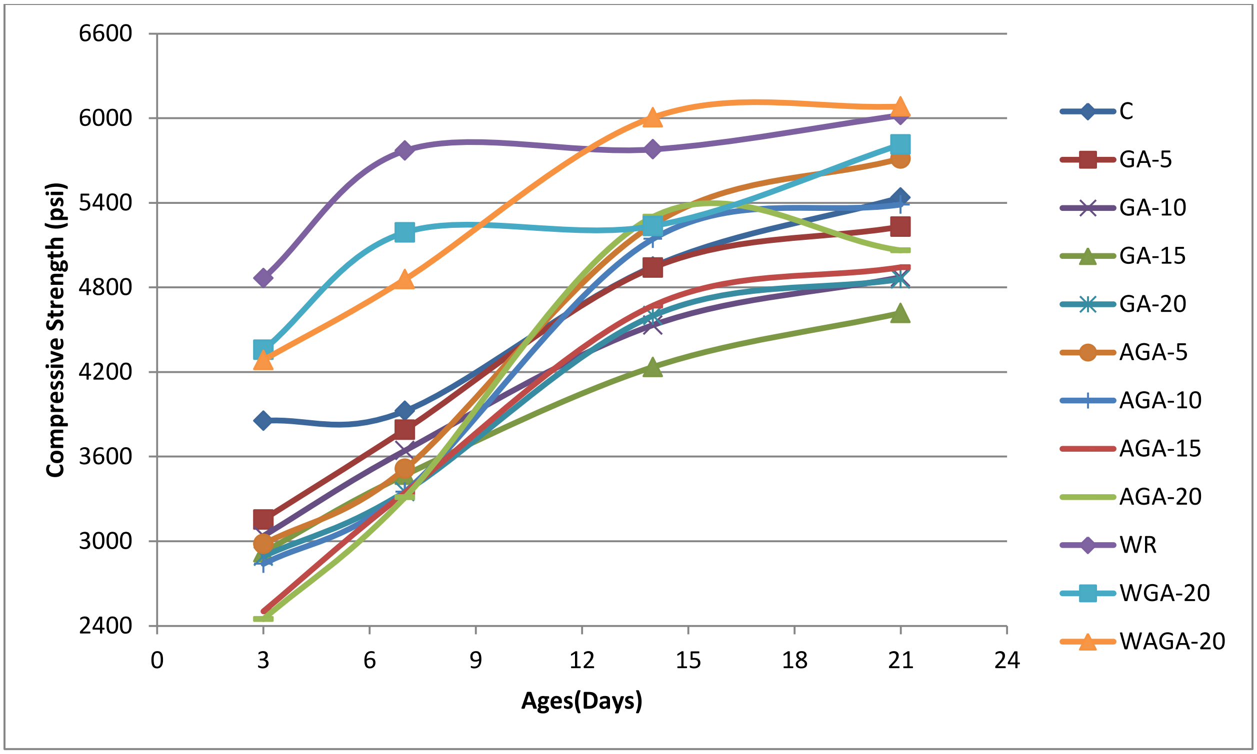

Figure 4.8. Compressive strength development for control mix and all mixes in sets 2, 3, and 4

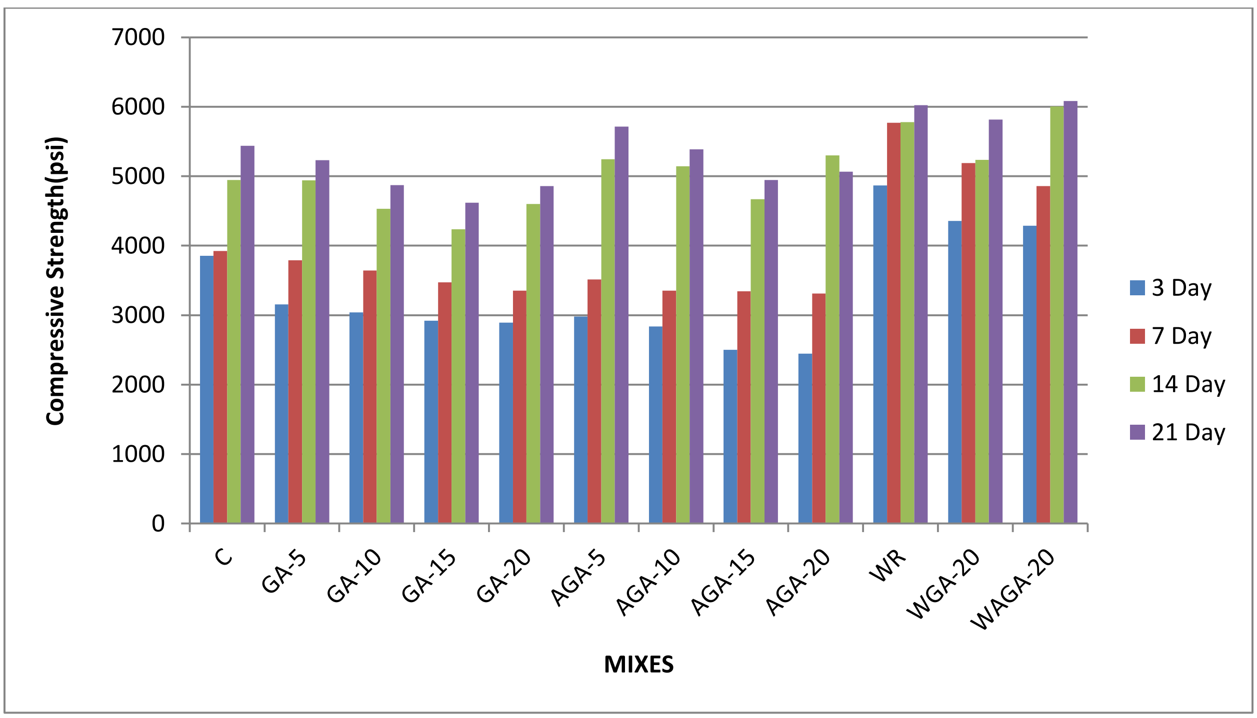

Figure 4.9. The comparison between the values of the compressive strength for the control mix and all mixes in sets 2, 3, and 4

Figures 4.10, 4.11, and 4.12 show the compressive test method and the failure of the cube specimens.

Figure 4.10. The compression test for the cube specimens

Figure 4.11. The failure of the cube

Figure 4.12. The Failure of the cube

4.3.2. Splitting Tensile Strength Test

Glascrete is just as brittle as traditional concrete. [2] The properties of the splitting are very important because it decrease the influence of ASR. Generally, in wet conditions, the alkali-silica gel present in glascrete could expand and produce a tensile stress within the concrete structure. This may act as the main cause of cracking in concrete. [29,3 1] The splitting tensile strength test investigates the impact of glass aggregate structure on adhesion and bond strength at the interfacial transition zone. Splitting tensile forces for all mixes at age 3, 7, 14, and 21 days are shown in table 4.4. The splitting tensile strength for all mixes after being cured for age 3, 7, 14 and 21 days is presented in table 4.5 and plotted in figures 4.13 through 4.20. Figures 4.21, 4.22, and 4.23 show the splitting tensile strength and the failure shape (splitting shape) for cylinder specimens.

Table 4.4. Results of splitting tensile forces (lb.) for all mixes

SET	Details	Designation	W/C Ratio	Splitting Tensile Force(lb.) at ages of			
				3 Days	7 Days	14 Days	21 Days
1	Control Mix	C	0.54	22356	24856	26675	28424
2	Mixes with cement only and (GA) as partial replacement of sand	GA-5	0.54	20157	22594	26489	27329
		GA-10	0.54	19678	21865	24780	26384
		GA-15	0.54	18874	20990	23684	25072
		GA-20	0.54	16180	19678	21865	23756
3	Mixes with 12% by weight HRM as partial replacement of cement and GA	AGA-5	0.58	22227	22448	25424	26786
		AGA-10	0.58	21061	21646	24780	25639
		AGA-15	0.58	17492	20407	24051	25142
		AGA-20	0.58	16034	19658	23322	24267
4	Mixes with cement, sand, WRA,GA, and HRM	WR	0.45	25789	26454	27183	27638
		WGA-20	0.45	22499	25113	26712	27555
		WAGA-20	0.50	24051	26253	26891	29882

Table 4.5. Results of splitting tensile strength (psi) for all mixes

SET	Details	Designation	W/C Ratio	Splitting Tensile Strength(psi) at ages of			
				3 Days	7 Days	14 Days	28 Days
1	Control Mix	C	0.54	444.78	494.5	530.7	565.5
2	Mixes with cement only and (GA) as partial replacement of sand	GA-5	0.54	401.03	449.5	526.99	543.7
		GA-10	0.54	391.5	435.0	493.0	524.9
		GA-15	0.54	375.5	417.6	471.2	498.8
		GA-20	0.54	321.9	391.5	435.0	472.62
3	Mixes with 12% by weight HRM as partial replacement of cement and GA	AGA-5	0.58	442.2	446.6	565.5	572.7
		AGA-10	0.58	419.0	430.65	493.0	510.09
		AGA-15	0.58	348.0	406.0	478.5	500.2
		AGA-20	0.58	319.0	391.1	464.0	482.8
4	Mixes with cement, sand, WRA,GA, and HRM	WR	0.45	513.07	526.3	540.8	549.86
		WGA-20	0.45	447.60	499.61	531.42	548.19
		WAGA-20	0.50	478.5	522.3	535.0	594.5

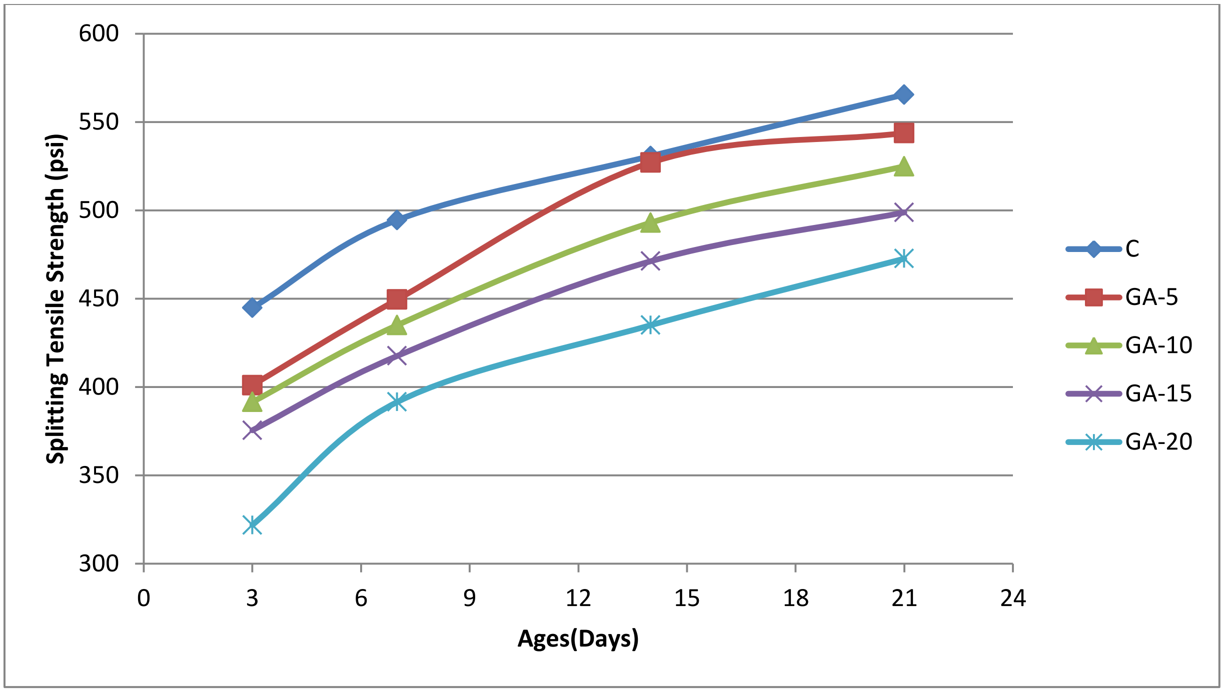

Figure 4.13. Splitting tensile strength development for the control mix and mixes containing different glass aggregate replacements

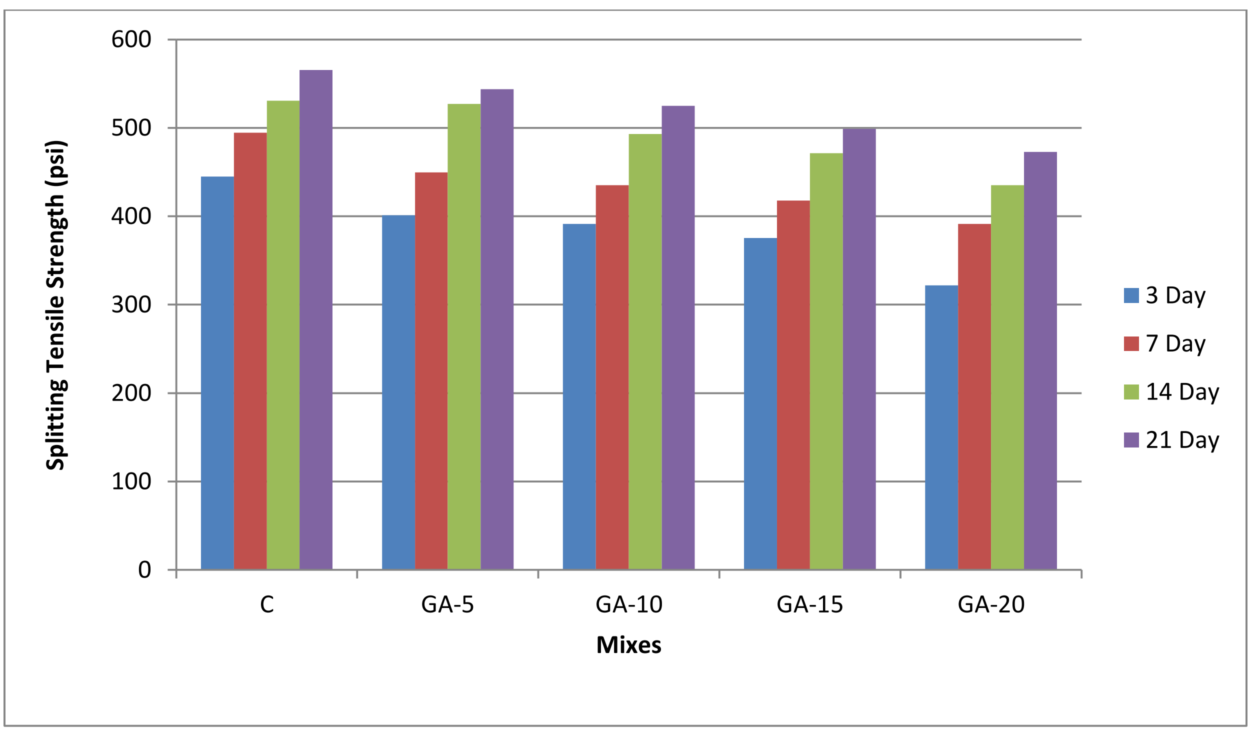

Figure 4.14. The comparison between the values of splitting tensile strength for the control mix and mixes containing different glass aggregate replacements

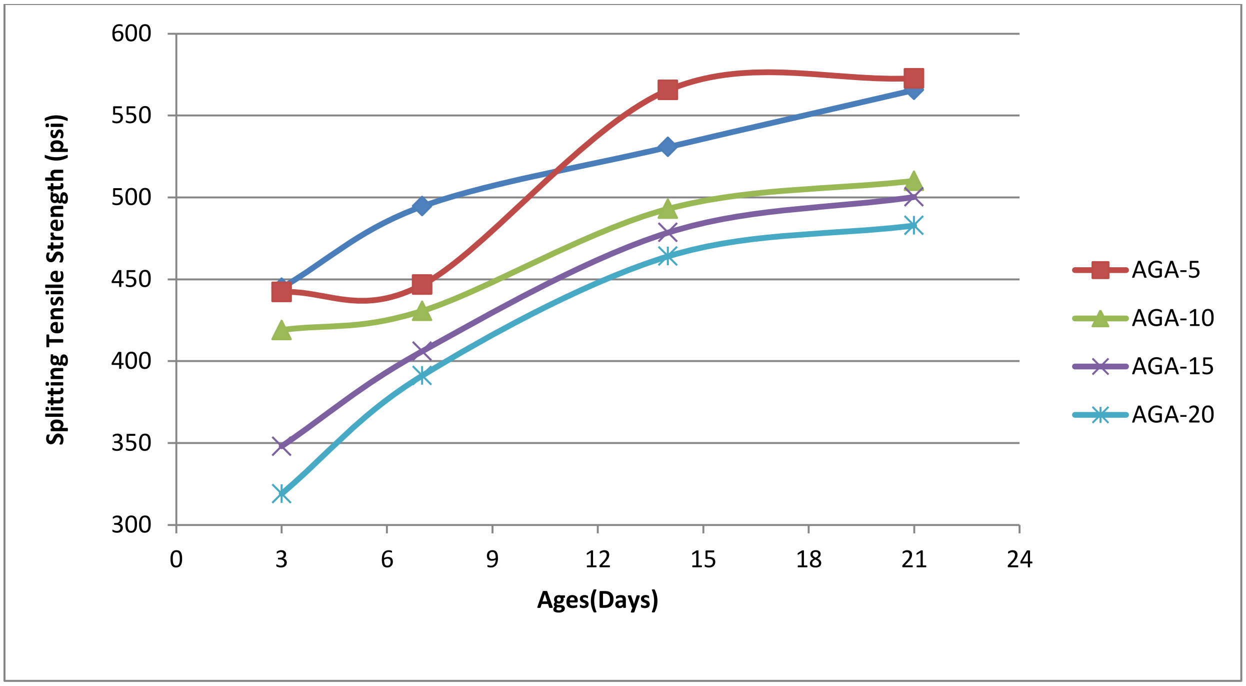

Figure 4.15. Splitting tensile strength development for mixes containing 12% HRM and different glass aggregate replacements

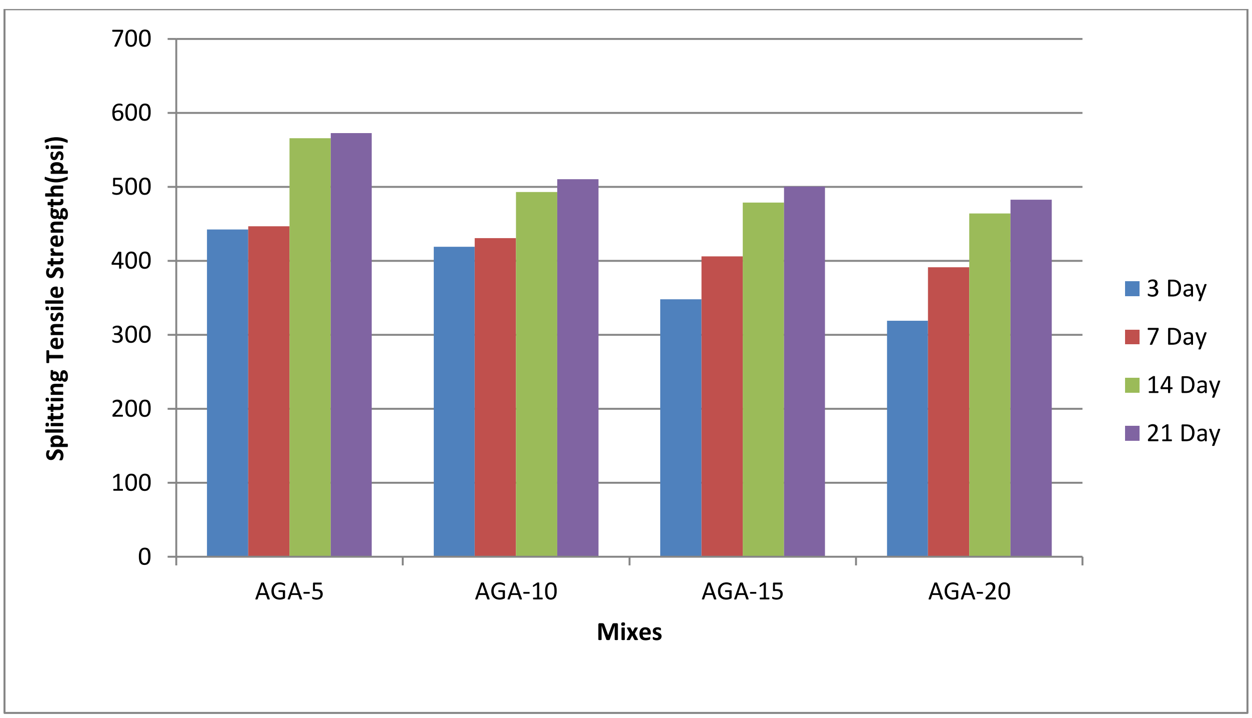

Figure 4.16. The comparison between the values of splitting tensile strength for mixes containing 12% HRM and different glass aggregate replacements

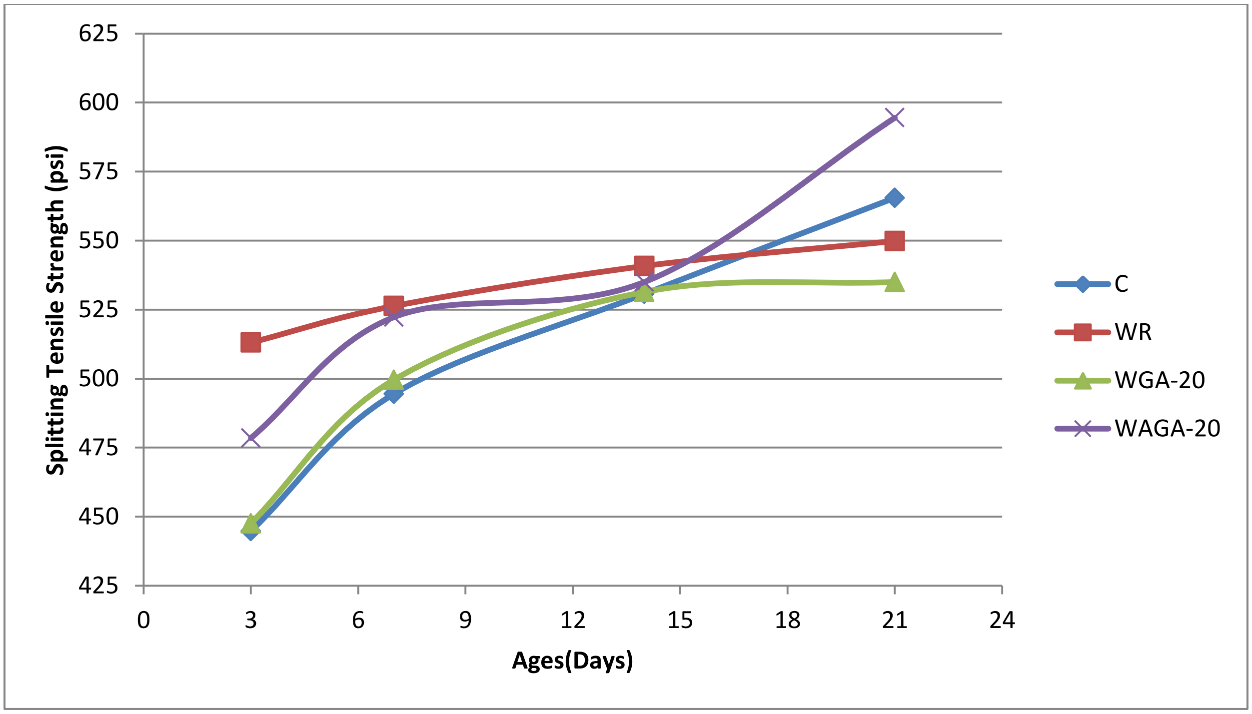

Figure 4.17. Splitting tensile strength development for WRA mixes

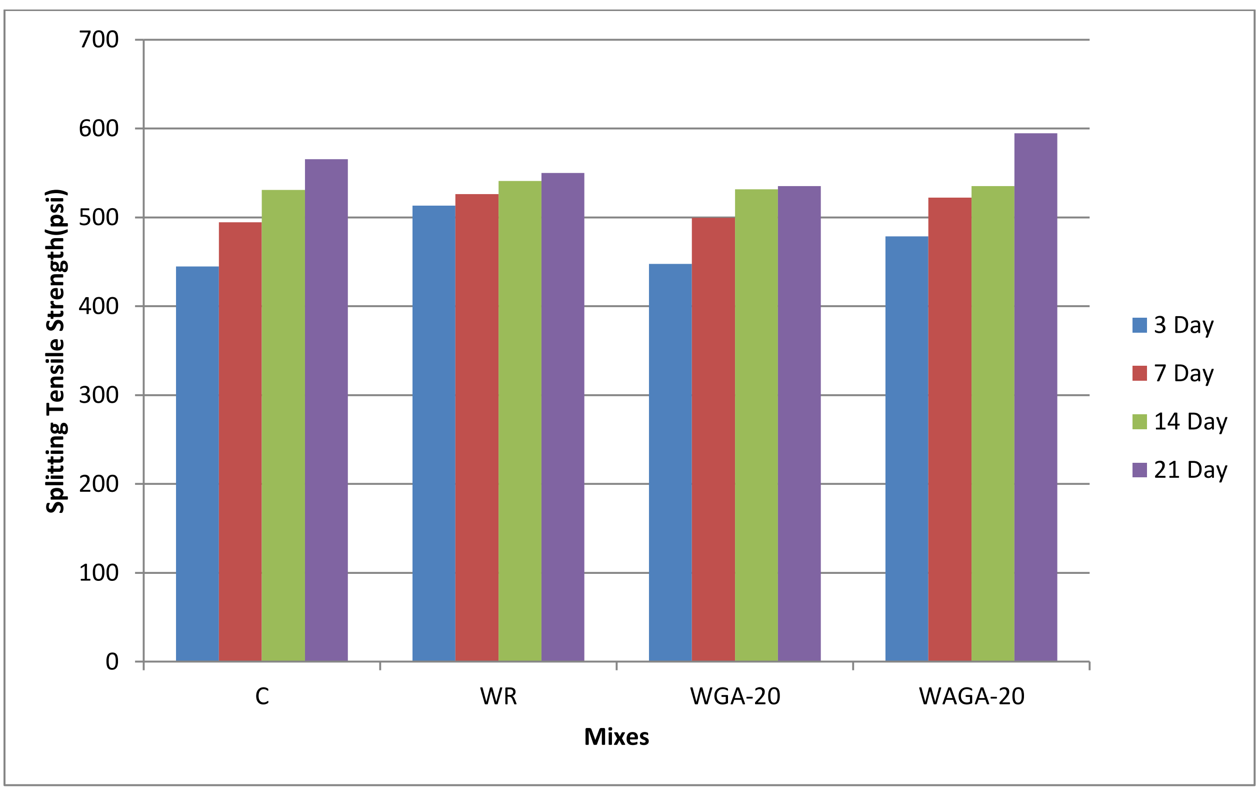

Figure 4.18. The comparison between the values of splitting tensile strength for WRA mixes

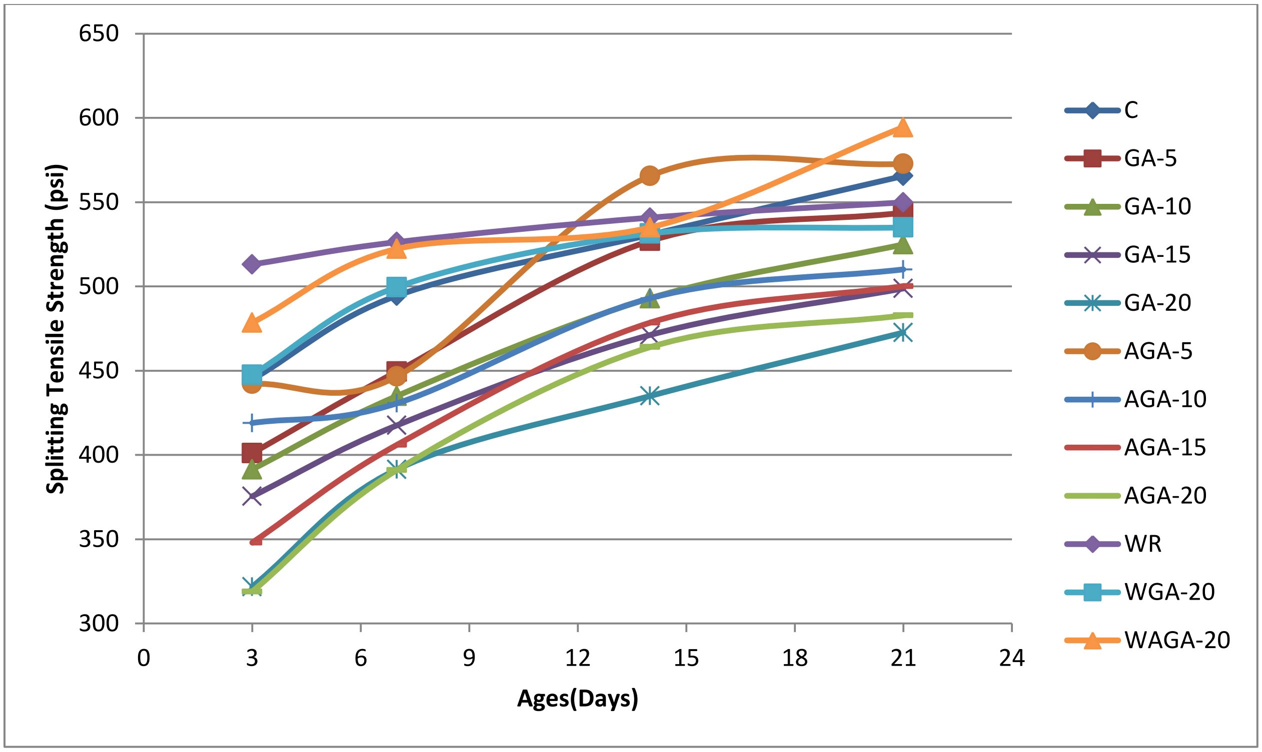

Figure 4.19. Splitting tensile strength development for the control mix and all mixes in set 2, 3, and 4

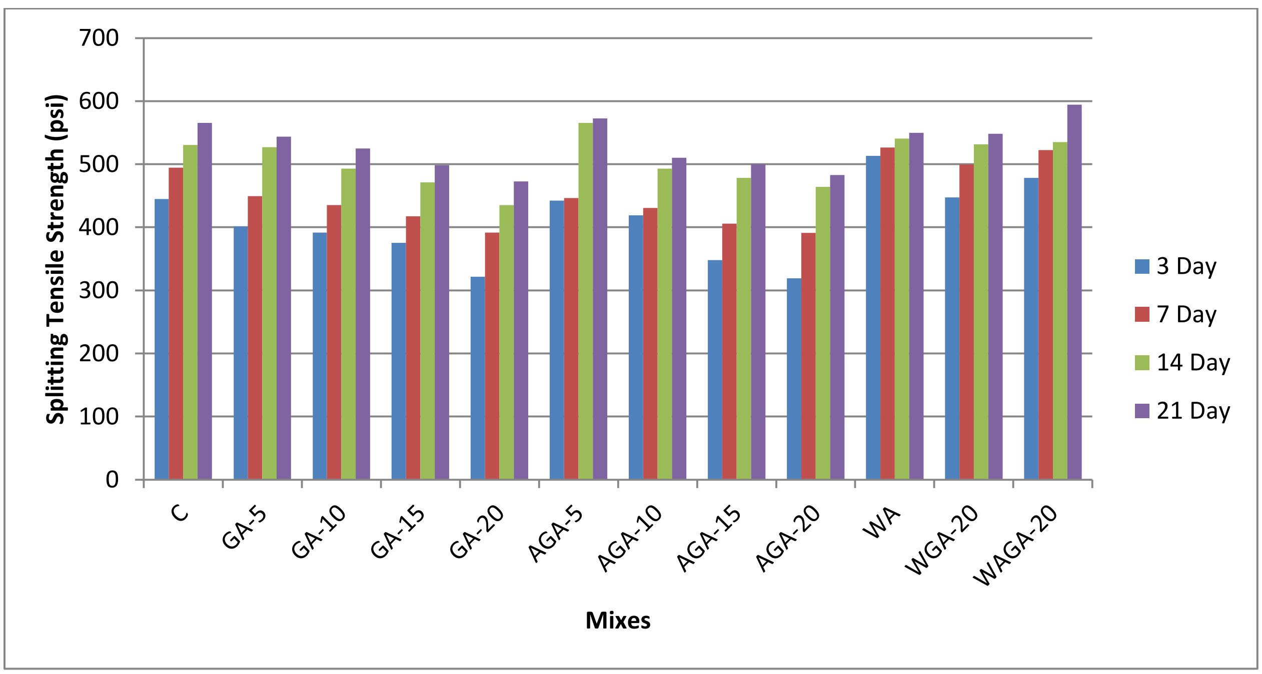

Figure 4.20. The comparison between the values of the splitting tensile strength for the control mix and all mixes in sets 2, 3, and 4

From these results, the following observations can be drawn:

1. There is a significant increase in splitting tensile strength for all mixes (control and admixture mixes) with age, due to the progress of hydration, and then reducing permeability and improving the transition zone.
2. Reduction in the splitting tensile strength for all glascrete mixes within set 2 and set 3 with the increasing of GA replacements. This behavior is because the weaker bond strength between glass aggregate and the cement paste as compared with bond in conventional mix.
3. Because the usage of the mineral admixture (HRM) in set 3, the transition zone is expected to improve. Then, improving the tensile strength with HRM mixes within set 3. Although it shows lower initial strength values (up to the 7-day age) as compared with the control mix and same mixes within set 2 (which refer to the lower cement content), HRM mixes still develop strength with time under moist cure conditions. At 14 days, HRM mixes improved the splitting tensile strength values and reached to the control mixture, and, at 21 days, almost more than the control mix. The developments clearly indicate the beneficial pozzolanic reaction of HRM.
4. The results of WRA mixes within set 4 shows important improvement in the splitting tensile strengths at all ages, as shown in figures 4.14 and 4.15. This improvement is because the reduction in w/c or w/cm ratios and to the uniform distribution of hydration products in the mortar system leading to a matrix with minimum porosity. For example, the percentage increases in splitting tensile strength at the 7-day age for WR, WGA-20, and WAGA-20 as compared with mixes R, GA-20, and AGA-20, are 6.4 %, 27.6%, and 33.5% respectively.

Figure 4.21. Splitting tensile strength for cylinder

Figure 4.22. The failure (splitting) shape

Figure 4.23. The failure (splitting) shape

CHAPTER FIVE. SOME PROPERTIES OF GLASCRETE PRODUCTS

5.1. General

Glascrete products can be classified as ware products and value-added products. For simple ware products, the main aim is to using it as much glass as possible. For value-added products, the aesthetic capability of the glass is used, because the glass is a very beautiful and attractive. Special application and decorative effects can be achieved with different glass colors, where the colors of glass aggregate could be coordinated to match a cement matrix. The choice of surface texture and treatment could also be designed to conform to different applications.

5.2. Review of Previous Researches

Many attempts have been carried out to develop a number of different commercial glascrete products such as paving stones, masonry blocks, tiles, and concrete panels. The most important and significant applications appear to be in the architectural application and decorative fields. One of the first products developed was the glascrete masonry block unit (17, 38, and 40). Meyer et al. (40) produced prototype blocks that contained waste glass as fine aggregate replacement and/or cement replacement. They suggested a replacement of 10% glass aggregate as fine aggregate replacement in one investigated mix, a cement replacement of 10% glass powder in another mix, while, in the third mix, both 10% of glass aggregate as fine aggregate replacement and 10% of glass powder as cement replacement. Their test results indicated that the 28-day compressive strength results are barely affected by the glass substitutions. Meyer et al (40) continued to develop this product until they produced blocks with 100% glass aggregate and 28-day compressive strengths exceeding 100 Mpa (14500 psi).

Producing glascrete pavers is another application developed to exploit the aesthetic effects of glass aggregate which possess novel colors and special surface texture effects, such as light reflections. Meyer [2] produced pavers containing up to 100% glass aggregate, as shown in figure 5.1. This product has other advantages in addition to aesthetic effects, including greatly reduced water absorption and significant abrasion resistance due to the high hardness of glass. Those pavers also showed a satisfactory freeze-thaw resistance where the tested samples survived 300 cycles with about 0.25% weight loss. Meyer [2] suggested that the glascrete paver might be reinforced with randomly distributed short fibers to offset the inherent brittleness of concrete in general and glascrete in particular.

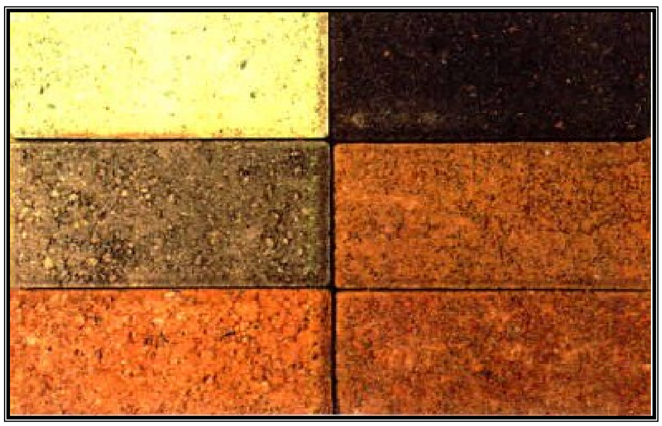

Figure 5.1. Glascrete paver [2]

The Waste and Resources Action Programmer (WRAP) and the University of Sheffield, in collaboration with 22 industrial partners, have funded the University of Sheffield's Center for Cement and Concrete to carry out two major investigations [17], with a total of 28 sub-projects (117 mixes) around the UK. The main objective for these two projects was to assess the performance of crushed and powdered glass in concrete products as a replacement for cement and/or aggregate. Some of these sub-projects are presented below:

CRH Group employed 6-12mm (0.25-0.47 in) glass aggregate of different colors and green glass powder in 16 concrete mixes to produce concrete architectural masonry units as shown in Figure 5.2. 30% by weight of total aggregate was replaced by glass aggregate, while 10% and 20% of green glass powder was used as a partial replacement by weight of cement. The test results indicated the significant effect of glass aggregate colors on the 28-day compressive strength. The higher compressive strength was recorded with clear glass aggregate followed by green, blue, and amber, where the exact compressive strength values at the 28-day age for those different colors were 26.6, 18.5, 15.1 and 10.7 MPa (3857, 2682.5, 2189.5, and 1551.5) respectively. These results also indicate the beneficial effect of green glass powder on the compressive strength.

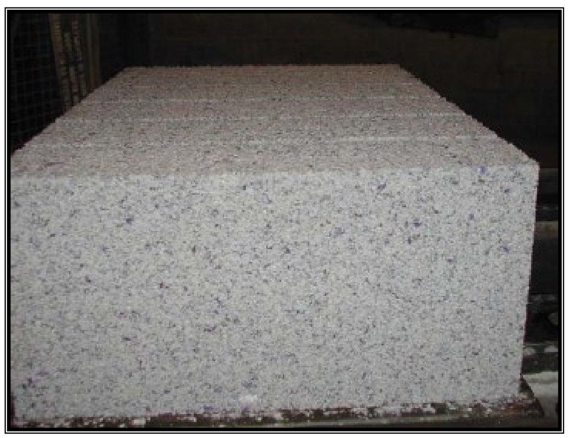

Figure 5.2. Architectural masonry units [17]

Marshalls Mono laboratory products wet cast exposed aggregate concrete flags as shown in figure 5.3. Ten concrete mixes were cast, including two reference mixes using normal aggregate and three mixes containing 40% of clear, green, and amber glass aggregate (as a partial replacement by weight of total aggregate) respectively. Except for one of the reference mixes, all mixes contained 10% green glass powder as a cement replacement. Two types of cement were used in this project, high alkali and low alkali cement relative to corresponding mixes made with high alkali cement at all ages of the test, as shown in figure 5.1 and 5.2. The results of the alkali-silica reaction test have shown that the colors of glass aggregate have various effects on expansion, and that the use of low alkali cement also to significant reduction in the recorded expansion relative to corresponding mixes with high alkali cement.

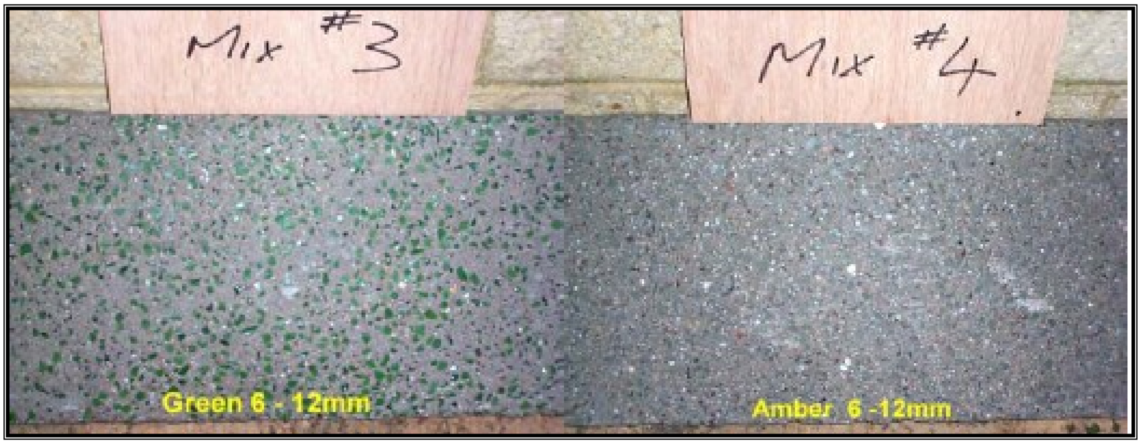

Figure 5.3. Wet cast exposed glass aggregate concrete flags [17]

At the full-scale facilities of Aggregate Industries UK, 3-6mm (0.12-0.24 in) blue glass aggregate and green glass powder were used to make wet pressed concrete curbs, as shown in figure 5.4. Three concrete mixes were cast, including a control mix using OPC and normal aggregate, a mix with 20% glass aggregate as a partial replacement by weight of sand, and a mix with 25% green glass powder as a partial replacement by weight of cement. The results indicated a higher flexural strength for glass aggregate curbs relative to control and glass powder mixes at 28 days. The 28-day flexural strength for control, glass aggregate, and glass powder mixes were 6.1, 6.3 and 5.8 MPa (884.5, 913.5, and 841 psi) respectively. The results also proved that curbs with glass aggregate have higher freeze-thaw resistance and higher abrasion resistance relative to control and glass powder mixes.

Figure 5.4. Wet pressed concrete

CHAPTER SIX. CONCLUSSION AND RECOMMENDATIONS

6.1. General

This study was carried out to investigate the characteristics of mortar mixes containing four different volume replacements (5, 10, 15, and 20%) of crushed waste glass as a partial replacement for sand. In addition, the study was concerned with evaluating the impact of replacing part of the cement with locally available mineral admixtures (met kaolin and HRM) and glass on mixes properties, with or without a water-reducing admixture. The conclusions derived from this study and recommendations for future research work are presented in this chapter.

6.2. Conclusions

According to the results of this investigation, the main conclusions that can be drawn are given below:

1. The use of glass aggregate (GA) as a partial replacement for natural sand does not reduce workability up to the specified range of replacement (20%), especially when glass aggregate is substituted on an equal volume basis and has a similar surface area. Figure 3.7 verifies this idea by used the same w/c ration with all set 2 mixes without any changing in workability. On the other hand, the use of the mineral admixture (HRM) in different ratios as a partial replacement by weight of cement does significantly affect the mixes' workability. These effects are not similar and vary according to the type, dosage, and fineness of mineral admixtures. The 12% replacement of cement by highly reactive met kaolin increases the water demand of glascrete mixes by 6.7% relative to the control mix. The use of a water-reducing admixture produces significant reduction in w/c or w/cm ratios ranging from 7.4% to 16.7% relative to the control mix according to mix ingredients,

2. The use of glass aggregate as a partial replacement by volume of sand reduces the fresh and air dry densities as the glass aggregate replacements are increased, because the specific gravity of glass lower than the specific gravity of sand. HRM produces lighter mixes; the reason is stand for the specific gravity of mineral admixture lower than the specific gravity of Portland cement. While the water-reducing admixture increases mixes densities, because the uniformity of mixture and the strong structure of mortar and also all the voids of mix filled by the small particles of glass and pozzolanic material.
3. Glascrete mixes with fine glass aggregate replacement up to 20% do not cause serious reduction to the compressive strength. At 7 days, the reduction in compressive strength ranges from 9.1% to 20.8% for mixes with glass aggregate replacement ranging from 5-20% by volume of fine aggregate because the weak bond between the cement paste and glass aggregate due to the smooth surface of glass. The figures 4.2 and 4.3 show these results carefully. The mineral admixture (HRM) used throughout this study improved the adequacy of glascrete mixes with regard to compressive strength, and produced mixes with compressive strength values very close to the control mix, especially at later ages because the small particles of glass react as a pozzolanic material with cement. And the figures 4.4 and 4.5 represent this value very clear. The use of 1.2% water-reducing admixture by weight of cement significantly improved the compressive strength at all ages because the combined influence of mineral admixture with water reducing admixture. Figure 4.6 and 4.7 showed that.
4. Glascrete is just as brittle as traditional concrete, because the concrete is a compression member not tension member, the glass in concrete making it brittle because the glass properties. The splitting tensile strength for glascrete mixes is slightly lower than the control

mix due to the lower adhesion and bond strength between glass aggregate and cement paste. The percentage of reduction in splitting tensile strength for glascrete mixes with different glass aggregate replacements ranging from 9.1% to 20.8% at 7 days and from 3.9% to 16.4% at 21 days, relative to their control mixes, table 4.5 represents this data. The splitting tensile strength tests were done in a compression machine but the test was at the tension side. Because we still need to know the behavior of concrete in tension as well.

6.3. Recommendation for Further Work

1. It is recommended to investigate the influence of particle size (very fine particle size), particle color, and glass aggregate contaminants on glascrete properties.
2. More studies are recommended to evaluate the engineering properties of glascrete with different mineral admixtures, such as glass powder, and any other minerals as a partial replacement of cement instead of the HRM used in this study.
3. Very important to evaluate long time investigation to study the durability and strength of glascrete mixes, it recommended testing the specimens after 90 days or more with regard to the alkali-silica reaction.
4. Many works are needed to evaluate the impact of higher replacement values of glass aggregate on glascrete properties (more than 20% with different application)
5. The possibility of using waste glass as a high value market instead of using it in low value market such as road base material, so it recommended using it within the architectural and decorative field and needs to be investigated on a wider range of applications. It is of special importance to evaluate each application from an economic standpoint.

6. It is recommended to study the microstructure properties of glascrete mixes with and without admixtures in order to clarify the effect of admixtures on glascrete durability and to find out the micro cracks could happen inside the concrete structure.

REFERENCES

1. Jin, W., Meyer, C., and Baxter, S., "'Glascrete'- Concrete with Glass Aggregate'', ACI Materials Journal, Vol. 97, 2000, P. 208-213.
2. Meyer, C. ''Glass Concrete'', Concrete Materials Research at Columbia University, USA, 2003, P.55-58.
3. Concrete Technology Unit, "Realizing a High-Value Sustainable Recycling Solution to the Glass Cullet Surplus," Guidance for the use of Crushed or Powdered Glass in Concrete, University of Dundee, Dundee, DTI Research Contract No.GW-12.10-108. 2003, P.2-9.
4. Reindl, J. ''Reuse/Recycling of Glass Cullet For Non-Container Uses'', Report by Recycling Manager, Dane County Department of Public Works, USA, 2003, P.25-125.
5. Peploe, R. '' Best Practice Guidelines for the Use of Alternative Materials and Processes in Road Construction with Respect to Environmental Issues'', Transit New Zealand Technical Memorandum, New Zealand, 2006, P. 16.
6. South Dakota School of Mines & Technology. '' A Touch of Glass'', USA.
7. Sagoe, K., Brown, T. and Taylor, A. '' Guide Specification on Recycled Glass as Sand Replacement in Premix Concrete'', CSIRO Building and Construction Engineering, Australia, 2001, P.7-36.
8. Parkinson, M. and Visco, C. ''Sustainable Markets for Waste Glass from Fluorescent Tubes and Lamps'', Final Report Supported by Biffa Ward, 2002, P.30-33.
9. Weitz, T. '' Counties Reap Benefits from Reclaimed Glass in Aggregate Base'', University of Minnesota, 2005.
10. Sherman, G.'' Crushed Glass for Use in Asphalt Concrete or Cement Treated Base,'' Final Report.

11. McIntyre, J. ''Recycled Materials: Substitutes for Mining Products Used in Road Construction'', the Rural Conservation Alliance.
12. Hadlington, S. ''Recycling Beyond the Glass Ceiling'', Report for The Independent.co.uk.
13. Shaopeng, W., Wenfeng, Y. and Yongjie, X. ''Preparation and Properties of Glass Asphalt Concrete'', Key Laboratory for silicate Materials Science and Engineering of Ministry of Education, Wuhan University of Technology, Wuhan, China 2003.
14. Solid and Hazardous Waste Education Center, ''Alternative Uses for Post-Consumer Glass,'' Wisconsin Recycling Programs, Wisconsin Department of Transportation, 2004.
15. Smith, A. ''Green Bricks from Green Glass'' Report for the CERAM Building Technology, 2004.
16. Shayan, A., ''Value added Utilization of Waste Glass in Concrete'', Cement and Concrete Research, Vol.34, No.1, 2004, P.81-89.
17. Byars, E., Zhu, H. and Morales, B. ''Conglasscrete I'', Center of Cement and Concrete, Final Report, University of Sheffield, 2004, P.3-51.
18. Siddiqui, A., Choudhury, A. and Merchant, I. ''Acoustic Emission Monitoring of the Fracture Behavior of Concrete Containing Various Size and Shape of Glass Aggregates'', School of Engineering, Robert Gordon University, School hill, Aberdeen, AB10 1FR, U.K. 2004, P.115-121.
19. Shehata, I., Varzavand, S., Elsawy, A. and Fahmy, M., ''the Use of Solid Waste Materials as Fine Aggregate Substitutions in Cementitious Concrete Composites'', University of Northern Iowa, Department of Industrial Technology, USA.
20. Naik, T. and Wu, Z., ''Crushed Post-Consumer Glass as a Partial Replacement of Sand in Concrete'', Fifth CANMET /ACI International Conference on Recent Advances of Concrete

Technology, SP-200, V.M. Malhotra, ed., American Concrete Institute, Farmington Hills, Mich.,p.553-568.

21. Naik, T. and Kraus, R. ‘’Use of Glass Cullet as Aggregates in Flow able Concrete with Fly Ash’’, CBU-1999-03, UWM Center for By-Products Utilization, University of Wisconsin-Milwaukee, P.66.
22. Dhir, R., Dyer, T., Tang, A. and Cui, Y., ‘’Maximizing The Value and Sustainable Use of Glass’’, Published Paper for the A to Z Building, Vol.38 No.1, 2004, P.38-40.
23. Meyer. C., ‘’Cracking an ASR Barrier’’, Concrete Materials Research at Columbia University, P.4-9.
24. Pattengill, M. and Shutt, T. ‘’Use of Ground Glass as a Pozzolan’’, Symposium on the Utilization of Waste Glass in Secondary Products, New Mexico
25. Byars, E., Morales, B. and Zhu, H. ‘’Conglasscrete II’’, Center of cement and concrete, Final Report, University of Sheffield, UK, 2004, P.4-27.
26. Stanton, T., ‘’Expansion of Concrete through Reaction between Cement and Aggregate’’ American Society of Civil Engineering, P.1781-1811.
27. Shao, Y., Lefort, T., Moras, S., and Rodriguez, D., ‘’ Studies on Concrete Containing Ground Waste Glass’’, Journal Article for the Cement and Concrete Research, Vol.30, 2000, P.91-100.
28. Engineering and Design – Standard Practice for Concrete for Civil Works Structures, EM 1110-2-2000, Appendix D ‘’ Alkali-Silica Aggregate Reactions’’ P.1-6.
29. ACI 221.1R-98, ‘’State-of-the-Art Report on Alkali-Aggregate Reactivity’’, ACI Committee 221, 1998.

30. Phiilips, J. and Cahn, S., ''Reuse Glass Aggregate in Portland cement'', Proc. 3rd Mineral Waste Utilization Symposium, P.385-390.

31. Zdenek, P., Aleander, S., '' Mathematical Model for Kinetics of Alkali- Silica Reaction in Concrete'' Cement and Concrete Research, Department of Civil Engineering and Materials Science, Northwestern University, Evanston, USA, 1999, P. 419-428.

32. Yunping, X., Yue, L., Zhaohui, X., and Jae, S., ''Utilization of Solid Wastes (Waste Glass and Rubber Particles) as Aggregates in Concrete'', University of Colorado, Boulder, CO 80309, USA, 2003, P.45-49.

33. ASTM C 150- 02a, ''Standard Specification for Portland cement'' Annual Book of Standard American Society for Testing and Material, Vol.04.01, 2003.

34. VITROHUE Glass Aggregate, ''Using Recycled Glass with Portland Cement'', Technical Bulletin VH-002, 2002.

35. Clean Washington Center, '' Recycled Glass in Portland cement Concrete'', Clean Washington Center Report BP-GL4-05-01 1996.

36. Nan Su[a], Buquan Miao[b] ''A new method for the Mix Design of Medium strength flowing concrete with low content cement '' Cement Concrete Composites, Vol.25, Issue 2, Feb.2003. P.215-222.

37. Nan Su[a], Kung – Chung Hsu[b], His- Wen Chai[c] '' A simple Mix Design method for self-compacting concrete'' Cement and Concrete Research, Vol. 31, Issue 12, Dec.2001 P. 1799-1807.

38. ''Use of Recycled Glass for Masonry Blocks", New York Energy Research and Development Authority (NYSERDA)

39. Mix Design Manual. Durocrete, Engineering Services Pvt.Ltd. Construction Quality Assurance, Mix Design.

40. Meyer, C., Egosi, N., and Andela, C., "Concrete with Waste Glass as Aggregate", International Symposium Concrete Technology Unit of ASCE and University of Dundee, 2001.

41. ASTM C 494/C 494M-99, "Standard Specification for Chemical Admixtures for Concrete", Annual book of Standard American Society for testing and material, Vol. 04.02,2003

42. Neville A. M. "Properties of concrete", Long Man of Group Limited, London, 4th Edition.

43. Joy M. Justice " Evaluation of Metakaolins for use as supplementary cementitious materials" Thesis, Georgia Institute of Technology, 2005