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Synergistic Effects of Fly Ash and Silica-Based Materials on Concrete Properties

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Abstract - The demand for construction materials is rapidly increasing due to ongoing urbanization and modernization. These materials are primarily sourced from natural resources, leading to significant environmental concerns such as resource depletion and pollution. Recycling construction waste [1] is a sustainable solution to mitigate these issues. Among the various waste materials, glass is one of the most abundant. If not properly managed through collection, cleaning, and recycling waste glass can severely impact the environment and public health.

In many developed countries, glass recycling systems are well-established, effectively reducing landfill use and environmental damage. However, in Oman and several other developing nations, glass recycling remains underutilized. Most waste glass ends up in landfills, representing both an environmental hazard and a missed economic opportunity. Not all types of waste glass are suitable for traditional recycling, but they can be repurposed in construction, particularly in concrete production.

This research explores the potential of using crushed waste glass as a partial or full replacement for natural sand in concrete. Eight concrete mixes were prepared, incorporating waste glass at 20%, 50%, and 100% replacement levels. Additionally, Class C fly ash [2] was used to replace 30% of Portland cement in all mixes. These modified concretes were tested in both fresh and hardened states to evaluate their performance.

The results showed that incorporating waste glass [3] had minimal negative effects on the physical and mechanical properties of concrete. Moreover, the combination of fly ash and glass improved certain concrete characteristics. This study demonstrates that using waste glass in concrete not only maintains acceptable performance standards but also contributes to environmental sustainability by reducing landfill waste and conserving natural resources. Thus, integrating waste glass into construction materials presents a viable strategy for sustainable development in Oman and similar regions.

Keywords**:** fine aggregate, mechanical properties, sustainable concrete, thermal conductivity, waste flat window glass.

1. Introduction

Concrete is a material that composed mainly of cement, aggregate, and water. It is the heart of construction materials in construction projects. Projects foundations and structures are made mainly with concrete (concrete structure). The fresh state of concrete can affect hardened state of concrete in a different way. Concrete properties are very important for its service life and durability.

Concrete has been used for a long time ago by using lime as a cementitious material and it was used by the Chinese and the Romans. In fact, the dome of the Pantheon and the Colosseum in Rome as well as nearly 5,600 km of Roman roads largely consist of concrete.

The composite material (Reinforced concrete) was invented in 1849 when Joseph Monier combined metal bars (steel bars) with concrete to create reinforced concrete. Since then, it has become the basic civil engineering material for reinforced concrete structure with its high performance and formability and intrinsic versatility, design, flexibility and above all, natural durability.

Reinforced concrete structures [4] are dominant structures in the world nowadays, since they have many advantages relating to their low-cost relative to steel structures and its durability and fire resistance. Concrete structures are basically made with mild steel which embedded in concrete in fresh state in reworked framework to make the desired shape of the element. Concrete materials components are available everywhere and that is the main reason for its dominancy. Reducing of concrete components by using recycled materials in concrete will reduce the huge extraction of raw materials and reducing the emission of CO2.

Mineral and chemical admixtures are also a good solution of reducing the cost of producing high performance concrete with high durability. Minerals admixture especially used to enhance long term properties such as porosity, compressive strength, etc. Whereas chemical admixture used to enhance fresh properties and long-term properties also.

2. Materials and Methods

2.1 Fly Ash and Ordinary Portland Cement (OPC)

Fly ash is a fine byproduct of coal combustion, composed mainly of silicon dioxide (SiO_2), calcium oxide (CaO), aluminium oxide (Al_2O_3), and iron oxide (Fe_2O_3). Unlike bottom ash, which is heavier and unsuitable for structural concrete, fly ash can be used as a pozzolanic material in concrete. Although it lacks inherent cementitious properties, it reacts with calcium hydroxide in the presence of moisture to form cementitious compounds like calcium-silicate hydrates (C-S-H), enhancing concrete strength over time. In high-volume fly ash concrete (HVFAC), these reactions improve long-term durability and performance. For Cement, Ordinary Portland cement OPC was used in this research complying with ASTM type I.

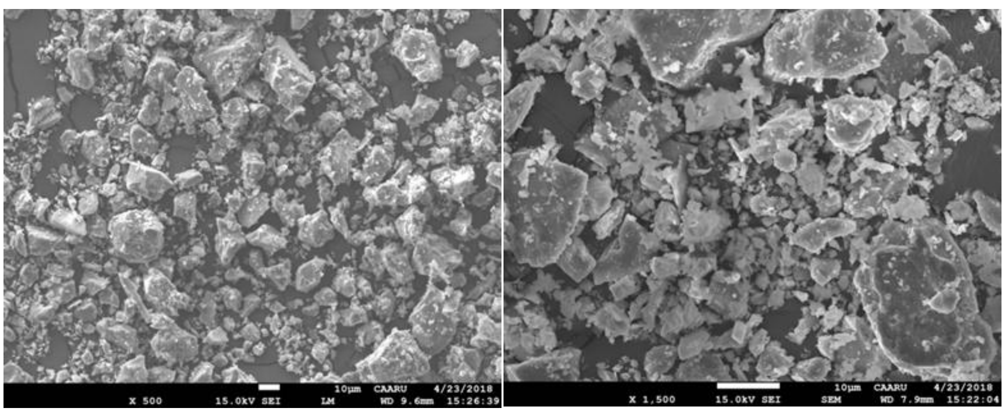

Fig 2.1: SEM Micrograph of Portland cement used

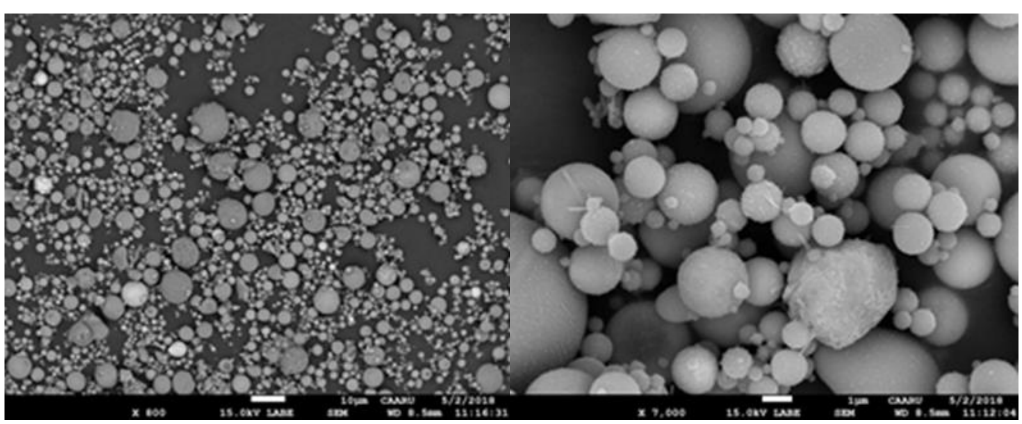

Fig2.2: SEM Micrograph of fly Ash use

2.2 Chemical Admixture

A brown liquid form of a sulphated naphthalene based high range water reducing concrete admixture produced by Sika company labelled " Sikament 500" complying with ASTM C494 type G and EN 934-2 having density 1.21 pH value 7-9 and free of chloride was used in all mixes to reach the target slump values range set for this study.

2.3 Aggregate

Aggregate is a solid coarse material that used as a filler material in concrete. It includes gravel, crushed stone, sand, slag, recycled concrete and geosynthetic aggregates. Aggregate is divided according to their size to coarse aggregate and fine aggregate, and it forms around 40%-80% of concrete volume. Aggregate properties affect concrete properties. For a good concrete mix, aggregates need to be clean, hard, strong particles free of absorbed chemicals or coatings of clay and other fine materials that could cause the deterioration of concrete. Aggregates are divided into either 'coarse' or 'fine' categories.

Coarse aggregates are particles that are greater than 4.75 mm. The usual range employed is between 9.5 mm and 37.5mm in diameter. Fine aggregates are usually sand or crushed stone that are less than 9.5 mm in diameter. Typically, the most common size of aggregate used in construction is 20 mm. A larger size, 40 mm, is more common in mass concrete. Larger aggregate diameters reduce the quantity of cement and water needed.

2.4 Water

Water is essential in concrete because it is responsible for hydration process of concrete, and it should be according to the standard. Adding water to the mix sets off a chemical reaction when it meets the cement. The water used in the mixing of concrete is usually of a potable standard. Using non-drinking water or water of unknown purity could affect the quality and workability of the concrete.

2.5 Crushed Waste Glass

Crushed waste glass was used in this research as a replacement of natural sand. Glass mainly composes of SiO_2 (Silicon Dioxide) and Lime CaO (Calcium Oxide) [5].

3. Tests

3.1 Splitting tensile strength

The test is carried out using cylinders measuring (150 x 300 mm) according to ASTM C496-11 [6] (Fig 3.1). Each cylinder was filled up by three layers of concrete, where each layer was tamped 25 times, finished and then covered with plastic sheet to prevent water evaporation. After demoulding at 24 hours, the cylinders were cured in water tank in the curing room until the day of the test.

Fig. 3.1: Splitting tensile strength testing set up

3.2 Flexural Strength Test

The flexural strength is carried out using prisms (100 x 100 x 500 mm) according to ASTM C78-10 [7]. Each prism was filled up by three layers of concrete, where each layer was tamped 25 times and then covered with plastic cover to prevent the evaporation of the water. After 24 hours demoulding process was carried out and the prisms were cured in the curing room until 28 days of the test. The test was carried under 4 points flexural loading (Fig. 3.2).

Figure 3.2. Flexural strength test set up

3.3 Compressive Strength Test

The test is conducted using cylindrical specimens measuring (100 x 200 mm) according to ASTM C39-12 [8]. Each cylinder was filled up by three layers of concrete, where each layer was rodded 25 times. Immediately after casting, all specimens were covered with plastic sheet to prevent water evaporation and were kept in laboratory environment for the first 24 hours. After demoulding at 24 hours, the cylinders were stored in a water tank in the curing room until the day of testing. To ensure a uniform distribution of the load, a hard cap was used for the cylinders before testing. The test was conducted using compressive machine test at a constant rate of 2 kN/s as specified by ASTM C39-12 (Fig. 3.3).

Figure 3.3. Compressive strength testing machine

4. Results

4.1 Splitting tensile strength of concrete

The Splitting tensile strength of all mixes was tested at 28 days of water curing on cylinders measuring 150 × 300 mm according to ASTM C496-11.

The splitting tensile strength is calculated using the following formula:

$$\sigma_t = \frac{2P}{\pi DL}$$

where

σ_t is the splitting tensile strength

P is the compressive load at failure

L is the length of cylinder

D is the diameter of cylinder

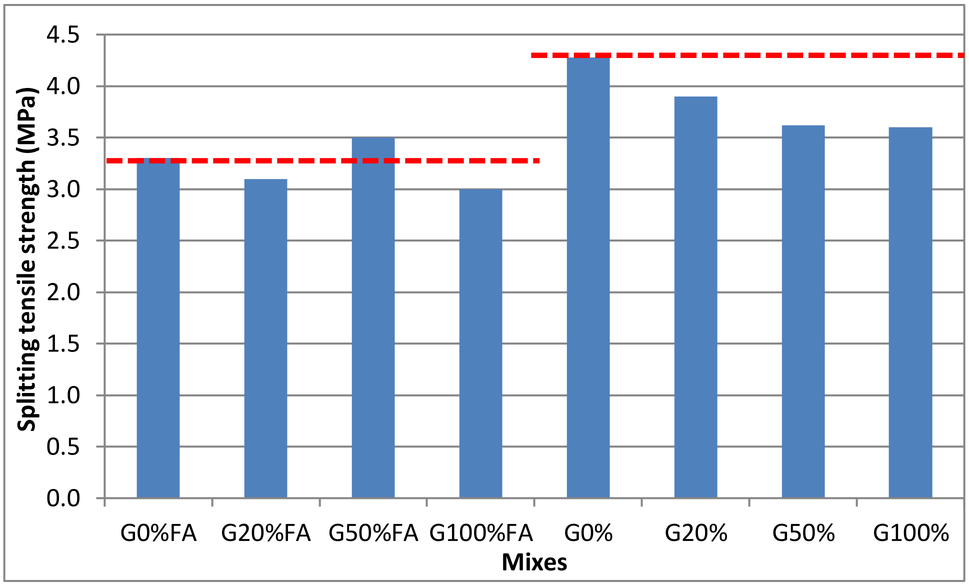

Figure 4.1. Splitting tensile strength of all concrete mixes at 28 days.

The results of the 28-day splitting tensile strength of all concrete mixes investigated are shown in the Fig 4.1. The results indicate a small decrease in the splitting tensile strength of concrete when introducing different content of glass aggregate. The decrease is more when higher content of glass is included. The combination of glass aggregate and FA has further reduced the splitting tensile strength compared to the control mix without glass and FA. This could be due to the slow reaction of FA compared to PC. Nevertheless, the highest reduction in the splitting tensile strength recorded was 1.28 MPa for the mix G100%FA.

4.2 Flexural strength of concrete

Flexural strength of all mixes was tested at 28 days of water curing on prisms measuring 100 × 100 × 500 mm according to ASTM C78-10 and the results are illustrated in Figure 4.17.

The flexural strength calculated as a modulus of rupture using the following formula: $R = \sigma_f = \frac{PL}{bd^2}$

where

R is the modulus of rupture.

P is the load at failure.

L is the prism span between support.

B is the width of prism

D is the depth of the prism

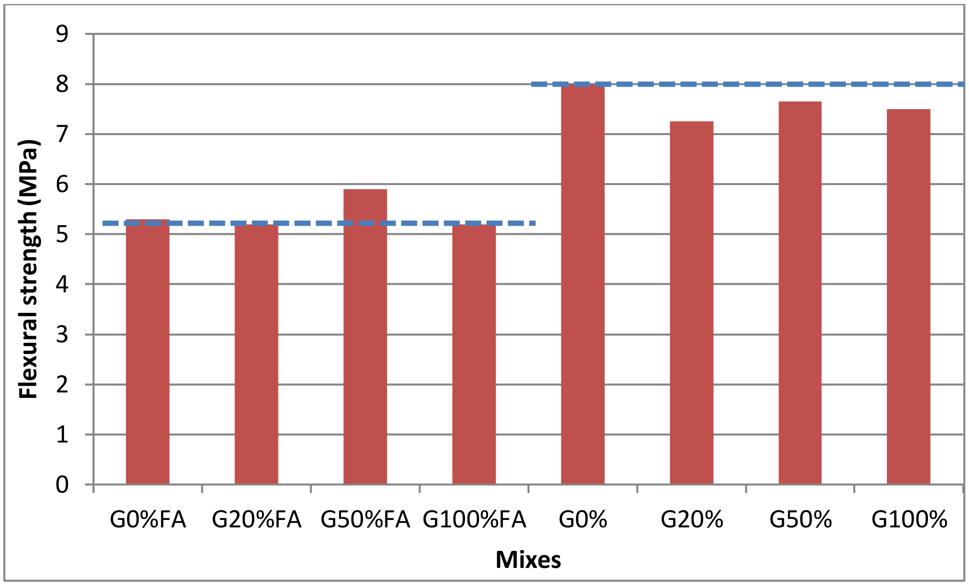

Figure 4.2. Flexural strength of all concrete mixes at 28 days.

The results of the flexural strength showed a small decrease when glass aggregate content increases in the mix. This decreases maybe due to the smooth surface and probable weak bonding strength between some glass grains and the cement paste. However, the addition of FA to the glass concrete mixes seems to provide a better bonding and hence no reduction in the flexural strength was noted even a small increase was recorded with the mix G50%FA.

4.3 Compressive strength of concrete

The Compressive strength of the control mixes and concrete with 0%, 20%, 50% and 100% of waste glass used as partial replacement of natural sand was measured on cylindrical specimens according to ASTM C39-12 standard test at 1, 3, 7, 28, and 91 days of water curing conditions. The results obtained are presented in Figure 4.3. It could be seen that glass content has a minor effect on the compressive strength development. It is clearly indicating no negative impact of using glass fine aggregate as partial or even full replacement of natural sand on the compressive strength of concrete.

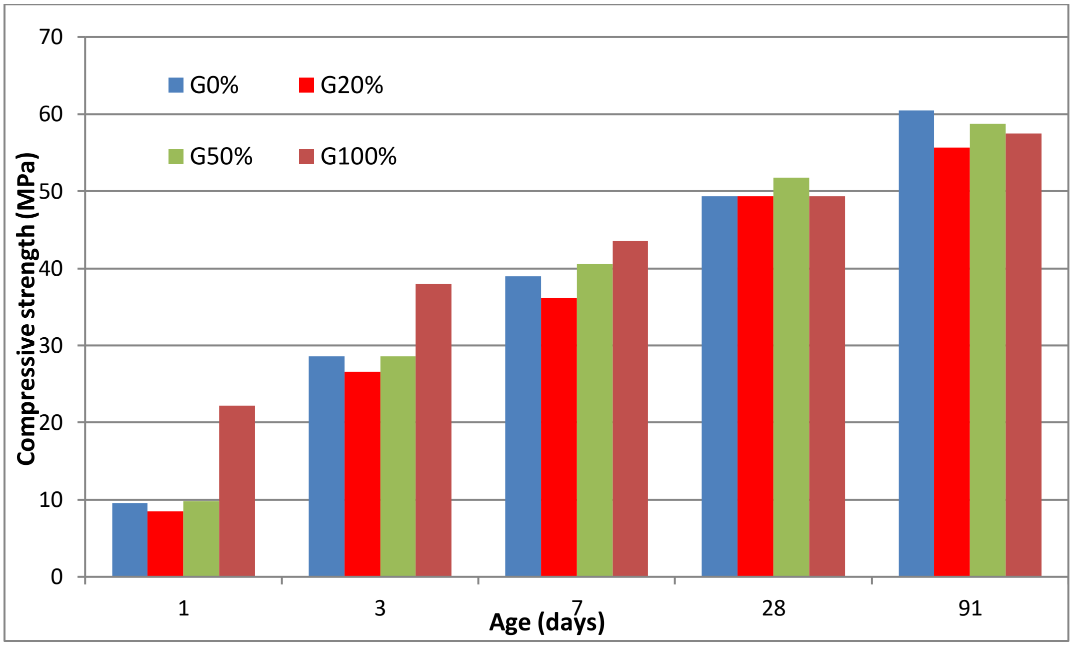

Figure 4.3. Compressive Strength of concrete mixes

Quite similar trend with a slight decrease of the compressive strength of concrete was observed also when combining waste glass aggregate as a substitute of natural sand and 30% FA as a partial substitute of Portland cement in the concrete mix as shown in Figure 4.4.

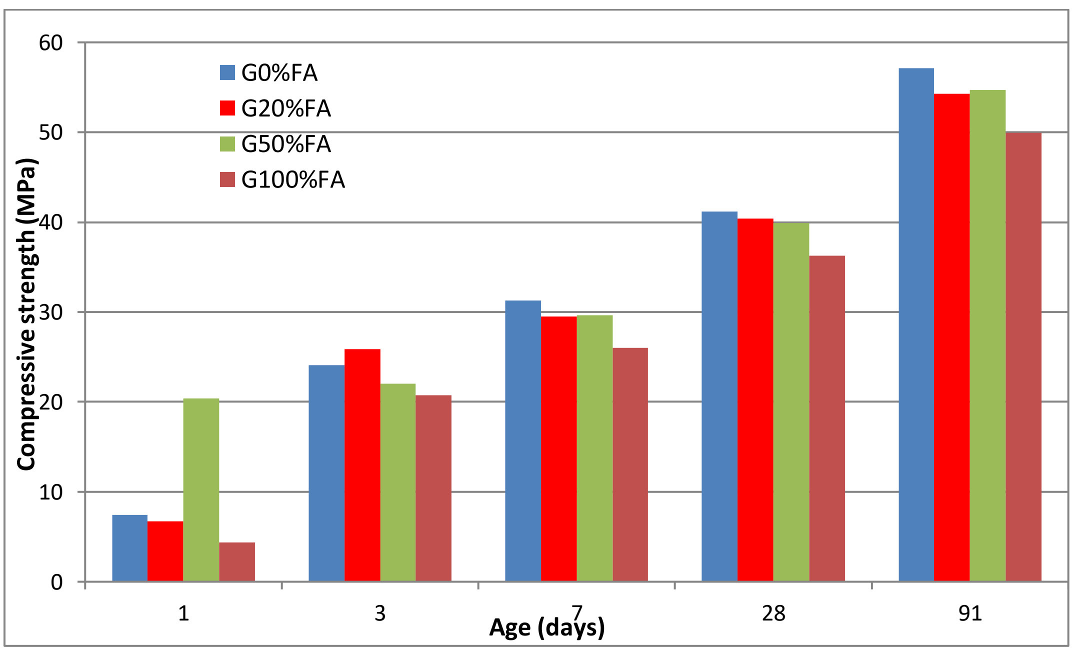

Figure 4.4. Compressive Strength of concrete mixes with 30% FA

5. Conclusion

The current study proved that glass aggregate produced from crushed waste glass could efficiently be used in concrete production as a partial or even a full replacement of natural sand with negligible to low negative impact on concrete properties.

Crushed mixed colour waste Glass could be an alternative and viable aggregate material to natural aggregate when properly prepared and adjusted in terms of granularity. Workability was slightly reduced when using glass aggregate and slight reduction of the fresh density was also noticed when glass is used.

The results of compressive, flexural and splitting tensile strengths indicate a slight decrease when adding various contents of glass aggregate as a partial/full replacement of natural sand. Porosity and water absorption were reduced when adding glass aggregate to concrete mix. Ultrasonic pulse velocity was increased when using glass as substitute of natural sand which indicates a good to excellent quality of concrete. Lastly, the thermal conductivity showed a decrease when adding glass aggregate which makes glass concrete more insulating material than control mix without glass. The combination of 30%FA with various percentage of glass aggregate has further improved strength and durability related properties (porosity and absorption) by its cementitious/pozzolanic action.

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