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Strength Properties of Carbon Fiber-Reinforced Concrete Using Waste Glass as Partial Replacement for Coarse Aggregate

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ABSTRACT

Carbon fiber-reinforced concrete (CFRC), a composite material, has gained significant attention in recent years due to its enhanced mechanical properties and durability. This research explored the incorporation of waste glass (WG) as a partial replacement for coarse aggregate in CFRC, and to investigate its effects on the strength properties of the composite material. The literature review presents an overview of the properties of carbon fiber, waste glass, followed by an analysis of previous studies on CFRC incorporating waste glass. The findings suggest that waste glass can improve the mechanical properties of CFRC, such as compressive strength, flexural strength, and impact resistance. The methodology includes density of CFRC, slump, durability compressive strength and split tensile strength tests. The slump test results showed that the workability was a true slump for all replacement percentage of waste glass and this result showed the presence of sufficient cohesion in the mix to prevent shear or collapse slump at the levels of replacement considered. The 7-, 14-, 28- and 60-days curing regime showed an overall decline in compressive strength with increase in percentage WG as the 0%, 5%, 10% outshining the latter 15% and 20% partially replaced specimens. The 90 days specimens showed persistent growth in compressive strength with increasing in percentage WG replacement in accordance with the well-established pattern of compressive strength growth. The 0%, 15% and 20% waste glass replacement showed progressive increase in splitting tensile strength with aging curing regime. The durability water absorption test showed that, by partially replacing coarse aggregate with crushed waste glass, the rate at which the concrete absorbs water decreases with increasing percentage of waste glass. The use of waste glass contributes to sustainable construction practices by reducing the environmental impact associated with glass waste disposal.

1. INTRODUCTION

Carbon fiber-reinforced concrete (CFRC) is a composite material that combines the benefits of both carbon fiber and concrete (Li, *et. al.*, 2022). The addition of carbon fibers to the concrete matrix improves its strength, ductility, and crack resistance. This has led to its increased application in various structural elements such as beams, columns, and slabs. Additionally, the use of waste materials as replacements for traditional aggregates in concrete production has emerged as an effective approach for sustainable construction practices (Zhang & Wang, 2023).

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Waste glass, generated from various sources such as bottles, containers, and construction debris, poses a significant environmental challenge. However, its incorporation into concrete as a partial replacement for coarse aggregate offers a potential solution to both waste management and the reduction of natural resource consumption (Silva, *et. al.*, 2021). The unique properties of waste glass, such as high silica content and pozzolanic activity, can contribute to the improvement of concrete's mechanical and durability properties (Liu & Poon, 2022).
This study aims to investigate the strength properties of CFRC incorporating waste glass as a partial replacement for coarse aggregate. The focus is primarily on the compressive strength, flexural strength, and split tensile strength of CFRC specimens with varying percentages of waste glass substitution. The findings will provide insights into the feasibility and potential of waste glass as a sustainable alternative aggregate material in CFRC production.

1.1 Carbon Fiber-Reinforced Concrete

Carbon fibers are thin, strong, and lightweight materials with high tensile strength and excellent resistance to corrosion and fatigue. When added to concrete, carbon fibers can enhance its ductility, durability, and load-bearing capacity. Previous studies have demonstrated the positive effects of carbon fibers on the mechanical properties of concrete, including compressive strength, flexural strength, and impact resistance (Nguyen & Al-Tayyib, 2023). The improved performance is attributed to the bridging effect of carbon fibers, which helps to prevent crack propagation and enhances the energy absorption capacity of the concrete (Topçu, 2021).

1.2 Waste Glass as Aggregate Replacement

Waste glass is a byproduct of various industrial processes and post-consumer glass products. It possesses pozzolanic properties, making it a suitable candidate for use in concrete. The use of waste glass in concrete can mitigate the environmental impact associated with glass waste disposal and conserve natural resources (Raut & Ralegaonkar, 2020).
Several researchers have investigated the use of waste glass in concrete production. Studies have demonstrated the potential of waste glass as a partial substitute for coarse aggregate, offering advantages such as reduced environmental impact and enhanced thermal insulation properties. The chemical and physical properties of waste glass have been evaluated to ensure its compatibility with concrete (Zhang, *et al.*, 2021).
Recent studies have reported significant improvements in the strength properties of CFRC using waste glass as a partial replacement for coarse aggregate. For instance, a study by Li *et al.* (2022) demonstrated a 15% increase in compressive strength and a 20% increase in flexural strength with a 20% replacement of coarse aggregate with waste glass.
Li *et al.* (2021), suggested that the use of crushed waste glass as an aggregate in concrete has several advantages in terms of strength. The relative abundance of glass makes it available for production of concrete; this will consequently lead to low cost of production thereby making concrete structures (buildings) relatively cheap. On this note, the percentage of glass in concrete should not be much.
Zhang *et al.* (2022) deliberated the various steps that need to be taken by recyclers to collect the glass, separate it from the other materials, clean it and crush it to obtain the suitable grading and to meet the require specifications for the detailed applications as an aggregate in the concrete.

Green, & Brown, (2021), considered waste glass as coarse aggregates in the concrete mix. The effects of waste glass on workability and strength of the concrete with fresh and hardened concrete tests were analysed. As per the result of the research conducted, the waste glass was shown not to have an important effect on the results of the workability on the concrete and later it only shows small decreasing in its strength.

Smith & Johnson, (2022), studied the three probable uses of the waste glasses in the manufacture of cement and in concrete, whereas their results shown can be summarized as follows: Firstly, with the use of waste glasses as a concrete aggregate has a little negative effect on the workability, strength and the action of freezing-thawing resistance of cement concrete. Also, the waste glasses can be used in the raw materials for cement production as a siliceous source. Therefore, the effect will be reliant on the quantity of waste glass used. Therefore, it may be said that if the percentage of waste glass used in the raw materials is lesser, the effects will be very minimal.

Zainab and Enas, (2009) investigated the properties of concretes containing waste glass as fine aggregate. The strength properties and the alkali silica reaction (ASR) expansion were analysed in terms of waste glass content, the total quantity of 80 kg of crushed waste glass was partially swapped with sand at 10%,15%, and 20% within the 900 kg quantity of the concrete mixtures. The results showed 80% of pozzolanic strength activity given by the waste glass after the 28 days.

Nada & Haider, (2018), examined the properties of recycled glass cullet on the fresh and the hardened properties of self-compacting concrete. The Recycled glass was added to replace the river sand (in the different proportions of 10%, 20% and 30%), and 10 mm granite in (5%, 10% and 15%) and hence making the self-compacting concrete mixes. The results showed that the compressive strength, tensile splitting strength and static modulus of elasticity of the recycled glass self-compacting concrete mixes were decreasing with increasing in the recycled glass aggregate quantity.

Onyeka, (2019) worked on the effect of partial replacement of coarse aggregate by crushed broken glass on properties of concrete. It was observed that the specific gravity of the glass used for the study fell below the specific gravity in the normal coarse aggregate by about 1.3 times and this caused a reduction in the overall weight and densities of the concrete. It was observed that the percentage of water absorbed by the concrete decrease at the increase in the percentage of the glass. This could be attributed to the impermeable nature of the glass, and this reduced the effects the curing would have hardened on the strength of the concrete. The workability of the concrete increase with increase in the glass percentage owing to the fact that the bond between the aggregates and the reduced to the reduction in the plasticity of the concrete at the increase in the glass content. The compressive strength of the concrete reduced gradually at the increase in the percentage of the coarse aggregates replaced with coarse glass aggregate. It was observed that the 7days strength of the glass concrete was higher than that of the normal aggregate, but the strength as the curing days increased could not improve more than that of normal concrete. The control mix generally gave more strength than that of the glass concrete, but the best strength of the concrete was achieved at the 25% replacement with glass. The 25% compressive strength is 25.04 kN/m^2 which is just about 3.8% lower than that of the normal concrete mix therefore it was concluded that the aggregates can be replaced effectively by waste glass up to 25%. Utilization of waste glass in concrete production will invariably help to reduce the negative impact of these waste on the environment and will reduce in no small measure the over cost of concrete production.

2. MATERIALS AND METHODS

2.1 Materials

The materials used for this investigation were:

a. Cement (Elephant Portland Limestone Cement)
b. Fine aggregates (River sand)
c. Coarse aggregates (Granite)
d. Waste glass bottles
e. Carbon fiber material (Fiberglass Net)
f. Water

2.2. Sample Preparation

The coarse aggregate (granite) is replaced partially by crushed waste glass bottles in percentages 5, 10, 15 and 20% by weight of granite. This is done and the final mix design table is obtained for batching and casting operations.

The weight of the materials used for the different days of casting and curing are represented in the Table 1 as shown below.

Table 1: A mix design for different curing days using 1:1.5:3 (M20) mix ratio

S/N	% Replacement	Cement (kg)	Fine Aggregate (kg)	Coarse Aggregate (kg)	Crushed Waste glass (kg)
1.	0	63.34	95.01	190.02	0
2.	5	63.34	95.01	180.52	9.50
3.	10	63.34	95.01	171.02	19.00
4.	15	63.34	95.01	161.52	28.50
5.	20	63.34	95.01	152.02	38.00

2.2.1 Mixing operation

The materials were mixed on an impermeable surface to avoid the loss of water manually with a spade.

2.2.2. Moulding

The wooden moulds (size: 150 x 150 x 150 mm) and (size 100 x 100 x100 mm) were used for compressive strength and durability test respectively as seen in Figure 1 left side. For the tensile strength a P.V.C pipe (150mm by 300mm) was used as seen in Figure 1 right side.

Figure 1: Wooden moulds and P.V.C cylindrical moulds (pipes)

2.2.3. Moulds Oiling

Black engine oil was applied to interior surface of the moulds before pouring concrete with a paint brush in order to demould easily when the concrete is set.

2.2.4. Compacting operations

The fresh concrete is poured into the moulds in three layers and tamped twenty-five (25) times in each layer.

Curing

This investigation was subjected to six different curing days (7, 21, 28, 60 and 90 days) after demoulding the set concrete form the formwork.

2.3. Tests on Concrete Constituents

This involved verifying the chemical composition of the concrete constituents' waste glass and granite.

2.3.1 Slum Test

The slump test was carried out as shown in Figure 2 to assess the workability characteristic of the concrete specimens with respect to their replacement value.

Figure 2: Slump test

2.3.2. Durability Test

Procedures for water absorption:

I. Heat the concrete specimen in an oven at 98-100°C, until its weight was constant. (Figure 3)

II. Cool the concrete specimen at room temperature for 24 hours.

III. Thereafter, coat the four sides of the specimens with silicon sealant to a height of 5mm.

IV. Measured and record the mass of the coated specimen.

V. Immerse the specimen into shallow water to a depth of 5mm. (Figure 4)

VI. Take the specimens out at one-hour immersion in water.

VII. Wipe out excess surface water from the specimen.

VIII. Then, I weigh the soaked concrete specimens.

IX. Thereafter calculate the coefficient of the water absorption.

Figure 3: Drying of concrete specimen in an oven.

Figure 4: Immersion of the concrete specimen in water.

2.3.3. Compressive Strength Test

The compressive strength test was conducted on 150 mm x150 mm x 150 mm cube specimens, in accordance with BS EN 12390-2 (2000). A total of 75 concrete cubes was cast. The materials were mixed at an ambient temperature with a manual mix.

Immediately after the completion of the mixing process, the fresh concrete was sampled for slump test. After the slump test, the fresh concrete was placed in a concrete cube mould in three layers. Each concrete layer was compacted by tampering at 25 blows each, the concrete was allowed to set for 24 hours before demoulding and curing. The concrete cube specimens were cured by complete immersion in water in a curing tank.

The compressive strength of the concrete cube was determined at ages of 7, 14, 28, 60 and 90 days respectively, in accordance with BS EN 12390-3(2009) with the use of a testing machine by crushing as shown in Figure 5.

Figure 5: Crushing of concrete cubes.

2.3.4. Density Test

Procedures for density test:

1. Weigh the concrete specimen using a weighing balance to determine its mass (kg) as shown in Figure 6.
2. Using the formula for the volume of the specific concrete specimen by its form (cube, cylinder, rectangle etc) calculate for the volume (m^3) of the concrete specimen.
3. Determine the density (kg/m^3) by diving the mass of the concrete specimen by the volume it occupies.

Figure 6: Weighing of concrete cube for density determination.

2.3.5. Splitting Tensile Strength Test

Procedures for Splitting Tensile test:

1. After curing, wipe out water from the surface of specimen.
2. Using a marker, draw diametrical lines on the two ends of the specimen to verify that they are on the same axial place.
3. Measure the dimensions of the specimen.
4. Keep the plywood strip on the lower plate and place the specimen.
5. Align the specimen so that the lines marked on the ends are vertical and centred over the bottom plate.
6. Place the other plywood strip above the specimen and bring down the

upper plate to touch the plywood strip.

7. Apply the load continuously without shock at a rate of approximately 14-21 kg/cm^2/minute (Which corresponds to a total load of 9.9 ton/minute to 14.85 ton/minute) as shown in Figure 7.
8. Write the breaking load (P)

3. RESULTS AND DISCUSSION

The results of the chemical properties performed on the waste glass and coarse aggregate are presented in Table 2.

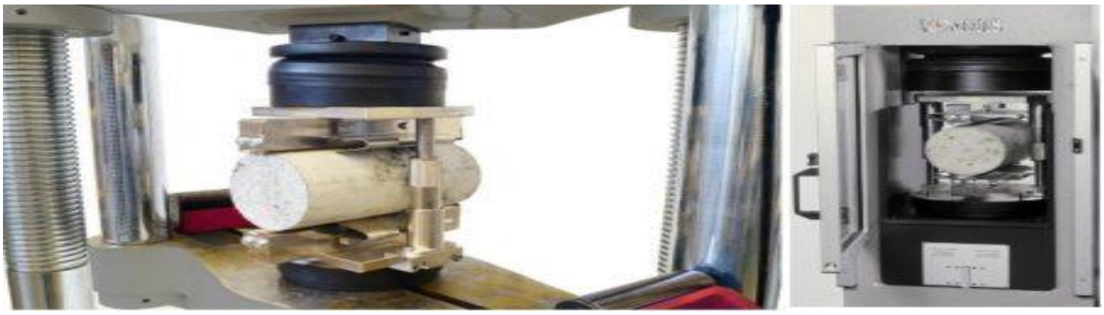


Figure 7: Splitting tensile test of concrete specimen.

Table 2: Result of chemical analysis on waste glass and coarse aggregate (granite)

Chemical Composition	**Waste Glass (%)**	**Coarse Aggregate (%)**
Silicon Oxide (SiO_2)	64.31	72.04
Aluminum Oxide (Al_2O_3)	19.98	14.42
Iron Oxide (Fe_2O_3)	6.25	1.22
Iron (II) Oxide (FeO)	_	1.68
Potassium Oxide (K_2O)	0.74	4.12
Sodium Oxide (Na_2O)	12.52	3.69
Calcium Oxide (CaO)	10.61	1.82
Magnesium Oxide (MgO)	0.63	0.71
Titanium Oxide (TiO_2)	0.02	0.30
Sulphide (SO_3)	0.25	3.70
Phosphorus Pentoxide (P_2O_5)	_	0.12
Manganese Oxide (MnO)	_	0.05
Chromic Oxide (Cr_2O_3)	1.47	_
Loss on Ignition (LOI)	1.47	2.1

3.1. Workability

The effect of waste glass on the workability of the concrete specimen is shown in Table 3. It can be observed that the slump values remained grossly unchanged with increase in percent waste glass. The result is most likely due to the fact that waste glass does not possess water retaining properties or any other property that would disturb the homogeneity of the mix thereby resulting in a harsh mix.

According to Neville, (2011) the slump values placed the specimens under concrete of low workability.

Table 3: Results of the Slum test

Crushed Waste Glass Replacement (%)	Slump	Workability	Type
0	2	Very low	TRUE
5	3	Very low	TRUE
10	3	Very low	TRUE
15	5	Very low	TRUE
20	6	Very low	TRUE

3.2. Density of Specimens

The knowledge of density of concrete specimen is required for effective and efficient structural performance. According to ACI 213, (2003) and (Adetayo & Olatunji, 2019) lightweight concrete has densities that are less than 2200kg/m^3, normal weight concrete has densities between 2200 and 2550kg/m^3 and heavyweight concrete has densities above 2550kg/m^3.

All the concrete samples, at all the replacement values considered, developed densities between 2200 kg/m^3 and 2550 kg/m^3. This means that the specimens can be considered as normal weight concrete. This is very instructive when waste glass is to be used for structural concrete. The Table 4 (cubes) and Table 5 (cylinders) reveals that the densities did not follow a particular incremental or declining pattern with curing age at all the replacement values, but the results were rather random within the range 2161 and 2710kg/m^3.

Table 4: Density for Concrete Cubes (150mm x 150mm x 150mm) in Kg/m^3

Crushed Waste Glass Replacement (%)	7 days	14 days	28 days	60 days	90 days
0	2471	2459	2220	2398	2270
5	2291	2100	2325	2426	2155
10	2368	2165	2246	2366	2133
15	2293	2039	2189	2416	2102
20	2396	1894	2285	2250	2159

Table 5: Density for Concrete Cylinders (150mm dia, 300mm length) in Kg/m^3

Crushed Waste Glass Replacement (%)	7 days	14 days	28 days	60 days	90 days
0	2560	2530	2516	2609	2546
5	2599	2446	2575	2554	2392
10	2563	2256	2624	2481	2208
15	2557	2409	2641	2557	2477
20	2577	2264	2671	2501	2461

3.3. Compressive Strength of Specimens

The compressive strength of CFRC specimens is evaluated at different curing ages. The results indicate that the incorporation of waste glass up to a certain percentage lead to comparable or even improved compressive strength compared to conventional concrete. However, excessive replacement of coarse aggregate with waste glass may result in reduced strength due to its lower stiffness.

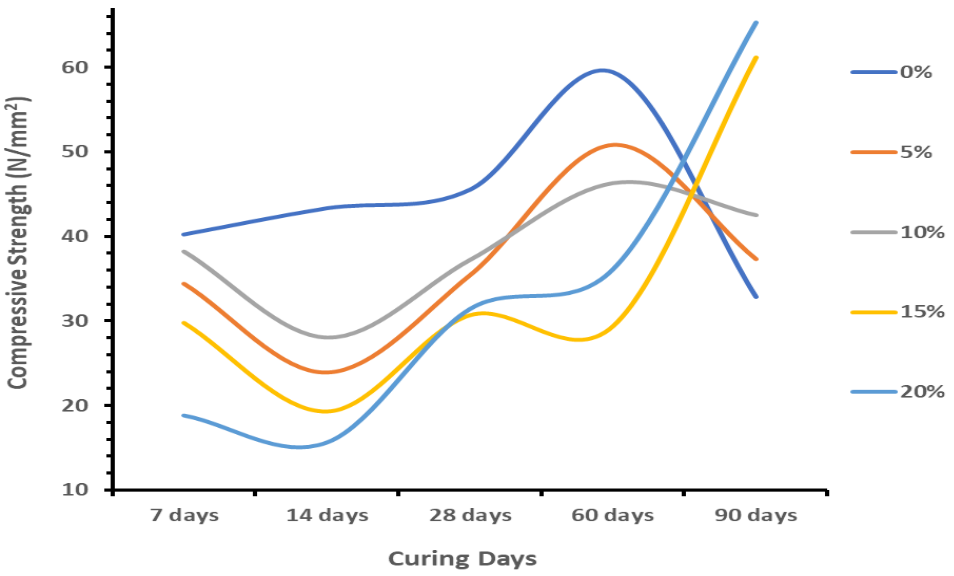
The effect of waste glass CFRC on the compressive strength of the specimens is shown in Figure 8. From the overview of the Table 6 below, it showed the overall compressive strength for the 0%, 5%, 10% increased progressively for the 7-, 14-, 28- and 60-days curing regime. However, this was not the case in the 90days curing regime which showed a steady increase in compressive strength for 0%, 5%, 10%, 15% and 20% W.G replacement.

The 7-, 14-, 28- and 60-days curing regime showed an overall decline in compressive strength with increase in % W.G as the) 0%,5%,10% outshining the latter 15% and 20% specimens.

The 90 days specimens showed persistent growth in compressive strength with increasing % W.G replacement in accordance with the well-established pattern of compressive strength growth (Neville, 2011).

Table 6: Compressive strengths of concrete specimens

S/N	Crushed Waste Glass Replacement (%)	Compressive Strength (N/mm^2)				
		7 days	14 days	28 days	60 days	90 days
1	0	40.2	43.3	45.5	59.4	32.8
2	5	34.4	23.9	35.4	50.8	37.3
3	10	38.2	28.0	37.2	46.3	42.5
4	15	29.8	19.3	30.7	29.4	61.2
5	20	18.8	15.6	31.4	36.1	65.3



Figurer 8: Compressive strength graph

3.4. Splitting Tensile Strength of Specimens

The split tensile strength of CFRC was evaluated to assess its resistance to tensile stresses. The results demonstrated that carbon fiber reinforcement enhances the split tensile strength of concrete.

The results of the effect of waste glass and CFRC on the splitting tensile strengths at 7, 14, 28, 60 and 90 days of curing ages are presented in in Table 9 and Figure 2. It can be seen from Table 6, that the splitting tensile strength increased progressively with aging curing regime for the 0%, 15%, 20% waste glass content and also same for the 5% and 10% the strengths increased progressively with increasing curing age until the 90 days curing regime which saw a sharp decline in strength compared to others. The strength growth pattern was in line with the standard requirement prescribed by (Neville, 2011). However, the decrease in the splitting tensile strength for the 5% and 10% W.G content 90 days specimen shows weakness in the use for concrete production.

From the results, the 0%, 15% and 20% waste glass replacement showed progressive increase in splitting tensile strength with aging curing regime in line with the standard requirement prescribed by (Neville, 2011).

The splitting tensile strength increased progressively in the 5% and 10% waste glass content with aging curing regime but exhibited a sharp decline in strength in the 90 days specimen compared to others.

Table 7: Splitting tensile strengths of concrete specimens.

S/N	**Crushed Waste Glass Replacement (%)**	**Split Tensile Strength (N/mm^2)**				
		7 days	**14 days**	**28 days**	**60 days**	**90 days**
1	0	2.4	2.8	2.9	3.2	3.3
2	5	1.8	1.9	2.4	2.6	1.7
3	10	1.9	2.0	2.4	2.9	1.1
4	15	2.2	2.2	2.4	2.7	3.5
5	20	1.3	1.3	2.7	2.6	2.8

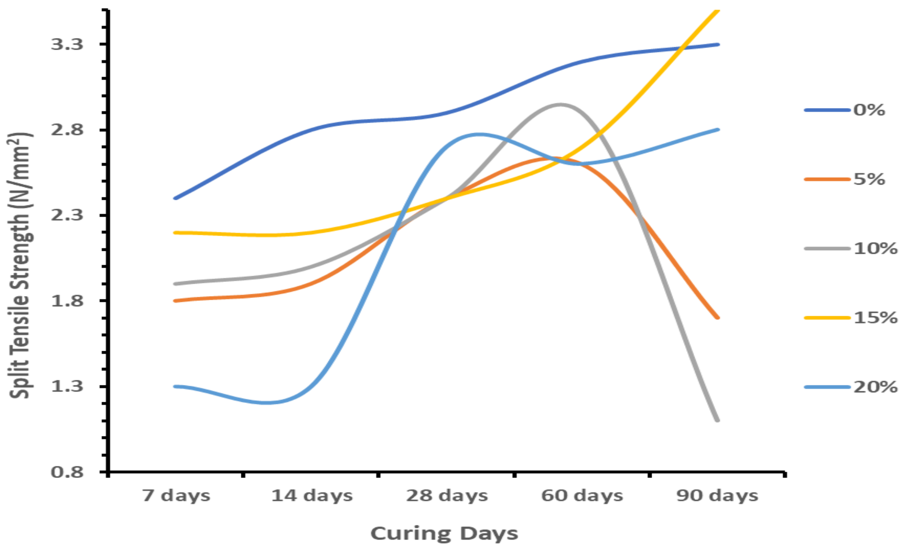


Figure 9: Splitting Tensile strength graph.

3.5. Durability Test (Water Absorption Test)

After the end of the following curing regime of 28, 60 and 90 days the 100mm x 100mm x 100mm concrete cubes were prepared and oven dried for 24hrs until constant weight is attained. The dry weight is noted as W_1 and the final weight (wet weight) is the weight of the concrete cubes after immersion in water for another 24hrs and noted as W_2. The amount of water absorbed by the concrete cubes are calculated by its initial weight. The amount of water absorption in cured cubes is calculated and compared. The results showed an average of 3 - 4% gain in moisture for all curing regimes and waste glass replacements. Tables 8, 9, 10, 11, 12 showed the results obtained from the water absorption test and the percentage gain in moisture of the concrete specimens and the overview of the results is shown in Figure 10.

Table 8: Water absorption for glass concrete (0% waste glass of 0.5 w/c ratio)

Crushed Waste Glass Replacement (%)	**Curing days**	**Weight before immersion (kg)**	**Weight after immersion (kg)**	**Absorption gain (kg)**	**% Gain in moisture**
	28	2.26	2.34	0.08	3.54
0	60	2.33	2.46	0.13	5.58
	90	2.43	2.54	0.11	4.53

Table 9: Water absorption for glass concrete (5% waste glass of 0.5 w/c ratio)

Crushed Waste Glass Replacement (%)	**Curing days**	**Weight before immersion (kg)**	**Weight after immersion (kg)**	**Absorption gain (kg)**	**% Gain in moisture**
	28	2.24	2.36	0.12	5.36
5	60	2.28	2.42	0.14	6.14
	90	2.37	2.45	0.08	3.38

Table 10: Water absorption for glass concrete (10% waste glass of 0.5 w/c ratio)

Crushed Waste Glass Replacement (%)	**Curing days**	**Weight before immersion (kg)**	**Weight after immersion (kg)**	**Absorption gain (kg)**	**% Gain in moisture**
	28	2.34	2.47	0.13	5.56
10	60	2.45	2.54	0.09	3.67
	90	2.39	2.46	0.07	2.92

Table 11: Water absorption for glass concrete (15% waste glass of 0.5 w/c ratio)

Crushed Waste Glass Replacement (%)	**Curing days**	**Weight before immersion (kg)**	**Weight after immersion (kg)**	**Absorption gain (kg)**	**% Gain in moisture**
	28	2.23	2.35	0.12	5.38
15	60	2.42	2.50	0.08	3.31
	90	2.46	2.55	0.09	3.66

Table 12: Water absorption for glass concrete (20% waste glass of 0.5 w/c ratio)

Crushed Waste Glass Replacement (%)	**Curing days**	**Weight before immersion (kg)**	**Weight after immersion (kg)**	**Absorption gain (kg)**	**% Gain in moisture**
	28	2.39	2.48	0.09	3.77
20	60	2.32	2.39	0.07	3.02
	90	2.43	2.48	0.05	2.06

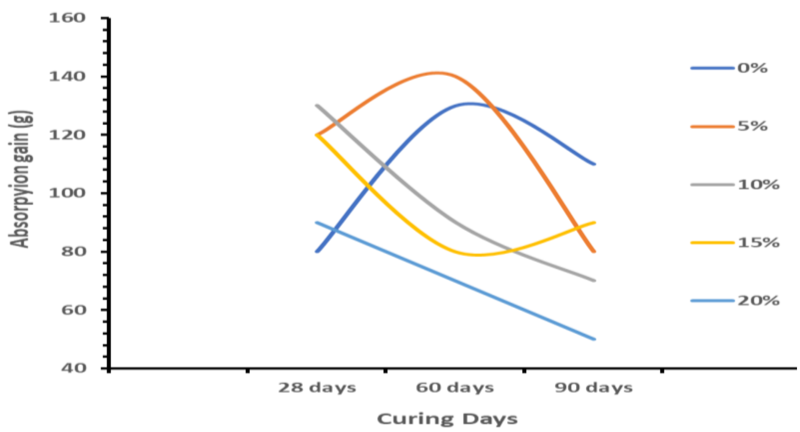


Figure 10: Water absorption graph

4. CONCLUSION

This study highlights the potential of utilizing waste glass as a partial replacement for coarse aggregate in CFRC. The incorporation of waste glass not only reduces environmental impact by recycling a waste material but also improves the sustainability of CFRC. The test results indicated that CFRC with waste glass can achieve adequate strength properties for various structural applications.

Based on the investigations, test conducted, and result obtained in this research, the following conclusions can be drawn:

1. The physical composition analysis showed that values of weight parameters like density and specific gravity of coarse aggregate is higher than waste glass, which is an indication that, the inclusion of waste glass in concrete will result in lighter product.
2. The workability was a true slump for all replacement percentage of waste glass and this result showed presence of sufficient cohesion in the mix to prevent shear or collapse slump at the levels of replacement considered.
3. The 7-, 14-, 28- and 60-days curing regime showed an overall decline in compressive strength with increase in percentage WG as the 0%, 5%, 10% outshining the latter 15% and 20% partially replaced specimens.
4. The 90 days specimens showed persistent growth in compressive strength with increasing in percentage WG replacement in accordance with the well-established pattern of compressive strength growth (Neville, 2011)
5. The 0%, 15% and 20% waste glass replacement showed progressive increase in splitting tensile strength with aging curing regime in line with the standard requirement prescribed by (Neville, 2011).
6. The durability water absorption test chart shows that partially replacing coarse aggregate with crushed waste glass, the rate at which the concrete absorbs water decreases with increasing percentage of waste

glass and this is most likely due to the fact that waste glass does not possess water retaining properties or any other property that would disturb the homogeneity of the mix thereby resulting in a harsh mix.

7. The optimum level of coarse aggregate which could be advantageously replaced by the crushed waste glass was achieved at 20% for the water absorption test.

Further research is recommended to explore the long-term durability, microstructural properties, and economic feasibility of CFRC incorporating waste glass as a partial replacement for coarse aggregate. Additionally, the influence of other factors, such as fiber content, curing conditions, and mix design optimization, should be investigated to enhance the performance and practical application of CFRC with waste glass.

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