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Mechanical Performance of Concrete with Partial Fine Aggregate Replacement Using Pulverized Waste Glass Bottles: A Comparative Study of Mix Grades

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ABSTRACT
This study investigates the mechanical performance of concrete incorporating pulverized waste glass (PWG) as a partial replacement for fine aggregates in two distinct mix ratios: 1:1.5:3, representing higher-grade concrete, and 1:2:4, representing lower-grade concrete. Compressive strength tests were conducted at 7, 14, and 28 days on concrete samples with PWG replacement levels of 0%, 10%, 20%, 50%, 75%, and 100%. The results reveal that higher-grade concrete, with a greater reliance on aggregate interlocking and matrix bonding, is more sensitive to PWG content, showing significant reductions in compressive strength at a 100% replacement level. However, moderate replacement levels, specifically up to 75%, did not substantially affect long-term compressive strength, suggesting a tolerance for partial substitution in higher-grade mixes. In contrast, lower-grade concrete exhibited a notably positive response to PWG replacement, particularly at 75%, where compressive strength reached a peak of 32.15 N/mm². This outcome indicates that PWG can enhance the packing density of lower-grade mixes, compensating for its lack of angularity and bonding characteristics compared to natural aggregates. These findings underscore the potential of PWG as a sustainable and effective alternative to fine aggregates, particularly suited to applications in lower-grade concrete, while maintaining mechanical performance standards.

Keywords: Pulverized waste glass, fine aggregate replacement, compressive strength, sustainable concrete, mix grades.

I. INTRODUCTION

Concrete plays a critical role in modern construction, forming the backbone of infrastructure projects such as buildings, bridges, and roads due to its high strength and widespread availability (Almeshal et al., 2022). Traditionally, concrete is made from a mixture of cement, water, fine aggregates (sand), and coarse aggregates (gravel or crushed stone). However, with the rapid growth of the construction industry, there is an increasing demand for these natural materials, particularly sand, leading to concerns over resource depletion and environmental degradation.

Sand, as a key component of fine aggregates in concrete, is being consumed at unsustainable rates. This over-extraction has resulted in significant environmental consequences, such as habitat destruction, riverbank erosion, and the lowering of water tables (Gautam & Srivastava, 2012). As a result, researchers have been exploring sustainable alternatives to sand in concrete production. One promising alternative is the use of pulverized waste glass, which can partially replace fine aggregates and offer both environmental and practical benefits.

Improper disposal of waste materials, particularly glass, is another major environmental issue. Glass is non-biodegradable and can remain in the environment for centuries, contributing to long-term pollution (Jani & Hogland, 2014). Most waste glass, derived from packaging, household goods, and industrial processes, ends up in landfills due to contamination or a lack of market demand (Metwally, 2007).Incorporating waste glass into concrete production as a fine aggregate replacement can address two critical problems:

reducing the environmental impact of glass waste and conserving natural resources.

In recent years, the construction industry has increasingly turned to recycled materials to minimize the carbon footprint of concrete production, which contributes significantly to global greenhouse gas emissions (Khan et al., 2020). Cement production is an energy-intensive process, and integrating recycled materials such as pulverized waste glass bottles (PWGB) into concrete can help reduce these emissions. Studies have shown that using waste glass in concrete not only offers environmental advantages but also presents potential economic benefits (Metwally, 2007).

Waste glass contains silica, a fundamental component of concrete, making it a suitable candidate for fine aggregate replacement (Lam et al., 2007). When finely ground, waste glass exhibits pozzolanic properties, reacting with calcium hydroxide in the presence of water to improve the strength and durability of concrete. However, challenges such as alkali-silica reaction (ASR), which can lead to expansion and cracking, must be addressed. Fortunately, using glass in its pulverized form mitigates these risks, making it a more viable option for sustainable concrete production.

Numerous studies have examined the impact of using crushed glass as a fine aggregate on the compressive strength of concrete. These studies consistently show an increase in compressive strength when recycled glass sand (RGS) is utilized (Bataynehi et al., 2007; Oliveirai et al., 2008; Ismail & Al-Hashmi, 2009; Du & Tan, 2014a; Wang et al., 2016). The compressive strength rises steadily with increasing RGS content, peaking at an optimal level before beginning to decline (Dumitrui et al., 2010;Al-Qatani et al., 2011; Maliki et al., 2013; Hunagi et al., 2015).

Further research supports these findings, demonstrating that waste glass can be a viable partial replacement for fine aggregates. For instance, Haider et al., (2009) found that replacing up to 20% of fine aggregate with waste glass resulted in concrete with mechanical properties comparable to conventional concrete. Similarly, Gautam and Srivastava (2012) reported improved strength and durability when waste glass was used, along with a reduction in waste accumulation. These studies indicate that PWGB has the potential to be a sustainable and cost-effective material in concrete production.

Moreover, Corinaldesi et al., (2005) found that replacing 30–70% of fine aggregates with waste glass posed no significant ASR-related issues when particle sizes were limited to 100 µm, and the mechanical performance of the concrete improved. The mix design of concrete, particularly the water-cement (w/c) ratio and aggregate proportions, plays a crucial role in determining its strength, durability, and workability (Neville & Brooks, 2010). As such, the incorporation of waste glass into concrete production holds promise for developing more sustainable, durable, and environmentally friendly construction materials.

II. MATERIALS AND METHODS

2.1 Materials

2.1.1Ordinary Portland cement (OPC)

Ordinary Portland Cement (OPC) was used as the binder in the concrete mixtures. The specific type of OPC used in this study was classified as Grade 42.5, meeting the requirements of **BS EN 197-1**. OPC was used in all mix designs without any modifications.

2.1.2 Fine Aggregates

Fine aggregates in conventional concrete are typically composed of natural river sand obtained in commercial dealers in Amassoma Bayelsa State. However, to partially replace this natural sand, pulverized waste glass bottles (PWGB) were incorporated into the mix. The natural sand used in this study conformed to **BS 882:1992** standards for particle size distribution, cleanliness, and grading. The particle size distribution was tested using a standard sieve analysis as illustrated in table 1 to 3.

2.1.3 Coarse Aggregates

Crushed granite was used as coarse aggregate in the concrete mix. The size of the coarse aggregates was selected in the range of 10–20 mm to ensure good interlocking and compaction in the concrete matrix. The coarse aggregates complied with **BS 882:1992** standards

2.1.4Pulverized Waste Glass Bottles (PWGB)

The waste glass bottles used in this study were sourced from local recycling facilities. They were first cleaned, dried, and crushed using a pulverizing machine to obtain fine particles as shown in figures 1. The particle size of PWGB was controlled to fall within the same size range as natural fine aggregates (0.075 mm to 4.75 mm) to ensure uniformity in the mix.

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Figures 1: Sourced waste bottles and pulverization process

2.1.5Water

Water was used for mixing and curing the concrete samples. Potable water, free from impurities, was sourced locally and met the specifications outlined in **BS EN 1008** for mixing water.

2.2Mix Design

The mix design of the concrete was based on varying proportions of PWGB as a partial replacement for fine aggregates, combined with water-cement (w/c) ratio of 0.5. A total of six concrete mixtures were designed, with PWGB replacing natural sand at levels of 0%, 10%, 20%, 50%, 75% and 100%. For each replacement level, two different mix were investigated: 1:1.5:3 and 1:2:4.

2.3Preparation of Concrete Specimens

Figure 2: preparation of test samples

Concrete specimens were prepared in accordance with **BS EN 12390-2:2009**, which outlines standard methods for making and curing concrete test specimens. The mixing process was carried out in a hand mixer, ensuring uniform distribution of materials. For each mix, sufficient quantities were prepared to cast standard cube specimens of dimensions 150 mm x 150 mm x 150 mm as shown in figure 2. The cubes were compacted in three layers using a tamping rod to eliminate air voids and ensure adequate compaction.

Once cast, the concrete specimens were left to cure in molds for 24 hours at ambient temperature. After demolding, the specimens were submerged in a curing tank with clean water at a constant temperature of 20°C. The curing period was set to 7, 14, and 28 days to evaluate the development of compressive strength over time.

2.4 Testing Methods

2.4.1 Compressive Strength Test

The primary test conducted in this study was the compressive strength test, which is the most commonly used method for determining the strength of concrete. Compressive strength tests were performed in accordance with **BS EN 12390-3:2009**. A compression testing machine with a capacity of 2000 kN was used to load the concrete specimens until failure. The compressive strength was calculated by dividing the maximum load applied to the specimen by its cross-sectional area. Tests were conducted at 7, 14, and 28 days for each mix design.

2.4.2 Particle size Distribution Test

The Sieve analysis study was done in the Geotechnical Laboratory, Department of Civil Engineering of Niger Delta University. The fine aggregate was sieved via a 600µm sieve and found to have a specific gravity of 2.67, confirming its classification as zone II per BS EN 12620:2002+A1 (2008).

III. RESULTS AND DISCUSSION

3.1 Sieve Analysis Result

The sieve analysis was conducted to evaluate the particle size distribution of both the natural sand and the pulverized waste glass used in the concrete mixes. This analysis is crucial for determining the suitability of PWGB as a fine aggregate replacement and its impact on the overall gradation of the concrete mix. The particle size distribution of natural sand fell within the acceptable range for fine aggregates, with a well-graded curve typical of river sand.

The pulverized waste glass, however, exhibited a slightly different gradation profile, with a higher proportion of particles in the finer size range (passing the 600 µm). This is due to the crushing process of the glass, which produced finer particles compared to natural sand. The finer nature of PWGB contributed to a tighter particle packing within the concrete matrix, potentially enhancing the strength properties at lower replacement levels.

Table 1: Sieve Analysis of fine aggregates

Sieve Size(m)	Mass Retained(g)	%Retained on Sieve	Cumm.%Retained	%PASSING
2	0	0	0	100.00%
1.18	60	6.00%	6.00%	94.00%
0.84	178	17.80%	23.80%	76.20%
0.3	686	68.60%	92.40%	7.60%
0.15	69	6.90%	99.30%	0.70%
PAN	7	0.70%	100.00%	0.00%
TOTAL	1000	i	I	i

Table 2:Sieve analysis of 20 mm coarse aggregates

Sieve Size(m)	Mass Retained(g)	%Retained on Sieve	Cumm. %Retained	%PASSING
25.4	0	0	0	100.00%
19.1	150	15.00%	15.00%	85.00%
12.7	480	48.00%	63.00%	37.00%
9.52	310	31.00%	94.00%	6.00%
6.35	50	5.00%	99.00%	1.00%
PAN	10	1.00%	100.00%	0.00%
TOTAL	1000	i	i	i

Table 3: Sieve analysis of pulverized waste glass

Sieve size (mm)	Mass Retained (g)	%Retained	% Passing	Cumulative% Retained	ASTM Standard Specification
4.75	0	0	100	0	95-100
2.36	1.7	0.17	99.83	0.17	80-100
1.18	357.7	35.77	64.04	35.94	50-85
0.60	230.9	23.09	40.97	59.03	25-60
0.30	200.2	20.02	20.95	79.05	5-30

0.15	113.2	11.32	9.63	90.37	0-10
PAN	96.3	9.63	0	0	0
Fineness Modulus of glass aggregate=i∑F/100i =264.56/100 =2.64				264.56	

3.2 Compressive Strength results

Table 4 to 6 provides valuable insights into the relationship between glass replacement percentages, density, and compressive strength in concrete mixes. These findings are essential for optimizing concrete mix designs, considering both strength and density characteristics.

Table 4: The Strength of concrete mixed with the various glass contents and cured for 7 Days

MIX RATIO	% REPLACEMENT	WEIGHT kg	DENSITY kg/m^3	LOAD KN	COMPRESSIVE STRENGTH N/mm^2
1:1.5:3	0	8.51	2520.49	580.00	25.78
	10	8.40	2488.89	350.00	15.56
	20	8.45	2502.72	360.00	16.00
	50	8.44	2500.74	346.67	15.41
	75	8.24	2440.49	220.00	9.78
	100	8.08	2393.09	380.00	16.89
1:2:4	0	8.25	2445.43	310.00	13.78
	10	8.19	2427.65	350.00	15.56
	20	8.20	2429.63	275.00	12.22
	50	8.17	2420.74	295.00	13.11
	75	8.14	2411.85	345.00	15.33
	100	8.06	2389.14	395.00	17.56

Table 5:The Strength of concrete mixed with the various glass contents and cured for 14 Days

MIX RATIO	% REPLACEMENT	WEIGHT(Kg	DENSITY(kg/m^3	LOADi KN	COMPRESSIVE STRENGTH N/mm2
	0	8.60	2546.67	603.33	26.81
	10	8.53	2528.40	600.00	26.67
1:1.5:3	20	8.50	2518.52	492.50	21.89
	50	8.34	2470.12	533.33	23.70
	75	8.14	2411.85	517.50	23.00
	100	7.97	2361.48	432.50	19.22
	0	8.18	2422.22	450.00	20.00
1:2:4	10	8.16	2417.78	547.50	24.33
	20	8.14	2411.85	590.00	26.22
	50	8.13	2407.41	602.50	26.78

75	8.12	2405.93	606.67	26.96
100	8.07	2391.11	408.33	18.15

Table 6: The Strength of concrete mixed with the various glass contents and cured for 28 Days

MIX RATIO	% REPLACEMENT	WEIGHT kg	DENSITY kg/m^3	LOAD kN	COMPRESSIVE STRENGTH N/mm2
1:1.5:3	0	8.63	2557.04	716.67	31.85
	10	8.54	2529.38	676.67	30.07
	20	8.44	2501.73	640.00	28.44
	50	8.39	2485.93	640.00	28.44
	75	8.20	2429.63	673.33	29.93
	100	7.89	2336.79	466.67	20.74
1:2:4	0	8.29	2455.31	553.33	24.59
	10	8.19	2425.68	681.67	30.30
	20	8.16	2417.78	655.00	29.11
	50	8.14	2411.56	678.33	30.15
	75	8.12	2406.81	723.33	32.15
	100	8.03	2379.26	555.00	24.67

3.3 Discussion of results

The use of pulverized waste glass (PWG) as a fine aggregate replacement in concrete is increasingly being explored due to its potential benefits in sustainability and resource conservation. The analysis of results in figures 2 to 4deduces how two distinct concrete mix ratios 1:1.5:3 (higher grade concrete) and 1:2:4 (lower grade concrete) perform under varying percentages of glass replacement, specifically examining compressive strength over 7, 14, and 28 days. The discussion highlights how the compressive strength changes as the glass content increases in each mix, providing insight into the compatibility of PWG as a substitute for traditional fine aggregates.

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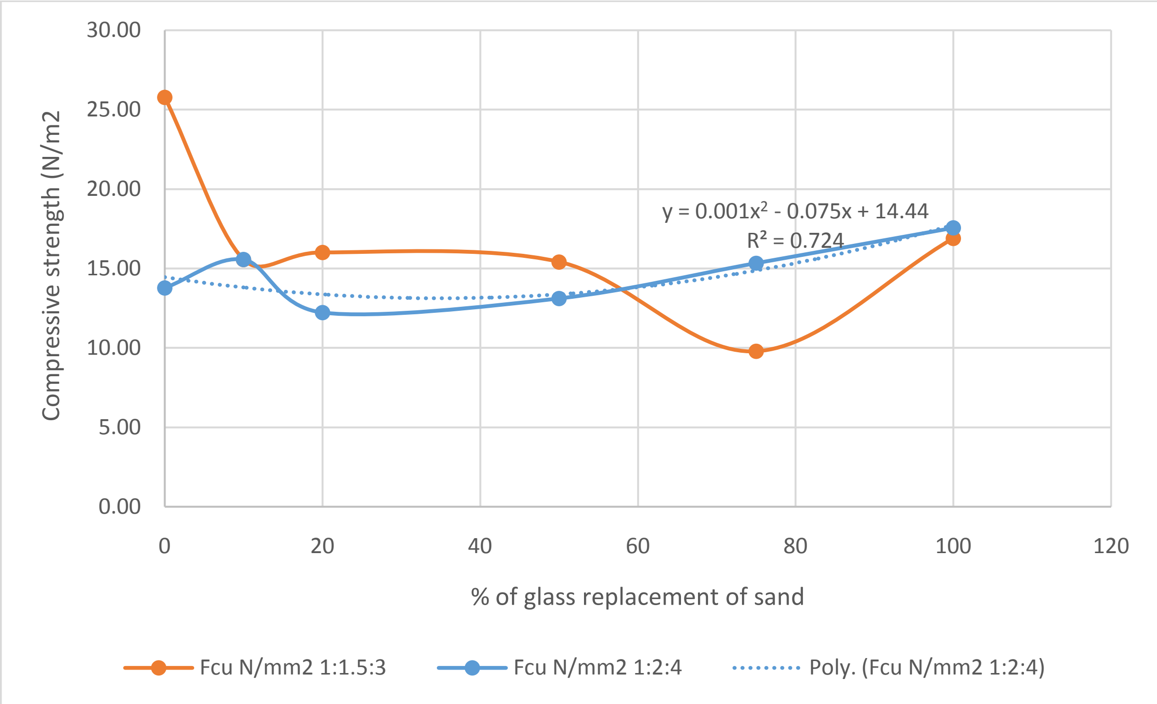

Figurei3: Effect of glass replacement on strength of Concrete cured for 7 Days

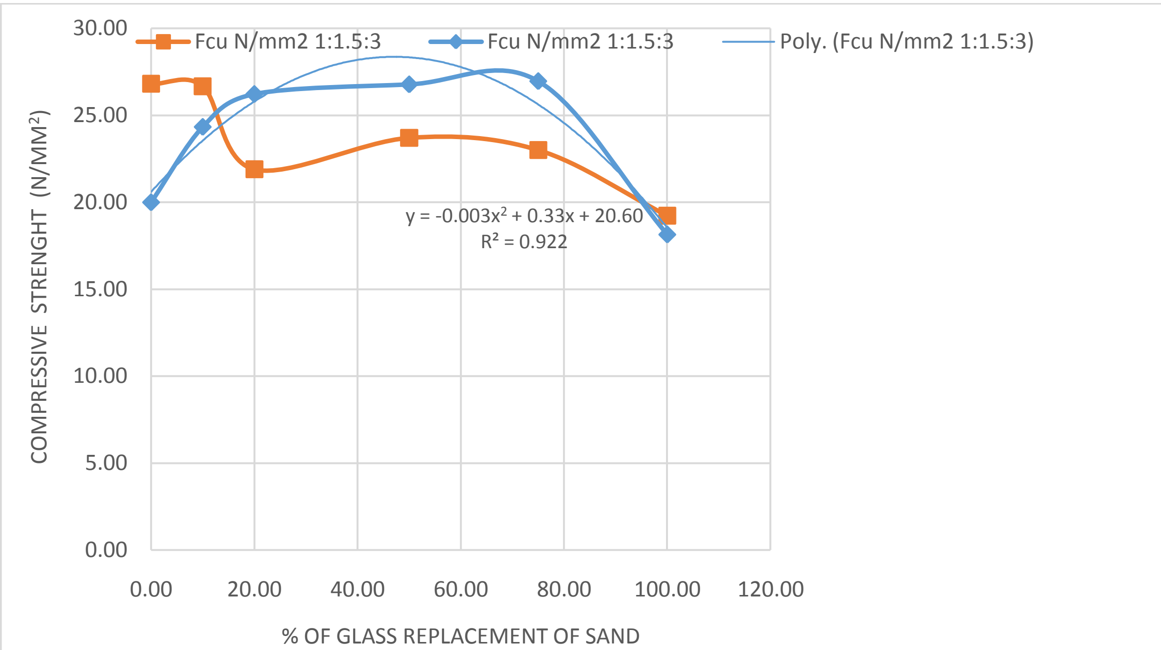

Figure 4: Effect of glass replacement on strength of Concrete cured for 14 Days

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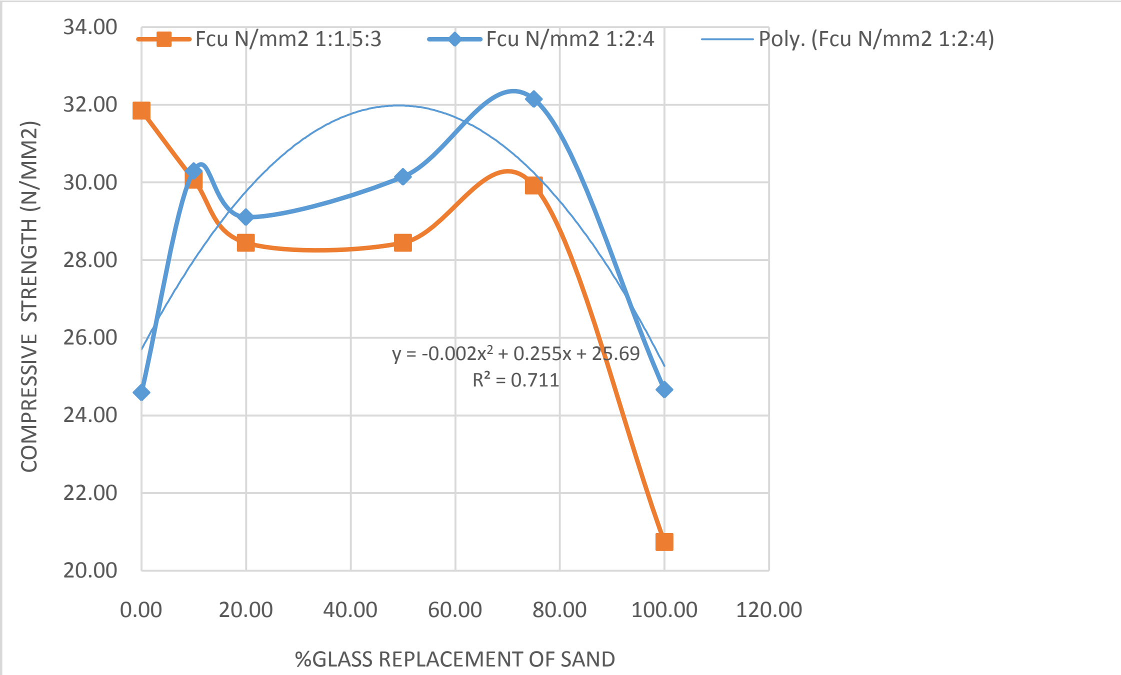

Figure 5: Effect of glass replacement on strength of Concrete cured for 28 Days

3.3.1. Compressive Strength Performance of 1:1.5:3 Mix (Higher-Grade Concrete)

In the 1:1.5:3 mix, the control sample (0% replacement) exhibited a compressive strength of 31.85 N/mm² at 28 days as shown in Figure 5, demonstrating the typical strength gain of higher-grade concrete due to continuous hydration and microstructure densification.Khatibet al. (2012) reported similar results, attributing the strength gain to ongoing hydration, especially beyond the 7-day curing mark.

In Figure 3 at 10% PWG replacement, the compressive strength dropped to 15.56 N/mm² at 7 days but recovered to 30.07 N/mm² at 28 days as demonstrated in Figure 5, nearly equaling the control. This delayed strength gain may be due to the slow pozzolanic reaction of PWG, as suggested by Tan and iDu (2013) who observed that pulverized glass contributes to long-term strength improvement.

For 20%, 50%, and 75% replacements, the 28-day compressive strengths were between 28.44 N/mm² and 29.93 N/mm², indicating that moderate PWG replacement does not significantly impair strength. Park et al. (2004) observed that finely ground glass particles could improve concrete's microstructure, contributing to long-term strength by filling voids.

However, at 100% replacement, the compressive strength dropped to 20.74 N/mm² at 28 days, highlighting the limitations of using PWG as a complete replacement for fine aggregates in higher-grade concrete. Ismail & Al-Hashmi, (2009) attributed this reduction to the smooth, angular shape of glass particles, which reduces the bond strength between the cement matrix and aggregate.

3.3.2. Compressive Strength Performance of 1:2:4 Mix (Lower-Grade Concrete)

From figure 5, the 1:2:4 mix, the control sample achieved a compressive strength of 24.59 N/mm² at 28 days, typical of lower-grade concrete, which has a higher water-cement ratio and lower cement content. Terro, (2006) noted that such mixes exhibit slower strength gain due to the higher porosity of the cement matrix.

Interestingly, at 10%, 20%, 50%, and 75% PWG replacements, the 28-day compressive strengths surpassed those of the control, ranging from 29.11 N/mm² to 32.15 N/mm². The highest strength was observed at 75% replacement, suggesting that PWG enhances the packing density in lower-grade concrete by filling voids between coarse aggregates (Zhao, et.al. 2013).

At 100% replacement, the strength reduced to 24.67 N/mm², but the decline was less pronounced than in the higher-grade mix. Islam et al. (2017) observed that while 100% PWG reduces strength, its impact is less severe in lower-grade mixes due to their lower mechanical demands.

3.3.3 Effect of Replacement Percentage

Partial replacement of natural aggregates with glass (10%–75%) leads to either the maintenance or improvement of compressive strength in both mixes. This observation supports the findings of Ismail and Al-Hashmi (2009), who concluded that partial glass replacement can enhance compressive strength due to the improved packing and pozzolanic activity of the glass. However, full replacement (100%) results in a reduction in compressive strength for both mixes, aligning with Shayan and Xu's (2004) conclusion that excessive glass usage weakens concrete due to diminished aggregate interlock and bonding efficiency.

IV. CONCLUSION

This study explored the mechanical performance of concrete with partial and full replacement of fine aggregates using pulverized waste glass (PWG) bottles, comparing two mix grades (1:1.5:3 and 1:2:4). The results indicate that the inclusion of PWG as a partial fine aggregate replacement (10%–75%) does not significantly reduce the compressive strength of concrete, and in some cases, it even enhances the strength, particularly in the lower-grade mix (1:2:4). Specifically, a 75% replacement in the 1:2:4 mix resulted in a compressive strength of 32.15 N/mm² at 28 days, which outperformed the control mix and the higher-grade concrete. However, full replacement (100%) of fine aggregates with PWG led to a noticeable decrease in strength in both mix grades, with the higher-grade mix showing a more pronounced reduction.

The findings suggest that while PWG can be effectively used as a sustainable material to partially replace natural fine aggregates in concrete, care must be taken with higher replacement levels, especially in higher-grade concrete, where full replacement is not advisable due to significant strength reductions.

V. RECOMMENDATION

i. Based on the findings, partial replacement of fine aggregates with PWG, particularly between 10% and 75%, is recommended for both lower-grade and higher-grade concrete mixes. This range maintains or enhances compressive strength and offers an environmentally friendly alternative to natural aggregates.

ii. PWG is especially suitable for use in lower-grade concrete (1:2:4), where it not only improves compressive strength but also contributes to sustainability by reducing the reliance on natural sand.

iii. Given the strength reductions observed at 100% replacement, further research is recommended to investigate methods of enhancing the bond between PWG particles and the cement matrix, such as surface treatments or blending with other waste materials, to make full replacement more viable.

iv. It is recommended that construction industries and policymakers consider incorporating PWG as a partial fine aggregate replacement in concrete production, particularly in non-structural applications or where lower-grade concrete is required. This could lead to significant environmental benefits through waste reduction and resource conservation.

Conflict of interest

The authors declare that there are no conflicts of interest regarding the publication of this paper

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