Synergistic Effects of Pulverized Glass Bottle Incorporation and Mix Design Variations on the Mechanical Properties of Sustainable Mortar

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Abstract- The increasing demand for sustainable construction materials has spurred research into the use of industrial waste products, such as pulverized glass bottles, in concrete and mortar applications. This study investigates the synergistic effects of pulverized glass bottles (PGB) and mix design variations on the mechanical properties of sustainable mortar. PGB was incorporated as a partial replacement for fine aggregates, with mechanical performance evaluated through compressive and flexural strength tests. Results indicate that compressive strength was significantly influenced by the water-cement (W/C) ratio and mix proportions. The 1:3 mix with a 0.6 W/C ratio achieved the highest compressive strength (16.30 N/mm²), surpassing the control mix (14.54 N/mm²). However, in the 1:6 mix, the control mortar (9.62 N/mm²) outperformed the glass mortar (7.52 N/mm²) at a 0.5 W/C ratio. Flexural strength trends mirrored those of compressive strength, favoring the 0.6 W/C ratio. Cement paste achieved the highest flexural strength (8.00 N/mm²), exceeding the control (7.67 N/mm²) and glass mortar (5.67 N/mm²) in the 1:3 mix. In leaner mixes, such as the 1:6 ratio, the control mortar (4.00 N/mm²) outperformed the glass mortar (3.00 N/mm²).The findings highlight the potential of PGB to reduce waste and contribute to sustainable construction practices, with optimal performance observed at 10%–20% replacement levels. However, the reduction in flexural strength in leaner mixes underscores the importance of optimizing mix designs and W/C ratios. This study demonstrates that balancing sustainability with structural performance is achievable, paving the way for the broader adoption of PGB in construction applications.

Indexed Terms- Synergistic, Pulverized Glass, Mechanical Properties, Sustainable, Mortar

I. INTRODUCTION

The rapid urbanization and industrialization across the globe have intensified the extraction and consumption of natural resources, creating a pressing need for sustainable materials in construction. Waste glass, a significant contributor to solid waste, poses environmental challenges when improperly managed. Recycling waste glass into construction materials is a promising solution to mitigate environmental pollution and reduce dependency on natural resources. Pulverized waste glass has shown potential as a replacement for traditional fine aggregates in mortar and concrete, influencing both the mechanical properties and sustainability of these materials (Bisht & Ramana, 2018; Jani & Hogland, 2014).

Numerous studies have examined the effects of using recycled glass sand (RGS) as a fine aggregate in concrete, focusing on its impact on compressive strength. Research shows that incorporating RGS can enhance compressive strength up to an optimal replacement level, after which strength tends to decline (Oliveirai et al., 2008; Ismail and Al-Hashmi, 2009; Du and Tan, 2014a). This decline is often linked to poor bonding caused by insufficient cement paste, leading to the formation of microscopic voids in the concrete mix (Adaway and Wang, 2015).Extended curing periods further improve the performance of RGS mixes. For instance, significant strength gains are observed after 91 and 365 days of curing, attributed to pozzolanic reactions between the glass particles and cement paste, which enhance the microstructure of the interfacial transition zone (Taha and Nounu, 2009; Ismail and Al-Hashmi, 2009).

The particle size of the glass plays a critical role. Smaller particles, particularly those below 600 µm, have been shown to increase compressive strength, while larger particles tend to reduce it (Lee et al., 2013). Some studies also report variations in strength depending on the color of the glass used (Chen et al., 2006). When replacing fine aggregates in mortar, RGS often leads to reduced compressive strength. However, higher water-cement ratios can mitigate this effect and even improve performance in some cases (Corinaldes et al., 2005).

For coarse aggregate replacement, studies suggest that higher amounts of RGS weaken flexural strength due to the smooth surfaces and inherent flaws of glass particles, which disrupt bonding (Topçu and Canbaz, 2004; Sharifi et al., 2013). Nonetheless, using smaller quantities of RGS can improve adhesion between cement paste and glass particles, enhancing flexural strength compared to control mixes (Sharifi et al., 2013).

In addition to its use as an aggregate, waste glass powder has also been explored as a partial cement replacement. Studies indicate that it can improve workability and reduce water demand due to the smooth geometry of the particles (Khatibi et al., 2012; Soliman and Tagnit-Hamou, 2016). However, higher glass powder content may slow early cement hydration, affecting initial strength development (Soliman and Tagnit-Hamou, 2016).

The use of pulverized glass in mortar offers several advantages, including improved durability and reduced environmental impact. However, its integration into construction materials requires careful consideration of mix proportions and water-cement (W/C) ratios to optimize performance (Lye et al., 2017). This study investigates the synergistic effects of incorporating pulverized glass bottles into mortar, focusing on the mechanical properties under various mix design parameters.

II. MATERIALS AND METHODS

2.1 Materials

- Cement: Ordinary Portland Cement (OPC) conforming to ASTM C150.
- Fine Aggregate: River sand was used as the natural aggregate, meeting ASTM C33 specifications.
- Pulverized Glass Bottles: Waste glass bottles were crushed and sieved to achieve a particle size distribution similar to fine sand as shown in figure 1.
- Water: Potable water was used for mixing and curing.

2.2 Mix Design and Preparation

Figure 1: Sample preparation

Mortar mixes were prepared with varying percentages (0%, and 100%) of pulverized glass bottles replacing natural fine aggregate by volume as shown in figure 1. Water-cement ratios of 0.25, 0.30,0.35, 0.5, and 0.6 were selected to evaluate the impact on compressive and flexural strength. The mix proportions followed a 1:3 and 1;6 cement-to-aggregate ratio by weight.

2.3 Testing Methods

- Compressive Strength: Cubic mortar specimens (150 × 150 × 150 mm) were cast and tested at 7, 14, 21 and 28 days according to ASTM C109.
- Flexural Strength: Beam specimens (40 × 40 × 160 mm) were tested for flexural strength as per ASTM C348.

III. RESULTS AND DISCUSSION

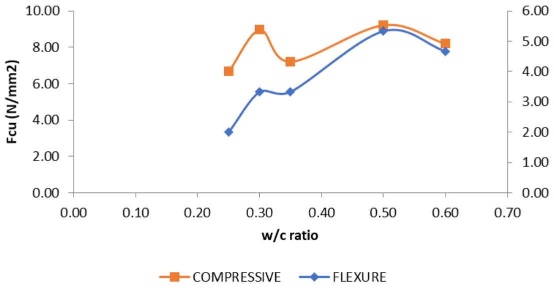

Figure 2: Concrete Strength and W/C ratio (Control) for 7 Days cured beam at 1:3 mix

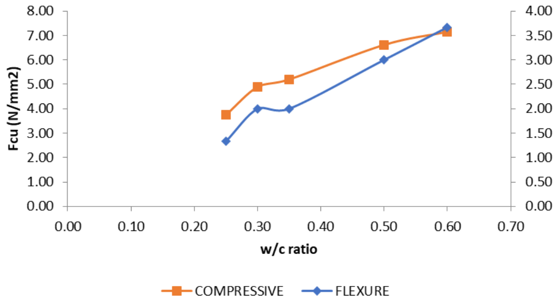

Figure 3: Concrete Strength and W/C ratio (Control) for 7 Days cured beam at 1:6 mix

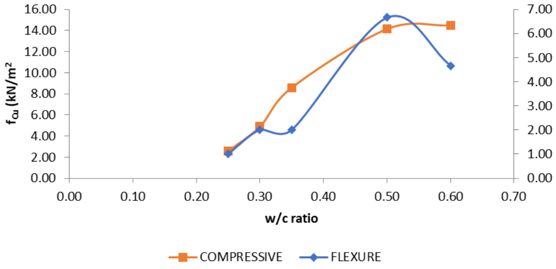

Figure 4: Concrete Strength and W/C ratio (Glass bottle) for 7 Days cured beam at 1:3 mix

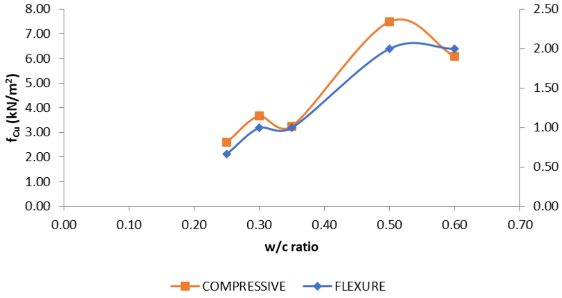

Figure 5: Concrete Strength and W/C ratio (Glass bottle) for 7 Days cured beam at 1:6 mix

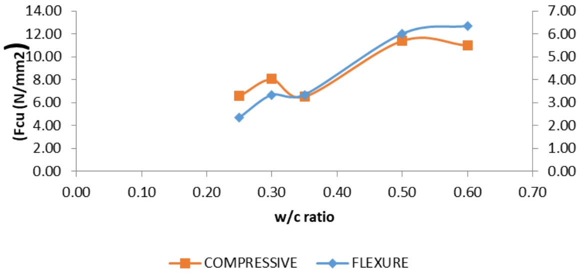

Figure 6: Concrete Strength and W/C ratio (Control) for 14 Days cured beam at 1:3 mix

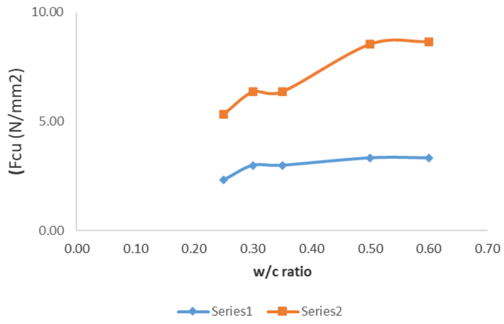

Figure 7: Concrete Strength and W/C ratio (Control) for 14 Days cured beam at 1:6 mix

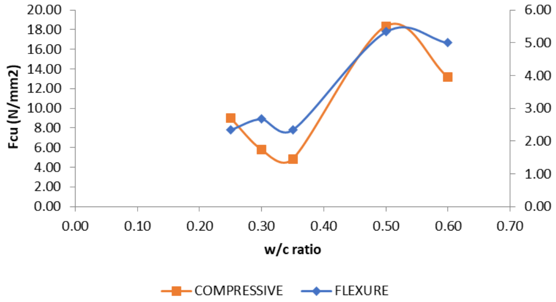

Figure 8: Concrete Strength and W/C ratio (glass mortar) for 14 Days cured beam at 1:3 mix

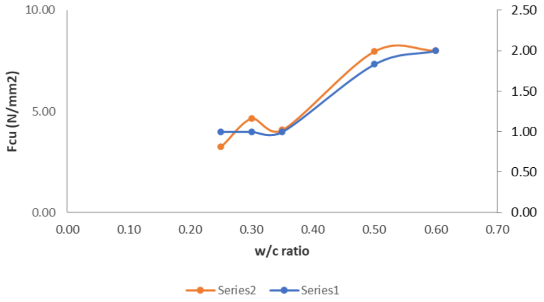

Figure 9: Concrete Strength and W/C ratio (glass mortar) for 14 Days cured beam at 1:6 mix

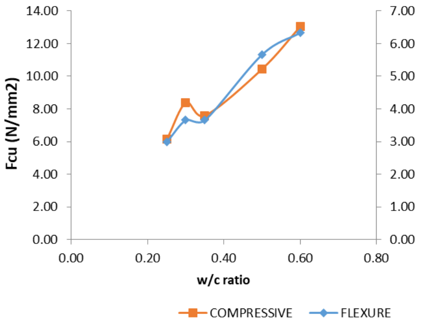

Figure 10: Concrete Strength and W/C ratio (Control) for 21 Days cured beam at 1:3 mix

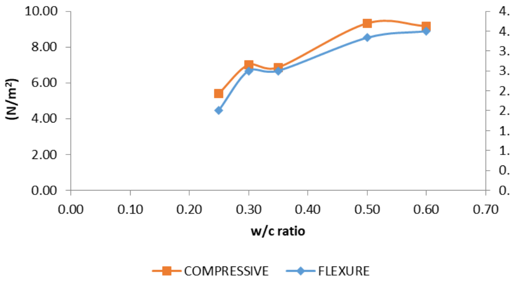

Figure 11: Concrete Strength and W/C ratio (Control) for 21 Days cured beam at 1:6 mix

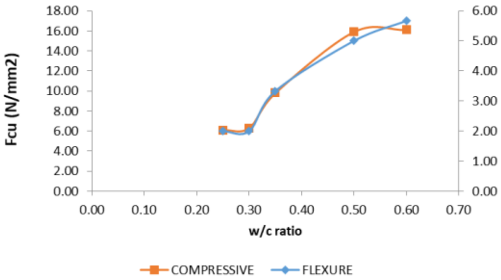

Figure 12: Concrete Strength and W/C ratio (glass mortar) for 21 Days cured beam at 1:3 mix

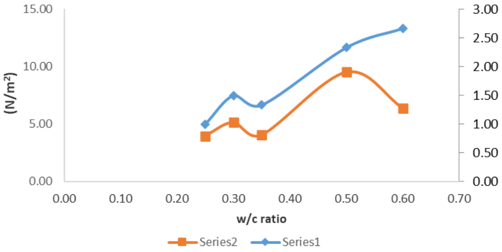

Figure 13: Concrete Strength and W/C ratio (Glass mortar) for 21 Days cured beam at 1:6 mix

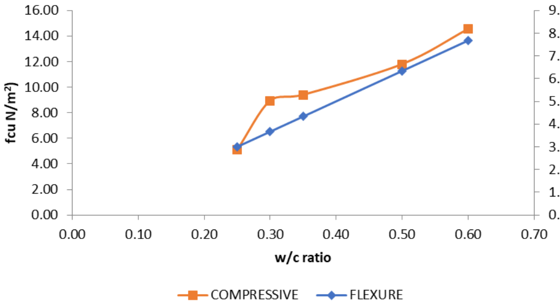

Figure 15: Concrete Strength and W/C ratio (Control) for 28 Days cured beam at 1:3 mix

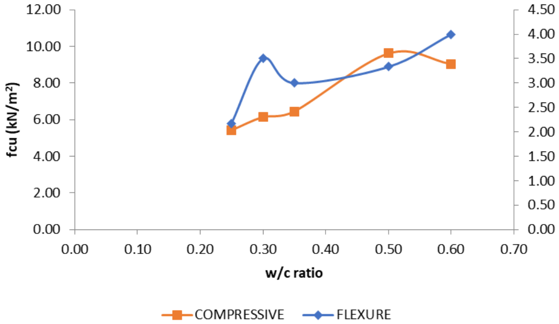

Figure 16: Concrete Strength and W/C ratio (Control) for 28 Days cured beam at 1:6 mix

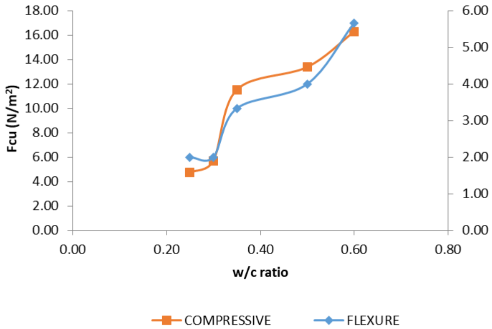

Figure 17: Concrete Strength and W/C ratio (glass mortar) for 28 Days cured beam at 1:3 mix

Fcu (N/mm2)

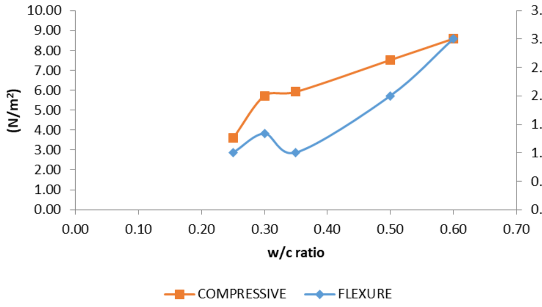

Figure 18: Concrete Strength and W/C ratio (glass mortar) for 28 Days cured beam at 1:6 mix

3.1 Compressive Strength

This study observed how water-cement ratios and curing periods influenced the strength of mortar beams containing glass aggregate. The results showed that the highest compressive strength was achieved at different curing periods for two concrete mix ratios. For the 1:3 concrete mix, the peak strength was 16.30 kN at a 0.6 water-cement ratio after 28 days of curing. Meanwhile, the 1:6 concrete mix reached its maximum compressive strength of 9.54 kN at a 0.5 water-cement ratio after 21 days of curing.

These findings highlight that 16.30 kN and 9.54 kN represent the critical strength values where optimal performance and failure occur for the 1:3 and 1:6 mixes, respectively. Moreover, the results clearly indicate that the 1:3 concrete mix is better suited for applications requiring high load-bearing capacity and structural stability, as it consistently showed higher compressive strength.

3.2 Flexural Strength

The flexural strength results revealed notable trends influenced by the water-cement ratio, mix proportions, and material composition. Across all mixes, the optimal flexural strength was consistently achieved at a 0.6 water-cement ratio, indicating this ratio's effectiveness in balancing workability and strength development. Increased glass content resulted in reduced flexural strength due to weaker bonding in the ITZ, as evidenced by SEM imaging (Lye et al., 2017). For the 1:3 mix ratio, the flexural strength of the cement paste was the highest at 8.00 N/mm², surpassing both the control mortar mix (7.67 N/mm²) and the glass mortar mix (5.67 N/mm²). This hierarchy highlights the significant role of cement paste in contributing to flexural strength while suggesting that incorporating glass aggregate slightly diminishes the strength compared to the control mortar.

In the 1:6 mix ratio, the control mortar mix exhibited a flexural strength of 4.00 N/mm², which was notably higher than the 3.00 N/mm² recorded for the glass mortar mix. This further emphasizes the trend that the inclusion of glass aggregate in a leaner mix (1:6) results in a more pronounced reduction in flexural strength.

CONCLUSION

This study demonstrates the potential of using pulverized glass bottles as a sustainable replacement for fine aggregates in mortar. The findings reveal that optimal performance was achieved with 10%–20% replacement levels, showing promise for reducing waste while maintaining acceptable mechanical properties. The compressive strength of the mortar was significantly affected by the water-cement (W/C) ratio and mix proportion. For instance, the 1:3 mix with a 0.6 W/C ratio delivered the highest compressive strength (16.30 N/mm²), surpassing the control mix (14.54 N/mm²). However, in the 1:6 mix, the control mortar (9.62 N/mm²) outperformed the glass mortar (7.52 N/mm²) at a 0.5 W/C ratio.

Similar trends were observed for flexural strength, which also favored the 0.6 W/C ratio. Cement paste achieved the highest value (8.00 N/mm²) compared to the control mortar (7.67 N/mm²) and glass mortar (5.67 N/mm²) in the 1:3 mix. However, in leaner mixes, such as the 1:6 mix, the flexural strength of the control mortar (4.00 N/mm²) exceeded that of the glass mortar (3.00 N/mm²).

The reduction in flexural strength, particularly in mixes with lower cement content, emphasizes the trade-off between sustainability and structural performance. These results highlight the critical need to optimize mix designs and W/C ratios when incorporating glass aggregates. By doing so, it is possible to balance environmental benefits with structural adequacy, paving the way for the broader use of waste glass in construction applications.

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