International Journal of Research Publication and Reviews

Journal homepage: www.ijrpr.com ISSN 2582-7421

Optimizing Water-Cement Ratios for Enhanced Flexural Performance of Sustainable Mortar Beams with Crushed Glass Bottle as Fine Aggregate Replacement

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ABSTRACT

This study investigates the impact of varying water-cement (W/C) ratios on the flexural strength of mortar beams made with both conventional materials and crushed glass as a partial fine aggregate replacement. By substituting natural sand with finely processed waste glass powder, the study aims to introduce sustainable practices into mortar production while examining the effects on mechanical properties and durability. Flexural strength tests were conducted at 7, 14, 21, and 28 days for W/C ratios ranging from 0.25 to 0.60. The findings reveal that lower W/C ratios (0.25 and 0.30) restrict hydration, resulting in suboptimal strength development in both conventional and glass mortar beams. Ratios between 0.50 and 0.60 demonstrated the highest flexural strengths, with the 0.60 ratio supporting steady, long-term strength growth in glass-mortar beams. However, conventional mortar beams achieved stable strength retention at both 0.50 and 0.60 ratios, indicating a well-developed microstructure conducive to durability. These results suggest that crushed glass can effectively serve as a sustainable fine aggregate alternative, provided optimal W/C ratios are maintained. For applications demanding high flexural performance, a W/C ratio of 0.50 to 0.60 is recommended, balancing workability and strength across both mortar types. The study highlights the potential of incorporating recycled materials in construction while maintaining structural integrity, making it a valuable contribution to sustainable concrete technology and environmentally responsible construction practices.

1.0 Introduction

The construction industry's extensive reliance on natural resources, particularly sand as a fine aggregate in concrete, has raised significant sustainability concerns. Sand extraction, driven by high demand, is often carried out at unsustainable rates, adversely affecting ecosystems, biodiversity, and natural landscapes (Mehta & Monteiro, 2014). As a response to these environmental pressures, recycled materials such as crushed glass have gained attention as potential substitutes for traditional aggregates, offering an avenue for reducing environmental strain (Zhang & Zhao, 2013). Glass bottles, which are frequently discarded as waste, present an underutilized resource that can be recycled as fine aggregate in concrete. Studies suggest that, when combined with optimal water-cement ratios, crushed glass can contribute positively to certain mechanical properties of concrete, including compressive and flexural strength (Shi & Zheng, 2007).

The shift towards sustainable construction practices emphasizes the reduction of waste and the incorporation of recycled materials to conserve resources and minimize ecological impact. Waste glass, specifically, has been increasingly used as a sand substitute in concrete, serving dual purposes: it aids in conserving natural materials while also reducing the burden of waste disposal. Additionally, crushed glass offers potential durability benefits if processed to control alkali-silica reactions (ASR), a known durability issue in concrete (Dhir et al., 2001). ASR can be mitigated with proper processing techniques, allowing crushed glass to act as a viable, eco-friendly material in concrete applications (Federico & Chidiac, 2009).

The utilization of alternative materials in concrete not only addresses sustainability but also promotes the enhancement of certain performance characteristics. Waste glass powder, for example, has demonstrated promising pozzolanic activity, which can improve concrete’s long-term durability and mechanical properties by enhancing the binding capacity of calcium silicate hydrate (C-S-H) and refining the microstructure through reduced capillary pores and improved interfacial transition zones (Nassari & Soroushian, 2011). Research has shown that, depending on the proportion and application, glass powder can also improve flexural strength, especially when used as a partial cement replacement (Kamali & Ghahremaninezhad, 2015). Thus, the use of waste glass in concrete formulations represents an innovative approach to enhancing both the durability and sustainability of construction materials.

The focus on sustainability has also driven the use of other supplementary cementitious materials, such as fly ash and ground granulated blast furnace slag (GGBFS), which help reduce greenhouse gas emissions associated with concrete production. Flower and Sanjayan (2007) found that substituting cement with fly ash reduced CO_2 emissions by 13–15%, while GGBFS reduced emissions by approximately 22% compared to traditional concrete.

Similarly, Jiang et al. (2014) reported that using waste glass powder as a partial cement replacement lowered greenhouse gas emissions by 5% to 19% across different concrete strengths, further emphasizing the environmental benefits of recycled materials in concrete.

An essential parameter influencing concrete's mechanical properties is the water-cement (W/C) ratio. The W/C ratio has a direct impact on workability, setting time, and strength. Typically, lower W/C ratios increase compressive strength due to reduced porosity, while higher W/C ratios improve workability at the expense of strength (Neville, 2011). For concrete containing crushed glass, studies suggest that the optimal W/C ratio can further influence the matrix, potentially enhancing performance metrics when combined with glass as a fine aggregate (Shi & Zheng, 2007).

This study aims to explore the effect of various W/C ratios on the flexural strength of mortar beams made with crushed glass as a sand replacement. By investigating the optimal W/C ratio, this research seeks to contribute to the development of high-performance, environmentally sustainable construction materials, demonstrating that recycled glass not only mitigates environmental impacts but also offers the potential to improve concrete's mechanical performance.

2.0 Materials and Methods

2.1 Materials

For this study, we used Ordinary Portland Cement (OPC), conforming to **ASTM C150** standards, was selected as the primary binder due to its reliable strength development, durability, and compatibility with a wide range of aggregates (ASTM C150, 2023). For fine aggregate, natural sand obtained from Amassoma Community in Bayelsa State. The sand was graded according to **ASTM C33** specifications for concrete aggregates to ensure uniform particle size distribution and compatibility with the cement paste, which is critical for achieving workability and consistency in the mix.

Crushed glass powder, produced from finely ground waste glass obtained from a waste disposal site in Bayelsa state as shown in figure 1, was used as a pozzolanic material, in compliance with **ASTM C618** for pozzolanic materials in concrete and mortar. Potable water, conforming to **ASTM C1602** standards for mixing water used in mortar, was used to ensure consistent hydration. Water quality is essential in concrete and mortar production because impurities can impact setting time and the long-term durability of the cementitious matrix. The high-quality water enabled controlled hydration, essential for achieving strength and stability across all specimens (Neville, 2011).

Figure 1: Glass bottles obtained from a waste disposal site

2.2 Mix Design

Mortar mixes were prepared with mix ratios of mix 1:3 and W/C ratios of 0.25, 0.3, 0.35, 0.5, and 0.6 each with 100% crushed glass replacing sand.

Additionally, plain mortar beams (160 mm x 40 mm x 40 mm) incorporating conventional natural sand serve as control and another set of mortar beams incorporating grinded glass bottles for fine aggregates were prepared as samples. This comprehensive approach allowed for an in-depth comparison between conventional and glass-replaced mortar and concrete samples across multiple W/C ratios.

2.3 Specimen Preparation

For each W/C ratio, mortar beams with dimensions of 160 x 40 x 40 mm were cast as illustrated in figure 2. The mixing process involved combining the cement, sand, or with glass powder, followed by the gradual addition of water until a homogeneous mix was achieved. Care was taken to ensure that the mixing was uniform, and no segregation occurred. Once mixed, the mortar was poured into beam molds, compacted to remove air voids, and finished with a smooth top surface, and subsequently curing.

Figure 2: Sample preparation of mortar beams

2.4 Testing Procedures

Sieve analysis

The sieve analysis was conducted in the Geotechnical Laboratory at the Department of Civil Engineering, Niger Delta University, under the supervision of the laboratory technologist. Fine aggregate samples were processed using a 600 µm sieve to assess particle distribution and ensure compliance with grading requirements. The fine aggregate displayed a specific gravity of 2.67, aligning with **BS EN 12620:2002+A1 (2008)** standards and classifying it within grading zone II. This classification is commonly associated with quartzite materials, which exhibit desirable grading properties suitable for concrete applications. The analysis confirmed the fine aggregate's suitability, aligning with industry standards for particle size and specific gravity essential for structural applications.

Flexural Strength:

Flexural strength testing was conducted using a three-point bending test, following the ASTM C348 standard and B.S. 1610: Part 1:1992, using a universal testing machine (UTM) to accurately measure the maximum load and corresponding flexural strength. The dimensions of the concrete beams used for testing were 160 mm in length, 40 mm in width, and 40 mm in depth, which is standard for mortar flexural strength testing.

Specimens were cast and allowed to cure under controlled conditions, and tests were conducted at 7, 14, and 28 days to evaluate the development of flexural strength over time. After the maximum load (P) is recorded, the flexural strength Fr of the specimen is calculated using the following formula:

$$Fr = \frac{PL}{bd^2} \text{ i} \qquad (1)$$

Where:

Fr : Flexural strength (MPa)

P: Maximum applied load (KN)

L: Length of the specimen (mm)

b: Width of the specimen (mm)

d: Depth of the specimen (mm)

3.0 Results and Discussion

3.1 Sieve Analysis results

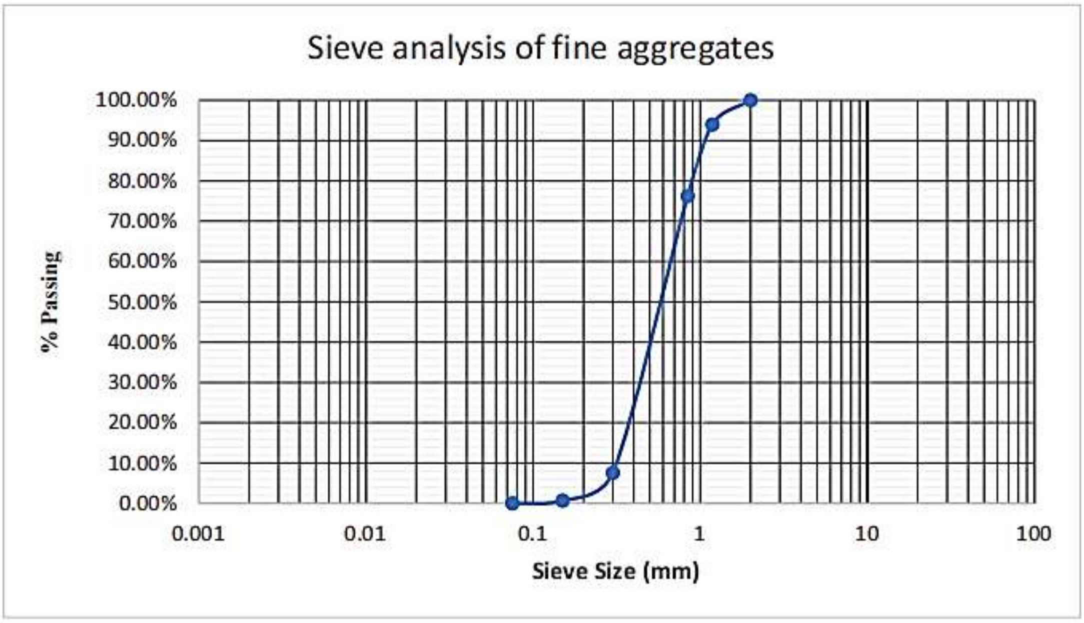

Figure 3: i ParticleisizeidistributioniforiFineiAggregate

Table 1: Sampleiqualityigradation for fine aggregate

Quality of Gradation				
D60	0.7	Mm	Cu = D_{60}/D_{10}	2.33
D30	0.43	Mm	Cc=$D30^2$/D10xD60	0.88
D10	0.30	Mm		Cui <4 poorly graded
				1> cc>3i gap graded
				Cui > 4i well graded
				1≤ cc ≤3i well graded

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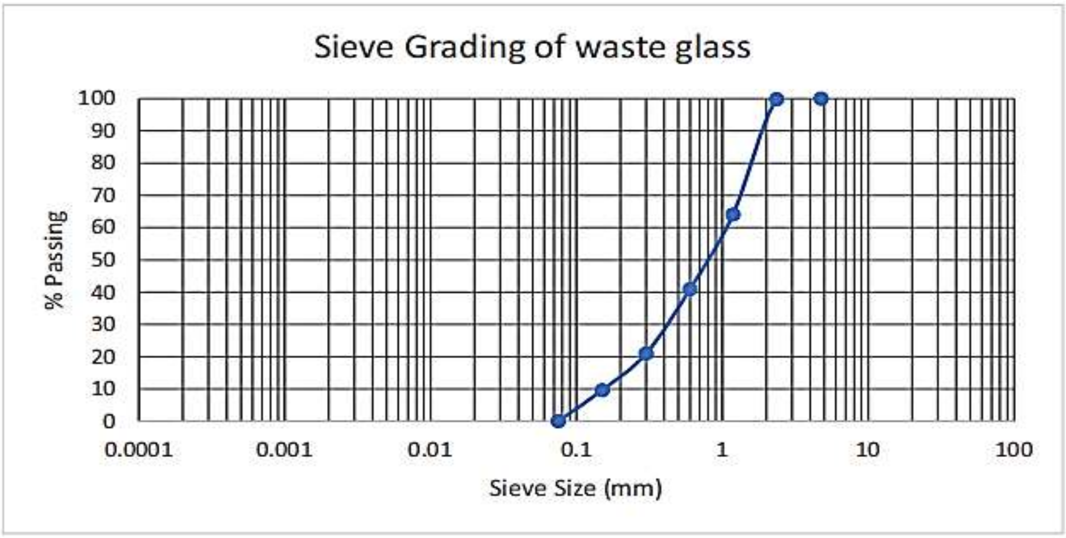

Figure 4 : ParticleiSizeiDistributioniforiWasteiGlass

Tablei2.iSampleiqualityigradation of crushed glass waste

Quality of Gradation				
D60	16	Mm	C_U=D60/D10	5.88
D30	13	Mm	C_C=D30^2/D10/D60	0.94
D10	10	Mm		Cui <4 poorly graded
				1>cc>3i gap graded
				Cui >4i well graded
				1≤cc≤3i well graded

1≤ 0.93 ≤ 3i Thereforeifineiaggregatesiconstituentsiareiwelligraded

3.2 Flexural Strength result Analysis

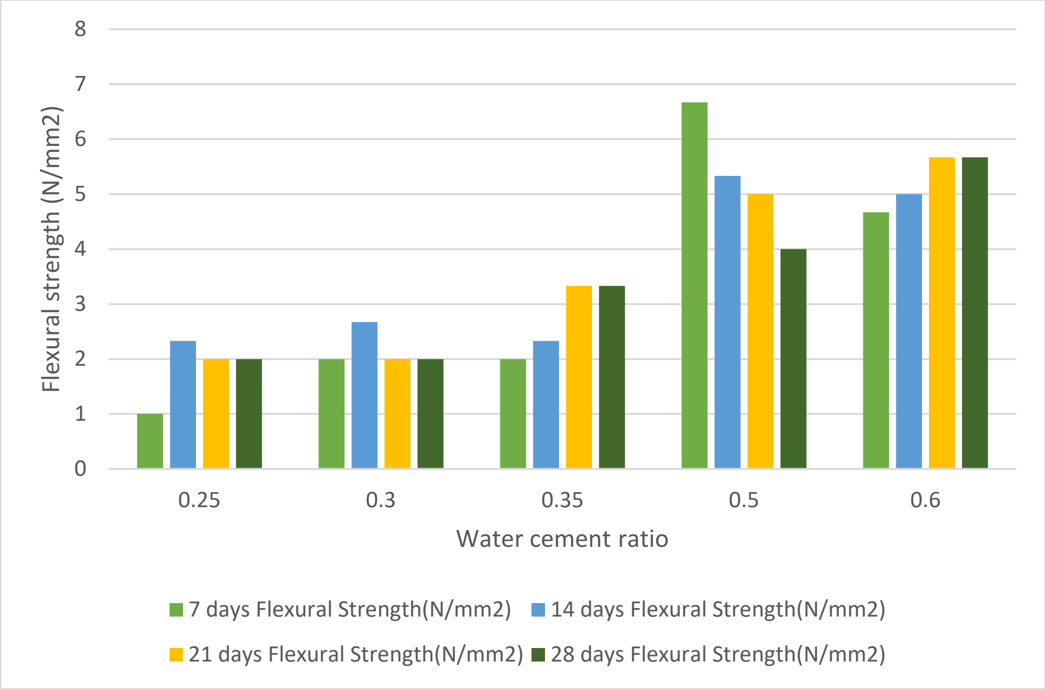

Figure 5: Flexural strength results of Mortar beams for control (conventional fine aggregates) samples with 1:3 Mix ratio

Figure 5 demonstrate the flexural strength tests on mortar beams with varying water-cement (W/C) ratios reveal the influence of water content on mortar's strength development over time. At a low W/C ratio of 0.25, flexural strength was limited, reaching only 3.00 N/mm² at 28 days, due to restricted hydration. A slight increase to a 0.30 ratio improved early-age strength, though it remained modest, suggesting that a slightly higher water content could enhance the mortars microstructure.

At a W/C ratio of 0.35, strength development was more pronounced, with a significant increase to 4.33 N/mm² by 28 days, indicating balanced hydration. A 0.50 W/C ratio showed optimal results, reaching 6.33 N/mm² at 28 days, as this ratio provided ample hydration and microstructural integrity without excessive porosity.

The 0.60 ratio achieved the highest strength of 7.67 N/mm² but may risk long-term durability due to increased porosity. Overall, W/C ratios of 0.50 to 0.60 achieved the best performance, striking an ideal balance for structural applications requiring high flexural strength.

Lastly, Kwan and Ng (2013) discuss how a higher W/C ratio, such as 0.60, can maximize early strength but potentially increase porosity, affecting durability—consistent with this study's peak strength of 7.67 N/mm² at 28 days, which could pose long-term risks.

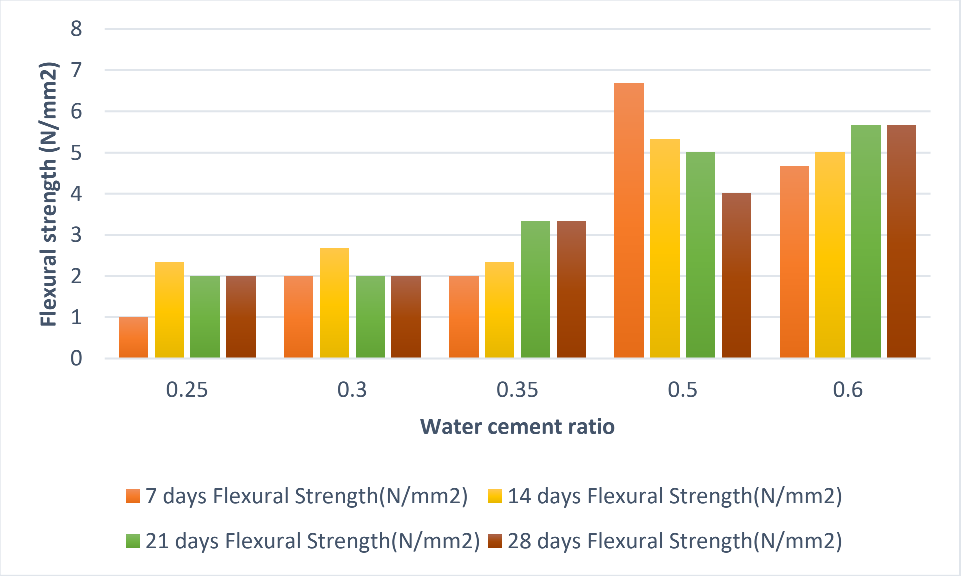

Figure 6 : Flexural strength results of Mortar Glass beams for 1:3 Mix ratio

Figure 4 illustrates the flexural strength results for glass-mortar beams which shows a clear relationship between water-cement (W/C) ratios and how well the material develops strength over time. Starting with the lowest W/C ratio of 0.25, the beams had low initial flexural strength, measuring just 1.00 N/mm² at 7 days, which only slightly increased to 2.33 N/mm² at 14 days before settling at 2.00 N/mm² by 28 days. This limited water content seems to have restricted hydration, leaving the internal structure underdeveloped and weak in the long run. Increasing the W/C ratio to 0.30 provided a small improvement in early strength, reaching 2.67 N/mm² at 14 days. However, this mix also leveled off at 2.00 N/mm², suggesting it still lacked enough water to support continuous strength growth. At a 0.35 ratio, the beams showed a steadier rise in strength, reaching 3.33 N/mm² by 28 days—indicating a more balanced hydration process that enabled stronger matrix formation.

The mix with a 0.50 W/C ratio exhibited the highest initial strength at 7 days, with 6.67 N/mm², but the strength gradually decreased over time, likely due to porosity from the extra water content. Finally, the 0.60 ratio showed continuous strength development, peaking at 5.67 N/mm² by 28 days, making it ideal for long-term durability.

3.3 Comparison with Conventional Mortar

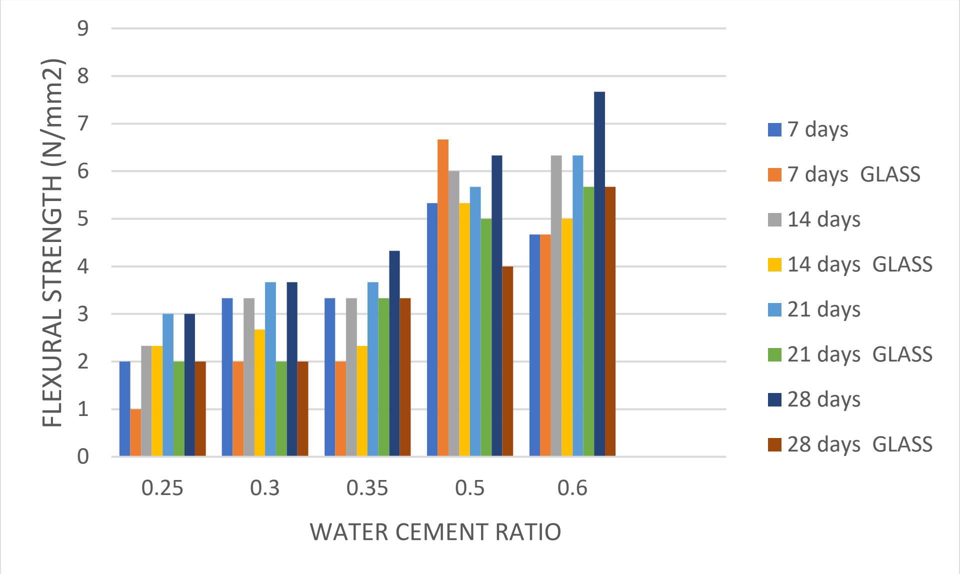

Figure 4 : Flexural strength results of Mortar Glass and control samples beams at varying water cement ratio for 1:3 Mix ratio

The comparison between conventional mortar beams and those incorporating crushed glass as a partial fine aggregate replacement reveals significant differences in flexural strength across various water-cement (W/C) ratios. In conventional mortar beams, lower W/C ratios such as 0.25 resulted in limited hydration due to insufficient water, yielding a flexural strength of 2.00 N/mm² at 7 days and increasing modestly to 3.00 N/mm² by 28 days. This slow strength gain aligns with Neville's (1996) findings, which indicate that lower W/C ratios can hinder complete cement hydration, leading to weaker microstructures. Similarly, a 0.30 W/C ratio showed only a slight improvement, reaching 3.67 N/mm² at 28 days, suggesting that while increased water content enhances hydration, it may still be inadequate for significant strength development (Kosmatka et al., 2002).

Conversely, at a W/C ratio of 0.35, conventional mortar beams demonstrated a more balanced hydration process, achieving a flexural strength of 4.33 N/mm² by 28 days. This improvement reflects a denser and stronger microstructure, consistent with Mehta and Monteiro's (2014) observations that moderate W/C ratios optimize hydration and strength. Further increasing the W/C ratio to 0.50 and 0.60 resulted in substantial flexural strengths of 6.33 N/mm² and 7.67 N/mm², respectively, indicating that higher water content facilitates thorough hydration and robust microstructural development (Aïtcin, 1998). However, as Kwan and Ng (2013) note, excessively high W/C ratios can introduce porosity, potentially compromising long-term durability despite initial strength gains.

In contrast, mortar beams with crushed glass exhibited different strength trends. At the lowest W/C ratio of 0.25, flexural strength was significantly lower, starting at 1.00 N/mm² at 7 days and only reaching 2.00 N/mm² by 28 days. This limited strength development underscores the challenges of achieving adequate hydration and cohesive bonding in glass-mortar mixes with low water content. Similarly, a 0.30 W/C ratio provided only modest improvements, with flexural strength peaking at 2.67 N/mm² at 14 days before stabilizing at 2.00 N/mm², indicating that additional water still fell short of sustaining continuous strength growth.

However, at a W/C ratio of 0.35, glass-mortar beams showed a more favorable trend, achieving a flexural strength of 3.33 N/mm² by 28 days. This suggests that a balanced W/C ratio enhances hydration and microstructural bonding in glass-mortar mixtures, similar to conventional mortars. Notably, at a 0.50 W/C ratio, glass-mortar beams initially achieved high flexural strength of 6.67 N/mm² at 7 days but experienced a decline to 4.00 N/mm² by 28 days, likely due to increased porosity from excess water. In contrast, the 0.60 W/C ratio maintained a more consistent strength growth, reaching 5.67 N/mm² at 28 days, indicating that while higher water content improves workability and early strength, it must be carefully managed to prevent durability issues (Shi & Zheng, 2007).

Conclusively, both conventional and crushed glass mortar beams achieve optimal flexural strength at higher W/C ratios of around 0.50 to 0.60. Conventional mortars demonstrate better strength retention over time, whereas glass-mortar beams require careful balance to maximize strength without compromising durability. These findings suggest that while incorporating crushed glass offers sustainable benefits, maintaining an optimal W/C ratio is crucial for ensuring both high flexural performance and long-term durability in structural applications.

4.0 Conclusion

The findings of this study indicate that water-cement (W/C) ratios have a significant impact on the flexural strength and durability of both conventional mortar beams and those incorporating crushed glass as a sustainable fine aggregate replacement. Generally, a W/C ratio between 0.50 and 0.60 provided the optimal balance, allowing for adequate hydration while maintaining structural integrity across both mortar types. For conventional mortar, this range yielded steady strength growth and retention, suggesting a well-developed microstructure conducive to long-term durability. Crushed glass mortar beams, though initially achieving strong early-age flexural strength at a 0.50 W/C ratio, exhibited slight declines over time, likely due to increased porosity introduced by higher water content. Nevertheless, the 0.60 ratio consistently supported stable strength growth in crushed glass beams, demonstrating that sustainable materials can perform well with the right mix proportions.

Therefore, the use of crushed glass in mortar is promising for enhancing sustainability without severely compromising strength, especially at higher W/C ratios where hydration and particle bonding are optimized. For applications demanding high flexural strength and workability, a W/C ratio of 0.50 to 0.60 is recommended, as it provides the best performance for both conventional and glass-mortar mixes.

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