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Utilization of Waste Crushed Glass as a Partial Replacement for Fine Aggregate in M45 Grade Concrete

Tushar Malik[1], Vineet Kumar[2]
[1] Student, M.Tech Structure Engineering, U.I.E.T, M.D.U, Rohtak, tusharmalikce23346@gmail.com
[2]Assistant Professor, Depaartment. Of Civil Engineering, U.I.E.T, M.D.U, Rohtak

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Abstract
The depletion of natural sand and the increasing accumulation of industrial waste, such as glass, necessitate sustainable alternatives in concrete production. This study investigates the effect of using waste crushed glass as a partial replacement for fine aggregate in M45 grade concrete. The impact of different waste glass replacement levels (10%, 20%, 30%, and 40%) was evaluated through comprehensive testing of compressive strength, flexural strength, water absorption, density, and workability. Compressive strength tests at 7, 14, and 28 days revealed that up to 20% waste glass replacement maintains structural integrity, while higher levels reduce strength due to the inert nature of glass particles. Flexural strength showed similar trends, with reduced tensile resistance at higher replacement percentages. Water absorption increased with waste glass content, suggesting higher porosity, while density measurements confirmed a decrease in mass, beneficial for lightweight applications. Workability tests indicated reduced slump and compacting factor, requiring admixtures to maintain fluidity. The study concludes that waste glass can be safely incorporated up to 20%, offering environmental and structural benefits, promoting sustainable construction practices.

***Keywords**: Waste Glass, High-Strength Bricks, Compressive Strength, Durability, Sustainable Construction*

1 INTRODUCTION

Concrete is the most commonly utilized construction material because of its significant strength and durability. The over-extraction of river sand as fine aggregate leads to the depletion of natural resources and results in environmental degradation. Industrial waste, including crushed glass, contributes to pollution. The use of waste crushed glass in concrete offers a sustainable approach by minimizing waste buildup and preserving natural aggregates. This research assesses the mechanical, durability, and workability characteristics of M45 grade concrete that includes waste glass as a partial replacement for fine aggregate. The research seeks to identify the best replacement level by systematically examining its impact on compressive strength, flexural strength, water absorption, density, and workability, aiming to achieve a balance between sustainability and structural performance.

Akram Mhaya and colleagues (2024) performed a study on lightweight rubberized geopolymer (LRGP) mortars, which included metakaolin, waste glass, slag, and fine rubber, to evaluate their mechanical and thermal properties. The research indicated that a mixture of 10% metakaolin and 15% fine rubber achieved the greatest compressive strength of 27.47 MPa, whereas increased rubber content adversely affected both workability and strength. The addition of rubber decreased the total weight of the geopolymer mortar and improved its thermal insulation, resulting in an energy-efficient construction material.

Amira Ayat and colleagues (2022) investigated the application of waste glass powder (WGP) and brick dust (BD) in air-lime mortars for the restoration of historic buildings. The research indicated that a 30% replacement of WGP and BD notably increased compressive and flexural strength, while also improving workability and decreasing water absorption. This method is consistent with sustainable restoration practices, minimizing landfill waste and supporting circular economy principles. Ana Lima and colleagues (2024) examined strategies for circular economy (CE) in the construction sector aimed at minimizing material waste and carbon emissions. The research indicated that as much as 95% of steel bars are recyclable, cement usage can decrease by 60%, and brick production can reduce raw material consumption by 30-70%. While there are advantages, there are also challenges such as the requirement for advanced sorting technologies and the necessity of maintaining material quality during recycling processes. Anđelina Bubalo et al. (2023) investigated the application of sewage sludge ash (SSA) in brick production. Their findings indicated that bricks fired at 900°C exhibited the greatest compressive strength and decreased water absorption, thereby enhancing durability. SSA has been identified as a feasible option for sustainable brick production; however, additional optimization of SSA content and firing conditions is necessary. Aseel Hussien et al. (2024) investigated the incorporation of tea waste (TW) in unfired clay bricks. The findings indicated that adding 2.5% to 5% TW enhanced porosity and thermal insulation, thereby increasing the energy efficiency of the bricks. Nevertheless, an increase in TW content adversely affected compressive strength and durability, suggesting the necessity for a balanced material composition. Delphine Nzivulu and colleagues (2024) studied composite bricks made from red clay and waste glass for their effectiveness in radiation shielding. The increase in waste glass content improved gamma-ray attenuation, while also preserving sufficient compressive strength (10.30 N/mm²) and decreasing water absorption. The research indicates that waste glass bricks may be utilized for structural purposes as well as for radiation shielding.

Hassan Subhani and colleagues (2024) investigated the creation of recycled bricks utilizing waste plastic and foundry sand, resulting in a compressive strength of 8.23 MPa and enhanced thermal insulation. The research showed that the material has lightweight structural benefits, low water absorption, and ductile properties, emphasizing the environmental advantages of reusing plastic waste. Huabao Chen and colleagues (2022) included electric arc furnace slag (EAFS) in fired bricks, resulting in a 50% increase in compressive strength and a decrease in water absorption and porosity. EAFS played a role in creating stable microstructures and promoting environmental safety by reducing heavy metal leaching. Junaid Ahmed and colleagues (2024) studied the application of recycled brick waste powder (RBWP) in engineered geopolymer composites (EGC). The research indicated that RBWP enhanced compressive and tensile strength by 25% and 29%, respectively, while also decreasing setting times by more than 90%. This supports its potential as a sustainable substitute for fly ash and GGBS.

L. Crespo-López et al. (2023) investigated the incorporation of glass in handmade bricks, showing enhancements in vitrification and compressive strength. Variations in raw materials and firing conditions resulted in aesthetic inconsistencies, which could restrict applications in heritage restoration. Laura Crespo-López and colleagues (2024) investigated the application of tea waste as an additive in the production of bricks, emphasizing its environmental and economic advantages. The research indicated that tea waste enhanced porosity and water absorption, but decreased mechanical strength. It improved thermal insulation, which makes it appropriate for lightweight, insulating bricks. The research highlighted the necessity for additional optimization to achieve a balance between thermal efficiency and mechanical performance. In a different study, Laura Crespo-López and colleagues (2024) examined the use of recycled carbon fiber (RCF) from wind turbine blades in the production of bricks. The research indicated that RCF enhanced porosity and durability; however, compressive strength decreased by 25% at 5 wt% and by 50% at 10 wt%. The environmental benefits consisted of decreasing the demand for clay and recycling turbine blades, which is consistent with the principles of a circular economy. Laura M. Henao Rios and colleagues (2023) investigated the application of waste glass as a precursor, activator, and aggregate in the synthesis of geopolymers. The research indicated that fine glass aggregate increased compressive strength (from 8.9 to 27 MPa), decreased porosity, and enhanced durability. The findings indicate that waste glass can serve as a sustainable alternative in construction materials.

Linqiang Mao and colleagues (2020) examined how the size of waste glass particles affects fired bricks. The research indicated that larger glass particles increased compressive strength, decreased water absorption, and improved insulation as a result of the formation of a molten glass-ceramic phase during the firing process. Concerns regarding the leaching of hazardous metals emphasize the necessity for additional environmental safety measures.

Mandefrot Dubale et al. (2024) investigated the use of demolition roof tile waste (RTW) in fired bricks. Their findings indicate that incorporating up to 35 wt% RTW enhances strength and durability, while also decreasing the consumption of natural resources and the carbon footprint. Higher RTW content resulted in greater shrinkage and water absorption, necessitating temperature adjustments for optimal performance. Marcin Małek and colleagues (2022) created cement-glass composite bricks (CGCB) incorporating 75% waste glass and 10% PET-G. The research indicated that CGCB enhanced thermal insulation; however, there was a 30% reduction in compressive strength (maximum 41 MPa) attributed to a rise in air void content. This demonstrates the appropriateness of CGCB for non-load-bearing uses. Mario Flores Nicolás and colleagues (2024) investigated the low-temperature sintering of ceramic bricks made from clay, waste glass, and sand. The research demonstrated ASTM-compliant compressive strength of 11 MPa at a temperature of 800°C, which resulted in decreased energy consumption during the production of bricks. The results indicate that eco-friendly construction can be achieved through the integration of waste materials.

Mohamed Abdellatief and colleagues (2024) studied recycled medical glass (RMG) in alkali-activated concrete (AAC), resulting in compressive strengths ranging from 71.06 to 102.2 MPa. RMG also decreased water absorption to as low as 2.93%, enhancing durability and sustainability in difficult environments.

Mohammed Rihan Maaze and colleagues (2024) investigated geopolymer bricks produced from recycled brick waste (RBWB), showing significant durability and thermal stability. The research demonstrated a compressive strength of 17.53 MPa, showing minimal degradation when exposed to heat and acid, thereby supporting RBWB as a sustainable alternative. Mucteba Uysal and colleagues (2022) investigated geopolymers derived from industrial waste, discovering that substituting brick powder enhanced compressive strength by 74%. Excessive marble powder, however, diminished strength, highlighting the necessity for material optimization. Serdar Korpayev and colleagues (2023) studied the use of stone wool waste (SWW) from greenhouse agriculture in fired clay bricks to improve thermal insulation and mechanical properties. The research indicated that incorporating up to 10% SWW resulted in a 20.75% improvement in thermal insulation, a 13% reduction in bulk density, and an enhancement in freeze-thaw durability. The compressive strength was measured at 27 MPa, and the bending strength was recorded at 13.79 MPa, with both values conforming to ASTM standards. Higher concentrations of SWW, however, led to a reduction in both bulk density and strength, necessitating careful control of proportions to optimize performance. The results indicate that SWW is a sustainable material suitable for environmentally friendly and energy-efficient construction. Sikandar Ali Khokhar and colleagues (2023) created machine learning models to forecast the mechanical properties of bricks produced from recycled materials. The research examined different models, such as artificial neural networks (ANN), Gaussian process regression (GPR), support vector machines (SVM), and classification and regression trees (CART). The ANN model showed the highest accuracy, with an RMSE of 3.86 MPa for compressive strength. The results emphasize the possibilities of AI-based optimization in sustainable brick production, encouraging the effective use of recycled materials. Siwat Lawanwadeekul and colleagues (2023) investigated the incorporation of corn cob (CC) and waste glass (WG) into clay bricks to enhance thermal insulation and mechanical properties. The best combination of 10 wt% CC and 20 wt% WG, when fired at 900°C, achieved a compressive strength of 10 MPa and a water absorption rate of 21.3%. The incorporation of waste glass facilitated mineral formation, which led to improved mechanical strength, whereas the use of CC resulted in increased porosity, thereby enhancing insulation properties. The research indicates the incorporation of agricultural and industrial waste into construction materials.

Tuhin Sarkar and colleagues (2024) created environmentally friendly ceramic foams from industrial waste, attaining a high compressive strength of 109.75 MPa and effective thermal insulation. The foams showed a porosity of 33%, a bulk density of 2.14 g/cc, and a thermal conductivity of 0.93 W/m·K, which plays a crucial role in energy conservation. The study indicated a possible reduction in CO_2 emissions of 28.41×10^5 tonnes, highlighting the sustainability advantages of ceramic foams in construction.

Youcef Bali and colleagues (2024) added alfa plant powder and glass powder to fired earth bricks, resulting in a notable reduction in thermal conductivity by 42.36%, while the compressive strength remained at 8.561 MPa. The research showed that glass powder enhanced water absorption resistance, contributing to the advancement of energy-efficient construction materials. Yuecheng Xin and colleagues (2023) investigated the effects of waste-contaminated glass dust (WGD) in fired clay bricks. Their findings indicated that incorporating 15% WGD enhanced compressive strength and thermal performance, while also lowering firing temperatures and greenhouse gas emissions. Tests for heavy metal leaching demonstrated environmental safety, indicating that WGD can serve as a suitable alternative to clay in the production of bricks.

Yulin Patrisia and colleagues (2024) investigated the use of pond ash and recycled glass sand in the production of sustainable concrete bricks, which comply with AS/NZS 4455.1:2008 standards. The bricks demonstrated a compressive strength of 29.63 MPa, an improvement in insulation of 28.9%, and fire resistance for up to two hours. Although there were some minor mechanical issues, the study confirmed the effectiveness of incorporating waste materials into strong and environmentally friendly bricks.

2 MATERIALS AND METHODS

Ordinary Portland Cement (OPC) of 43 grade was utilized because of its high strength and durability. The fine aggregate, which was natural sand, had a fineness modulus (FM) of 3.70. In comparison, the waste crushed glass showed an FM of 3.68. This suggests that both materials have a similar particle size distribution and could potentially serve as a partial replacement for sand. The coarse aggregate (CA) exhibited a fineness modulus of 6.03, which facilitates appropriate gradation and interlocking within the concrete mixture. The specific gravity (SG) values for cement, fine aggregate, and coarse aggregate were 3.16, 2.63, and 2.71, respectively. These values were essential for accurately determining the mix proportions. Water absorption is an important factor, with fine aggregate showing an absorption rate of about 1% and coarse aggregate around 0.5%, which helps ensure proper moisture adjustment during mix preparation. The water utilized in the mixture adhered to IS 456:2000 standards, with a maximum limit of 186 liters per cubic meter, ensuring workability within the 25-50 mm slump range. Superplasticizer (SP) was added at 1.2% of the weight of cement, which led to a reduction in water content by 21.6% and resulted in a water-cement ratio of 0.37, thereby improving durability and strength. The ratio of coarse aggregate to fine aggregate was kept at 60.8, which ensured optimal particle distribution for improved compaction.

3 MIX PROPORTIONING

M45 grade concrete mix design followed IS 10262:2019 guidelines, maintaining a 0.37 water-cement ratio. The replacement levels were 0%, 10%, 20%, 30%, and 40% waste glass. The designed mix proportions ensured a balance between mechanical performance and sustainability. Each mix was prepared with precisely measured components to maintain consistency and comparability across tests.

4 TESTING METHODS

The performance of concrete mixes was evaluated using various standard tests:

- Compressive Strength (IS 516:1959): Standard 150mm × 150mm × 150mm cube specimens were cast and tested at 7, 14, and 28 days to assess strength development over time.
- Flexural Strength (IS 516:1959): Beam specimens of 100mm × 100mm × 500mm were subjected to two-point loading to determine their ability to withstand bending forces.
- Water Absorption (IS 2185:2005): Concrete specimens were oven-dried, immersed in water for 24 hours, and reweighed to determine their absorption capacity, which indicates permeability.
- Density (IS 15658:2006): Dry weight and volume were recorded to determine the compactness and mass distribution of the concrete.
- Workability (IS 1199:1959): Slump test, Vee-Bee test, and compacting factor were evaluated to measure flowability and ease of placement.

4.1 Results and Discussion

The study on M45 grade concrete incorporating waste crushed glass as a partial replacement for fine aggregate was conducted to evaluate its mechanical, durability, and workability properties. A series of tests, including compressive strength, flexural strength, water absorption, and density measurements, were performed to analyze the feasibility of using waste glass in concrete. The results provide valuable insights into the impact of waste glass on concrete performance and help determine the optimal replacement levels for sustainable construction applications.

4.2 Workability

The workability tests (slump test, Vee-Bee time, and compacting factor) showed that as waste glass content increased, workability slightly decreased. This is due to the smooth surface of glass particles, which reduces friction and adhesion with cement paste, leading to lower cohesion in the mix. The control mix had a slump value of 48 mm, while the 40% replacement mix had a slump of 35 mm, indicating reduced flowability. However, superplasticizers or water-reducing admixtures can be used to enhance workability in high-glass-content mixes.

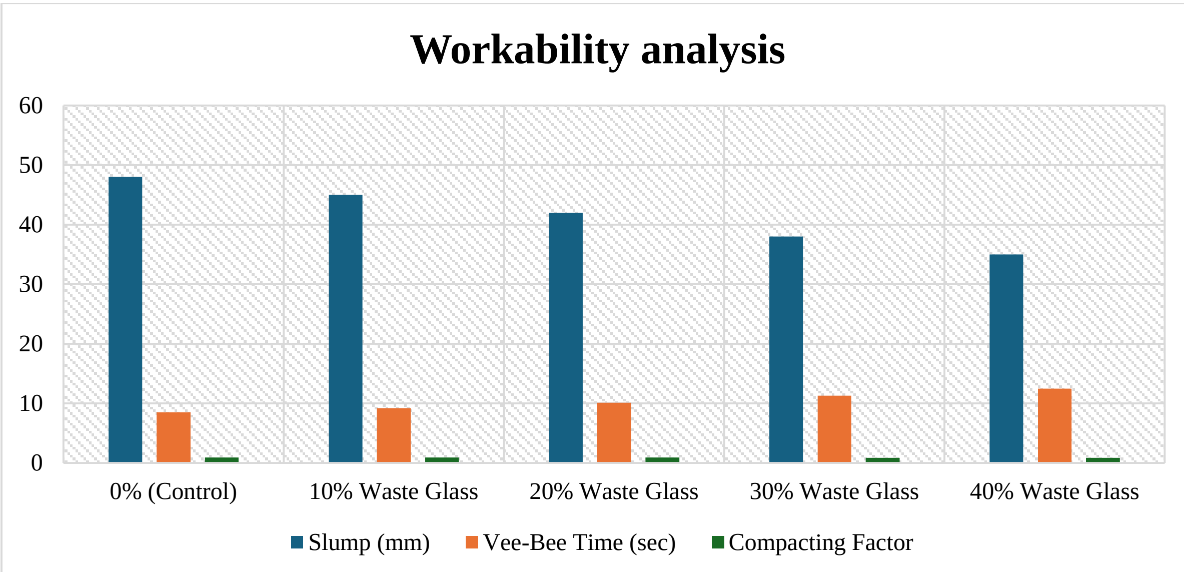

Figure 1: Workability analysis

4.3 Compressive Strength

The compressive strength results at 7, 14, and 28 days demonstrated that waste glass can be used up to 20% replacement without significantly compromising strength. At 7 days, early strength development was slightly lower for concrete with waste glass due to its non-hydraulic nature, meaning it does not actively contribute to the hydration reaction. However, by 14 and 28 days, the strength improved as the cement continued to hydrate, and the waste glass mix achieved values close to the control mix (0% glass replacement). The control mix reached 52.8 MPa at 28 days, while the 10% and 20% waste glass replacements attained 50.4 MPa and 48.0 MPa, respectively, which are within an acceptable range for M45 grade concrete. However, at 30% and 40% replacement levels, compressive strength decreased more significantly, indicating that higher waste glass content weakens the bond between cement and aggregates. Therefore, it is recommended that waste glass replacement should be limited to 20% to maintain high strength while promoting sustainability.

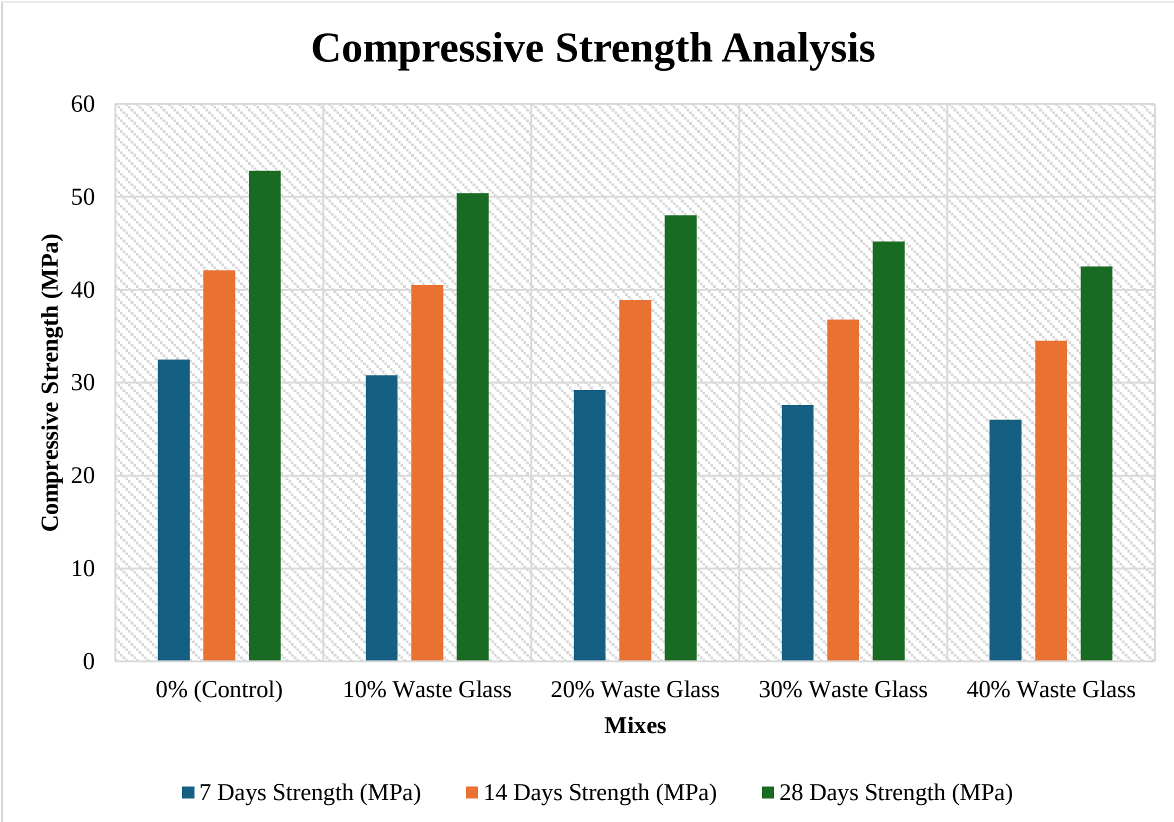

Figure 2: Compressive Strength Analysis

4.4 Flexural Strength

The flexural strength results followed a similar trend to compressive strength, where higher waste glass content led to a gradual reduction in bending resistance. The control mix achieved 7.2 MPa at 28 days, while the 10% and 20% waste glass mixes attained 6.9 MPa and 6.5 MPa, respectively. However, at 30% and 40% replacement, the flexural strength reduced more noticeably, reaching 6.1 MPa and 5.8 MPa, respectively. This decline is due to the smoother texture of waste glass particles, which reduces aggregate interlocking and overall tensile strength in the concrete matrix. For applications where high flexural strength is required, such as bridges, pavements, and slabs, waste glass replacement should not exceed 20% to ensure adequate bending resistance.

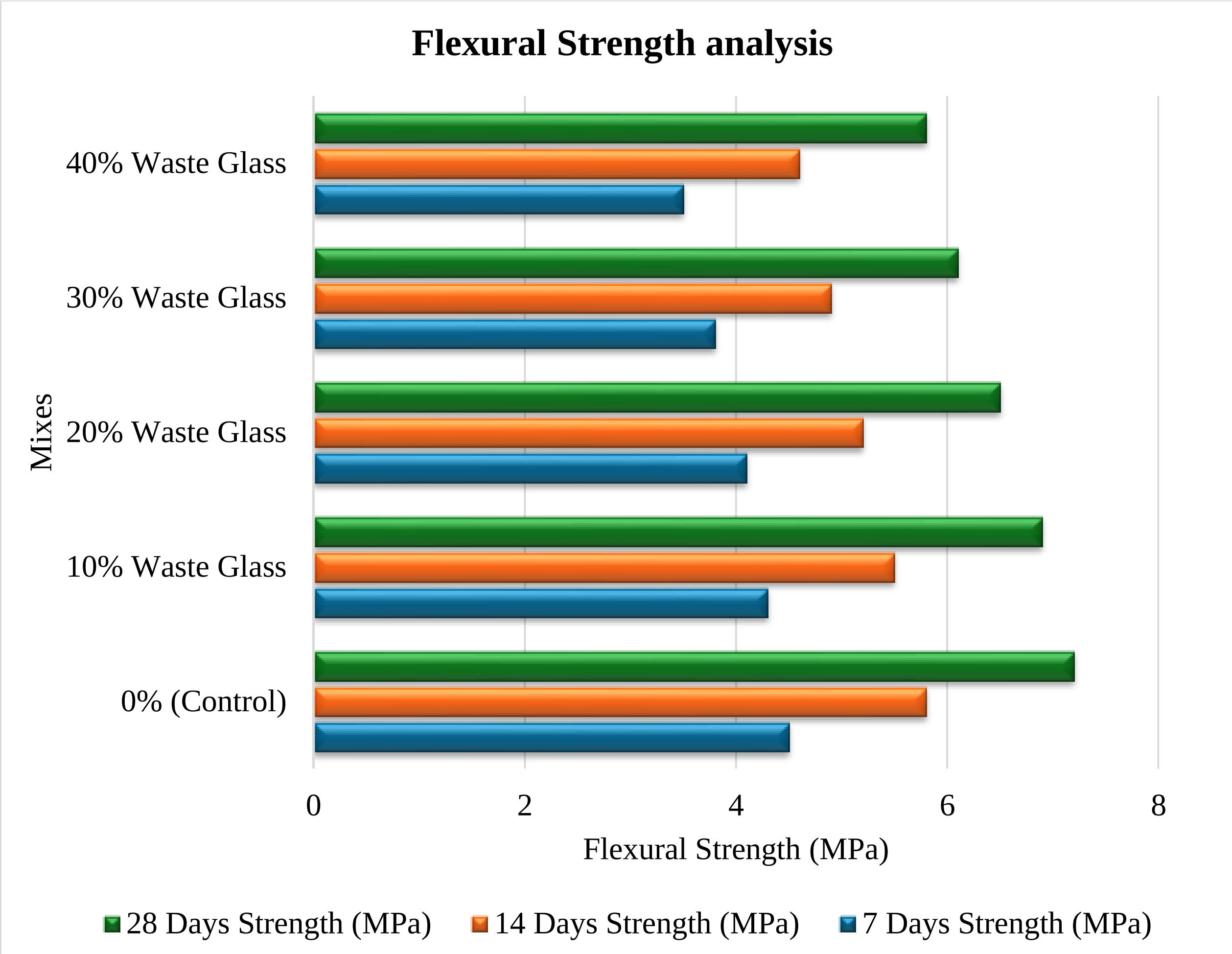

Figure 3: Flexural Strength analysis

4.5 Water Absorption

The water absorption test revealed that as the waste glass content increased, the concrete became more porous, leading to higher water absorption values. The control mix had the lowest absorption at 2.1%, while the 40% replacement mix absorbed 3.2% water, which is significantly higher. This increase is due to the smooth, non-porous nature of glass particles, which reduce the compactness of the concrete structure, allowing more water to penetrate. Higher water absorption can lead to increased permeability, making the concrete more vulnerable to moisture damage, freeze-thaw cycles, and chemical attacks. To maintain long-term durability, it is recommended that waste glass replacement should not exceed 20%, beyond which additional durability-enhancing measures (such as pozzolanic additives or waterproofing admixtures) would be required.

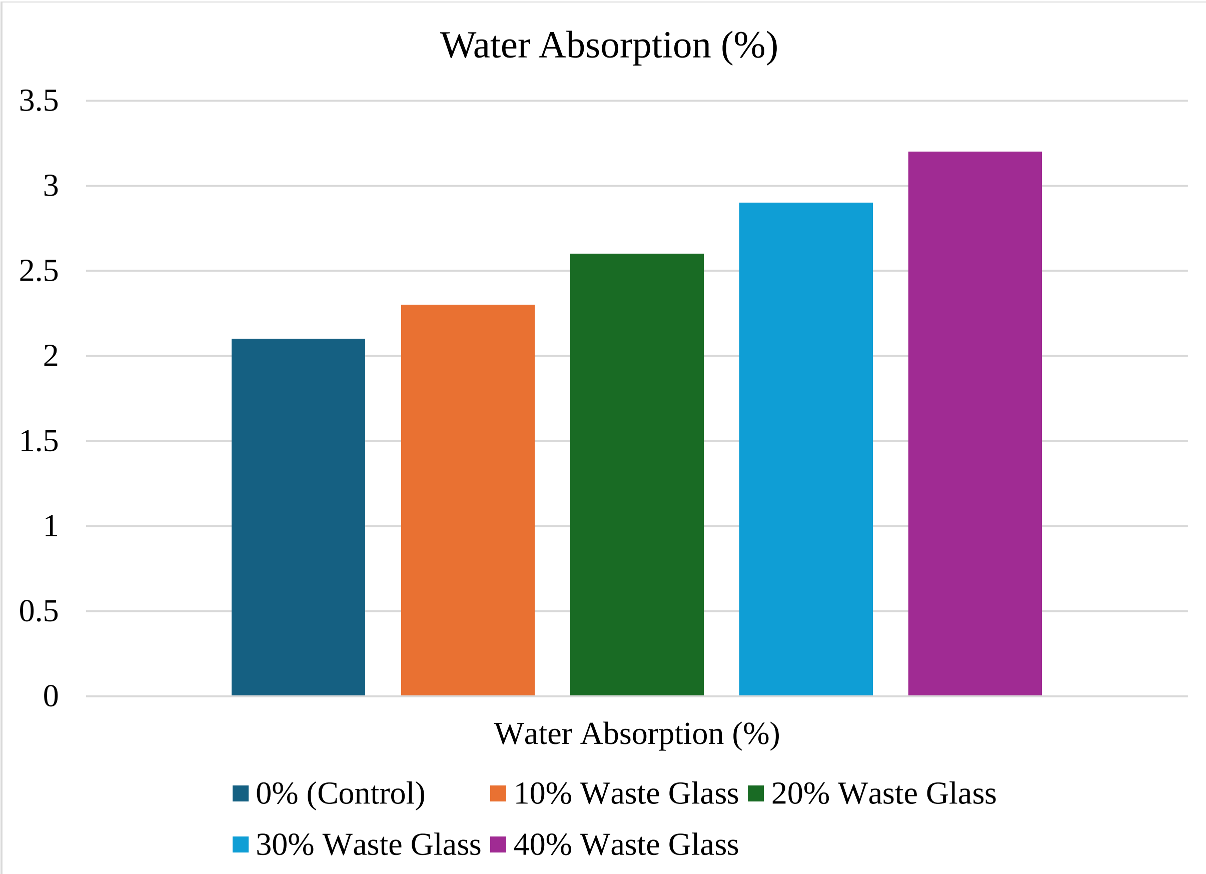

Figure 4: Water Absorption (%) analysis

4.6 Density

The density results showed a gradual reduction in concrete weight as waste glass content increased. The control mix had the highest density at 2450 kg/m³, while the 40% replacement mix had the lowest at 2315 kg/m³. The decrease in density is due to waste glass having a lower specific gravity than natural sand, leading to a lighter concrete mix. Lower density can be advantageous in lightweight construction applications, reducing dead loads on structures. However, excessive reduction in density can result in lower strength and increased porosity, potentially affecting the durability and mechanical performance of the concrete. The results suggest that waste glass replacement should be limited to 20% to maintain a balance between weight reduction and strength preservation.

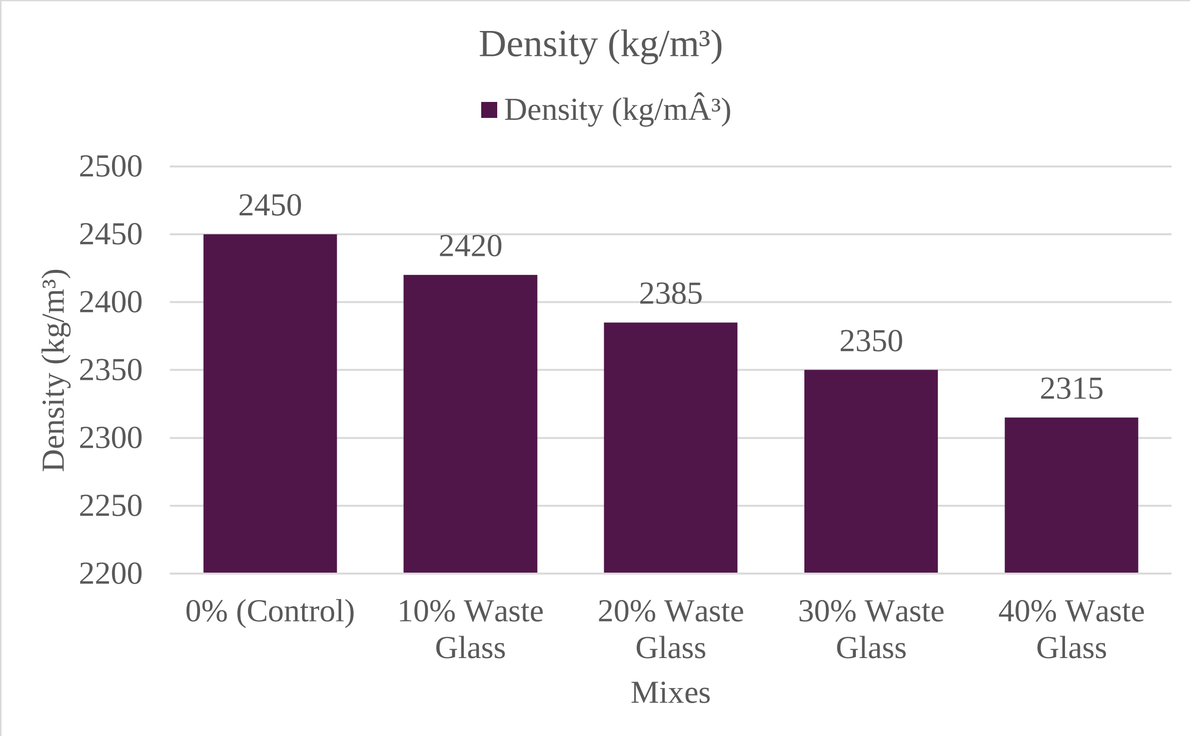

Figure 5:Density analysis

4.7 Conclusion

The study determines the appropriate waste glass replacement amount in concrete while retaining mechanical integrity and durability by assessing compressive strength, flexural strength, water absorption, density, and workability. Due to waste glass particles' smooth, non-porous surfaces, slump, Vee-Bee time, and compacting factor reduced as waste glass content rose. The control mix slumped 48 mm, but 40% waste glass substitution decreased it to 35 mm, suggesting lower flowability. The Vee-Bee duration rose from 8.5 to 12.5 seconds as waste glass content increased, stiffening the mix. Despite this decrease, superplasticizers or water-reducing admixtures can increase workability without affecting strength.

Higher waste glass content reduced compressive strength, especially at 30% and 40% replacement levels. The control mix attained 52.8 MPa at 28 days, whereas 10% and 20% waste glass mixes reached 50.4 and 48.0 MPa. However, 30% and 40% replacement levels showed significant strength losses, showing waste glass above 20% may impair the cementitious matrix. Flexural strength tests showed a progressive fall as waste glass content increased, with the control mix reaching 7.2 MPa at 28 days and the 40% replacement mix reaching 5.8 MPa. Waste glass's flat surface limits aggregate interlocking, decreasing flexural performance. These findings show that waste glass replacement should not exceed 20% for load-bearing systems requiring tensile strength. Permeability increased with waste glass content in water absorption tests. Lower absorption was 2.1% in the control mix and 3.2% in 40% replacement, suggesting that larger waste glass content may increase porosity and diminish durability. This shows that concrete with more than 20% waste glass replacement may need pozzolanic additives or waterproofing to avoid moisture penetration and long-term deterioration. The density studies showed that waste glass decreases concrete weight, with the control mix weighing 2450 kg/m³ and the 40% waste glass mix weighing 2315 kg/m³. This weight decrease is useful for lightweight applications, but severe density loss may weaken concrete.

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