

PERFORMANCE EVALUATION OF SUSTAINABLE CONCRETE USING RECYCLED GLASS POWDER AND GLASS SAND

Km Babli Gupta¹, Prince Yadav²

¹M.Tech Students, Department Of Civil Engineering, Institute Of Engineering And Technology, Lucknow, 226021, Uttar Pradesh, India.

²Assistant Professor, Department Of Civil Engineering, Institute Of Engineering And Technology, Lucknow, 226021, Uttar Pradesh, India

Abstract - The demand for sustainable building materials is driving researchers to look for alternative waste materials for use as construction materials. While there are many types of industrial and municipal waste products, recycled glass has been shown to have both pozzolanic properties and high silica content, which makes it an excellent supplemental material for concrete. This research examined the mechanical and durability performance of M50 concrete when using glass powder as a partial replacement for cement and glass sand as a partial replacement for fine aggregate. Glass powder was incorporated at levels of 0%, 5%, 10%, 15%, and 20%, and glass sand was included as part of the fine aggregate at levels between 0% and 30%. Research looked at compressive strength, split tensile strength, and flexural strength at different curing ages. In addition, researchers analyzed various durability characteristics such as water absorption, sorptivity, acid resistance, and sulfate resistance to determine the long-term performance of the newly developed concrete mixes. Microstructural investigations (including SEM, XRD, and FTIR) were performed on both the control and optimum mixes to study the hydration of the concrete during curing and to examine the distribution of materials inside the concrete. Overall, the study showed that using moderate percentages of glass powder and glass sand positively influenced the mechanical and durability performance of the concrete.

KeyWords: Waste glass material, sustainable construction, mechanical properties, Durability analysis, Microstructural Analysis

1. INTRODUCTION

Due to rapid urbanization, an industrial boom, and the global need for more infrastructure, the construction industry is consistently growing. Of all the construction materials available for use, concrete is by far the most widely used construction material because of its versatility, strength, and low cost. Due to the large amounts of cement and natural aggregate (sand and rock) used in normal concrete, there are serious issues related to the negative effects of carbon dioxide (CO₂) on the environment, the depletion of natural resources, and the disposal of industrial materials, namely cement. Cement production is one of the largest contributors to greenhouse gas emissions in the world (Mehta &

Monteiro, 2014). Additionally, when river sands are collected at excessive rates, significant damage is caused to aquatic ecosystems and the surrounding landscapes (Mehta & Monteiro, 2014). For these reasons, the search for alternatives that could reduce or eliminate the need for traditional concrete materials is becoming one of the primary research areas in today's modern Civil Engineering Materials.

Waste recycling strategies have been a popular subject of research in various sectors because they reduce the burden on the environment that results from industrial and municipal waste. Within the many types of recyclable materials generated by our society, waste glass is emerging as a suitable construction material. Due to its high content of silica, glass cannot be biodegraded and most often it can be found in many different forms, such as bottles, windows, containers, and electronics. Therefore, the high volume of glass waste being generated and the difficulty for recycling facilities recycle is creating great difficulties for efforts to divert our growing supply of glass from landfills. In addition to occupying large amounts of precious space, the accumulation of waste glass creates long-term environmental management issues (Siddique & Naik, 2004). As such, the use of waste glass in the production of concrete has both environmental and economic advantages in terms of reducing waste sent to landfills and limiting the need for the use of raw natural construction materials.

Amorphous silica in finely crushed glass powder has also demonstrated pozzolanic properties towards the cementitious materials, as silica and calcium hydroxide (produced from the hydration of cement) react to produce additional calcium silicate hydrates during cement hydration. This additional hydrates results in improved microstructural densification and an improvement concrete properties (Du & Tan, 2014). In addition, due to their suitable particle size distribution and relatively high hardness, crushed glass sands may be used as a partial replacement for natural fine aggregates.

There are many papers showing that when the maximum replacement levels of glass powder or glass sand are used, the mechanical performance of concrete is greatly improved. At moderate replacement levels of glass powder and glass sand, researchers measured increases in compressive

strength, splitting tensile strength, flexural strength, resistance to water absorption, and resistance to chloride penetration.

Research conducted previously has shown that moderate amounts of glass waste as a cement replacement had a positive impact on concrete's compressive strength, and ductility. Glass waste provided particulate effects (although there is no consensus yet on what this means), and allowed for additional strength through secondary hydration of fine grinds of glass (Ali & Al-Tersaway 2012). In particular, improved durability, and reduced water absorption, low permeability, and improved resistance against sulphate and acid environments have been achieved by using glass waste in high-strength concrete (Shi & Zheng 2007). Conversely, using higher concentrations may have an adverse effect on concrete due to bond strength and the potential for alkali-silica reactivity depending upon the conditions in which the concrete is exposed. In contrast with previous research that has been devoted to studying glass waste as either a cement replacement or aggregate replacement in concrete, there is limited research available concerning using both glass powder and sand in high-strength concrete. While a number of studies have reported on the mechanical properties of concrete using these types of materials, the existing literature does not provide detailed information on durability performance or micro-structural characteristics. Therefore, a thorough investigation on the effect of using these materials in concrete will be needed in order to determine appropriate guidelines for using glass waste in actual structural applications.

2. MATERIALS AND METHODOLOGY

This section describes the materials utilized in the concrete mix, the mix design methodology, specimen preparation process, and the experimental procedures carried out to assess the mechanical and durability performance of concrete incorporating waste glass powder and glass sand.

2.1 Materials

Ordinary Portland Cement (OPC) of 53 grade as per relevant Indian Standard specifications was the main binding material used for the preparation of concrete mixes. Fine aggregate used was natural river sand with suitable grading characteristics. Crushed coarse aggregate of nominal maximum size 20 mm was used in the study. The mixing and curing operations were conducted with potable water free from harmful impurities.

Waste glass powder (GP) was prepared from the waste glass materials collected from the local recycling sources. The collected glass was cleaned and dried and ground to a fine powder which passed through a 75 μm sieve. The finely processed glass powder was used as a partial replacement of cement due to its silica-rich composition and pozzolanic activity potential. Glass sand (GS) was obtained by crushing waste glass into fine aggregate particles and was used as partial replacement of natural river sand.

Polycarboxylate ether based super plasticizer was used to maintain the required workability of M50 grade concrete mixes at lower water cement ratios. To obtain uniform consistency and proper compaction of concrete specimens, the dose of chemical admixture was varied.

2.2 Mix Proportions

The concrete mix is designed for M50 grade concrete as per the relevant mix design guidelines. Glass powder was used as a partial substitute of cement at replacement levels of 0%, 5%, 10%, 15% and 20%. Glass sand was used as a partial substitute of fine aggregate at proportions of 0%, 10%, 20% and 30%.

The control mix was plain concrete without any glass-based replacement materials. Different trial mixtures were prepared in order to investigate the combined effect of GP and GS on the performance characteristics of concrete. All mixtures had a constant water-binder ratio to allow a uniform comparison of the concrete specimens developed.

2.3 Specimen Preparation and Casting

The concrete ingredients were mixed in a laboratory concrete mixer to ensure even distribution of the materials in the mixture. Dry materials such as cement, glass powder, fine aggregate, glass sand and coarse aggregate were mixed thoroughly. Then water and super plasticizer were added gradually to the mixing process until a homogeneous concrete mixture was obtained. Fresh concrete was placed in standard moulds in several layers and adequately compacted to avoid entrapped air voids. For compressive strength evaluation, cube specimens were prepared, cylindrical specimens were prepared for split tensile strength testing and prism specimens were prepared for flexural strength analysis. After casting, all specimens were kept for 24 hours under laboratory conditions before demoulding. The specimens were then cured in clean water up to the time of testing at the specified ages.



Fig-1: Casting and Curing of Specimen

2.4 Mechanical Performance Evaluation

Compressive strength, split tensile strength, and flexural strength were used to evaluate the mechanical properties of concrete. Compressive strength tests were performed at 7, 28, and 56 days of curing to evaluate the strength development characteristics of the concrete mixtures. Split tensile and flexural strength tests were conducted at later

curing ages to measure the tensile resistance and flexural behaviour of the concrete specimens that were developed. The mechanical performance of each of the glass incorporated concrete mixtures were compared to the control mix to determine the ideal replacement levels that provided maximum strength improvement.

2.5 Durability Assessment

Concrete was tested for durability performance via water absorption, sorptivity, acid resistance and sulphate resistance tests. To analyze the acid resistance of the concrete specimens, they were submerged into sulfuric acid solution for a defined exposure time period and then weighed and their retained compressive strength measured to determine the percentage of weight loss and residual compressive strength. Sulfate resistance was also evaluated by submerging the concrete specimens in sodium sulfate solution and analyzing the change of physical condition and performance strength of the concrete specimens after the prolonged exposure. The durability studies were performed to understand the resistance of concrete containing glass aggregates to highly aggressive weather conditions and to evaluate if glass aggregate containing concrete mixes could meet long-term structural use requirements.

2.6 Microstructural Characterization

Concrete samples selected for microstructural characterisation were subjected to assessment of the internal morphology and the way the concrete has hydrated. Scanning Electron Microscopy (SEM) was used to examine the surface texture, pore structure and the distribution of micro-cracks in the cement matrix.

X-ray Diffraction (XRD) was employed to identify the crystal phases and hydrated products formed during the hydration of cement and Fourier Transform Infrared Spectroscopy (FTIR) was also carried out to analyze the bonding characteristics and the amount of silica-based hydrated compounds in the concrete materials. The results of the microstructural characterizations allowed a link to be made between the internal morphology and the mechanical and durability performance of high-strength glass (increased) concrete.

3. Test Performed

3.1 Compressive Strength

The Compressive Strength tests were performed according to IS 516 (1959). The concrete cubes used were 150mm x 150mm x 150mm in size and underwent normal curing in a water tank. Three cubes were tested for each time period (7, 14 and 28 days of cure) via the CTM with a load capacity suitable for each day's test. The uniform application of the load at a constant rate continued until failure occurred, and the maximum load reached per specimen was noted for evaluating compressive strength.

3.2 Water Absorption

The water absorption test conducted on concrete cube specimens to assess their permeability characteristics followed ASTM C642. Samples were cured for 7, 28, or 90 days using normal water curing methods prior to being dried in an oven set at approximately $105 \pm 5^\circ\text{C}$ until they achieved constant weight. After drying, cubes were allowed to cool to room temperature, then weighed again before being completely submerged in water for 24 hours in the lab. Surfaces were then dried with a dry cloth to remove excess moisture before weighing again to obtain a saturated weight. The percentage of water absorbed can then be calculated by taking the weight difference between the original and saturated cubes' weights.

3.3 Sorptivity

The sorptivity test was conducted per ASTM C1585 to assess the rate at which water will be absorbed by capillarity into a concrete object. The discs were created by cutting from hydrated concrete cylinders after 7, 28 and 90 days of hydration to a uniform thickness of 50 mm. Prior to the absorption test, the specimen was placed in a controlled oven drying environment and epoxy coated around the perimeter to ensure that all absorbed water moves in a unidirectional manner (downward). The bottom of the discs were placed in 5 mm of water, and the increase in weight of the disc was measured at preselected time intervals on a digital scale. The sorptivity coefficient was determined by the relationship of cumulative water absorption versus square root of time.

3.4 Acid Resistance

This testing evaluates the behaviour of concrete in relation to its durability under acidic environmental conditions. Concrete cubes measuring 150 mm x 150 mm x 150 mm were made and cured in water for 28 days prior to being placed into a 5% sulphuric acid (H_2SO_4) solution to be exposed for 7, 28 and 90 days. The acid solution was maintained in a laboratory controlled environment and replaced periodically throughout the exposure period to ensure consistent concentrations of the acid throughout the exposure period. The test cubes were removed from the acid solution at the end of each respective exposure period, cleaned and weighed to determine the percentage weight lost.

3.5 Sulphate Resistance

A sodium sulfate (Na_2SO_4) solution was used to check how well concrete was able to resist sulfate attack. Concrete cubes of standard size were made and allowed to cure for 28 days before being immersed in 5% sodium sulfate solution for 7, 28 and 90 days. The sodium sulfate solution was periodically checked and replaced during the test to ensure a

constant concentration of sodium sulfate in the solution. The cubes were then inspected visually for any signs of damage, expansion, or cracking. After visual inspection, the cubes were weighed and then tested for residual compressive strength with an appropriate compression-testing device. This testing measured the resistance of the cubes to sodium sulfate attack.

3.6 Microstructural Analysis

The microstructural investigations were conducted to establish the relationship between hydration behavior, matrix densification, and the observed mechanical and durability performance of glass-incorporated M50 concrete. The microstructure of both control and optimal concrete mixtures was analyzed using scanning electron microscopy (SEM), X-ray diffraction (XRD), and Fourier transform infrared spectroscopy (FTIR) after 28 days of curing. SEM was used to investigate the morphology of the concrete surface, pore distribution and hydration products in the concrete matrix. XRD was used to determine the crystalline phases and the development of hydration products resulting from pozzolanic reactions over a diffraction angle of 10° to 80° (2θ).

4. RESULT AND DISCUSSIONS

The mechanical performance, durability performance, and microstructure of M50 concrete containing glass powder and glass sand are discussed in this section. Strength and durability test results were analyzed to determine how various replacement levels affected the performance of concrete. The microstructural characteristics of the developed concrete mixes were also evaluated using SEM, XRD, and FTIR.

4.1 Compressive Strength Results

Adding medium amounts of glass powder and glass sand to M50 Concrete had a positive effect on its compressive strength. M2 had the greatest 28-day compressive strength at about 11.8% over that of the Control Mix. The increase in strength is attributed to better packing of glass particles and refinement of the pore structure because of the pozzolanic reaction with the powder will densify the matrix and produce C-S-H gel in place of the typical hydration products. Replacement at too high a rate in M4 caused a decrease in compressive strength because of a weak bond and low amount of cementitious material in the concrete aggregate matrix.

Table -1: Compressive Strength of concrete mix

Concrete Mix	Compressive Strength (MPa)		
	7 days	14 days	28 days
CM	36.8	45.6	54.2
M1	38.2	47.9	57.1
M2	40.4	50.8	60.6
M3	39.7	49.9	59.3
M4	35.9	44.1	52.4

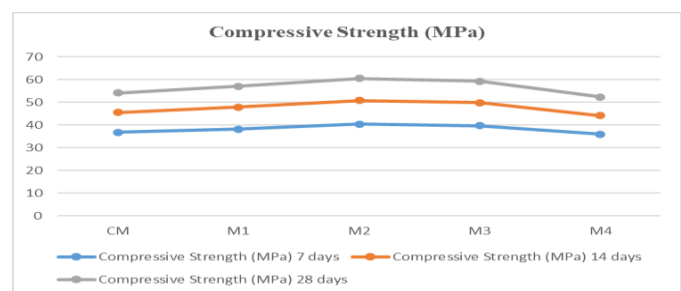


Chart -1: Compressive Strength Graph

4.2 Water Absorption Results

It was revealed through the results obtained from the water absorption tests that the addition of glass powder and glass sand has affected the permeability properties of M50 concrete. There was a declining tendency for water absorption from CM to M2 because of the denser matrix, less pore connectivity, fillers, and pozzolanic action of fine glass powder. It should be noted that the M2 mixture had the least water absorptions of 4.42%, 3.58%, and 3.16% after 7, 28, and 90 days, respectively. It is evident that the water absorption of M2 decreased by around 22.5% when compared to the control mixture.

Table -2: Water Absorption of concrete mix

Concrete Mix	Water Absorption (%)		
	7 days	14 days	28 days
CM	5.21	4.62	4.08
M1	4.86	4.11	3.74
M2	4.42	3.58	3.16
M3	4.57	3.74	3.31
M4	5.04	4.39	3.96

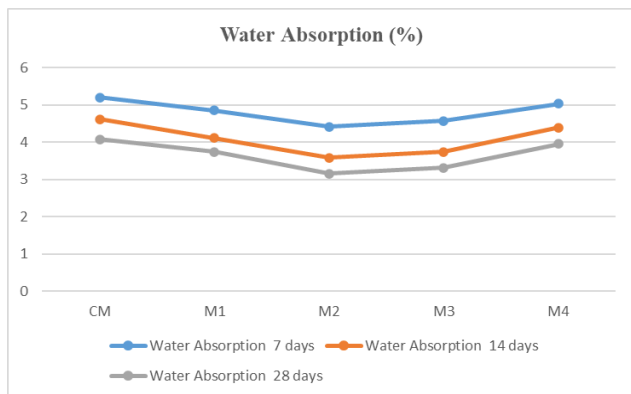


Chart -2: Water Absorption Chart

4.3 Sorptivity Results

Water absorption for all concrete mixes decreased with increasing curing age. At twenty-eight days, the control mix (M0) had a water absorption rate of 4.08% while each modified mix had less than 4.08%; therefore the addition of waste glass powder and glass sand enhanced the densities of the matrices and decreased the pore structures of each of the mixtures. Of all the mixtures, M3 had the lowest amount of water absorption (3.42%) at twenty-eight days and was approximately 16.18% less than the control mix amount.

Table -3: Sorptivity of different concrete mix (mm/min^{1/2})

Concrete Mix	Sorptivity(mm/min ^{1/2})		
	7 days	14 days	28 days
CM	0.182	0.142	0.118
M1	0.164	0.128	0.103
M2	0.149	0.109	0.086
M3	0.156	0.116	0.092
M4	0.176	0.137	0.112

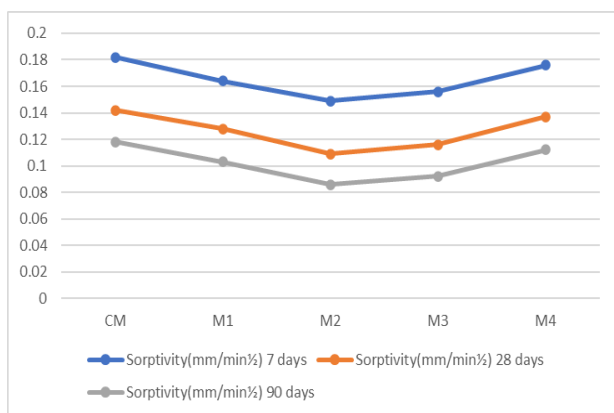


Chart -3: Sorptivity Measure Chart

4.4 Acid Resistance Test Results

The results for acid resistance showed that the addition of glass powder and glass sand increased the resistance of M50 concrete towards acidic attack. The residual compressive strength rose from CM to M2 mix at all curing ages, with the highest residual strengths being recorded at 7 days (37.8 MPa), 28 days (53.4 MPa), and 90 days (58.9 MPa). The increase in the residual compressive strength of M2 mix at 28 days was approximately 15.8% higher than the control mix. The better acid resistance was achieved because of lower connectivity of pores, densification of matrix, and higher pozzolanic reaction of glass powder, minimizing the entry of acidic ions into concrete matrix.

Table 4.3: Weight Loss after Acid Exposure

Concrete Mix	Weight Loss after Acid Exposure (%)		
	7 days	14 days	28 days
CM	4.92	6.84	8.31
M1	4.18	5.73	7.04
M2	3.46	4.68	5.89
M3	3.72	5.02	6.21
M4	4.71	6.31	7.96

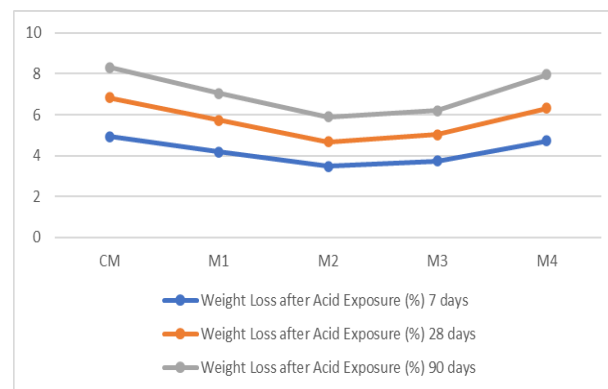


Chart -4: Acid Resistance Chart

4.5 Micro structural Analysis

SEM studies on the optimal concrete mix showed a denser microstructure than the control concrete mix. Lower porosity and fewer micro-cracks were found in glass-containing samples due to enhanced hydration properties and filling effect of fine glass powder.

XRD analysis confirmed the lower amount of peaks of calcium hydroxide and higher amounts of hydration compounds formed in the optimal concrete mix. The results proved the development of pozzolanic reaction caused by

glass powder addition. FTIR analysis proved the better performance of silicate hydration products.

5. CONCLUSION

This study demonstrates that the incorporation of glass powder and glass sand improves the mechanical and durability performance of M50 high-strength concrete. The optimum performance was achieved at 10% glass powder and 20% glass sand replacement. The major conclusions are as follows:

1. Compressive strength increased by approximately 11.8% at optimum replacement due to improved particle packing and pozzolanic reaction.
2. Water absorption and sorptivity values decreased by nearly 20–25%, reflecting reduced pore connectivity and improved impermeability of concrete.
3. Acid and sulphate resistance tests showed higher residual compressive strength and lower deterioration under aggressive exposure conditions.
4. Microstructural analysis confirmed denser hydration products, reduced microvoids, and enhanced C-S-H gel formation in the optimized concrete mix.

The study confirms that waste glass materials can be effectively utilized for producing sustainable and durable high-strength concrete suitable for modern construction applications

6. REFERENCES

- [1] Ali, E. E., & Al-Tersawy, S. H. (2012). Recycled glass as a partial replacement for fine aggregate in self-compacting concrete. *Construction and Building Materials*, 35, 785–791.
- [2] ASTM C1585. (2020). Standard Test Method for Measurement of Rate of Absorption of Water by Hydraulic-Cement Concretes. ASTM International, West Conshohocken, PA, USA.
- [3] ASTM C642. (2013). Standard Test Method for Density, Absorption, and Voids in Hardened Concrete. ASTM International, West Conshohocken, PA, USA.
- [4] Du, H., & Tan, K. H. (2014). Waste glass powder as cement replacement in concrete. *Journal of Advanced Concrete Technology*, 12(11), 468–477.
- [5] IS 10262. (2019). Concrete Mix Proportioning – Guidelines. Bureau of Indian Standards, New Delhi, India.
- [6] IS 12269. (2013). Ordinary Portland Cement, 53 Grade – Specification. Bureau of Indian Standards, New Delhi, India.
- [7] IS 456. (2000). Plain and Reinforced Concrete – Code of Practice. Bureau of Indian Standards, New Delhi, India.
- [8] IS 516. (1959). Methods of Tests for Strength of Concrete. Bureau of Indian Standards, New Delhi, India.
- [9] IS 5816. (1999). Splitting Tensile Strength of Concrete – Method of Test. Bureau of Indian Standards, New Delhi, India.
- [10] Islam, G. M. S., Rahman, M. H., & Kazi, N. (2017). Waste glass powder as partial replacement of cement for sustainable concrete practice. *International Journal of Sustainable Built Environment*, 6(1), 37–44.
- [11] Mehta, P. K., & Monteiro, P. J. M. (2014). *Concrete: Microstructure, Properties, and Materials*. McGraw-Hill Education.
- [12] Park, S. B., Lee, B. C., & Kim, J. H. (2004). Studies on mechanical properties of concrete containing waste glass aggregate. *Cement and Concrete Research*, 34(12), 2181–2189.
- [13] Rajabipour, F., Maraghechi, H., & Fischer, G. (2010). Investigating the alkali-silica reaction of recycled glass aggregates in concrete materials. *Journal of Materials in Civil Engineering*, 22(12), 1201–1208.
- [14] Shao, Y., Lefort, T., Moras, S., & Rodriguez, D. (2000). Studies on concrete containing ground waste glass. *Cement and Concrete Research*, 30(1), 91–100.
- [15] Shi, C., & Zheng, K. (2007). A review on the use of waste glasses in the production of cement and concrete. *Resources, Conservation and Recycling*, 52(2), 234–247.
- [16] Tamanna, N., Tuladhar, R., & Sivakugan, N. (2020). Performance of recycled waste glass sand as partial replacement of sand in concrete. *Construction and Building Materials*, 239, 117804.
- [17] Wang, H. Y., & Huang, W. L. (2018). Durability properties of concrete containing waste glass powder and aggregate. *Construction and Building Materials*, 171, 1–10.
- [18] Zhang, L. (2013). Production of bricks from waste materials – A review. *Construction and Building Materials*, 47, 643–655.

- [19] ASTM C1202. (2019). Standard Test Method for Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration. ASTM International, West Conshohocken, PA, USA.
- [20] IS 2386 (Part III). (1963). Methods of Test for Aggregates for Concrete. Bureau of Indian Standards, New Delhi, India.