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PERFORMANCE ASSESSMENT AND STATISTICAL ANALYSIS OF CONCRETE MIXES INCORPORATING GLASS WASTE POWDER

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A B S T R A C T

Worldwide, annual glass waste production surpasses 200 million tonnes, urging exploration of sustainable reuse avenues. This study evaluates the incorporation of waste glass powder (WGP) into concrete as a partial replacement for fine aggregate. Thirty concrete mixes, varying water-cement ratios and WGP levels, underwent comprehensive analysis. Findings reveal that as WGP percentage in sand increases, the slump of concrete rises marginally until reaching maximum glass powder replacement, with workability remaining within the 50 to 100 mm range. At a 10% replacement level, early and later age strength minimally impacts compressive strength. WGP's workability and strength hinge on particle geometry, indicating increased concrete strength when mixed with WGP featuring higher surface area and improved cement paste bonding. To enhance solid waste management, conserve sand, and bolster sustainability, WGP can replace up to 10% of sand weight in concrete at lower water-cement ratios. Positive correlation exists between slump and WGP percentage replaced. Both water-cement ratio and replacement amount significantly influence compressive strength, as confirmed by ANOVA. However, long-term mechanical strength and durability research is essential before recommending WGP for environmentally friendly and sustainable concrete applications, promising increased understanding through additional data collection and analysis.

1. INTRODUCTION

Infrastructure development is essential for a country's rapid economic growth and reduction of poverty. Industrialised nations have made significant investments in infrastructure, which is primarily made of reinforced or prestressed concrete. For many years, buildings, roads, bridges, and other structures have all been constructed using concrete. Concrete constructions have outlasted many civilisations and have withstood wars and natural disasters. In addition to its durability and strength, concrete is a fundamental construction component due to its affordability and ease of production. Every year, 30 billion tonnes of concrete are employed globally, which makes it the second most consumed material worldwide, right next to water. (Hamada et al, 2022; Sadek et al., 2016) It is the most extensively employed man-made material on the planet, and its demand is growing more steeply than that of any other construction material.

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Concrete is a composite material, mainly composed of Portland cement, different sizes of aggregates, water and admixtures. When these substances are combined, a workable paste forms that gradually solidifies over time. Consequently, the use of naturally deposited concrete resources has increased, making concrete one of the significant contributors to the carbon footprint of most structures and infrastructure assets. However, it stands as one of the most effective and suitable measures to swiftly reduce the carbon footprint embedded within the product.

The production of more environmentally friendly concrete mixtures has the potential to substantially cut down on the carbon footprint left by the construction industry. Materials such as ground granulated blast furnace slag (GGBFS), glass fibre, pulverised fuel ash, flyash (FA), GWP, stone waste, etc. can be used to reduce the carbon footprint of a concrete mixture (Santhosh et al., 2021; Taji et al., 2019; York & Europe, 2021; Jain et al., 2016).

Every year, more than 4.1 billion tonnes (2022) of Portland cement, more than 10 billion tonnes of fine and coarse aggregate, and more than 1.5 billion tonnes of water are used to build homes, dams, and other structures, which contribute significantly to global warming. As per various reports, the production of cement is responsible for 8% of all global greenhouse gas emissions. The primary cause of these emissions is the burning of fossil fuels to create electricity and fuel for cement kilns. Coal-fired power plants are required to produce cement. Hazardous pollutants such as SOx, NOx, mercury, and particulate matter are released by coal-fired power plants. The production of cement requires huge amounts of water. In fact, the amount of water consumed in producing 1 tonne of cement is equivalent to the weight of 2.5 tonnes of water. This means that each tonne of cement produced uses approximately 10,000 gallons of fresh water. Most of the concrete is made up of relatively inert filler materials called aggregates, which are expected to have an impact on the material's properties since they make up 68 to 85% of the concrete.

For all the reasons cited above, there is a huge demand to make concrete a sustainable material. As a result, using leftover by-products and wastes in construction materials as concrete substitutes is an attractive alternative to disposal and an environmentally friendly solution to the challenges of overuse and scarcity of non-renewable natural resources worldwide. However, the right kind of aggregate is necessary for cement concrete to perform its intended function. The natural river sand is the most common choice for the primary aggregate component in cement concrete. However, if the wrong sand is selected, the final product may have poor strength and durability.

In India, millions of tonnes of waste glass are produced annually. One effective way to prevent the waste glass from ending up in landfills and reducing pollution is to use it in concrete. Utilising WGP can help reduce the use of natural resources and the emission of greenhouse gases. WGP is a type of waste produced by manufacturing, commercial, and residential sectors. WGP comprises silica, alumina, iron oxide, calcium carbonate, sodium chloride, and water. It may be used as a substitute for natural river sand in concrete production. With properties like high density, low cost, non-toxic and environmentally friendly, WGP has become a popular choice for researchers to use this material in concrete. WGP is helpful because using it will save money, cut down on pollution, and make the environment better as a whole.

Most of the earlier studies analysed the properties of concrete made from waste and compared them to those of traditional concrete control samples by using simple tables and linear regression plots. The current research on using statistical equations to predict concrete properties is centred on studying individual variables. Statistical analysis is data exploration, collection, and interpretation to discover patterns and trends. It can be used for a variety of purposes, including identifying opportunities, research interpretations, statistical modelling, and designing surveys and studies. In this study, the authors aim to determine the significance of the GWP, fine aggregate, and water-cement ratio on the results of experimental tests. For this purpose, a general linear model for analysis of variance (ANOVA) and a Linear Regression model was adopted to investigate the interaction between the parameters and how each variable affects the others.

2. LITERATURE REVIEW

Aggregate mining activities can potentially modify the physical attributes of river currents, including channel configuration, bed height, composition of the substrate, and overall stability. These alterations can have notable adverse repercussions on the surrounding environment. (Ahmad et al., 2014)

Glass comprises a diverse array of chemical constituents, with silica (SiO_2), calcium oxide (CaO), magnesium oxide (MgO), and aluminium dioxide (Al_2O_3) being the most prevalent. Additionally, sodium fluoride (Na_2O) is also a minor constituent (Zulkarnain et al., 2020). It possesses desirable attributes similar to fine-grained materials, including strength, impermeability, inertness, and optical transparency; glass has emerged as a highly sought-after and adaptable substance in construction endeavours and various commercial items. Even though there is a possibility of complete glass recycling, challenges persist in achieving the requisite quality benchmarks for glass remanufacturing. Consequently, the portion that eludes recycling is often downgraded to landfills. The global annual estimate for glass landfill deposition hovers around 200 million tonnes, with recycling rates significantly suboptimal in countries like India and the United States, thus posing considerable environmental hazards. An avenue for addressing this difficulty involves reusing waste glass as a raw material for concrete production. Through the careful crushing and categorisation of appropriately sized waste glass remains, they can be transformed into aggregates, such as sand, or even utilised as pozzolanic materials for cement-based concrete. Notably, owing to its mass composition of 70% SiO_2, waste glass has the potential to deliver equivalent or superior performance to traditional aggregates (Liu et al., 2022 & Paul et al., 2022). This endeavour represents just one side of the broader initiative to harness waste materials for sustainable construction practices.

Chaudhary et al. carried out research on the utilisation of glass waste as a partial sand filler with a variation of the percentage that was equal to 8% of the volume of sand. When compared to regular concrete, they found that concrete with glass waste had a compressive strength increase of 8.12% at 14 days of concrete age. Compressive strength increased by 6.39% over the typical concrete at the age of 28 days.

Mani et al. found that the 1-day compressive strength decreased by 8%, and the 28-day compressive strength decreased by 11% when the recycled glass content increased to 40% in the concrete. They claimed that the smooth surface of recycled glass, which was also dense, caused this decrease in compressive strength by reducing the interfacial bond strength when it was used as fine aggregate particles. The poor gradation of waste glass negatively impacted the aggregate distribution's homogeneity.

Optimising a concrete mixture design involves seeking a blend that minimises ingredient costs while still upholding concrete performance benchmarks like workability, strength, and durability. Concrete's essential constituents can be divided into cement paste and aggregates. Aggregate properties influence the amount of cement paste required to attain the desired concrete quality, although the water/cement ratio remains the primary factor dictating cement paste quality. These attributes mainly encompass aggregate surface area and voids. Surface area is primarily governed by aggregate shape and maximum size, while the distribution of aggregate particle sizes predominantly affects void content. Various methodologies have been employed in the past to enhance concrete mix designs, including wholly empirical, entirely analytical, partially empirical, and statistical techniques.

Principal Component Analysis (PCA), as explored by Deepika, Mani et al., Kobaka et al., and Chawla (2020), along with ANOVA, as studied by Ahmad & Alghamdi (2014), and the utilisation of artificial neural networks, are commonly employed techniques in the creation of an optimal mix design for both traditional and waste-incorporating concrete. Opting for statistical methodologies over entirely empirical approaches is favoured due to their capacity to establish trial batches covering a spectrum of proportions for each mixture component. This stands as an advancement from the conventional practice of selecting a single initial mix ratio and iteratively refining it through trial and error. After this, the procedure advances to the execution of trial batches, their production, evaluation of test specimens, and interpretation of results through established statistical means. Among these techniques, one can be applied to fit empirical models for individual performance criteria. In the investigation conducted by Choudhary et al. (2021), the researchers adopted a general linear model for variance analysis (ANOVA) to assess the influence of marble waste slurry and coal-based fly ash on experimental outcomes (Leite & Lima, 2021).

3. MATERIALS AND METHODOLOGY

3.1 Material

All materials utilised in this study were locally sourced from Udaipur City and neighbouring industries and localities. The research was conducted using Fly Ash-based Portland Pozzolana Cement. The cement that was utilised had no lumps, and measures were taken to ensure that it did not absorb any moisture while it was being stored. The coarse aggregates confirming IS:383-2016, 2016 were procured from the local supplier. The locally available river sand was procured that passed through a 4.75 mm sieve as per IS: 383-2016 was used to create the fine aggregate for this study (IS:383- 2016, 2016). The specific gravity test and particle size distribution using sieve analysis were conducted according to the standard testing method. Bottles from local urban areas that had been collected were used to make glass powder. Green drink bottles were cleaned, dried, and then crushed in a ball mill. Various physical property tests were conducted on the aggregates used in this experimental analysis using the standard testing procedure, and the results are illustrated in Table 1.

Table 1. Coarse Aggregate, Fine Aggregate and Waste Glass Powder (WGP) Properties

Properties	Basalt aggregate	Sand	WGP
Specific gravity	2.70	2.63	2.59
Aggregate crushing value, %	23	-	-
Aggregate impact value, %	13	-	-
Water absorption, %	0.6	1.1	0.5
Particle size, mm	4.75–20 mm	<4.75 mm	<4.75 mm
Grade	-	II	I

3.2 Preparation of Specimen

Two types of plain concrete mixes were prepared for the study by using weigh batching method. The ingredients were mixed in the proportion of 1:2:4 (cement: fine aggregate: coarse aggregate) using a concrete mixer. Cubical moulds were cast for compressive strength testing. Soon after casting, they were kept at room temperature for 24 hours for drying. The first mixture was a control mix prepared using Portland Pozzolana Cement, coarse aggregate, and fine aggregate at three water binder ratios of 0.5, 0.45 and 0.40. Another type of mix was the replacement mixes, prepared by replacing fine aggregate with 5%, 10%, 15% and 20% of glass powder at all three water binder ratios.

3.3 Laboratory Testing

The workability of freshly made concrete was measured by slump cone test as per IS 1199:1959 (IS 1199, 1959). A compressive strength test was performed in accordance with IS 516:1959 (IS 516, 1959). At 7 and 28 days of maturity, 100 mm cubes were cast and tested on a 2000 kN compression testing machine.

3.4 Statistical Analysis/ Testing

To thoroughly examine the effect of replacement on concrete's compressive strength in relation to variations in the water-cement ratio, a two-way ANOVA analysis was conducted involving the water-cement ratio, percentage replacement, and compressive strength of the replacement mixes. All experimental data collected in the laboratory were meticulously analysed using OriginPro 2022b software. This comprehensive analysis provides a deeper understanding of the interplay between these key factors and their impact on concrete performance.

4. RESULTS AND DISCUSSION

The workability of the concrete exhibited a slight improvement with the increase in glass powder replacement, reaching up to 20% replacement levels, as illustrated in Figure 1.

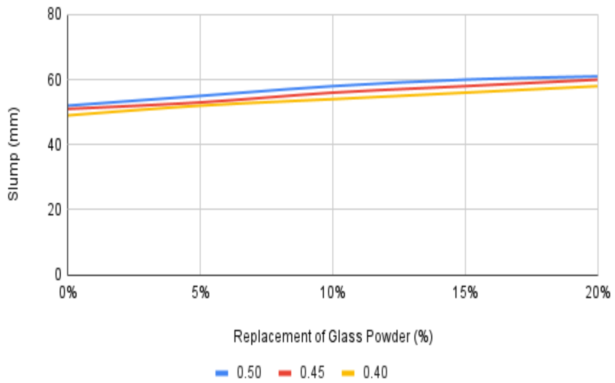
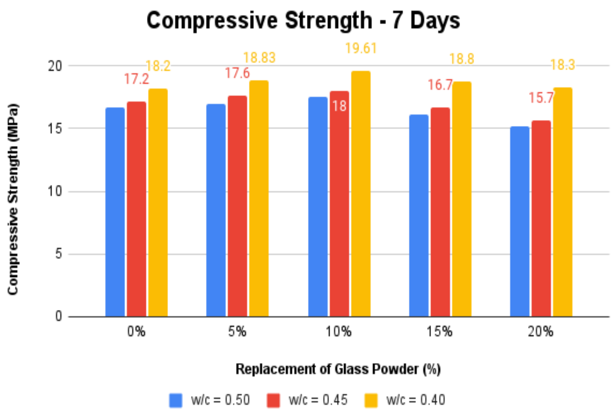
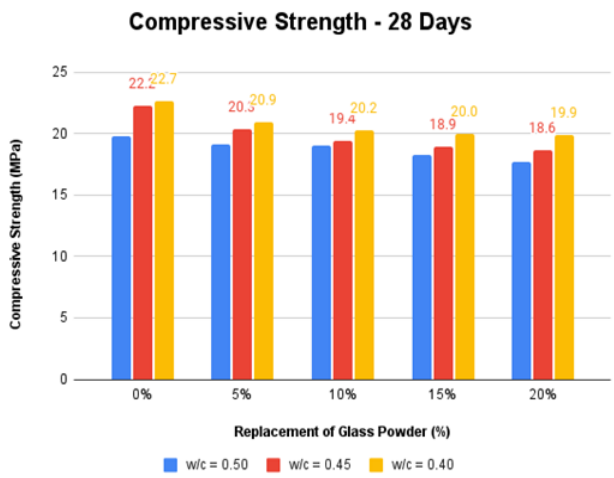


Figure 1. Workability of the mix: Slump (mm)

The variation in compressive strength between control concrete and WGP based concrete for curing times of 7-days and 28-days is evident, as shown in fig. 2. The findings show that using glass powder in place of natural sand improved the compressive strength of the concrete during the early stages of curing when compared to the control mixes of all water-cement ratios. The study revealed that the compressive strength experienced a decline as the replacement percentage increased, particularly noticeable at 28 days of curing.



(a)



(b)

Figure 2. (a) 7-Days and (b) 28-Days of Compressive Strength at the different water-cement ratios

Based on the F- ratios obtained from the analysis, it was observed that the water-cement ratio and percentage replacement significantly affected the compressive strength of the WGP-based concrete mixes.

Additionally, it was seen that the interaction between the replacement level and water-cement ratio was also significant, as shown in Fig. 3, ascertaining the fact that the introduction of the Glass powder greatly altered the overall configuration of the mix. Moreover, a linear regression analysis was performed between the two variables to investigate the influence of replacement percentage on the workability of the concrete mixes. The examination of slump values resulted in a correlation coefficient of 0.904, indicating a strong direct correlation between workability and the percentage of replacement, as depicted in Fig. 4. This finding highlights the notable impact of the replacement material on the concrete's flow properties.

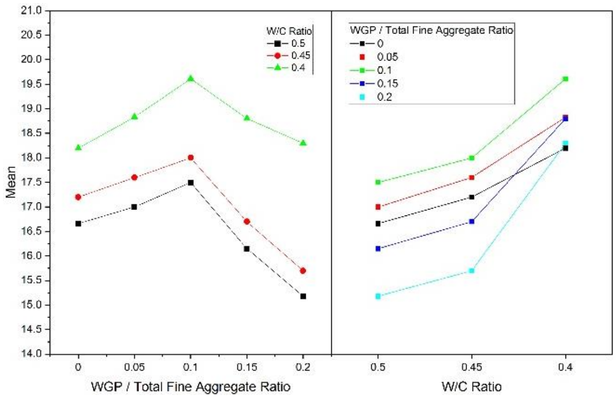


Figure 3. Interaction plots between Water-cement ratio and percentage replacement for 7-day compressive strength of the replacement mixes.

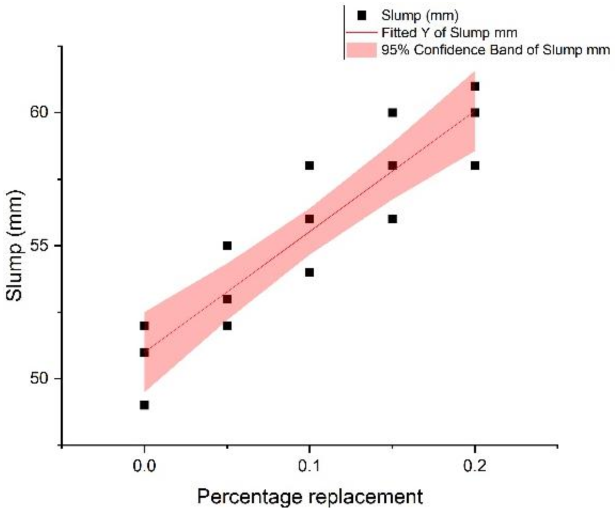


Figure 4. Slump v/s percentage replacement plot for the replacement mixes

5. CONCLUSION

The following conclusions can be drawn from this experimental and statistical analysis:

- As the replacement percentage of WGP in sand increases, the slump of newly produced concrete specimens increases marginally until the replacement percentage of glass powder reaches its maximum. However, the workability remains within the medium range of 50 to 100 mm.
- At a 10% replacement level, early and later age strength values have the smallest detrimental effect on compressive strength.
- Glass waste powder's workability and strength are dependent on particle geometry. The strength of the sustainable concrete produced will increase if it is mixed with WGP with a higher surface area and bonds better with cement paste.
- To improve solid waste management, conserve sand, and make concrete more sustainable, glass waste powder can replace up to ten per cent of the weight of sand in concrete at lower water-cement ratios.
- A positive direct correlation exists between a slump and the percentage of glass powder being replaced.
- According to an ANOVA, both the water significantly impacted the compressive strength of the replacement mixes to cement ratio and the amount of replacement.

However, additional research on the long-term mechanical strength and durability parameters of concrete made with WGP is required before this material can be recommended for use in environmentally friendly and sustainable concrete. Performing further research will result in the collection of additional data, which will, in turn, increase the probability that the data obtained contains beneficial information that can be interpreted and analysed. Past studies have shown that large amounts of data can lead to lower estimation variance and, improved prediction accuracy and useful correlation.

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