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Experimental Investigation of OPC Concrete with Incorporation of Glass Powder as Partial Substituent Material

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Abstract

This study presents an experimental survey aimed at evaluating the viability of incorporating glass powder (GP) as a partial substitute for cement in concrete matrix. The research focuses on assessing the effect of this sustainable alternative in concrete by investigating the various properties of fresh concrete such as workability, mechanical and durability aspects. Specimens were prepared with GP replacement to cement at 5%, 10%, 15%, and 20% levels, with comparative analyses conducted against conventional concrete. Fresh concrete properties, including workability, were examined to understand the initial behaviour of mix proportions. Mechanical characteristics, such as compressive, tensile, and flexural strengths, were evaluated at ages of 7, 28, and 56 days to determine the long-term performance of the concrete. Additionally, durable characteristics, such as water permeability, water absorption and rapid chloride permeability test (RCPT), were assessed to understand the concrete's resistance to environmental factors. The results indicated that the incorporation of glass powder led to variations in fresh concrete properties, with workability decreasing as the replacement level increased. However, the mechanical strengths of concrete showed promising trends, with certain replacement percentages exhibiting comparable or even superior performance to conventional concrete. Notably, at a 10% replacement level, the concrete demonstrated optimal mechanical properties. The durability assessments exposed that glass powder replacement influenced the concrete's resistance to water absorption and permeability. Generally, as the replacement level increased, improvements in durability were observed, indicating the potential for enhancing concrete's resistance to environmental degradation.

Keywords: Glass powder, compressive strength, durability, rapid chloride permeability, environmental degradation.

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INTRODUCTION

The advent of supplementary cementitious materials (SCMs) signified a remarkable advancement in the realm of concrete technology through the provision of substitutes or additives to Portland cement. SCMs, originating from by-products of various industrial processes, when incorporated into concrete, diminish the necessity for cement, resulting in environmental advantages and cost-effectiveness [1,2,3]. Prior to the extensive adoption of SCMs, concrete was heavily reliant on Portland cement as its principal binding element. Although Portland cement contributes to the robustness and longevity of concrete, it faces constraints such as excessive heat generation during solidification, vulnerability to cracking, and environmental repercussions linked to the substantial release of CO2 during its manufacturing process [2,3]. Nonetheless, research and development initiatives have yielded optimized mixture compositions where SCMs are included to meet performance criteria. The guidelines and suggestions pertaining to the incorporation of SCMs in concrete blends have advanced, providing engineers and concrete producers with guidance on dosage restrictions, performance criteria, and evaluation methodologies. Presently, SCMs have garnered widespread approval and are seamlessly integrated into concrete formulations to meet requirements related to performance, sustainability, and environmental directives. These materials play a pivotal role in the improvement of high-quality, enduring concrete customized for a variety of applications, including in infrastructure, buildings, and transportation systems [4]. The SCMs such as fly ash, silica fume (SF), slag, and metakaolin are commonly utilized in enhancing diverse characteristics of concrete. The impact of these materials on concrete performance varies based on the specific SCM used, the amount added, and the properties of the concrete mixture [5]. One such practice involves the integration of GP as a partial alternative for cement at varying proportions. Glass finds its primary application in everyday necessities such as windows, panels, and kitchen utensils within evolving infrastructures. Once this glass reaches the end of its lifespan, it becomes obsolete; however, this discarded glass can be repurposed in various ways. One approach is to crush the glass into a fine powder, which can then serve as alternative materials for certain components in concrete [6,7,8,9]. The utilization of glass powder holds significant potential for recycling and aligns with sustainability objectives.

However, several experimental studies were surveyed in literature to understand the utility of glass powder in preparation sustainable concretes. Tahwia AM et al. [10]. aims to produce sustainable Ultra High-performance Concretes (UHPC) by lowering CO_2 emissions through substituting a large proportion of cement with recycled waste glass powder. UHPC is considered promising for reducing environmental impact due to its superior properties and reduced cement requirements, which can lower manufacturing costs and environmental harm. Seven distinct mixes have been formulated, fabricated, and assessed using different proportions of Recycled Waste Glass Powder (RWGP). The mechanical characteristics, resilience, and microstructural features of the newly created concrete have been ascertained and analyzed. The findings indicate that the mix incorporating 10 % RWGP as replacement for cement attains superior mechanical attributes across various time intervals. Nassar R et al. [11]. conducts field studies of Glass powder concrete conducted in a large-scale field practice comprising of various sectors subjected to harsh weather conditions and service load over a duration of three years. While the laboratory cured nominal and Glass powder concrete samples were assessed in compression and flexure at various concrete ages ranging from 3 days to 300 days. Test observations of the field Glass powder concrete have illustrated enhanced compressive strength, up to 57% reduction in moisture absorption and up to 61% reduction in abrasion weight loss in comparison to conventional concrete at concrete of age 300 days. The physical inspection of these practices has demonstrated no signs of deterioration or material failure during and after three years of service life of concrete. Chand G et al. [12] proposes a sustainable solution to the methodology of cement production, which is not environmentally friendly, while ensuring the high quality of the resulting concrete. The initial stage of investigation involved cement partially substituted with distinct cementitious materials like glass powder, metakaolin and silica fume (SF) at distinct percentages by weight of cement. The mechanical characteristics of concrete were explored to obtain optimum percentages for each sustainable material. Moreover, a hybrid form of concrete was proposed that contains cement, glass powder, metakaolin, silica fume (SF). The CS results of this hybrid concrete show an increment by 13.42% contrast to conventional at 28 days of concrete age. Muhedin DA et al. [13] investigates the mechanical characteristics of concrete that contains waste glass powder (WGP) as partial substitution of cement and sand. Tests were executed to verify the mechanical characteristics of concrete such as CS and split tensile strength with different percentages like 0, 5, 10, 15 and 20 partial substitutes for cement and sand separately by WGP after 7, 28, 60 and 90 days of curing. Later, these replacement concretes were evaluated by scanning electron microscopy (SEM) and X-ray diffractometry (XRD) to recognize the effect of WGP on the microstructure of concrete. The experimental findings indicated that the CS of concrete can be significantly enhanced at 7, 28, 60, and 90 days by incorporating WGP as a alternative

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for cement at levels of 5%, 10%, and 15%. This proportion is deemed appropriate for the development of durable concrete. However, higher replacement rates led to a decline in compressive strength. Ibrahim KIM [14] investigates the effectiveness in use of WGP as partial substitution for cement in ordinary and other concretes possessing SF and Pulverized Fly Ash (PFA). The investigation involved the study mechanical and other characteristics of these concretes at both hardened and fresh stages, employed with WGP for replacement percentages of 0, 5, 10,15 and 20 by cement weight. The results showed that the use of 5% WGP ratio has shown increment values in compressive and tensile strengths of ordinary concrete by 8% and 13%, respectively when compared to the concrete with no glass powder. Whereas for concretes containing Silica Fume (SF) and Fly Ash (FA) at all mix ratios of WGP replacement, the compressive and tensile strengths have shown decrement values contrast to conventional concrete. This decrement was around 13% to 14% respectively at 20% WGP replacement. Furthermore, the Mass and water absorption of ordinary, Silica Fume, Fly Ash concretes with 5 to 20% WGP proportions as partial replacement for cement exhibited a decrement in comparison to conventional concrete with no glass powder.

Moreover, the review of the following above literature on GP concrete, this research aims to experimentally investigate the practicality of incorporating GP as a partial substitute for cement in concrete mixtures. The study primarily objectives to assess various properties of fresh concrete such as workability, mechanical, and durable characteristics of the replacement concretes. Initially, the investigation commends with proposal of the replacing percentages of GP with cement in weight at 0,5, 10, 15, 20. The chemical and physical properties of materials utilized for experimental investigation were discussed in Section 2.

MATERIALS

Cement

Cement serves as the binding agent in concrete, mortar, and other construction materials, providing durability and strength to structures. It primarily consists of four main components: limestone, clay, gypsum, and additives. Limestone and clay serve as the primary sources of calcium and silica, essential for cement's binding properties. Gypsum regulates the setting time of cement, while the additives such as FA or slag enhance specific properties like strength or workability [15,16,17]. However, the present study was employed with OPC 53 grade cement during cast of concrete specimens. The physical and chemical properties of cement are shown in Table 1&2.

Fine Aggregate

Fine aggregates, referred to as sand, are essential elements in concrete mixtures as they serve to fill the gaps between coarse aggregates and cement paste. Factors such as their particle size distribution, and surface characteristics have a significant impact on the fresh and hardened properties of concrete, rendering them a crucial aspect to consider in the formulation of mixes. Understanding these characteristics enables engineers to select suitable aggregates and optimize concrete performance. However, fine aggregate utilized for current experiment was resourced river sand graded at Zone-II and was passed from 4.75mm sieve. The physical properties are displayed in Table 1.

Coarse Aggregate

Coarse aggregates, typically consisting of gravel, crushed stone, form the skeleton of concrete, add volume and stability to the mix. Their particle size distribution, shape, and surface texture have a notable impact on the workability and mechanical characteristics of concrete, making them a critical component in construction. The maximum size of coarse aggregate adopted for experimental study was 20mm at 60% in proportion and the remaining 40% were in 10-12mm size with specific gravity of 2.65. However, the physical properties of this coarse aggregate were illustrated in Table 1.

Glass Powder (GP)

The expansion of the need for sustainable alternative materials has sparked encouragement in the application of industrial by-products, such as glass powder, in the fabrication of concrete. Being a waste-derived substance, glass powder presents an eco-friendly option to conventional cementitious materials while also helping to reduce waste generation and preserve natural resources [8,9]. Glass powder, derived from the crushing and milling of discarded glass, being amorphous and containing relatively large quantities of silicon, displays pozzolanic and hydraulic attributes that are beneficial for concrete construction. The chemical composition, size distribution of particles, surface properties, and reactivity of GP impact on its performance as a cementitious material and its compatibility with concrete blends. Introducing glass powder as a partial substitute for cement in concrete mixtures can result in various advantages and effects on concrete qualities. These advantages encompass enhancements in workability, compressive strength, and longevity [18,19,20]. However, the optimal replacement level and concrete performance depend on factors such as glass powder fineness, dosage, and curing conditions. The current experimental investigation utilizes this GP as replacement for cement at percentages of 5, 10, 15, 20. The physical and chemical characteristics of GP are demonstrated in Table 1&2.

Chemical Admixture

In this investigation a Polycarboxylate Ether (PCE) based chemical admixture, Hi-FORZA at 1% by weight of cement was used. It functions as an accelerator, to enhance the quality of concrete while helping to avoid air entraining, shrinkage, and water reduction.

EXPERIMENTAL INVESTIGATION

Mix Details and Preparation of Trail Mix Specimens

The following experiment was conducted with five different proposed mix proportions, having cement replacement with GP at varying percentages of 0%, 5%, 10%, 15%,20% respectively. The conventional concrete ranked with N1 mix ID has 0% GP for replacement. Whereas mix proportions from G1 to G4 mix IDs have GP replacement percentages of 5, 10, 15, 20 respectively. The mix ratios relating to the proposed mix proportions were illustrated in Table 3.

The constituents required for various Trail mixes were carefully measured; the essential volume of water was added and blended using a tilting drum concrete mixing machine. To guarantee the consistent blending of these constituents, certain precautionary measures were employed. The samples were shaped in a steel mold and consolidated on a vibrating Table. Cube specimens measuring 150 mm × 150 mm × 150 mm were formed, specifying the maximum size for coarse aggregates up to 20 mm, for assessing CS at different stages and durability characteristics. The curing process commenced once the concrete's surface in the specimen's mold had sufficiently solidified. Initially, wet gunny bags were put over the samples for 24 hours following casting to initiate the curing process. Later, the specimens were promptly detached from the molds and submerged in water for extended curing.

Table1. Physical Properties of Materials.

S N	Materials	Specific gravity	Bulk density (kg/m^3)	Size
1	Cement	3.14	1860	90µ
2	Fine aggregate	2.70	1680	4.75(down)
3	Coarse aggregate	2.73	1345	20-10mm
4	Glass powder	3	-	0.-25µm
5	Chemical admixture	1.22	-	

Table 2. Chemical Properties of Materials.

S.N.	Chemical properties	*Chemical %*	
		Cement[11]	*Glass powder[11]*
1	SiO_2	20.25	72
2	Na_2O	0.34	11.5
3	CaO	64.5	10.5
4	Al_2O_3	6.15	8
5	MgO	2.50	1
6	K_2O	0.50	<1
7	Fe_2O_3	2.55	<1
8	LOI	2.0	0.6

Workability

The term "workability" in relation to concrete pertains to its ability to be easily manipulated, positioned, and compressed without experiencing segregation or bleeding. It plays a pivotal role in assessing the effectiveness of construction activities. In current study this fresh property of concrete, workability for the M30 conventional mix and the replacement mixes were assessed in the current investigation from the resultant slump values from the conducted slump cone test as shown Figure 1.

Mechanical Properties

Compressive strength (CS)

Compressive strength refers to the maximum compressive stress that a concrete specimen can sustain under axial loading before failure occurs. This test is frequently used to assess the concrete's mechanical characteristics. The replacement concrete's CS was ascertained by cast of cube specimens in dimensions of 150×150×150mm for each mix proportion and cured them for age intervals of 7,28, and 56days. On Completion of each curing period, all these cube specimens were experimented using Compressive testing machine (CTM) under a uniform rate of compressive load. Before the test, these concrete specimens were ensured to achieve SSD condition by drying out the moisture on concrete surfaces. The CS result variations with respect to the percentage of substitution of cement by GP and number of curing days are shown in Figure 2.

Table 3. Mix ratios for M30 concrete with Glass Powder replacement.

Mix ID	Mix proportions (C:GP: FA:CA)	w/c ratio	% of chemical admixture used
N1	1:0:1.9:3.3	0.45	1%
G1	1:0.052:1.54:2.92	0.4	1%
G2	1:0.11:1.62:3.06	0.4	1%
G3	1:0.17:1.71:3.22	0.4	1%
G4	1:0.25:1.80:3.41	0.4	1%

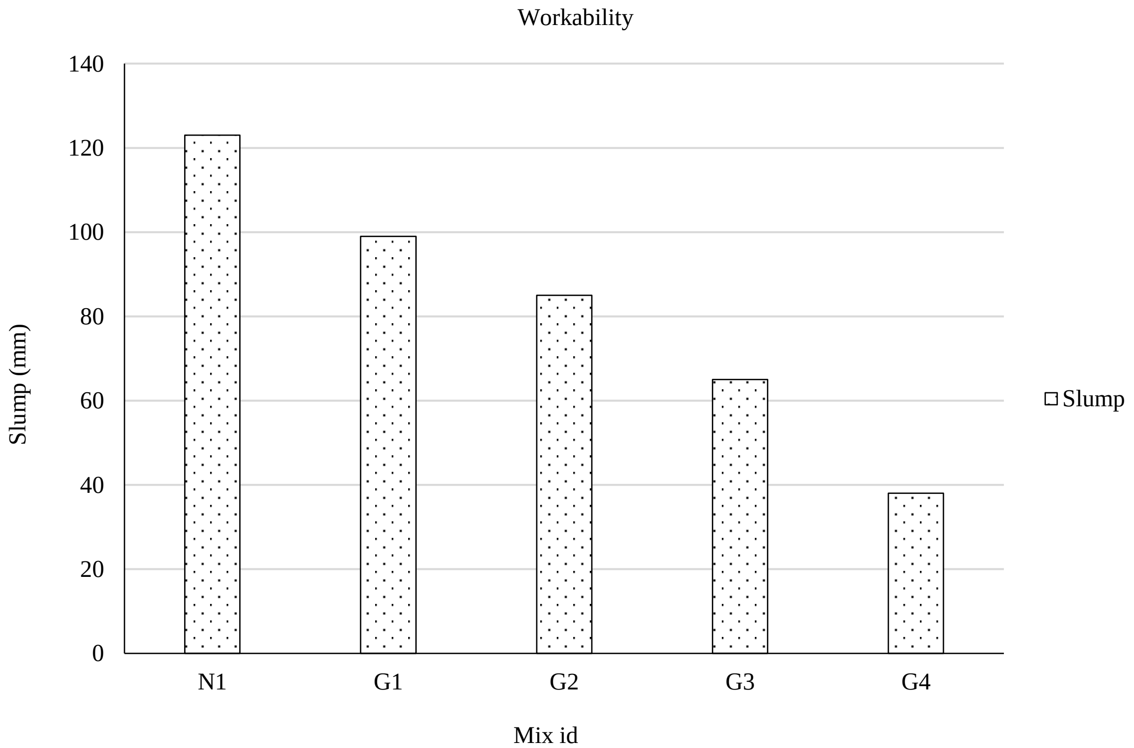

Figure 1. Comparison in workability of M30 conventional and GP concretes.

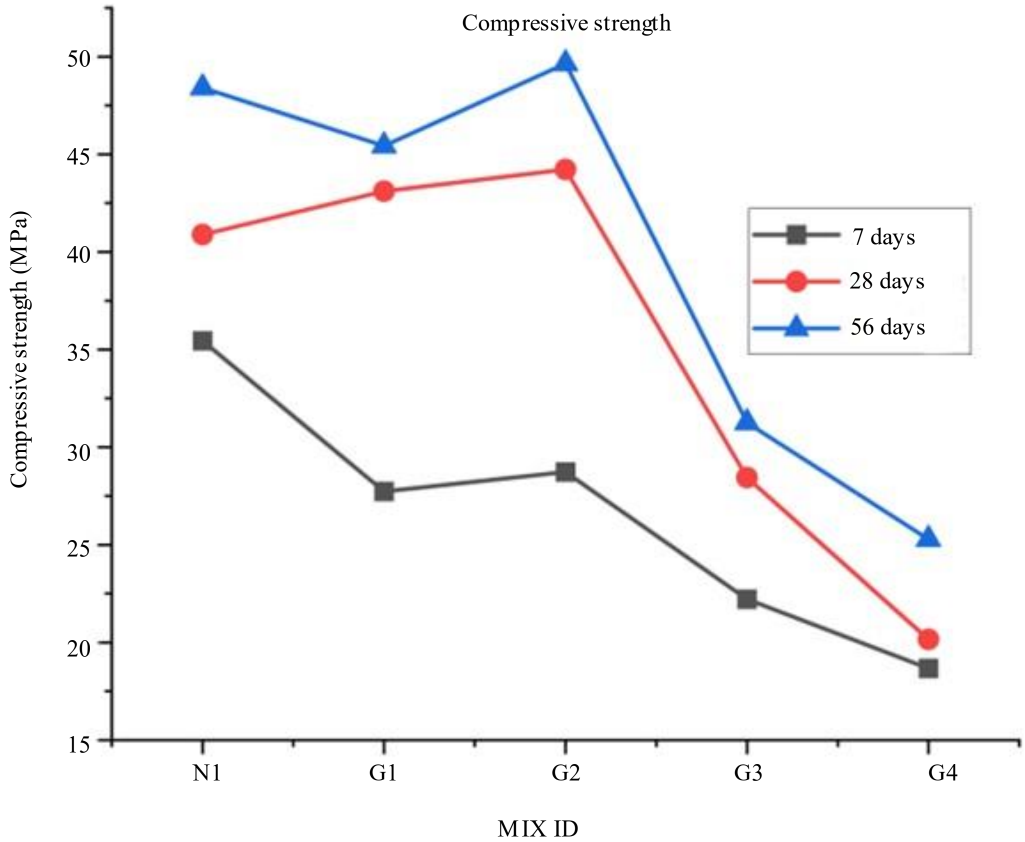

Figure 2. Comparison in compressive strength of M30 conventional and GP concretes.

Split tensile strength (STS)

The Split tensile test is one of the most significant tests which can be utilized to assess the specimens of hardened concrete's tensile strengths. The concrete cylinder with dimensions of 150mm in diameter and 300mm in height for different mix proportions corresponding to curing intervals of 7, 28, and 56 days were proposed to cast for finding out the STS of these replacement concretes. During this test, each cylindrical specimen was positioned horizontally at the compressive machine and applied with compressive loads at constant rate. The deviation in tensile strength of concretes of different mix proportions were illustrated in Figure 3.

Flexural strength

Flexural strength is the measure of concrete's resistance to flexural or bending pressures. This test is essential for assessing the structural performance of concrete elements such as beams and slabs under various loading conditions that result in bending. For experimentation the concrete prismatic concrete specimens with proposed mix proportions were cast with the specified size to calculate the flexural strength. The test involves loading each of these prismatic concrete specimens positioned over with two supports and applying a constant rate of loading until its failure. However, the variation in obtained results of flexural strength for distinct mixes are interpreted as shown in Figure 4.

Young's Modulus

Material stiffness is measured by its young's modulus, also identified as modulus of elasticity. It evaluates the relationship between stress and strain in a material that is subjected to axial loading within its elastic range. The procedure for determining Young's modulus entails applying different stress levels to concrete samples and measuring the resulting deformations, allowing engineers and scholars to precisely characterize the material's elasticity. The testing process commences by preparation of concrete specimens, ensuring their compliance with standardized dimensions. These specimens

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typically exhibit a cylindrical or prismatic shape, designed to accurately depict the performance of concrete under various loads. The concrete specimens' young's modulus can vary based on various factors such as concrete mix, curing circumstances and age of concrete. The resulting strength variation for distinct concrete mixes were displayed in Figure 5 and 6.

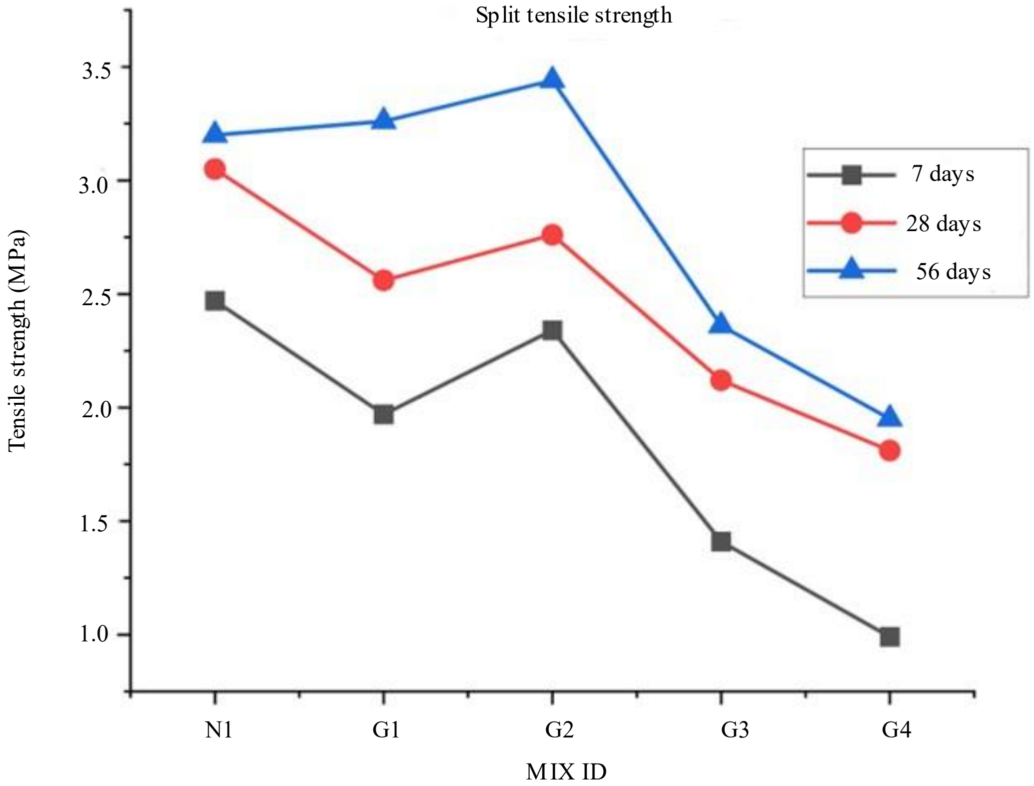

Figure 3. Comparison in tensile strength for M30 conventional and GP concretes.

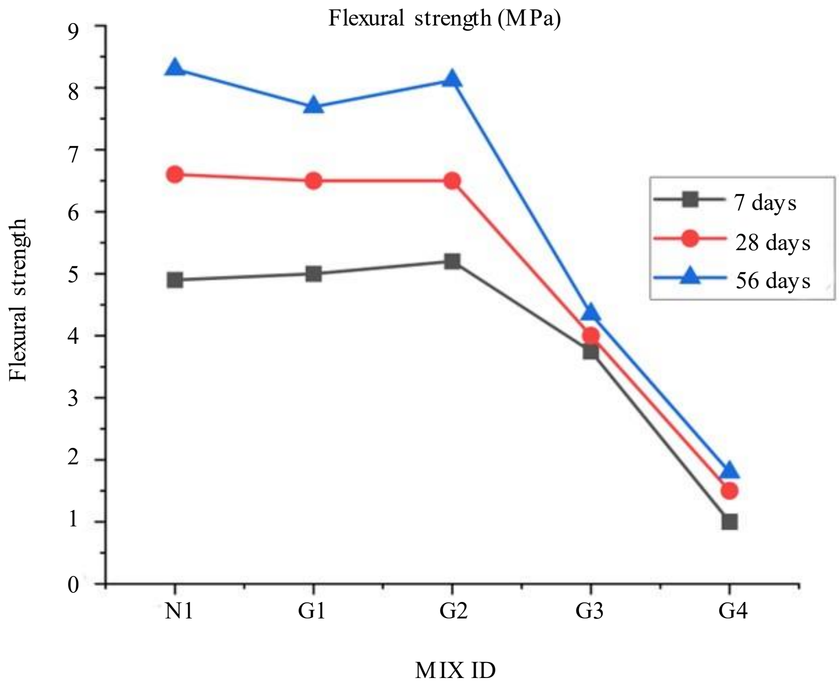

Figure 4. Comparison in flexural strength for M30 conventional and GP concretes.

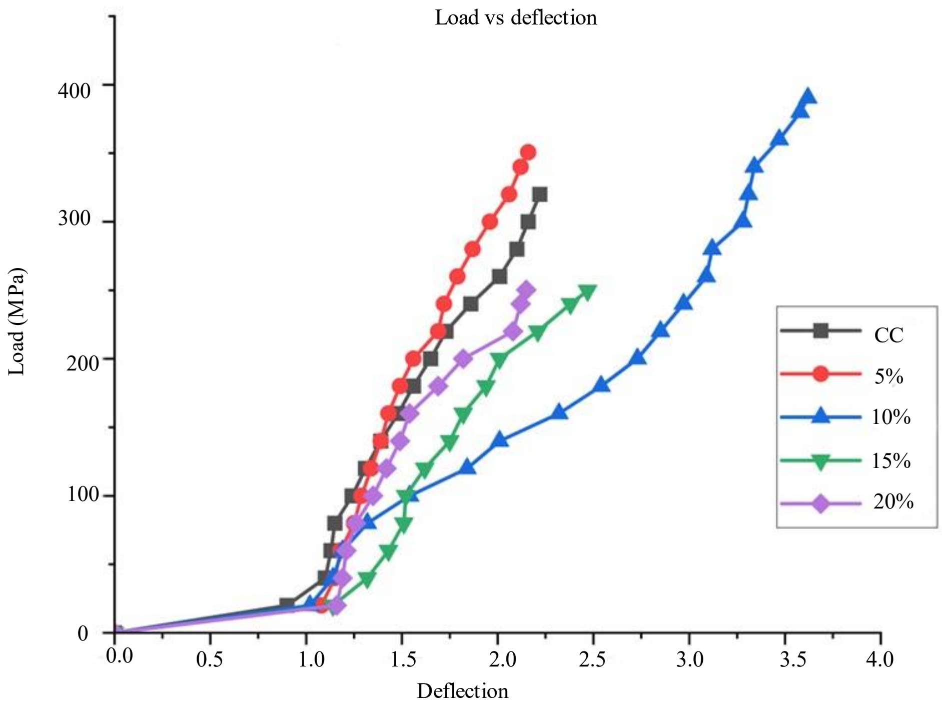

Figure 5. Comparison in Load versus Deflection curves of M30 Conventional and GP concretes.

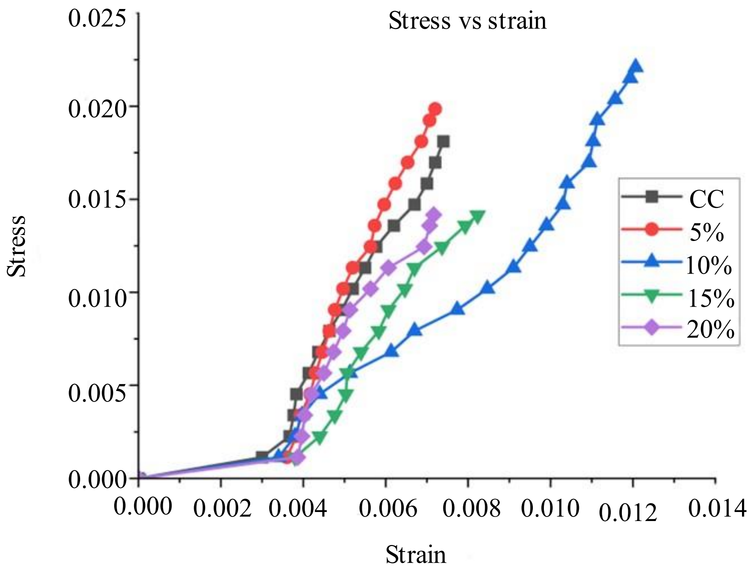

Figure 6. Comparison in Stress versus Strain curves of M30 conventional and GP concretes.

Durable Properties

Water absorption

One important characteristic of concrete that affects its performance, resilience to different climatic conditions, and longevity is water absorption. Due to its porous nature, concrete can allow water to seep in and cause several harmful consequences, including chemical erosion, freeze-thaw damage, and corrosion of the reinforcing. Ensuring the long-term durability and serviceability of concrete structures requires an understanding of the ability to control water absorption. Capillary action and pore structure are the main mechanisms via which water is absorbed in concrete. Water can enter concrete through tiny holes called capillary pores, which are affected by capillary forces. Water can also travel through

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absorption and diffusion thanks to the concrete's interconnected network of bigger pores and spaces. However, the resultant values of water absorption competence test for concretes with varying mix proportions were demonstrated in Table 4.

Water permeability

The term "water permeability" in concrete describes the water's capacity to permeate its voids, capillaries, and pores when subject to diffusion or hydraulic pressure. The probability with which water might infiltrate through concrete is determined by its pores, pore structure, connectedness, and tortuosity. These factors all affect permeability. Standardized test procedures like the ASTM C1202 [21] (Rapid chloride permeability test) and ASTM are frequently used to determine the water permeability of concrete. In this experiment, the rate of water penetration or flows through concrete samples was measured when subjected to hydraulic pressure or diffusion. The results of water permeability for different mixes were displayed in Table 5.

Table 4. Water Absorption capacity of concretes with varying mix proportions.

Mix ID	Initial weight (W_1 in kgs)	Final weight (W_2 in kgs)	Water absorption (%)
CC	8.26	8.54	3.38
G1	8.17	8.38	2.57
G2	8.12	8.46	2.92
G3	8.075	8.47	3.21
G4	7.93	8.49	3.057

Table 5. Water permeability of concrete with different mixes.

Mix ID	Water permeability at 28 days (m/sec)
CC	1.86×10^{-12}
G1	1.37×10^{-12}
G2	1.29×10^{-12}
G3	1.15×10^{-12}
G4	1.07×10^{-12}

Rapid chloride permeability test (RCPT)

The Rapid Chloride Permeability Test (RCPT) is a quick test developed to measure permeability of concrete through the rate of chloride ions passage. For this test, concrete specimens cured for 28 days are divided into two parts and enclosed within a container with a diameter of 90 mm. One section of the container is occupied by a 3% sodium chloride solution and was linked to the anode terminal of the power source, while the other section contains sodium hydroxide solution and is connected to the cathode terminal. The current flow was recorded at 30-minute intervals throughout a 6-hour duration. The charge passing through the concrete was obtained will indicate the concrete resistance to chloride permeability [21,22,23]. From the graph displayed in Figure 7, the results obtained predict that the concrete upon the increase of replacement of GP in cement. The increase in replacement percentages of GP also increases the durability property of concrete.

RESULTS AND DISCUSSIONS

The experimental work done on the concrete consisting of Glass Powder (GP) has given the following conclusions. The waste GP is an efficient supplementary material towards sustainability.

- The workability of concrete is increasing with the increase glass powder percentage in concrete.
- The mechanical characteristic of concrete is increasing up to 10% replacement of cement with glass powder and strength decreases gradually to 20%.
- Use of waste GP helps in reducing global warming and is environmentally friendly material.
- It is also determined that the increase of strength properties in concrete would alter depending on the type of glass powder used (based on chemical composition).

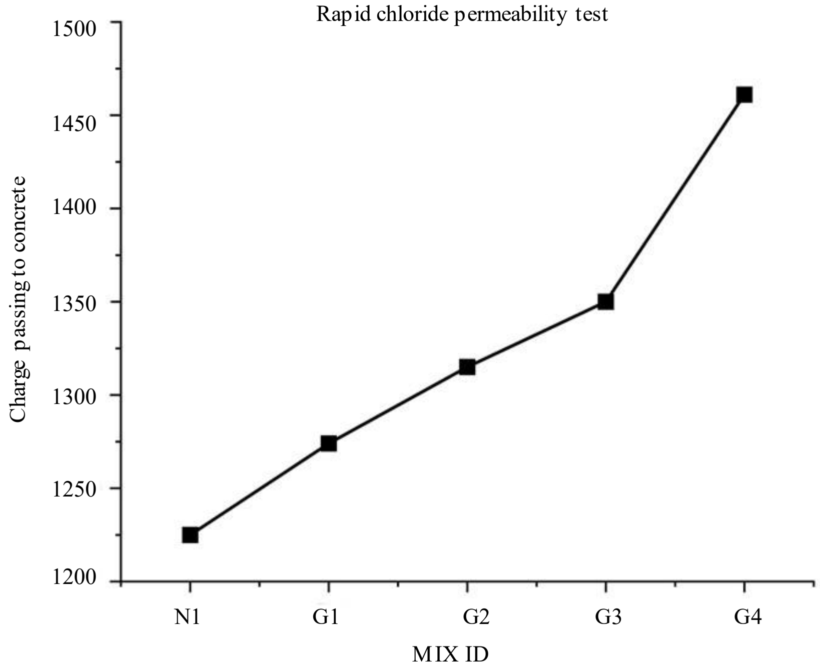

Figure 7. Comparison in RCPT results of M30 conventional and GP concretes after 28 days curing age.

CONCLUSIONS

- Glass powder can effectively replace cement at a 10% ratio without compromising the compressive and tensile strengths of the material. However, when the GP ratios increase to 15% and 20%, both CS and STS decrease. This decline is likely attributed to the exceptionally smooth texture of recycled glass powder, which can result in cracks that hinder proper adhesion between the glass powder and the cement matrix interphase.
- Substituting 10% of cement with GP in regular concrete resulted in an approximate 8% increase in CS and a 13% increase in tensile strength.

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