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Experimental study on durability of glass modified concrete: resistance to acid and sulphate attack

Mahim Mathur[1]* and R.C. Chhipa[2]
Research Scholar, Department of Civil Engineering, Suresh Gyan Vihar University, Jaipur, India[1]
RCTEWM Coordinator, Department of Chemistry, Suresh Gyan Vihar University, Jaipur, India[2]

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Abstract

Amid the pressing global issue of waste generation and its escalating environmental impact, an innovative avenue for sustainability emerges through the integration of waste glass (WG) into concrete production. By replacing conventional materials, WG not only reduces cement consumption but also capitalizes on its silica-based composition to catalyse the formation of secondary calcium-silicate-hydrates (C-S-H) via interactions with cement particles. The study encompassed varying levels of WG (2% to 10%) in concrete mixes with a consistent water-to-binder ratio, assessing key properties including compressive strength, workability, and resistance to acid and sulphate exposure. Compressive strength for individual samples were examined after 7, 28, and 90 days of curing. Resistance to acid and sulphate exposure was examined by noting change in weight and strength after immersing samples in individual solutions after 7, 28, and 90 days. Remarkably, the most favourable outcomes were achieved with a 10% cement replacement by WG, resulting in a notable enhancement of compressive strength. Furthermore, the incorporation of WG yielded augmented workability, alongside reduced water absorption and density, attributed to the creation of C-S-H gel through pozzolanic reactions. Encouragingly, the concrete specimens showcased heightened resistance to sulphate exposure over a 90-day span, indicating its potential for enduring durability. These compelling findings underscore WG as an ecologically responsible and economically viable resource, offering a sustainable solution for advancing concrete production while addressing the imperative of responsible waste management, thereby steering construction practices toward heightened environmental conscientiousness.

Keywords

C-S-H gel, Acid resistance, Sulphate resistance, Beverage glass.

1.Introduction

In recent years, the global landscape has witnessed a significant surge in industrial development, consequently amplifying the demand for construction materials and placing an increasing strain on natural resources essential for the production of raw construction materials such as sand and aggregates [1, 2]. This escalating pressure has prompted an urgent need to identify alternative materials that can supplant these resources while also serving as environmentally friendly alternatives. Notably, cement stands as a cornerstone in concrete production; however, its manufacture results in the emission of approximately 0.7 tons of carbon dioxide per ton of cement produced. This gas, recognized as a potent greenhouse gas, plays a pivotal role in driving the phenomenon of global warming.

The adverse environmental consequences linked with open land disposal of waste glass (WG) have been well-documented, encompassing ecological degradation and land consumption [3, 4]. Amidst this context, an opportunity for sustainable progress arises through the integration of WG into the production processes of cement-based products.

Prior research has explored the utility of WG as a potential substitute for cementitious materials or natural sand in the creation of concrete, necessitating comprehensive analysis of resultant concrete properties. Historical data indicates a staggering annual production of approximately 130 million tons of WG in 2005. Yet, the prevailing practice of indiscriminate WG disposal on open lands precipitates severe environmental degradation and engenders economic ramifications. Attaining sustainable construction practices hinges on judicious

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*Author for correspondence

resource management in an environmentally responsible manner. Central to the composition of concrete is cement, which concurrently is notorious for its polluting production process and the generation of greenhouse gases. A pathway towards ecological harmony entails incorporating supplementary cementitious materials (SCMs) into concrete formulations, strategically substituting traditional cement constituents [5].

In the realm of concrete engineering, durability emerges as a critical attribute, signifying the material's capacity to withstand diverse environmental conditions and external stresses across time. These encompass corrosive exposures to acids and sulphates, both capable of undermining concrete integrity, inducing deterioration. This study delves into the prospect of leveraging WG to bolster concrete durability, particularly in the context of acid and sulphate resistance. To this end, the research design encompassed rigorous testing procedures, evaluating concrete's performance under the influence of these challenging conditions [6, 7]. The empirical findings underscored the substantive enhancement of concrete's durability through WG incorporation, substantiating its superior resistance to acid and sulphate exposures relative to the control concrete mix. This underscores the promising potential of WG as a strategic enhancer of concrete's long-term performance in arduous environmental conditions.

Against this backdrop, the study aims to illuminate key aspects: (1) the introduction offers a concise overview, articulating the underlying issue, research significance, and objectives; (2) the literature review probes into the complexities and gaps identified in earlier research endeavors; (3) the material and methodology section intricately elaborates on the materials utilized and the systematic testing protocols deployed to fulfill the research objectives; (4) the results section systematically unveils the empirical outcomes derived from the conducted experiments; (5) the discussion section meticulously dissects and contextualizes the outcomes vis-à-vis pertinent phenomena and prior research; and (6) the conclusion and future work segment encapsulates the study's culminating insights, furnishing recommendations for forthcoming research trajectories. Through this comprehensive organization, the study endeavored to shed light on the pivotal intersection of WG integration, concrete durability enhancement, and sustainable construction paradigms.

2.Literature review

Many researchers have employed various waste material for partial replacement with cement and found promising positive impacts on the mechanical as well as the chemical properties of the concrete, the materials like ground granulated blast-furnace slag (GGBS), silica fume (SF), fly ash were considered in various studies. On another hand, except of above discussed materials, in the experimental studies of SCM, the WG is very less incorporated due to its lower commercial achievements, whereas, it is found to be more feasible [4]. Recycled WG is proven to be feasible for the incorporation in the preparation of the concrete. United States has been witnessed with the disposal of about 9.2 million ton of WG in year 1994 [5]. Whereas in the Hong Kong this waste disposal measure is estimated as 300 tons [6]. On a major scale the whole glass waste is nearly impossible to be recycled due to economy and other manufacturing issues, whereas, a part of this in glass production units is easily recycled. Hence, this has made the researcher to think on an alternative solution like utilisation of this in the production of the concrete. The chemical analysis of the WG has depicted the amorphous structure of the element calcium in it and large amount of the silicon were also observed in it, hence, it has the capability of pozzolanic substance and even it can act as cementitious material [7]. Hence, the utilization of the WG is incorporated in the form of aggregate or in place of cement as the partial substitution.

Partial replacement of WG for concrete preparation in place of cement as fine grinded form has more potential of environment and economy benefits with enhanced chemical reaction amid cement hydrates and WG [8]. Expansion cracks tends to deteriorate the concrete as well as tend to reduce the actual strength of the concrete prepared from the portland pozzolana cement (PPC), and this phenomenon takes place due to the alkali-silica reaction (ASR). In a broad consideration, commonly, this phenomenon takes place due to the reaction of pore alkaline solution with the silica present on aggregates that is reactive or semi reactive. The reaction propagation can be classified in to three levels: in first level, the formation of Si-OH and Si-O-R are formed due to the reaction of alkali ions (R+) and weak bond of (_Si-O-Si_) which are present in the reactive aggregates. After this, extra silica gel is formed due to the reaction of silicic acid along with the alkalis. At the last level, the expansion takes place in the concrete body since the formed gel tend to absorb the moisture from the nearby environment [9]. Hence, it can be said that, the ASR aggressiveness is highly depended on the reactive silica amount as well as on pore solution intensity level of the alkalinity.

Amin et al. [10] in his research aimed to develop environmentally friendly and cost-effective ultra-high performance concrete (UHPC) with the consideration of substituting ground waste (GW) for PPC. The study concluded that replacing 20% of PPC with GW and keeping ground substitution constant resulted in optimal mechanical properties. Increasing GW content up to 20% improved compressive strength at an interval of 7, 28, and 91 days. The highest values achieved were: compressive strength (176.3 MPa), splitting tensile strength (18 MPa), flexural strength (25.7 MPa), and modulus of elasticity (57.82 GPa) at 28 days. Higher ground substitution led to improved workability, while increasing GW reduced water permeability and drying shrinkage. These findings provide insights for producing eco-friendly UHPC with economic benefits.

Gebremichael et al. [11] in his research demonstrates the potential of utilizing crushed and GW glass has been considered for the partial replacement for cement, fine aggregate, as well as for the coarse aggregate in concrete. Improvement in durability as well as the enhancement in resistance to deterioration mechanisms has been observed in the findings of experimental investigation with incorporation of glass in the concrete mix. While the addition of glass may affect setting time and decrease certain hardened concrete properties, the study identifies optimum replacement proportions of 10% for cement, along with the 15% and 20% of the fine aggregate and coarse aggregate respectively. By carefully considering project requirements and conducting further testing, it’s use in concrete holds promise for creating sustainable and durable construction materials.

Hamada et al. [12] systematic review highlights the durability and microstructure of environmentally friendly UHPC and its potential for low-carbon production. It reveals that incorporating solid waste as replacements for binder or aggregate in UHPC maintains a dense microstructure, enhancing impermeability and resistance to carbonation and high temperatures. Properly proportioned solid waste improves UHPC performance, benefiting from the filling effect and pozzolanic activity. This eco-friendly strategy reduces carbon emissions, global warming potential, and fossil fuel usage. However, further research is needed on aggressive environments, volume stability enhancement, solid waste reactivity, innovative combinations, and multi-scale behavior of eco-friendly UHPC. Overall, this review emphasizes the feasibility of utilizing solid waste for sustainable UHPC production with enhanced durability.

Baikerika et al. [13] investigates the use of WG as a replacement for cement and fine aggregates in concrete, aiming to reduce landfill waste and promote sustainable infrastructure. The findings indicate that including glass particles enhances workability and reduces water absorption, resulting in improved concrete performance. Optimum compressive and split tensile strength are achieved with specific combinations of glass powder (GP) and sand. The use of glass particles also leads to lower dry density, reduced water absorption, and low chloride ion penetration, highlighting the impervious and low porosity nature of glass. While GP enhances the microstructure and contributes to overall concrete enhancement, poor bonding may occur at higher replacement levels, leading to microcracking. Considering the positive results obtained for mechanical and durability parameters, this research encourages the production of eco-friendly concrete using WG, effectively reducing the amount of glass waste sent to landfills.

Ahmad et al. [14] investigates in his research, WG and marble waste were used to replace binding material and fine aggregate in concrete. Workability decreased with increasing percentages of waste materials, but mechanical performance improved due to pozzolanic reaction and micro filling effects. Concrete with 20% WG and 50% waste marble showed 21% and 12% higher compressive strength than the reference. The statistical optimum of waste materials resulted in 38% higher compressive strength. The highest split tensile strength was achieved at 15% WG and 30% waste marble, 65% higher than the reference. Concrete density, water absorption, acid resistance, and dry shrinkage increased compared to the reference, but overall, utilizing waste materials in concrete is considered an eco-friendly and sustainable option, preserving natural resources.

Ahmad and Zhou [15] study focuses on utilizing WG as an ingredient in self-compacting concrete (SCC) to reduce resource consumption in construction. The review summarizes existing research on WG in SCC, highlighting benefits, mechanisms, and current progress. It examines chemical and physical properties, strength, durability, and environmental advantages. Future research directions for optimizing SCC with WG will also be assessed, promoting sustainable construction practices.

Ahmad et al. [16] research focused on sustainable concrete by partially substituting WG and rubber. WG replaced 10%, 20%, and 30% of the binder, while 20% waste rubber was used as coarse aggregate throughout. Flowability decreased with WG substitution due to increased friction. Mechanical and durability properties improved due to pozzolanic reaction, forming a denser concrete. Compressive strength peaked at 20% substitution (24% higher than reference). Acid resistance increased, but tensile strength remained weak. Further research with fibers is recommended for improved tensile capacity. Overall, WG shows promise for eco-friendly and sustainable concrete production, reducing resource depletion caused by traditional materials.

Gholampour et al. [17] paper explores geopolymer mortars with natural fiber reinforcement. The addition of fibers reduces flowability due to moisture absorption. Ramie, hemp, and bamboo fibers enhance compressive and tensile strengths, while coir, sisal, and jute fibers have a slight negative effect. Water absorption increases with fiber reinforcement, and drying shrinkage is lower in ramie, hemp, and bamboo fibers but higher in jute, coir, and sisal fibers. Certain code expressions closely predict tensile strength for specific geopolymers. The study shows promise in developing sustainable construction materials using natural fibers and waste-based materials as replacements.

Bameri et al. [18] study evaluated concrete containing SF, WG, and GGBS. The enhancement in the mechanical properties of concrete was observed when the incorporation levels were kept as 5%, 10% and 10% for the SF, GGBS and WG respectively. However, SF decreased concrete's resistance to magnesium sulfate attack. On another hand, binary mixtures containing the incorporation level as 15% each for WG and GGBS depicted the optimum resistance for this attack. Ternary mixtures exhibited high resistivity and low chloride ion penetrability, indicating no risk of reinforcement corrosion. Quality of the concrete observed with the improvement due to pozzolanic reactions and particle packing and this lead to reduce the water absorption. Overall, SF, WG, and GGBS show promise for enhancing concrete properties.

Da et al. [19] investigates the durability of concrete with WG as a partial substitute for cement. WG offers a cost-effective and environmentally friendly alternative to mitigate carbon dioxide emissions from cement manufacturing. The study aims to assess its performance compared to conventional concrete, identifying advantages for civil construction in new builds, rehabilitation, or maintenance. Durability is crucial for concrete performance, and this research explores the potential of eco-friendly concrete solutions in the construction industry.

Saeed and Singh [20] explores strategies to reduce moisture transport in concrete that leads to the enhancement of its durability. Strategies include using fly ash, SF, milled WG as partial cement replacements, and incorporating hydrophobic additives and polymer emulsion. Test results showed improved compressive strength, moisture resistance as well as the durability found to be improved in modified mixes, especially with fly ash and SF. The findings provide valuable guidelines for designing durable concrete exposed to aggressive environments.

Peng et al. [21] low-carbon and corrosion-resistant concrete was developed using recycled aggregates (RAs) as well as the waste GP. The combined utilization of RAs and GP showed promising results in terms of compressive strength, also, the characteristics like chloride penetration resistance, and steel corrosion resistance were found to be enhanced. The incorporation of GP improved the corrosion resistance of the concrete, even surpassing natural aggregate concrete. The enhancement mechanism was attributed to pore refinement and increased alkalinity due to GP's pozzolanic reaction. The GP-RA concrete system demonstrated economic benefits as well as it also imparts in betterment of ecology by reducing energy consumption, CO_2 emissions, and costs throughout the concrete's life cycle.

Hanif [22] investigates the use of organic light-emitting diode (OLED) and liquid crystal display (LCD) glass wastes as SCMs in concrete. The research shows that incorporating these waste materials enhances the concrete's mechanical strength after 28 days, improves its durability, microstructure, and overall performance. The presence of high alumina and amorphous silica in the glass wastes contributes to this positive effect through pozzolanic activity. Additionally, using LCD and OLED wastes as partial cement replacements reduces environmental burden and concrete costs, promoting sustainable development in the construction industry. Janowska-Renkas et al. [23] investigates the effects of fly ash, WP, along with this the incorporation of two types of graphene along with the hydrophilic/hydrophobic nanosilica considered to investigate electrical, physical, and mechanical properties were investigated. The composites with fly ash, graphene, and hydrophobic nanosilica exhibited excellent electrical conductivity and high strength gain, indicating their potential for advanced applications.

In recent studies, the potential of WG in manufacturing bricks and ceramics has been demonstrated [24]. The properties of concrete are influenced by factors such as pozzolans, fineness, pore solution, and the chemical composition of WG [25]. Shayan et al. conducted a study in 2006 [26] and found that WG particles smaller than 300 lm exhibit pozzolanic behavior, and even with reduced cement content, particles smaller than 100 lm display pozzolanic properties after 90 days of curing.

Many countries including India made strong restriction for such practices as a result many industries made their way to export this waste to the foreign boundaries, this ultimately creates hike in the process and also affects the economy of all operations. The ban implied on the uses of plastic has raised the demand of utensils made from glass, so as to keep food hygienic for long duration. All these factors propagate the generations of waste that is biologically non-degradable. In year 2014 a review study by Rashed [9] depicted there were not much differences in the properties like workability and hardened concrete properties like strength were not affected much compared to control mix than the mix prepared with the WG, the study concluded only the economical part of considering WG as substitute material to cement. The particle work was propagated by employing substitution to cement to prepare concrete and mortar. To investigate flow and strength the specimens of the mortar were made by following specifications of codes. For determination of the compressive strength the cube specimens were tested with compression testing machine until failure. Furthermore, opting some specimen of mortar with glass and use of superplasticizer, the specimens were assessed for the pozzolanic effect and packing. The restrictions set on the utilization of natural resources have made material scientist to find alternative material in place of these natural materials, thus, the waste utilization in production of construction material have taken prime focus, although the concrete prepared with utilization of waste material has a prime concern of durability characteristics, so as to confirm the life span of the prepared concrete [27].

The practice of utilization WG has been in commiseration for a long time, whereas, it has been also observed that mixes tend to depict formation of cracks in it [28–30]. On other hand, many researches depicts that in the production of concrete incorporation of finely grinded WG has been considered as the substitution to the key ingredient cement [31]. In some of the studies this waste has been incorporated in the form of raw siliceous material [32]. The formation of $2CaSO_4•K_2SO_4$ has been observed in the mix while the WG utilised in mix, it leads to the quick setting of the cement in the mixes and this might be due to the elevated alkali content [33]. Negative effects observed on the concrete due to the ASR, this chemical reaction takes place due to the reactivity of alkaline and silica which tend to retain the forms of metastable and these are generally found to be present in aggregates [34].

The OH- ions have a nature to propagate nucleophile attack and it tends to decompose the structure of silica, this leads to the coagulation of silica and in this form its nature become hydroscopic and it produce the ASR gel. The formation of this tend to produce crack in concrete since stress is developed due to the expansion of gel.

The cracks are formed in the concrete while the incorporation of WG is made in mixes, this might be due to the production of ASR gel that tend to propagate the silica decomposition [35]. On other hand, consideration of WG incorporation in the form of fine grinded powder as a SCM will tend to inhibit the ASR expansion [36]. This characteristic is co-related to the fact which explain it as WG particle size highly affects the phenomenon of ASR expansion, and the same has been observed in the experimental researches, hence its utilisation in the form of pozzolanic material is proved to be feasible [37]. Along with this, it was also observed that when the WG particles utilized are lesser than the size as 75 μm, then the ASR is found to be initiated in the mixes [38]. Also, particles from 1.18mm - 2.36 mm, were observed to create the propagation of ASR [39]. On the other hand, when the size of WG particles that was used in the mix preparation is lesser than 0.30 mm, then mixes do not depict ASR expansion, whereas, when the particle size taken beyond 0.60

mm, then it has been observed that ASR starts initiating in the mix [40]. Whereas, it is still an issue of technical and experimental argument about WG particle size that can be considered as critical to inhibit the side effects of ASR in mixes [41].

The literature review provides comprehensive insights into the utilization of WG in concrete production as a sustainable and environmentally friendly alternative. Various studies have investigated the potential of WG as a partial replacement for cement and fine aggregates in concrete mixes, highlighting its positive impacts on mechanical properties, durability, and sustainability. Researchers have explored different aspects, such as pozzolanic activity, particle size, and the effects of incorporating WG on ASR expansion. The findings indicate that finely GW glass can serve as a SCM inhibiting ASR expansion and enhancing concrete performance. Additionally, studies have shown that WG can be used to improve UHPC, reduce moisture transport, and enhance resistance to aggressive environments. Moreover, the potential use of WG in manufacturing bricks and ceramics has been demonstrated. While challenges such as crack formation and particle size effects have been discussed, overall, the research underscores the feasibility of WG utilization in creating sustainable and durable construction materials, with positive implications for both the environment and the economy.

3.Material and methodology

3.1Materials

Cement

The preparation of the mixes was done as per the specification of IS 10262:2009, also ordinary portland cement (OPC) 43 grade cement was utilised confirming to the specifications of IS 8112-2003 for sample preparation. The w/c ratio for preparation of mixes was kept as 0.45. Whereas, the potential of hydrogen (pH) of utilised water was confirmed to be 6.5. *Figure 1* depicts the microscopic image of cement particles. The incorporation of superplasticizer has been made in the mix preparation which was SP-431, to achieve the standard workability.

Aggregates

In this work the size range of coarse aggregate which were used for mix preparation was 10 to 20 mm, whereas the specific gravity of the utilised aggregates was as 2.66. In this work the percentage finer for the fine aggregates utilised was 99.4, and this was procured from the local market of Jaipur and material is received from Banas River, Rajasthan. the size range of fine aggregate which were used for mix preparation was 4.75 mm to 150 µm, whereas the specific gravity of the utilised aggregates was as 2.62. In this work, the 1.0 mol/L chemical reagent has been utlised and the preparation of NaOH solution has been done with the use of Na_2O.

Waste glass (WG)

WG was collected from scrap and after that crushed in desired shape and size in in industrial crusher. Before the incorporation of it in mix, the size has been discerned and it has been kept below the 75 µm. Whereas, the specific gravity of this was as 2.55. As per the IS 1727:1967, the least requisite amount of SiO_2+Al_2O_3+ Fe_2O_3 must have to be 70%, and standard composition of the requisite material in mix that is pozzolana has been observed in the sample of WG. *Figure 2* depicts the microscopic image of glass particles. Good binding is achieved in the mix when the shape of the particles is irregular along with the edges being sharp and the same has been observed in the SEM image of WG.

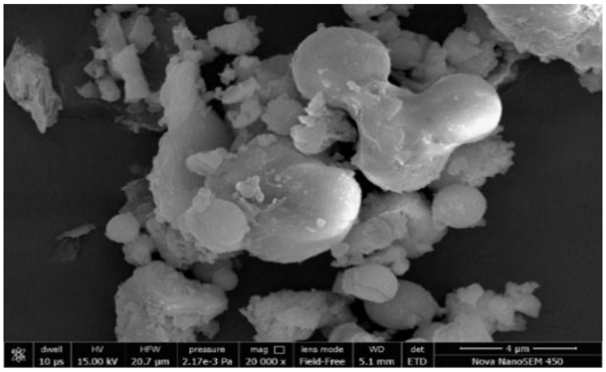

Figure 1 Higher magnification image of cement particles

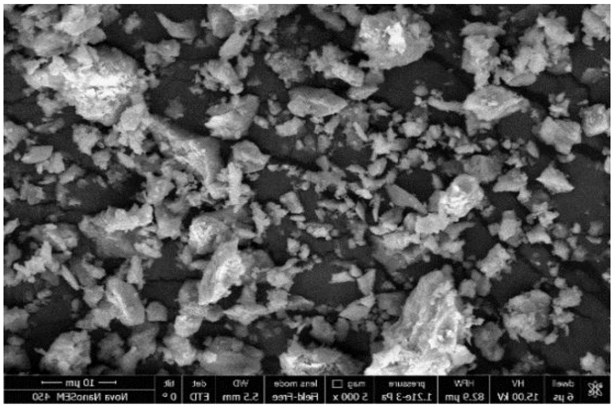

Figure 2 Higher magnification of glass particles

Particle size distribution of cement and glass particles is done to ensure the gradation of raw material for replacement is shown in *Figure 3*. Properties of raw ingredient required to prepare concrete is displayed in *Table 1*.

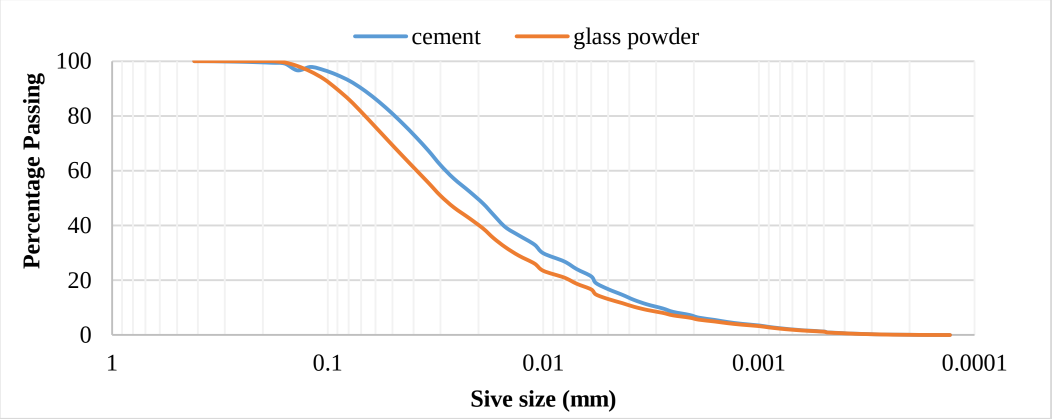

Figure 3 Gradation curve of WG and OPC

Table 1 Concrete preparing ingredients properties

Material	Specific gravity	Colour	pH
Fine Aggregate	2.62	Light brown	-
Coarse Aggregate	2.66	Greyish white	-
WG (WG)	2.55	Dark grey	-
Water	-	Colourless	7-6.5

3.2Mix proportioning

The grade M20 concrete is adopted in this, whereas, as per the standards of BIS 10262 the w/c ratio is adopted as 0.45. To achieve the favoured workability for concrete the admixture is utilized and it has been proportioned by weight. *Table 2* depicts the levels of replacement kept for experiment, the substitution levels were kept from 0 to 10% and the gap were kept as 2% for the substitutions.

Table 2 Mix proportioning in Kg/m^3

Mix	Waste glass powder(WGP)	Cement	WGP	Fine aggregate	Coarse aggregate		Water	w/c ratio
					10 mm	20 mm		
GP00	0%	340.0	0.0	510	672	448	153	0.45
GP02	2%	333.2	6.8	510	672	448	153	0.45
GP04	4%	326.4	13.6	510	672	448	153	0.45
GP06	6%	319.6	20.4	510	672	448	153	0.45
GP08	8%	312.8	27.2	510	672	448	153	0.45
GP10	10%	306.0	34.0	510	672	448	153	0.45

3.3Testing program

The standards of IS 1199 were adopted to perform compaction factor test and the workability of the specimen were analysed. A level of compaction factor was achieved as 0.9 by adjusting the dosages of the superplasticizer. As per the standards of IS 516, the compressive strength was assessed for the samples of size 100 mm cube at 7 and 28 days after proper curing of the specimens. American Society for Testing and Materials (ASTM) C 267 standards were followed for the testing of sample for acid attack, the exposure of the samples were kept for a time of 7 and 28 days before testing. The evaluation of the resistance against the chemical is done as per test recommendations, to stimulate the conditions of the chemical environment, 3% sulphuric acid was incorporated. 100 mm cube size sample were initially drowned in the acidic solution after observing its weight. Total three samples were tested under this procedure and the final weight after said time is observed and compared for analysis with the results of 28 days cured samples compressive strength. Proposed methodology is explained in *Figure 4.*

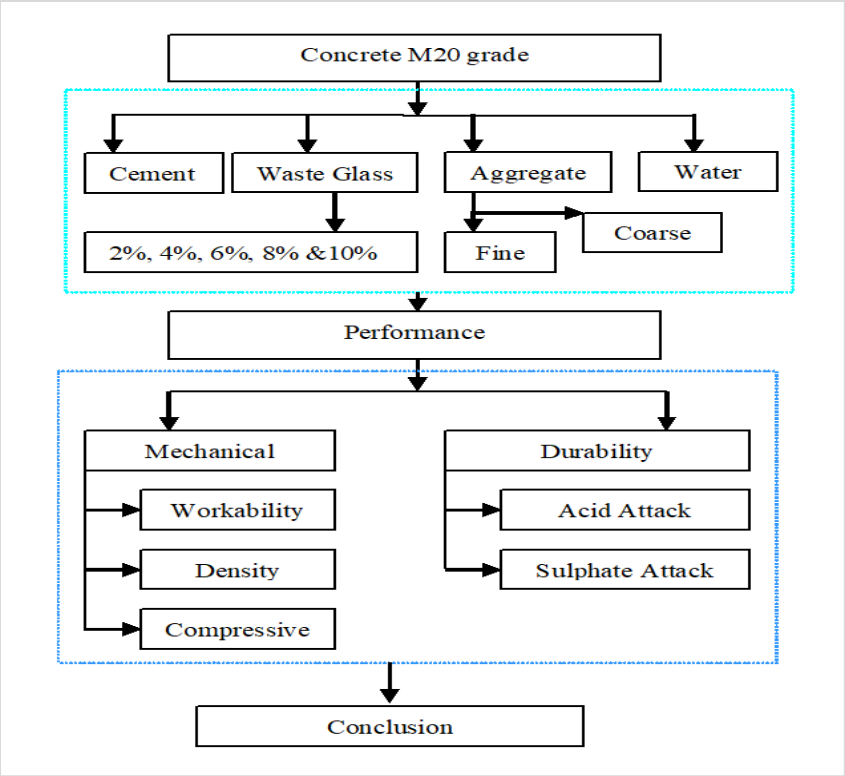

Figure 4 Block diagram of methodology

4.Results

4.1Fresh properties

Dosage of superplasticizer were adjusted in each mix to achieve the compaction factor near to 0.9. requirement of SP dosage for individual mixes are displayed in *Figure 5*. From *Figure 6* can be seen that demand of super plasticizer is reduced with addition of waste GP.

4.2Compressive strength

Three sample of size 100 mm were tested and results of compressive strength for WG modified concrete computed for 7- and 28-days water curing samples. *Figure 7* below represented the different compressive strength value for mixes.

4.3Acid attack

Figure 8 depicts the weight of the samples after 7 and 28 days of exposure to the acid medium. The trend of the weight alteration at 7 days testing has been noted in the various mixes, As the amount of the WG raised in the mixes, the weight gain has been noted in the reducing trend, whereas, the sample GP00 has been noted with the highest weight gain. *Figure 9* depicts the alteration in the compressive strength for the samples which are tested for acid attack. The variation in the strength of the various samples is related to the composition of chemical products during the process of exposure to the acidic medium.

4.4Sulphate attack

Figure 10 depicts the alteration in the weight of the samples after 7 and 28 days of exposure to the magnesium sulphate medium. It has been noted for the samples that as the increment made in the level of substitution, the samples have depicted weight reduction for 7 days as well as 28 days exposure. *Figure 11* depicts the 7- and 28-days testing alteration in the compressive strength for the samples which are exposed to sulphate solution. The control sample at 7 days testing were noted with considerable strength increment with sulphate curing compared to the other specimen with WG.

A complete list of abbreviations is shown in *Appendix I.*

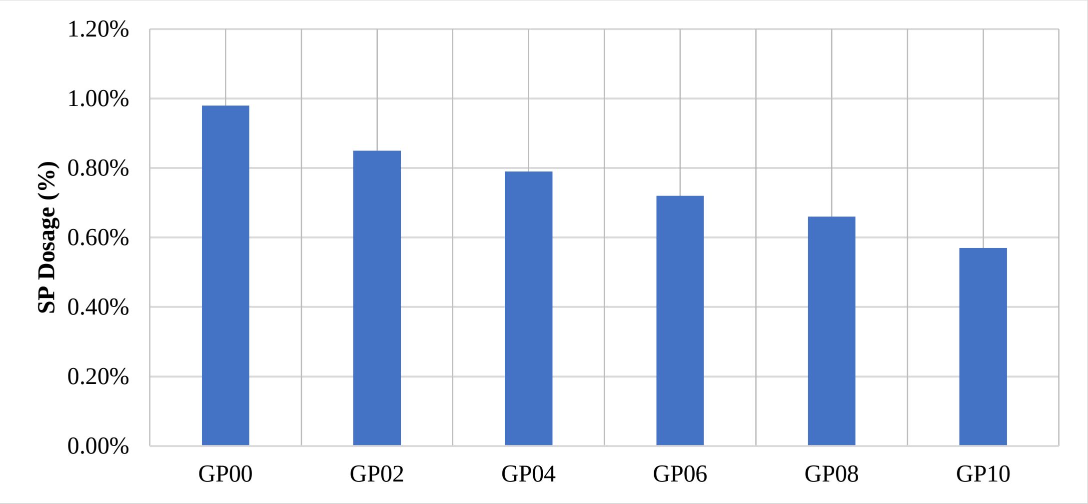

Figure 5 Workability of concrete mixes with WG percentage

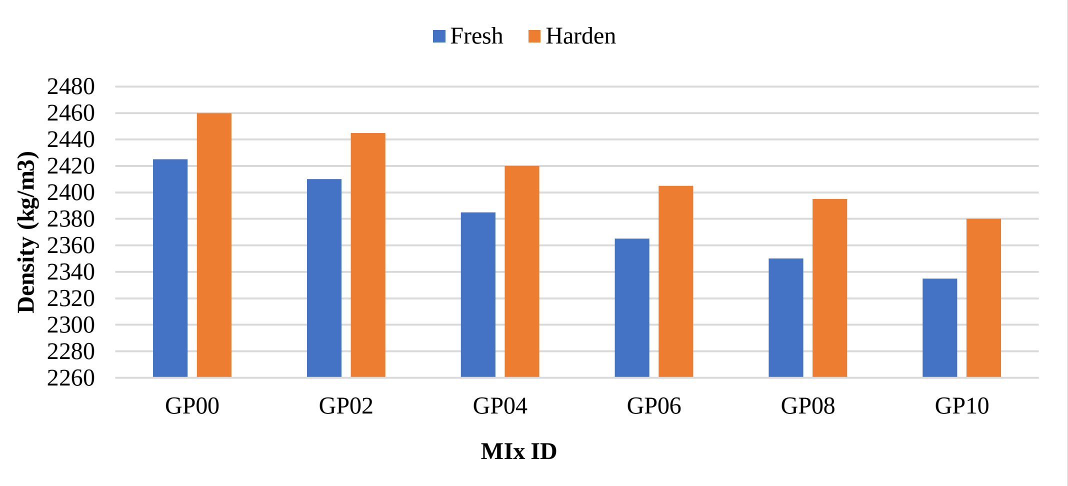

Figure 6 Density comparison of concrete mixes with WG

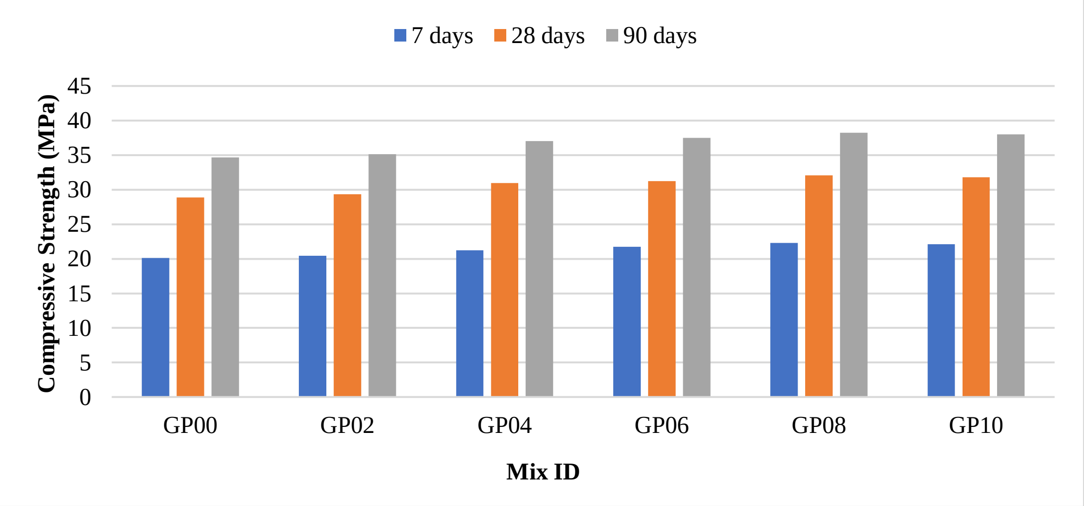

Figure 7 Compressive strength for different concrete mixes

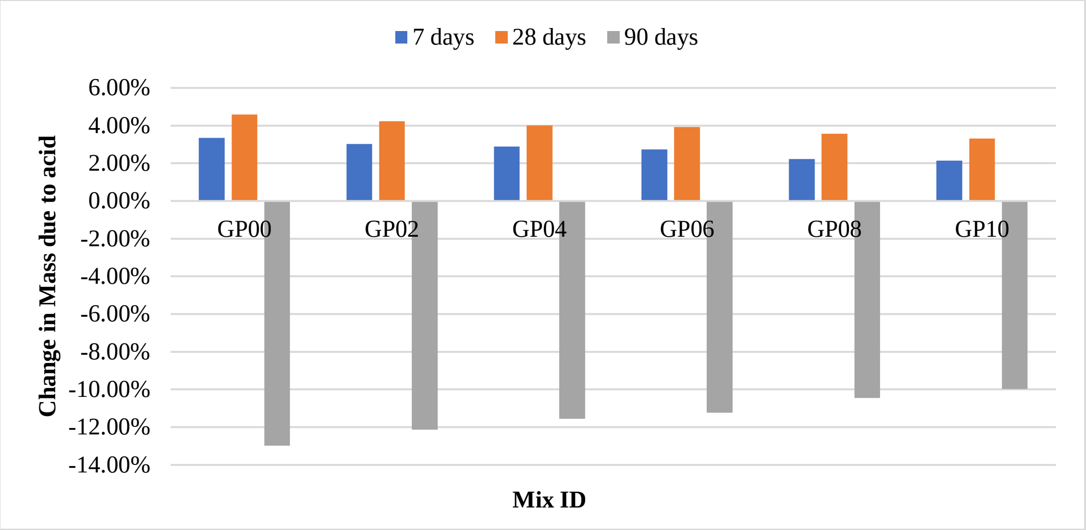

Figure 8 Weight Loss with acid attack for different concrete mixes

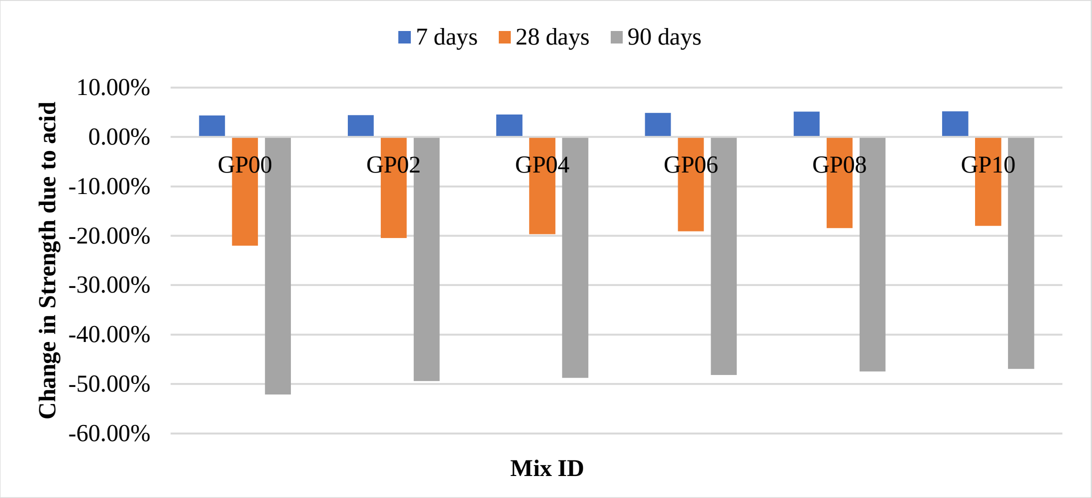

Figure 9 Compressive strength losses due to acid exposure for different concrete mixes

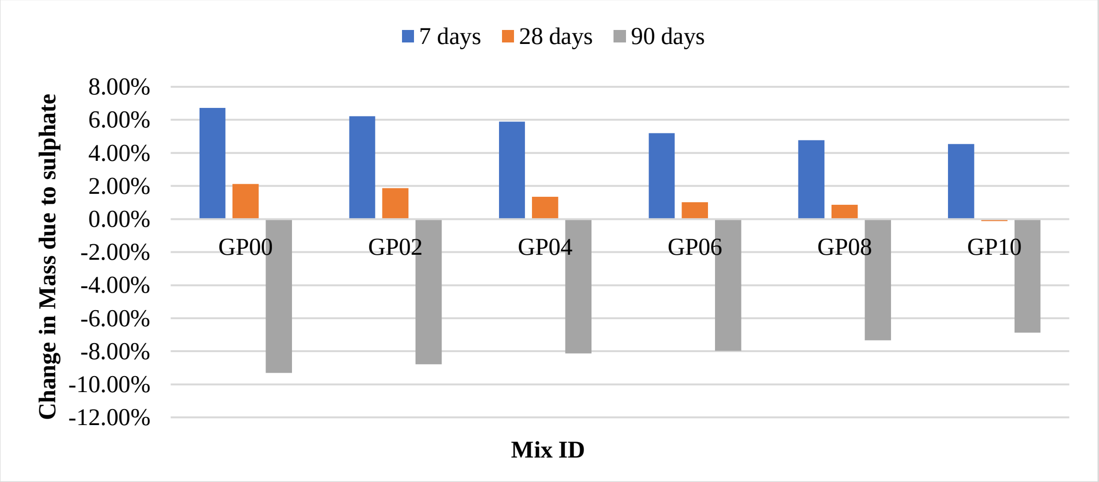

Figure 10 Change in mass due to sulphate for different concrete mixes

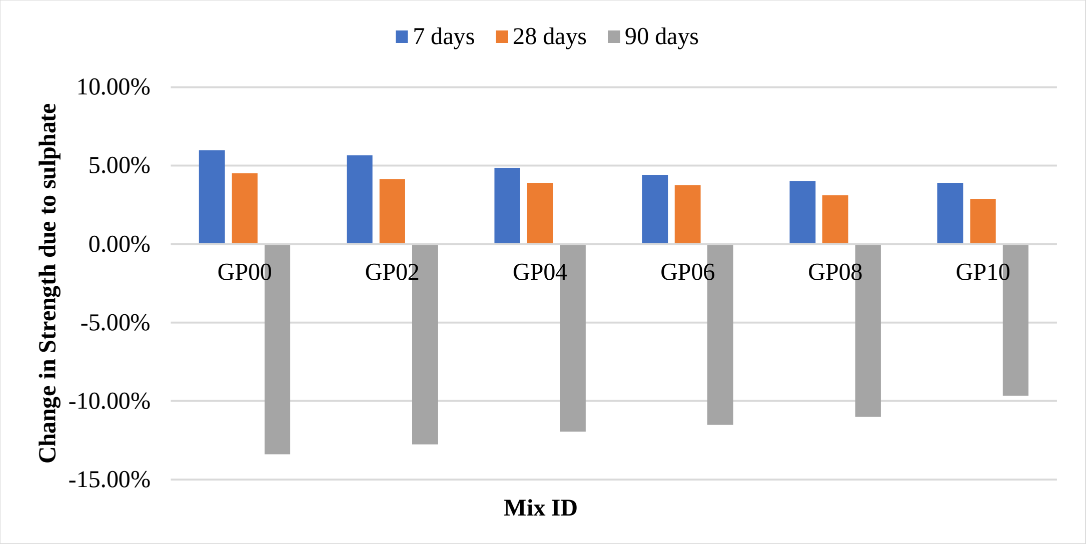

Figure 11 Change in compressive strength due to sulphate for different concrete mixes

5.Discussion

5.1Fresh properties

The decrease in density observed in WG-modified concrete can be attributed to the lower specific gravity of WG compared to cement, which naturally leads to an overall reduction in composite density upon incorporation. Additionally, factors like suboptimal particle packing, the introduction of porosity due to WG's inherent micro-pores, and potential air entrapment during mixing contribute to the observed decrease in density. While this reduction is significant, it's vital to note that careful mix design and optimization can help balance density considerations with the overall mechanical and durability performance of the concrete [24].

5.2Compressive strength

The relationship between the percentage of WG and the resulting compressive strength in concrete exhibits a noteworthy trend. Specifically, the compressive strength tends to increase with the incorporation of WG up to a certain threshold, often denoted as GP08. This increase can be attributed to several scientific factors that impact the interplay between WG and the cementitious matrix. The strengthening effect observed in WG-modified concrete can be attributed to the presence of a strong interfacial transition zone (ITZ). This zone emerges due to the effective binding between the finer glass particles and the cement matrix. It is particularly pronounced in cases like GP08 due to a well-formed Ca-Si matrix.

WG is rich in silica, a key component that significantly contributes to the formation of calcium silicate within the concrete. This Ca-Si matrix enhances the overall strength of the concrete. One pivotal characteristic of WG is its pozzolanic behavior. This behavior involves the reaction of WG with the calcium hydroxide produced during cement hydration, leading to the formation of additional cementitious compounds. The pozzolanic behavior and the accompanying filler effect play pivotal roles in the observed strength enhancement. These mechanisms facilitate the development of additional cementitious bonds within the matrix, thereby contributing to an overall increase in strength [25, 42, 43, 44]. However, it's crucial to note that when these concrete samples come into contact with alkaline solutions, they exhibit the phenomenon of mass loss. This can be attributed to the formation of (SiO_4) 4- ions, which occurs due to the fracture of Si-O-Si bonds triggered by the presence of OH- ions. This process becomes more reactive in environments with elevated pH levels. Interestingly, the presence of Ca_2+ ions in the medium tends to give rise to the formation of polymeric metal silicates. In summary, the relationship between the percentage of WG and compressive strength in concrete showcases a complex interplay of factors. The strong interfacial transition zone and enhanced binding between glass particles and the cement matrix, along with the pozzolanic behavior and filler effect, contribute to the observed strength enhancement. However, the interaction of WG-modified concrete with alkaline solutions underscores the intricacies of these processes, with the formation of specific ions dependent on the environmental pH and chemical composition.

5.3Acid attack

The investigation reveals significant insights into the behavior of WG-modified concrete samples, particularly regarding weight changes and compressive strength response when exposed to acid mediums. The remarkable weight loss observed in the GP 10 sample, with a reduction of 3.17% after 28 days of testing, indicates its vulnerability to acid attack. In contrast, the samples with lower levels of substitution (up to 10%) showcased relatively lower weight losses. The formation of gypsum and ettringite, resulting from the interaction with acidic solutions, could contribute to weight gain due to the incorporation of sulphate products. This shift in weight, however, can also be linked to a complex phenomenon—when the volume of the sulphate product surpasses its forming constituents, weight reduction may occur. This disparity in volume, termed the "internal stresses due to volume expansion," can lead to crack formation in the concrete. Interestingly, WG-modified concrete exhibits a sacrificial behavior when subjected to acidic conditions. In comparison to products generated during cement hydration, those formed from WG tend to exhibit higher resistance to acid-induced damage. This finding aligns with an experimental study [29] that underscores the sacrificial nature of WG. Analyzing the compressive strength changes further enriches the discussion. The compressive strength increase of 3.04% in the GP 10 sample, compared to the significant 7.21% change in the GP 00 sample, is attributed to the formation of CSH gel. This gel densifies the cement paste around aggregates, enhancing acid resistance by limiting penetration into the concrete structure. The formation of ettringite within voids contributes to this effect by providing a filler effect, ultimately augmenting the specimen's strength. The lower void ratio in the GP 10 sample underscores its improved compressive strength a minor ettringite composition supports convenient pore filling, fostering higher strength increments than in samples with more voids from WG.

Crucially, the sacrificial nature of WG plays a pivotal role in the compressive strength response. The production of non-expansive compounds by WG mitigates alterations in the compressive strength of WG-modified concrete. This consistent behavior can be attributed to the nature of compounds generated by WG, which remain stable and minimize the impact on concrete strength. In essence, the investigation's findings underscore the intricate interplay between WG and concrete when exposed to acid mediums. The sacrificial behavior of WG, coupled with its role in filler effects and compound formation, influences both weight changes and compressive strength responses. These insights contribute to a deeper understanding of WG-modified concrete's durability and mechanical properties in challenging environments.

5.4Sulphate attack

The weight changes observed in the GP08 and GP10 specimens provide valuable insights into the durability of WG-modified concrete under testing conditions. The GP08 sample demonstrated the highest weight increment, with increases of 0.09% and 0.32% after 7 and 28 days of testing, respectively. Similarly, the GP10 specimen displayed a weight increment of 0.03% after 7 days and 0.19% after 28 days. This weight enhancement can be attributed to the sacrificial nature of WG, a concept previously discussed [45, 46]. This sacrificial behavior contributes to the stability and reduced mass alteration observed in WG-incorporated samples, even when they possess more voids compared to control specimens. The incorporation of WG triggers the formation of compounds, including calcium-silicate-hydrates (C-S-H), through chemical reactions with cement hydration products. This process plays a crucial role in inhibiting the reaction of sulphate salts with cement hydration products, effectively impeding the formation of gypsum and ettringite. As a result, the weight alteration in the concrete is minimized due to the formation of these compounds, which have lower densities than their individual constituents.

Examining the strength changes over time reveals further insights. Beyond the initial 7-day period, the control specimen displayed the highest reduction in strength, while samples incorporating WG exhibited less pronounced strength declination. Specifically, the GP10 sample showed a 15% reduction in strength after 28 days of testing, whereas the GP00 sample experienced a 5% strength reduction. These trends are consistently linked to the observed mass changes.
The weight changes and corresponding strength variations collectively underscore the durability and mechanical performance of WG-modified concrete. The sacrificial nature of WG, along with its role in compound formation and inhibition of sulphate salt reactions, contributes to the stabilized weight alterations and reduced strength declination. These findings reflect the complex interplay between WG and the concrete matrix, ultimately influencing the material's response to testing conditions.

5.5 Limitation of study

- The microstructural behavior of WG-modified concrete will be examined for further in-depth analysis.
- X-ray diffraction of WG-modified concrete will be analyzed to confirm the increase in strength.
- Statistical analysis of data from various results will be conducted to more accurately analyze the use of WG.
- Moreover, the exposure duration to acid and sulphate attacks may not fully simulate long-term environmental conditions. Further research with varying parameters and extended exposure periods can provide a more comprehensive understanding of WG-modified concrete's performance.

6.Conclusion and future work

The aim of this study was to investigate the durability performance of concrete mixes that were prepared using WG as a partial replacement for traditional aggregate materials. To achieve this goal, a series of experimental tests were conducted to assess the long-term strength and stability of the concrete mixes. The results of these tests were then analyzed and used to draw conclusions about the effectiveness of using WG in concrete. In the conclusion of this study, the findings were summarized and their importance was discussed in the context of sustainable construction practices. Additionally, the conclusion highlighted any gaps in the current research on this topic and recommended areas for further investigation. However, it should be noted that the final conclusion has been excluded from this study for unknown reasons.

- ASR expansion shows that smaller particles of WG improve the resistance against alkali silica reaction.
- Compressive strength results indicated that WG increased up to 10% replacement with OPC increased the strength. The increment variation as 8.44% at 28 Days and 7.14% at 90 days as compared to control. The pozzolanic behaviour or the filler effect might be the reason of this enhancement.
- The weight of concrete exposed for 7- and 28-days acid curing depicts that for 7 days period the increment in the WG proportion tend to decrease the weight gain. Sample with 10% substitution of WG has been noted with the highest decrease in the weight having a value as 3.17% after 28 days testing, whereas, mixes have depicted lowered weight decrement when the level of substitution were kept up to a level of 10%, which again was lesser for all mixes content.
- Whereas, the sample prepared with 10% WG have been noted with the highest compressive strength increment, this might be due to the formation of the ettringite in the voids that provide with filler effect and ultimately enhances the strength of the specimen when compared to samples which are having more voids of WG mixes.
- The alteration in the weight of the samples after 7 and 28 days of exposure to the magnesium sulphate medium have shown that specimen with 8% WG proportion have noted with highest weight increment as 0.09% and 0.32%, on other hand, specimen with 10% WG proportion have been noted with 0.03% increment for period of 7 days testing and 0.19% increment for period of 28 days testing.

In conclusion, this study sheds light on the multifaceted effects of WG incorporation in concrete. The decrease in density due to WG can be attributed to its lower specific gravity and suboptimal particle packing, among other factors. The enhancement in compressive strength, attributed to strong interfacial transition zones, Ca-Si matrix formation, pozzolanic behavior, and filler effects, showcases the promising potential of WG-modified concrete. The response to acid and sulphate attacks highlights the sacrificial nature of WG, its compound formation, and its role in inhibiting harmful reactions. While limitations exist, these findings contribute to the understanding of WG's impact on concrete's properties and performance, providing valuable insights for sustainable construction materials.

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Conflicts of interest

The authors have no conflicts of interest to declare.

Author’s contribution statement

Mahim Mathur: Concept and formulation, method of analysis, writing -original draft, analysis and interpretation of results. **Dr. R.C. Chhipa:** Supervision, final correction, investigation on challenges and draft manuscript preparation.

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Mahim Mathur is a research scholar in the department of civil engineering, Suresh Gyan Vihar University, Jaipur. He completed his post-graduation in the structural engineering branch in the year 2016. He has 3 research publications in national and international journals.
Email: mahimphd@gmail.com

Dr. R.C. Chhipa is coordinator of RCTEWM, and professor in department of chemistry, Suresh gyan vihar university, Jaipur. He has 65 publications in national and international journals. He is Scientist, Academacian, Researcher and Technologist.
Email: rc.chhipa@mygyanvihar.com

Appendix I

S. No.	Abbreviation	Description
1	ASTM	American Society for Testing and Materials
2	ASR	Alkali-Silica Reaction
3	CaO	Calcium Oxide
4	CSH/C-S-H	Calcium Silicate Hydrate
5	GGBS	Ground Granulated Blast-Furnace Slag
6	GP	Glass Powder
7	GW	Ground Waste
8	IS	Indian Standard
9	ITZ	Interfacial Transition Zone
10	LCD	Liquid Crystal Display
11	OPC	Ordinary Portland Cement
12	OLED	Organic Light-Emitting Diode
13	pH	Potential of Hydrogen
14	PPC	Portland Pozzolana Cement
15	RA	Recycled Aggregate
16	SCM	Supplementary Cementitious Material
17	SiO_2	Silicon Dioxide
18	SF	Silica Fume
19	UHPC	Ultra-High Performance Concrete
20	WG	Waste Glass
21	WGP	Waste Glass Powder