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Research Article

Experimental evaluation on the durability characteristics of ternary blended concrete with ground granulated blast furnace slag and hydrated lime exposed to harsh environmental conditions

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Abstract

This study investigates the durability characteristics of ternary blended concrete prepared by partially substituting Ordinary Portland Cement (OPC) with Ground Granulated Blast Furnace Slag (GGBS) and Hydrated Lime (HL). Fifteen different mix combinations were developed by varying GGBS from 10% to 70% and HL from 10% to 20%, with a fixed water-to-binder ratio of 0.36. Durability characteristics of the ternary concrete mixes were evaluated using water absorption, permeability, rapid chloride penetration, acid resistance, and sulphate resistance tests. Among the fifteen designed mix proportions, the C40G50L10 blend (40% OPC, 50% GGBS, 10% HL) consistently produced superior durability characteristics. It achieved a 41% and 44% reduction in water absorption at 56 and 84 days, respectively, and a 47.4% and 40.2% decrease in water permeability compared to the control mix with 100% OPC. Chloride ion penetration was significantly reduced in the C40G50L10 mix, showing 428 and 386 coulombs at 56 and 84 days, reflecting a reduction of 58.3% and 55.2%, respectively. Furthermore, this mix also exhibited the least compressive strength reduction and weight loss under acid, sulphate, and chloride exposure, highlighting its resistance to chemical attack. Conversely, mixes with high GGBS (70%) and HL (20%) combined with low OPC (10%), such as C10G70L20, showed the highest deterioration, primarily due to inadequate matrix cohesion and increased porosity. The experimental findings demonstrate that optimizing OPC with GGBS and HL, particularly at a 40:50:10 ratio, produces concrete with enhanced durability characteristics, ideal for applications in chloride-heavy marine structures, sulphate-rich soil conditions, and acidic industrial environments exposed to aggressive conditions.

1. Introduction

Concrete ranks as the second most consumed material globally after water, with an estimated annual production of nearly six billion tonnes, highlighting its widespread use in the construction industry [1]. Seeking to strike a balance between the growing needs of the construction industry and environmental sustainability is a big challenge to meet the demand for raw materials required for concrete and mortar [2]. Despite its widespread application, producing Ordinary Portland Cement (OPC), the key binding ingredient in concrete, is a primary source of anthropogenic carbon dioxide emissions, contributing approximately 7–8% of global carbon dioxide output [3]. Moreover, OPC manufacturing is energy-intensive and relies heavily on non-renewable raw materials. It is approximated that the production of one ton of cement results in the emission of about 0.8 to 0.9 tons of carbon dioxide into the atmosphere [4,5]. Given the growing environmental

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challenges, it is essential to explore alternative supplementary cementitious binders that offer similar mechanical performance and durability to conventional cement while reducing their ecological footprint [6]. In an effort to mitigate environmental impacts, numerous researchers have explored the incorporation of industrial by-products and waste materials like fly ash (FA) [7], ground granulated blast furnace slag (GGBS) [8], coal bottom ash (BA) [9], rice husk ash (RHA) [10], metakaolin (MK) [11], red mud (RM) [12], cement kiln dust (CKD) [13], waste glass powder (WGP) [14], silica fume (SF) [15], and sugarcane bagasse ash (SBA) [16] as alternative cementitious components for the development of environmentally sustainable concrete.

Due to its built-in hydraulic characteristics and proven pozzolanic behavior, GGBS has been extensively utilized as an alternative cementitious component in concrete production [17]. Its incorporation enhances the levels of alumina and silica within the mix, which in turn supports early-age strength development [18]. When used as a partial replacement for OPC, GGBS contributes to the formation of calcium-alumino-silicate-hydrate (C-A-S-H) gel, thereby improving the mechanical performance and durability of the composite [19]. This substitution leads to the formation of calcium aluminate or calcium sulfoaluminate phases [20], offering notable benefits such as reduced carbon emissions, enhanced compressive strength, improved resistance to tensile cracking, and decreased permeability and porosity through a refined microstructure [21,23].

Hydrated lime, typically available as a white powder or colorless crystalline substance, is produced by reacting quicklime with water. It has been observed that limestone-based fillers, such as hydrated lime, can improve both the mechanical strength and durability of concrete by refining the pore structure and enhancing compactness [24,25]. When introduced into OPC-GGBS systems, hydrated lime can enhance the pozzolanic reaction by supplying additional calcium hydroxide, promoting the formation of more calcium silicate hydrate (C–S–H) gels, and thereby improving the mechanical and microstructural performance of the composite [26].

Recent studies have highlighted the potential integration between HL and GGBS-based systems. For example, Ahmed [27] demonstrated that lime-slag limecrete mixes achieved compressive strengths above 25 MPa when optimally proportioned, indicating their feasibility as sustainable structural materials. Similarly, Bayat and Kashani [28] showed that incorporating HL with silica fume improved cohesiveness and rheological properties of cementitious mortars, supporting its role in advanced applications such as 3D printing. Shamseldeen and Dawood [29] further confirmed that partial replacement of cement with industrial by-products, including lime-based additives, enhances long-term strength and reduces carbon emissions by over 35%. In addition to these findings, our earlier study examined OPC–GGBS–HL ternary systems, where HL was shown to enhance workability, compressive strength, and microstructural performance by refining pore structure and promoting secondary gel formation [30]. While these outcomes confirmed the performance-enhancing role of HL, the focus remained on fresh, mechanical, and microstructural properties, with durability aspects receiving limited attention.

Previous investigations have also reported that durability improvements in blended concretes are most effective when GGBS replacement lies within the range of 40–70% of OPC, because of the enhanced pozzolanic activity and pore structure refinement [27, 28]. Similarly, HL additions above 20% resulted in excessive calcium hydroxide formation and increased porosity, whereas moderate HL levels of around 10% consistently improved performance in OPC–GGBS–HL systems [30]. Based on these important findings, the present study adopted substitution ranges of 10–70% GGBS and 10–20% HL to systematically evaluate both lower and higher replacement levels and identify the optimum blend for durability performance. Therefore, the present study investigates the feasibility of using HL as a partial binder replacement in ternary systems with OPC and GGBS, with a specific focus on durability. The study also aims to determine the optimum HL substitution level that can produce a durable and sustainable concrete matrix.

2. Experimental Program

2.1. Materials Used in the Study

This section presents a comprehensive overview of the physical and chemical properties of the raw materials used in formulating the ternary blended concrete, which includes OPC, GGBS, and HL. The OPC utilized in this study complies with IS: 269-2015 (Reaffirmed in 2020) specifications and is categorized as OPC 53 grade. GGBS used in the study was sourced from JSW Cements, Chennai, and HL was supplied by Astraa Chemicals, Chennai. To determine the chemical composition of the binder materials, X-ray fluorescence (XRF) analysis was performed, and the resulting oxide compositions are presented in Table 1. The XRF analysis revealed that the dominant oxides in GGBS were SiO_2 (34.60%), CaO (35.90%), and Al_2O_3 (20.42%). OPC was primarily composed of 60.31% CaO and 21.79% SiO2. In the case of HL, CaO was observed to be the primary component (69.82%), followed by very minor constituents, including Al_2O_3 and SiO_2.

Table 1. Physical and chemical characteristics of the binders employed in the study [30]

Oxide composition (%)	OPC	GGBS	HL
SiO_2	21.79	34.60	0.19
CaO	60.31	35.90	69.82
Al_2O_3	6.70	20.42	0.13
Fe_2O_3	3.80	0.64	0.15
MgO	1.72	6.01	0.52
SO_3	2.51	0.31	0.01
Na_2O	0.387	0.471	-
K_2O	0.42	0.491	0.03
Specific gravity	3.145	2.89	2.21
Color	Grey	Off white	White
Fineness (m^2/kg)	2.92	364	480

As per the specifications outlined in IS 383:2016, the fine aggregate used in this investigation was Manufactured Sand (M-Sand) with particle sizes passing through a 1.18 mm sieve, conforming to Zone II grading. The specific gravity of the fine aggregate was determined to be 2.63. The coarse aggregates, consisting of crushed stones procured from a local source, also adhered to the IS 383:2016 standards. The coarse aggregate blend included 20 mm and 12 mm nominal sizes, combined in 52% and 48% proportions, respectively.

2.2. Mix Proportion and Specimen Preparation

This study developed fifteen concrete mix designs, including a reference mix prepared by IS: 10262 guidelines [31]. The primary objective was to examine how varying levels of OPC replacement with GGBS (ranging from 10% to 70%) and HL (ranging from 10% to 20%) influenced key durability properties of ternary blended cement concrete mixes. All mixes were designed using M35 grade concrete, incorporating OPC of 53-grade. Notably, the authors previously investigated the same set of fifteen mix proportions to evaluate their workability, mechanical, and microstructural characteristics [30]. In continuation of that work, the present study focuses on assessing the durability performance of these established mixes. Although GGBS and HL generally increase water demand due to their physical and chemical characteristics, a constant water-to-binder ratio of 0.36 was maintained across all mixtures. To ensure adequate workability and retention time, a superplasticizer (Auromix 400) supplied by Fosroc Chemicals Private Limited was used uniformly at a dosage of 0.5% by weight of the binder. For all mixes, the quantities of binder, coarse aggregates, fine aggregates, and water were kept consistent at 400 kg/m^3, 1140 kg/m^3, 855 kg/m^3, and 144 kg/m^3, respectively, as presented in Table 2. The mix nomenclature follows the format CxGyLz, where C, G, and L represent the percentage contributions of OPC, GGBS, and HL, respectively (e.g., C40G50L10 denotes 40% OPC, 50% GGBS, and 10% HL).

Table 2. Mix proportion details for the ternary blended cement concrete mixes [30]

SI. No	Mix ID	OPC (kg/m³)	GGBS (kg/m³)	HL (kg/m³)	OPC (%)	GGBS (%)	HL (%)
1	C100	400	0	0	100	0	0
2	C80G10L10	320	40	40	80	10	10
3	C70G10L20	280	40	80	70	10	20
4	C70G20L20	280	80	40	70	20	10
5	C60G20L20	240	80	80	60	20	20
6	C60G30L10	240	120	40	60	30	10
7	C50G30L20	200	120	80	50	30	20
8	C50G40L10	160	200	40	50	40	10
9	C40G40L20	160	160	80	40	40	20
10	C40G50L10	160	200	40	40	50	10
11	C30G50L20	120	200	80	30	50	20
12	C30G60L10	120	240	40	30	60	10
13	C20G60L20	80	240	80	20	60	20
14	C20G70L10	80	280	40	20	70	10
15	C10G70L20	40	280	80	10	70	20

2.3. Testing Methods

To evaluate the durability performance of fifteen ternary concrete mixes, including a control mix, standard tests were conducted to assess resistance against deterioration mechanisms such as water penetration, water absorption, chemical attack, and chloride ion penetration. Water absorption was measured per ASTM C642 by comparing the weight of oven-dried concrete specimens before and after 24-hour water immersion, indicating the internal porosity. Water penetration was assessed as per DIN 1048 (Part 5), where concrete cubes were subjected to a water pressure of 5 bar for 72 hours, and the depth of water penetration was measured upon splitting the specimens. Chloride ion penetration was evaluated through the Rapid Chloride Penetration Test, following ASTM C1202, using cylindrical specimens exposed to a 60V DC for 6 hours across sodium chloride and sodium hydroxide solutions, with the total charge passed recorded to assess permeability.

Fig. 1. Effect Experimental test setup: (a) Water absorption test, (b) Rapid chloride penetration test, (c) Water penetration test, and (d) Acid and sulphate solution preparation

Acid resistance was tested by immersing standard-cured cubes in a 5% sulphuric acid solution, with mass and compressive strength losses monitored at 56 and 84 days. Sulphate resistance was similarly examined by submerging the specimens in a 5% sodium sulphate solution, with periodic solution replacement and stirring to prevent sedimentation, followed by strength and weight assessments at the same intervals. Finally, chloride resistance was assessed by immersing specimens in a 5% calcium chloride solution, observing variations in mass and compressive strength after 56 and 84 days of exposure. The photographs of the durability experimental setup used in the present investigation are presented in Fig. 1.

3. Results and Discussion

3.1. Effects of HL on The Water Absorption Properties of Ternary Concrete Mixes

Fig. 2 illustrates the water absorption of ternary concrete mixes in which OPC was partially substituted with varying amounts of GGBS and HL. The results, recorded after 56 and 84 days of water curing, show a general decline in water absorption characteristics as the GGBS content increases. However, HL content also plays a role in influencing this trend. Among all the mixes, C40G50L10 (containing 40% OPC, 50% GGBS, and 10% HL) exhibited the lowest water absorption values, 2.49% at 56 days and 2.08% at 84 days. These results represent a 41% and 44% reduction, respectively, compared to the control mix C100 (100% OPC), which showed absorption rates of 4.22% and 3.66% at the same time intervals. This demonstrates that the incorporation of 50% GGBS together with 10% HL effectively minimizes water ingress by refining the pore structure through pozzolanic reactions [32,33].

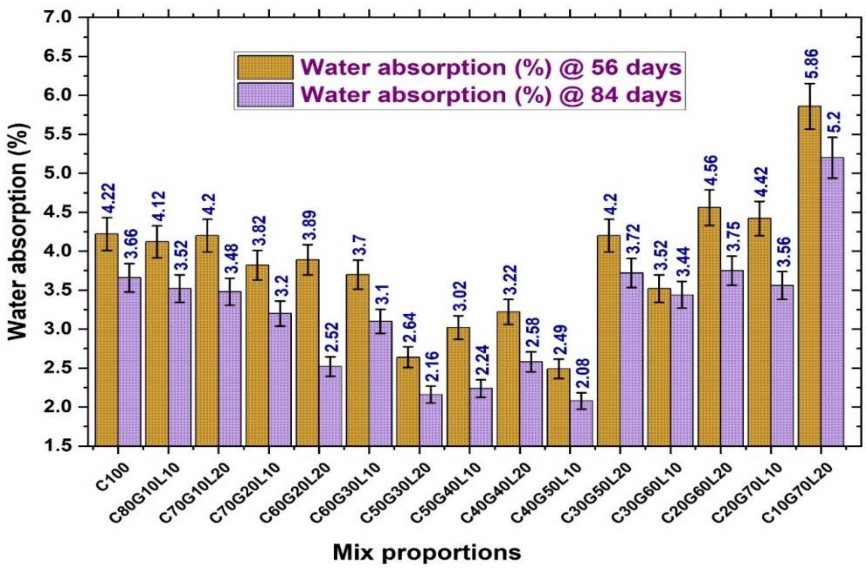

Fig. 2. Effect of HL and GGBS addition on the water absorption properties of ternary mixes

On the other hand, the mix C10G70L20 (10% OPC, 70% GGBS, 20% HL) recorded the highest absorption values, showing increases of 39% and 42% at 56 and 84 days, respectively, when compared with C100. This poor performance is mainly due to insufficient OPC for matrix development and the microstructural flaws introduced by excess HL, both of which increase permeability [34]. Notably, the C40G50L10 mix with 10% HL consistently outperformed similar mixes with 20% HL, such as the C50G30L20 mix, which had a slightly higher absorption rate of 2.64% in 56 days. This suggests that a moderate HL content (10%) is sufficient to refine the pore structure and reduce water absorption, whereas an excessive amount (20%) can compromise the mix by introducing microstructural flaws [35]. The test results confirm that C40G50L10 achieved more than a 40% reduction in absorption compared to the control mix, while C10G70L20 exhibited over 40% higher absorption. This quantitative contrast highlights the important role of balanced OPC–GGBS–HL proportions in achieving lower porosity and better water resistance.

The observed improvements in durability characteristics, particularly reduced water absorption and penetration in mixes containing 10% HL, were closely related to the microstructural densification and enhanced pozzolanic activity. These mechanisms were confirmed in our earlier work (Dhanesh and Shanmugasundaram, 2023), where detailed SEM–EDS analysis established the role of HL in pore refinement and secondary C–S–H gel formation. A summary of the key microstructural findings and their durability implications is presented in Table 3, providing a direct correlation between microstructural evidence and the results of the present study.

Table 3. Summary of the microstructural observations from earlier research

Microstructural evidence	Observations	Durability implications
Refined pore structure with denser gel matrix	Attained with 10% HL in OPC-GGBS mix	Reduced water absorption and penetration
Formation of additional C-S-H and C-A-S-H gels	HL inclusion produced additional $Ca(OH)_2$ to activated GGBS	Enhanced chloride resistance
Presence of unreacted particles at 20% HL	Excess HL resulted in porosity	Increases permeability and reduces resistance in 20% HL mixes
Homogeneous matrix with low microcracks	Observed in mixes with 40% to 50% GGBS and 10% HL	Enhanced chemical resistance under acid and sulphate condition

3.2. Effects of HL on The Water Penetration Test Results of Ternary Concrete Mixes

Fig. 3 presents the water penetration performance of the ternary concrete mixes with varying proportions of OPC, GGBS, and HL. The permeability results measured after 56 and 84 days of curing demonstrate that the level of OPC replacement showed a notable effect on permeability results. Among all the mixes tested, C40G50L10 (comprising 40% OPC, 50% GGBS, and 10% HL) produced the lowest permeability values, 9.85 mm at 56 days and 7.6 mm at 84 days. These results indicate a significant reduction of 47.4% and 40.2%, respectively, compared to the control mix C100 (100% OPC), which exhibited permeability results of 18.7 mm and 12.7 mm at the same intervals.

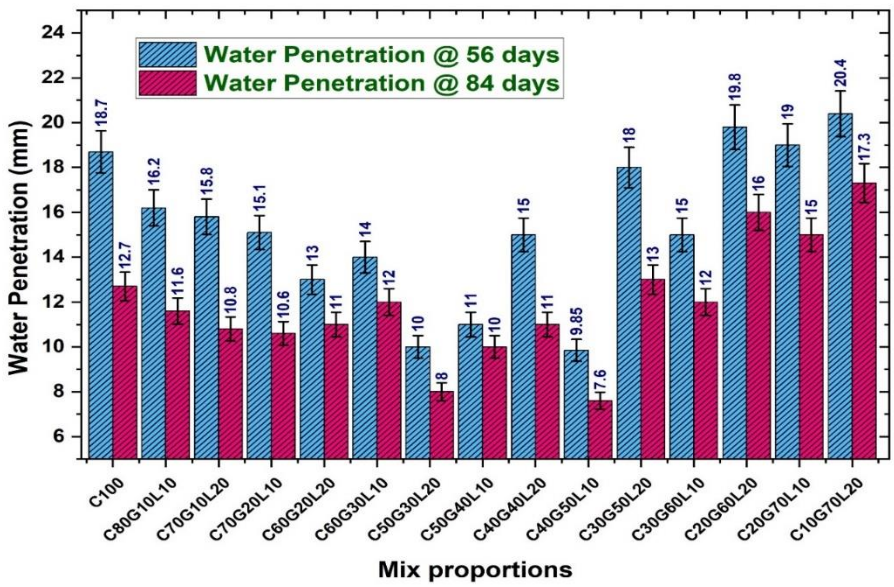

Fig. 3. Combined influence of HL and GGBS on the water penetration characteristics

The improved performance of the C40G50L10 mix is mainly because of the pozzolanic activity of GGBS, which refines the pore structure by filling capillary voids, while the inclusion of 10% HL further reduced water penetration by minimizing smaller pores [36], [37]. In addition, the 10% HL content further minimized water penetration by filling smaller pores present within the matrix. On the other side, the mix C10G70L20 (10% OPC, 70% GGBS, 20% HL) showed the highest penetration, registering increase in the penetration results of 8.9% at 56 days and 36.3% at 84 days compared to the C100 mix. This poor performance is due to the low OPC content, which resulted in a weakly bonded microstructure with larger interconnected pores [38], [39]. Although HL can act as a filler, its benefit is limited when combined with excessive GGBS and low OPC, as this composition prevents effective densification [40]. The optimized C40G50L10 reduced water penetration depth by nearly half compared to the control mix, while the C10G70L20 mix exceeded the control mix by over 36% at 84 days.

3.3. Combined utilization of HL and GGBS on RCPT Performance of Ternary Mixes

Fig. 4 illustrates the RCPT results of ternary blended concrete mixes after 56 and 84 days of curing. The control mix C100 (100% OPC) illustrated the highest charge passed, measuring 1028 coulombs at 56 days and 865 coulombs at 84 days, which corresponds to the moderate chloride ion penetrability category as per ASTM C1202. The optimized blend C40G50L10 (40% OPC, 50% GGBS, and 10% HL) recorded the lowest values of 428 coulombs and 386 coulombs at 56 and 84 days, respectively, placing it in the low chloride ion penetrability range. This substantial reduction of 58.3% and 55.2% compared to the control mix indicates the importance of GGBS in refining the pore structure and limiting ion transport, while the inclusion of 10% HL further enhanced matrix densification through secondary reactions [28], [41].

Mixes containing 10% HL, such as C40G40L10, C50G40L10, and C60G30L10, consistently exhibited low chloride permeability, whereas 20% HL blends (e.g., C20G60L20, C10G70L20) remained in the moderate range. This indicates that while a moderate dosage of HL (10%) effectively complements the pozzolanic reaction of GGBS, higher HL content promotes the formation of excess calcium hydroxide, which increases pore connectivity and reduces durability [42], [43]. Based on the experimental results from 15 mixes, the ASTM-based classification confirms that ternary mixes with 10% HL provide optimal resistance against chloride penetration compared to both the control and higher HL (20%) blends. The test results indicate that the chloride ion penetration in the C40G50L10 mmix was reduced to below 400 coulombs at 84 days, while mixes with 20% HL exceeded 700 coulombs.

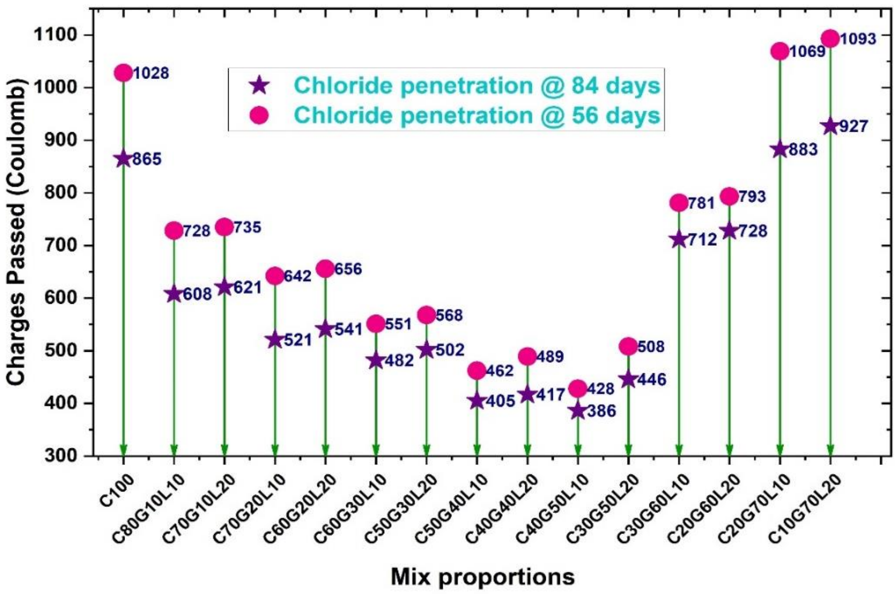

Fig. 4. Combined utilization of HL and GGBS on the chloride penetration of ternary mixes

3.4. Combined Impact of HL and GGBS on The Acid Resistance of Ternary Mixes

Fig. 5 presents the results of the acid resistance test on concrete mixes where OPC was partially replaced with varying substitution levels of GGBS and HL. Among the fifteen mixes, C10G70L20 (10% OPC, 70% GGBS, 20% HL) exhibited the highest loss in compressive strength, with reductions of 18.47% at 56 days and 33.62% at 84 days. In contrast, the C40G50L10 mix proportion (40% OPC, 50% GGBS, 10% HL) recorded the lowest strength loss at the same time intervals, 10.25% and

17.84%, respectively. The poor performance of C10G70L20 can be attributed to its very low OPC content, which plays a critical role in early-age strength development and acid resistance, coupled with excessive HL content (20%) that increased porosity [39], [44]. The superior performance of the C40G50L10 mix is mainly because of its well-balanced composition: 40% OPC ensures sufficient early strength and acid resistance, 50% GGBS contributes to long-term matrix refinement, and 10% HL likely helps reduce pore volume while supporting pozzolanic activity.

Fig. 6 presents the weight loss (%) experienced by the ternary mixes following acid exposure at the end of 56 and 84 days. Among the fifteen considered mixes, C40G50L10 demonstrated the least weight loss of 5.45% at 56 days and 7.42% at 84 days. In comparison, the control mix C100 exhibited weight losses of 8.12% and 10.58%, indicating reductions of 32.6% and 29.9%, respectively. C10G70L20 mix recorded the highest deterioration, with weight losses of 11.13% at 56 days and 14.95% at 84 days. These results suggest that despite high GGBS levels, the low OPC proportion and excessive HL dosage lead to unstable calcium hydroxide phases and inadequate matrix cohesion, thereby lowering acid resistance [45]. The C40G50L10 mix reduced the weight loss to below 8% and strength loss to below 18% after 84 days of acid exposure, whereas C10G70L20 showed nearly double the deterioration. This phenomenon indicated that limiting the 10% HL is very important for achieving better acid resistance in ternary blended systems.

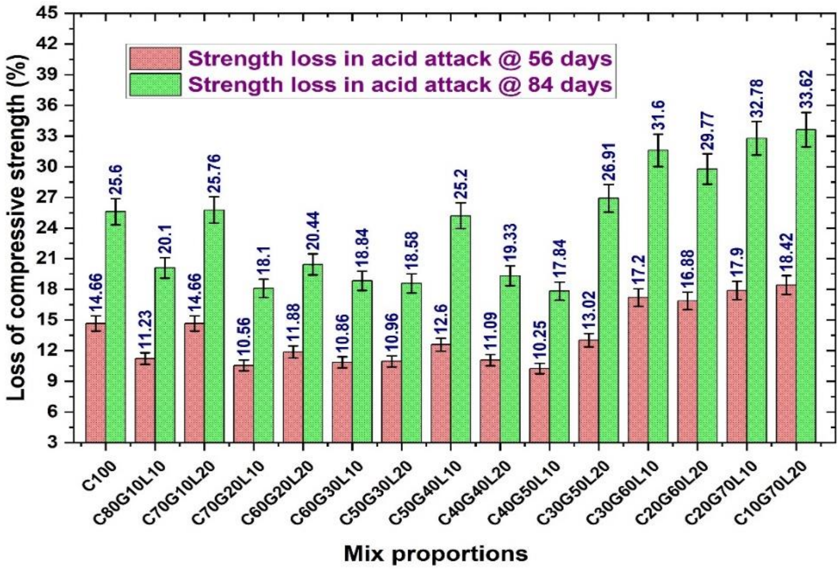

Fig. 5. Combined incorporation of HL and GGBS on the acid resistance test on ternary mixes

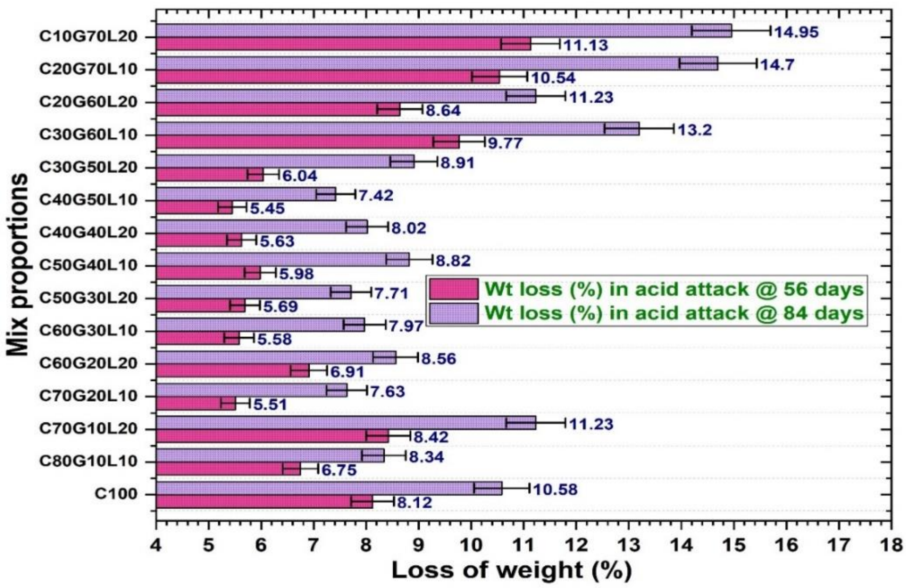

Fig. 6. Combined addition of HL and GGBS on the weight loss during acid attack

3.5. Influence of HL and GGBS Addition on The Sulphate Resistance Of Ternary Mixes

Fig. 7 illustrates the effect of incorporating GGBS and HL as partial replacements for OPC on sulphate resistance. The ternary mix comprising 40% OPC, 50% GGBS, 10% HL (C40G50L10) showed the lowest strength loss, with reductions of 3.56% at 56 days and 6.65% at 84 days, corresponding to 27.5% and 15.4% lower values compared to the control mix C100 (4.9% and 7.86%). On the other side, mix constituting 10% OPC, 70% GGBS, 20% HL (C10G70L20) recorded the highest strength loss of 5.1% and 9.10%, which represents an increase of 4.1% and 15.8% compared to the conventional mix (C100). The enhanced sulphate resistance of mixes like C40G50L10 and C50G40L10 is due to the pozzolanic action of GGBS, which helps create a denser internal structure and limits the formation of expansive compounds caused by sulphate reaction [46], [47]. However, in mixes with higher HL content, such as C10G70L20, the elevated porosity is attributed to the relatively weaker binding nature of HL, which results in deeper sulphate penetration, accelerating strength deterioration. Notably, mixtures containing 10% HL (e.g., C40G50L10, C50G40L10, C60G30L10) consistently retained more strength than those with 20% HL (C40G40L20, C50G30L20, C60G20L20), indicating that a moderate HL dosage may be optimal for improving sulphate environment [48], [49].

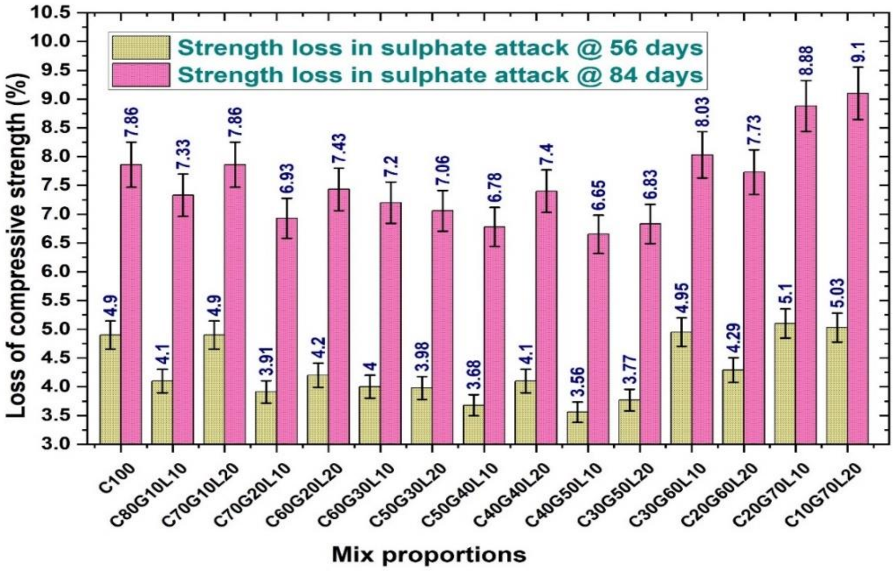

Fig. 7. Effect of HL and GGBS addition on the strength loss (%) during sulphate attack

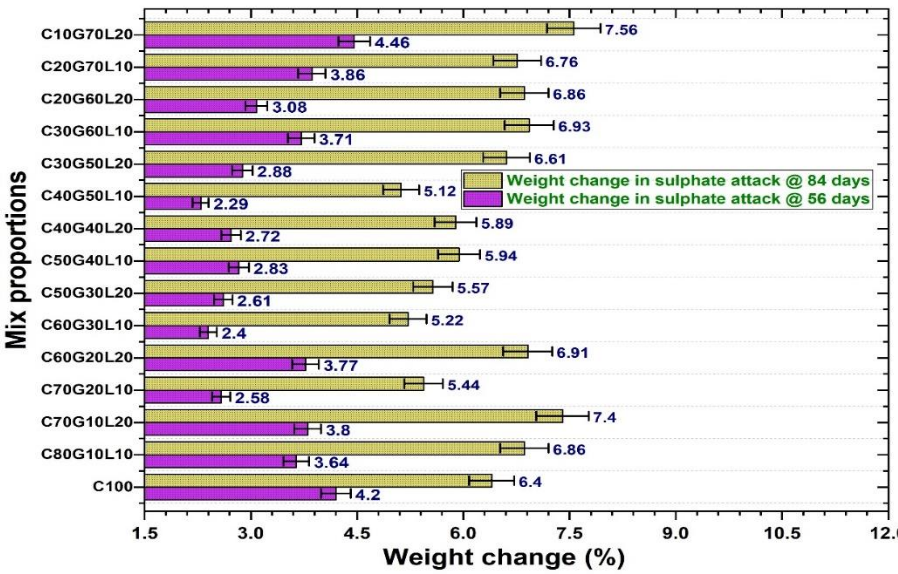

Fig. 8. Effect of HL and GGBS addition on the weight loss (%) during sulphate attack

Fig. 8 presents the percentage of weight loss experienced by the ternary concrete mixes after sulphate exposure at 56 and 84 days. Among the fifteen ternary mixes, C40G50L10 illustrated the lowest weight loss of 2.29% at 56 days (a reduction of 45.7% compared to C100) and 5.12% at 84 days (20.0% less than C100). The better performance of this mix is mainly due to the balanced combination of OPC, GGBS, and a moderate amount of HL, which enhances resistance to sulphate-induced degradation by reducing porosity and chemical penetration [50]. Conversely, the highest weight loss was observed in mix C10G70L20. Despite its high GGBS content, this mix exhibited marginally greater deterioration than the control, with weight losses of 4.46% at 56 days (6.2% higher than C100) and 7.56% at 84 days (18.4% higher). This suggests that the low OPC level and elevated HL dosage reduce the structural integrity of the matrix, allowing easier sulphate penetration [44].

3.6. Combined Influence of HL and GGBS on The Chloride Resistance of Ternary Mixes

The evaluation of chloride resistance of 15 ternary mix proportions, as depicted in Fig. 9, shows that the mix C40G50L10 (40% OPC, 50% GGBS, and 10% HL) recorded the lowest reduction in compressive strength of 3.63% at 56 days and 7.24% at 84 days, which is 30.3% and 10.0% lower than the control mix C100 (5.22% and 8.04%). On the other hand, the mix C20G70L10 (20% OPC, 70% GGBS, 10% HL) demonstrated the maximum reduction in strength, with losses of 5.7% and 9.51% at 56 and 84 days, indicating an increase of 9.2% and 18.4% over the control mix C100. The superior performance of C40G50L10 is mainly due to the ability of GGBS to bind chloride ions effectively, resulting in a compact microstructure that reduces chloride ingress and reinforcement corrosion. However, excessive GGBS proportion in C10G70L20 mix, reduces early-age strength and increases chloride-induced deterioration [51,52].

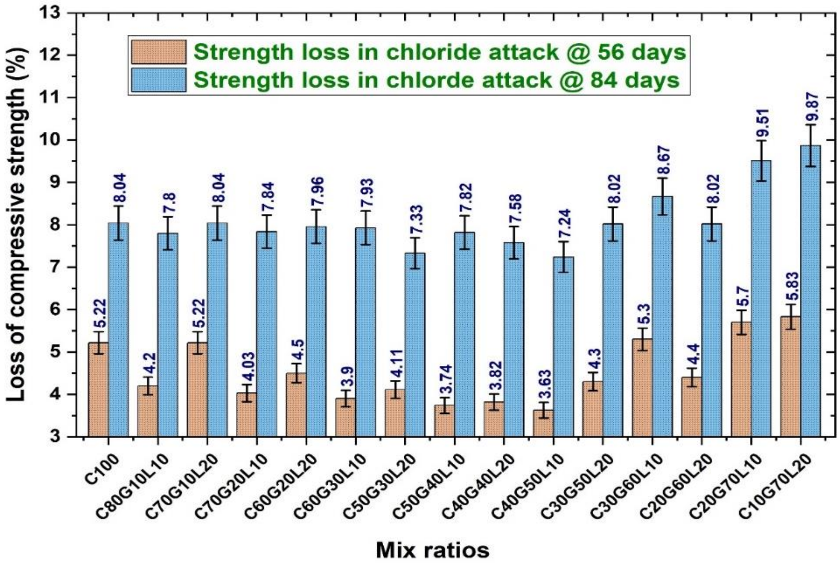

Fig. 9. Effect of HL and GGBS inclusion on the strength loss (%) during chloride attack

The mixes containing 10% HL (such as C40G50L10, C50G40L10, and C60G30L10) consistently retained more strength than the mixes incorporating 20% HL (C40G40L20, C50G30L20, and C60G20L20). This trend indicates that there may be an optimum HL content for resisting chloride attack, likely because moderate HL dosages contribute to pore structure refinement without significantly increasing permeability [53]. Fig. 10 supports these findings by illustrating weight loss percentages under chloride exposure. The C40G50L10 mix again performed best, with 3.26% loss at 56 days and 6.39% at 84 days, representing 20.7% and 18.1% reductions compared to C100 (4.1% and 7.8%). On the other hand, C20G70L10 exhibited the highest loss (5.7% and 9.51% at the same intervals), exceeding the control by 9.2% and 18.4%, respectively. Thus, chloride resistance is maximized with 50% GGBS and 10% HL, while excessive HL and very low OPC contents lead to performance deterioration.

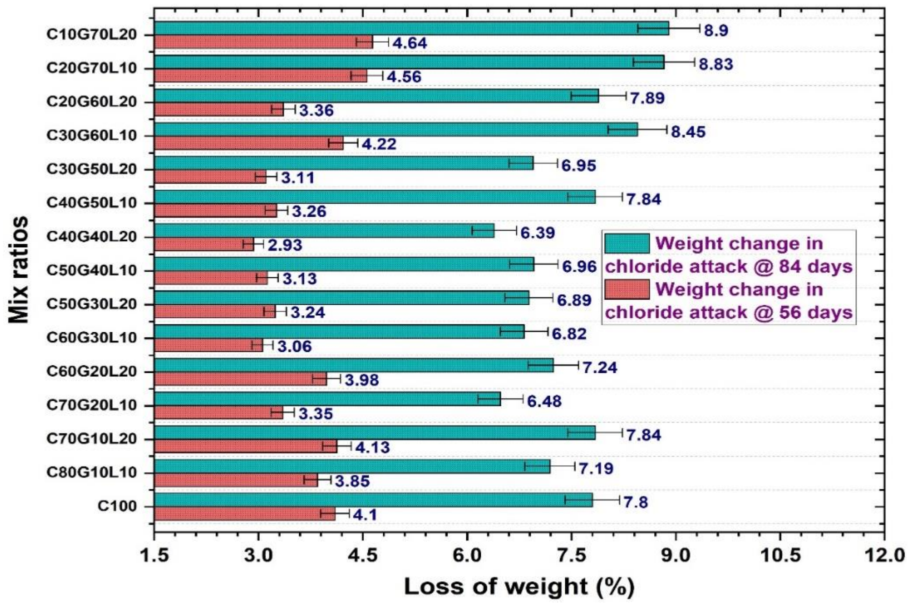

Fig. 10. Effect of HL and GGBS incorporation on the weight loss (%) during chloride attack

5. Conclusions

The study investigated the durability performance of ternary blended concrete incorporating varying proportions of GGBS and HL as partial replacements for OPC. The key findings are summarized as follows:

- Optimal Mix Performance: The C40G50L10 mix (40% OPC, 50% GGBS, 10% HL) exhibited superior durability across all tested parameters, achieving a 41% and 44% reduction in water absorption at 56 and 84 days, respectively, a 47.4% and 40.2% decrease in water permeability, and a 58.3% and 55.2% reduction in chloride ion penetration (428 and 386 coulombs) compared to the control mix (C100, 100% OPC).
- Role of GGBS: Higher GGBS content, particularly at 50% in the C40G50L10 mix, significantly enhanced durability by promoting pozzolanic reactions and reducing permeability, as evidenced by lower water absorption and chloride penetration values.
- Influence of HL Dosage: A moderate HL content of 10% (e.g., in C40G50L10, C50G40L10, C60G30L10) consistently outperformed mixes with 20% HL (e.g., C40G40L20, C50G30L20), indicating that 10% HL optimizes pore structure refinement.
- Poor Performance of High GGBS and HL Mixes: The C10G70L20 mix (10% OPC, 70% GGBS, 20% HL) showed the highest deterioration, with increased water absorption (39% and 42% higher than C100 at 56 and 84 days), water penetration (8.9% and 36.3% higher), and strength losses under acid (18.47% and 33.62%), sulphate (5.1% and 9.10%), and chloride (5.7% and 9.51%) exposures, attributed to insufficient OPC content and excessive HL-induced porosity.
- Chemical Resistance: The C40G50L10 mix demonstrated the least compressive strength reduction and weight loss under acid (10.25% and 17.84% strength loss; 5.45% and 7.42% weight loss), sulphate (3.56% and 6.65% strength loss; 2.29% and 5.12% weight loss), and chloride (3.63% and 7.24% strength loss; 3.63% and 7.24% weight loss) exposures, highlighting its suitability for aggressive environments.
- Practical Implications: The experimental findings of this study highlight that the C40G50L10 mix (40% OPC, 50% GGBS, 10% HL) provides a durable concrete matrix with excellent resistance to water ingress, chloride penetration, and chemical attack. This makes it highly suitable for marine structures exposed to seawater, foundations and substructures in sulphate-rich soils, and industrial environments prone to acidic exposure. By reducing permeability and enhancing chemical resistance, this mix can extend the service life of reinforced concrete structures while contributing to sustainability through lower OPC usage.

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