JOURNAL OF MECHANICS OF CONTINUA AND MATHEMATICAL SCIENCES
www.journalimcms.org

ISSN (Online) : 2454 -7190 Vol.-20, No.-8, August (2025) pp 36 - 51 ISSN (Print) 0973-8975

DEVELOPMENTS IN MECHANICAL STRENGTH, ACID RESISTANCE, SORPTION RESISTANCE, CARBON PERFORMANCE AND MICROSTRUCTURE OF CONCRETE THROUGH SPATIAL VARIATIONS USING DIFFERENT GRADES OF NORMAL CONCRETE

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https://doi.org/10.26782/jmcms.2025.08.00003

(Received: April 25, 2025; Revised: July 21, 2025; Accepted: August 08, 2025)

Abstract

Cement production significantly contributes to CO_2 emissions and climate change. To reduce cement use and enhance concrete efficiency, this study investigates graded concrete (GC), composed of two different concrete grades (M30 and M20) using Portland Slag Cement (PSC) and Portland Pozzolana Cement (PPC) in a 1:1 spatial variation. The study also examines the partial replacement of PSC (40–70%) in M30 with fly ash (FA) and lime to improve sustainability and performance. Mechanical properties were assessed through compressive and tensile strength tests at 7, 14, 28, 56, 91, and 182 days. Durability was evaluated via acid and sorption resistance, while the ecological aspect was assessed through embodied carbon analysis. Results showed that GC outperformed conventional M30 concrete, even with 50% cement replaced by 43% FA and 7% lime. GC demonstrated a 33% reduction in embodied carbon compared to M30. Microstructural validation through scanning electron microscopy confirmed the improved performance. Overall, the findings highlight the potential of GC as a sustainable and efficient construction material, promoting the beneficial use of industrial by-products like FA.

Keywords: Acid resistance, Embodied carbon, Fly ash, Graded concrete, Mechanical characteristics, Water sorption resistance

I. Introduction

Cement demand in concrete production continues to rise despite concerns over its high carbon emissions. To reduce cement use and enhance sustainability, Functionally Graded Concrete (FGC) has emerged as a promising alternative. FGC features a gradual variation in composition and structure, optimizing performance by placing higher-quality materials only where needed. This approach enhances durability, reduces waste, and lowers costs. It also allows the integration of recycled materials and industrial by-products, further supporting sustainable practices. Figure 1 illustrates the formation of graded concrete (GC) through a seamless transition between a higher-grade lower layer and a lower-grade upper layer, creating an efficient intermediate zone. Unlike distinct layering, GC uses a continuous grade transition to improve overall efficiency. Advancements in topology optimization and automated construction techniques are driving further interest in GC, enabling smarter material usage and more efficient, tailored structural designs. This innovation marks a significant step toward greener, more adaptable infrastructure.

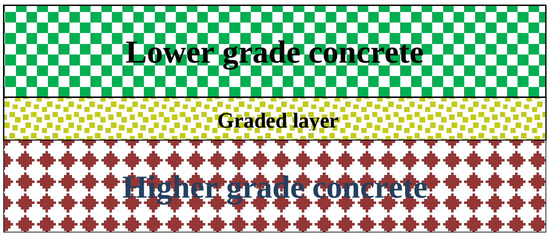

Fig. 1. Formation of a graded layer at the junction of two different layers in GC

II. Literature review

Ribeiro et al. [XXVIII] reported that functionally graded concrete (FGC) exhibited a lower carbonation coefficient than conventional concrete with water-cement (w/c) ratios of 0.45 (2.31 mm) and 0.55 (3.78 mm), though slightly higher than with a 0.35 w/c ratio (1.71 mm), indicating improved durability against carbonation. Sabireen et al. [XXIX] found that FGC demonstrated 27.6% higher compressive strength than plain cement concrete (PCC), particularly in fiber-reinforced mixes, highlighting superior mechanical performance. Maalej et al. [XXI] observed enhanced corrosion resistance in FGC beams using ductile fiber-reinforced composites, with only 6.6% steel loss after 83 days of accelerated corrosion compared to 10.1% in standard beams. Sahoo et al. [XXX] evaluated two-layered FGC with partial OPC replacement (20–50%) using GGBFS, noting up to 30% higher compressive strength than traditional concrete. The authors adopted various layer thickness ratios like 1:1, 2:1, 4:1, 5:1, and reported that the best results are obtained adopting a ratio of 1:1 [XXX]. Palaniappan et al. [XXVII] replaced cement with fly ash and red mud. FGC with 10% replacement achieved 35 MPa strength, and the first crack load was 1.58 times higher than that of conventional beams. These studies collectively highlight FGC's potential in enhancing durability, strength, and corrosion resistance. Chan et al. [VIII] investigated double-layered FGC with steel fiber-reinforced recycled aggregate concrete (FRRAC) at the bottom and plain cement concrete (PCC) at the top. An h/H ratio of 0.75 with 0.75% steel fiber increased compressive strength by 53%, while a ratio of 1.00 further enhanced hardening. Lai et al. [XIX] showed that placing hybrid steel fiber layers at the top improved impact resistance and reduced spalling. Kausar and Nikam [XVII] used M35 and dolomite-based lean concrete, finding that 30% dolomite replacement and a 75 mm interface gave the highest strength (46.22 MPa). Liu et al. [XX] used normal concrete over recycled aggregate concrete with a 20-minute delay, achieving a 48% cut in emissions and a 43% cost reduction. Buswell [VII] highlighted that excess vibration affects FGC stability and suggested self-compacting concrete (SCC) for better results, particularly in 3D printing, where fresh-state material tuning enhances spraying accuracy.

Strieder et al. [XXXIII] analyzed the potential of continuously graded concrete for reducing cracking caused by hydration heat in mass concrete, improving durability. Similarly, Maimouni et al. [XXII] and Torelli et al. [XXXIV] highlighted the challenges associated with the fresh-on-fresh casting method of functionally graded concrete, noting the need for further research to address issues such as shear stress resistance and layer interface stability. Nithya et al. [XXV] investigated FGC, varying the interface thickness at 25 mm and 50 mm using M25 grade concrete. Fly ash was used to replace OPC-53 in proportions of 5, 10, and 15%. The study found that compressive strength increased by 3.54, 4.32, and 6.50% with respective fly ash replacements. Ning et al. [XXIV] demonstrated that functionally graded linings, particularly two-layered linings, exhibited higher elastic load-bearing capacity compared to conventional single-layered linings, improving structural efficiency. Nes and Qverli [XXIII] developed a dual-layered reinforced concrete with a low-density fiber-reinforced bottom and control-density top layer, reducing overall weight by 42% compared to homogeneous concrete. Herrmann and Sobek [X] performed a numerical analysis on a 4-meter beam with graded porosity, achieving up to 62% mass reduction and enhanced structural efficiency. Satyanarayana et al. [XXXII] reported 12–15% higher compressive strength in FGC cubes with 30–50% fly ash, with high-volume fly ash mixes gaining an additional 4–5%. Nazari and Sanjayan [XIX] found that FGC compressive strength improved when load was applied parallel to the graded layers, with geopolymer FGC offering better mechanical performance and lower environmental impact. Acharya et al. [XX] observed a 7% increase in strength and durability when lime was used as a partial cement replacement in PSC and PPC.

II.i. Significance of the present study

Although some research exists on functionally graded concrete (FGC), practical application remains limited due to the high cost and complexity of using special concretes with fibers and polymers. Studies on FGC without such materials are rare, and most use ordinary Portland cement (OPC), which has high embodied carbon. This study addresses the gap by exploring an accessible FGC made from normal concrete (M20) and fly ash blended concrete (M30) activated with lime. Blended cements like Portland slag cement (PSC) and Portland pozzolanic cement (PPC), along with partial fly ash replacement, promote sustainability, economy, and practical feasibility for wider adoption.

III. Experimental program

Material properties

For the experimental analysis, Portland slag cement (PSC) and Portland pozzolana cement (PPC) were used, meeting the requirements of IS: 455-2015 [XXI] and IS: 1489 (P-1), 2015 [XXII], respectively. Lime and fly ash were sourced from a local vendor. Table 1 provides a detailed overview of the chemical properties of lime and fly ash. The concrete mix was prepared using fine aggregates that conform to Zone-III standards as per IS: 383-1970 (Reaffirmed 2002) [XXIII]. Crushed black hard stones, ranging in size from 12.5 mm to 20 mm and compliant with IS: 383-1970 (Reaffirmed 2002) [XXIII], were used as coarse aggregates. Fresh, pure drinking water with a pH of 7.2 was utilized in the study. Table 2 summarizes the physical characteristics of the aggregates.

Table 1: Chemical properties of FA and lime

Binders	CaO (%)	SiO_2 (%)	MgO (%)	MnO (%)	Al_2O_3 (%)	Fe_2O_3 (%)	SO_3 (%)	LOI (%)	K_2O, N_2O,TiO_2 (%)	Cl, IR (%)
FA	2.09	65.44	1.04	0.5	23.12	1.46	0.69	1.55	1.77	-
Lime	85.03	4.62	0.07	-	0.46	0.44	0.42	6.74	-	-

Table 2: Physical properties of fine and coarse aggregate

Aggregates	Bulk density (kg/m^3)	Specific gravity	Flakiness index(%)	Impact value(%)	Crushing value(%)	Water absorption(%)	Elongation index (%)
Fine Aggregate	1652	2.71	-	-	-	0.74	-
Coarse Aggregate	1698	2.83	14.2	16.5	24.5	0.25	14.4

IV. Methodology

Based on IS: 10262-2019 [XXIV], mix designs were developed for M20 and M30 grade concrete using two cement types: Portland Pozzolana Cement (PPC) and Portland Slag Cement (PSC). The control mixes, designated as 20P (M20 with PPC) and 30S (M30 with PSC), were prepared in Phase 1, and their properties were used as reference. In Phase 2, a graded concrete sample named 30S20P was developed with equal layer thickness: a bottom layer of M30 (30S) and a top layer of M20 (20P). The concept of equal thickness of layer was adopted based on the past reports [IV], [XXV]. This aimed to evaluate whether such hybrid layering could match or exceed the strength of the higher-grade concrete alone. The different cement types in each layer were intended to create a synergistic interface. In Phase 3, the top layer remained as 20P, while the bottom 30S layer was modified by partially replacing PSC with fly ash (FA) and 7% lime at replacement levels of 33%, 43%, 53%, and 63%. These mixes were designated as 30S6, 30S5, 30S4, and 30S3, respectively. This strategy leveraged the high CaO content of PSC and the SiO_2-rich nature of FA, aiming to benefit from both hydraulic and pozzolanic reactions. Lime was added based on findings by Acharya et al. [XXVI], [XXVII] to enhance hydration. The water-binder ratios were 0.45 for M20 and 0.43 for M30. Details of all mix ingredients are provided in Table 3.

Sample preparation

For compressive strength and durability tests (acid and sorption resistance), 150 mm concrete cubes were used. Split tensile strength was tested on 150×300 mm cylinders. Samples were demoulded after 24 hours and cured in water until testing at 7, 14, 28, 56, 91, and 182 days. Control samples (single-layered) made with PPC and PSC were cast and vibrated for 2 minutes. Graded concrete (GC) samples in phases 2 and 3 were cast in two layers: M30 as the top and M20 as the bottom, each vibrated for 1 minute. In phase 3, the bottom layer mix included 40–70% PSC replacement with fly ash and lime. Broken pieces from tests were used for SEM analysis. The samples were named as described in Table 4.

Table 3: Materials and mix identification for concrete

Type of mix	Mix name	Cement (kg/m^3)	FA (kg/m^3)	GGBFS (kg/m^3)	Lime (kg/m^3)	Fine aggregate (kg/m^3)	Coarse aggregate (kg/m^3)	Water (Kg/m^3)
PSC-based normal concrete	30S	447	-	-	-	614	1134	193
PPC-based normal concrete	20P	405	-	-	-	708	1283	183
PSC-based blended concrete	30S6	269	147	-	31	614	1134	194
	30S5	224	192	-	31	614	1134	194
	30S4	179	237	-	31	614	1134	194
	30S3	134	282	-	31	614	1134	194

Table 4: Sample details

	Mix details	Layers	Nomenclature
Phase 1: Normal concrete	M30 grade made of PSC	Single	30S
	M20 grade made of PPC	Single	20P
Phase 2: Graded concrete	Bottom layer 30S and top	Double	30S20P
Phase 3: Graded concrete adopting cement replacement with FA	Bottom layer 30S6 and top	Double	30S620P
	Bottom layer 30S5 and top	Double	30S520P
	Bottom layer 30S4 and top	Double	30S420P
	Bottom layer 30S3 and top	Double	30S320P

Testing procedures

Compressive strength was tested as per IS: 516-1959 (Reaffirmed 2004) [XXVIII], and split tensile strength was followed by IS: 5816-1999 (Reaffirmed 2004) [XXIX]. Acid resistance was assessed using the method by Acharya and Patro [XXX], where 28-day water-cured samples were immersed in 1% sulfuric acid for 28, 91, and 182 days, and residual strength was compared to water-cured samples. Water sorption was evaluated as per a previous report [XXX1], using wax-coated samples submerged 5 mm in water. Oven-dried weights were recorded initially and at intervals of up to 361 minutes. Sorption was calculated based on weight gain. The results of each test were determined using the average of three samples for accuracy.

V. Results and discussions

V.i. Resistance against compressive stress

The 20P and 30S samples, representing single-layered M20 and M30 grade concrete made with PPC and PSC, were tested at multiple curing intervals up to 26 weeks (Figure 2). Both mixes achieved their target mean strength at 28 days. At 7 days, they reached 58–66% of 28-day strength, and at 14 days, 20P and 30S achieved 73% and 77%, respectively. By 56 days, 20P gained 3% and 30S 1% over 28-day strength. Strength gains continued gradually, with 91-day results showing a 5–6% increase, and 182-day results showing an 8% gain over 28-day strength. Overall, the strength development was uniform across all samples.

When M20 and M30 grade concretes made with PPC and PSC, respectively, were cast in two layers in a 1:1 ratio, the sample 30S20P (M30 PSC as bottom and M20 PPC as top) exhibited remarkable strength gains of 17, 21, 5, 31, 31 and 34% higher than M30 (30S) at 7, 14, 28, 56, 91, and 182 days, respectively. Physical observation after failure revealed a distinct 10% thick transition zone herein termed the "graded layer" at the interface, differing in color and texture from the parent layers. This layer is likely formed due to pozzolanic reactions between fly ash in PPC and calcium hydroxide released from the hydration of GGBS in PSC, enhancing the formation of C-S-H and improving the interfacial transition zone (ITZ). Differential shrinkage, hydration rates, and thermal expansion between layers may contribute to densification at the interface, acting as a mechanical anchor that improves load transfer and overall strength. The early strength gain is attributed to the faster hydration of PPC, while PSC contributes to long-term strength through its finer particle size and higher slag content, which promote continued secondary reactions. These synergistic effects create a denser and more cohesive microstructure at the graded interface, enhancing compressive strength.

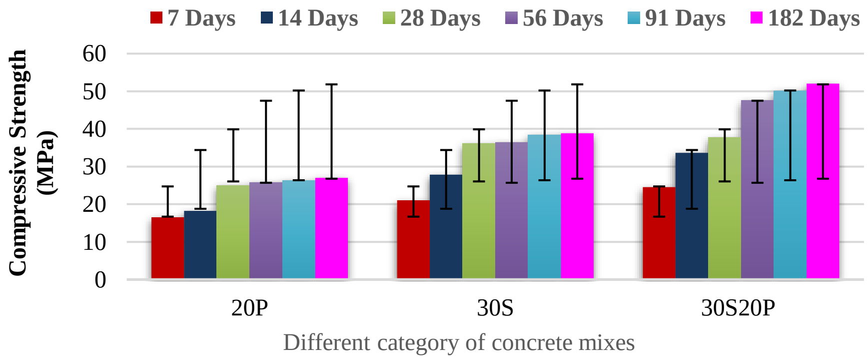

Fig. 2. Effect of layers on compressive strength

In addition to strength enhancement from layering, the study aimed to utilize both pozzolanic and hydraulic reactions by incorporating fly ash (FA) with PSC. Graded concrete samples 30S620P, 30S520P, 30S420P, and 30S320P were prepared using M20 PPC concrete (20P) as the top layer and M30 PSC concrete with varying PSC replacements (33–63%) by FA and 7% lime as the bottom layer. The corresponding bottom mixes were 30S6, 30S5, 30S4, and 30S3. Strength tests were conducted at 1st, 2nd, 4th, 8th, 13th, and 26th weeks. The results confirmed significant benefits of combining FA and lime with PSC. Sample 30S620P showed strength gains of 16, 28, 6, and 4% at 7, 28, 91, and 182 days over 30S20P. Similarly, 30S520P exhibited gains of 12, 16, 5, and 3%, while 30S420P achieved 3, 8, 4, and 1%. However, 30S320P (63% FA) showed strength reductions of 10, 14, 3, and 3% at the same intervals, indicating that excess FA negatively affects strength. The results are presented in Figure 3. The pozzolanic reaction of FA with $Ca(OH)_2$ forms additional C-S-H, enhancing long-term strength. Lime addition boosts calcium ion availability, accelerating pozzolanic activity. Thus, up to 53% FA replacement with 7% lime is beneficial, as seen in 30S420P. However, higher FA content likely reduces early hydration and strength due to dilution of hydraulic components and limited $Ca(OH)_2$ for reaction.

The interface between M30 PSC and M20 PPC acts as a zone of stress redistribution due to the difference in elastic properties and strengths of the two layers. The stiffer M30 PSC layer at the bottom attracts higher stresses under axial or flexural loads, while the top M20 PPC layer experiences lower stresses. The interface facilitates transfer of shear and normal stresses, supported by interfacial densification, which enhances bond performance. While this study is experimental, theoretical considerations based on composite theory and modular ratios support these observations. The findings are similar to the findings of the past reports [IV, XXXII]

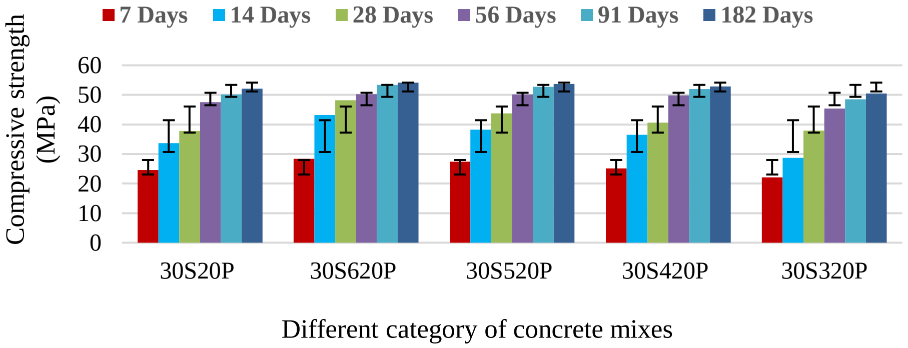

Fig. 3. Effect of replacement of PSC with fly ash and lime on compressive strength of graded concrete

V.ii. Resistance against tensile stress

Single-layered baseline mixtures like M20 grade with PPC and M30 grade with PSC (20P and 30S), when tested at the ages of 1,2,4, 8, 13, and 26 weeks, it was seen that all concrete mixes gained strength with age. 20P gained 3.53 MPa at 28 days, and its 7-day strength was almost 86% of its 28-day strength. This mix uniformly gained strength over all measured periods, and its strength gain at the end of 182 days was almost 44% over the 28-day strength. The mix 30S also showed a uniform strength development that 3.35 – 4.51 MPa from 7-28 days. The strength at 182 days was almost 35% of the 28-day strength. The results are presented in Figure 4.

The graded concrete sample 30S20P, composed of a bottom layer of M30 grade PSC concrete and a top layer of M20 grade PPC concrete, was tested for splitting tensile strength at 7, 14, 28, 56, 91, and 182 days. Results, shown in Figure 4, indicate that the layered system consistently outperformed the higher-grade 30S concrete alone. For example, while 30S exhibited tensile strengths of 3.35, 4.51, and 6.11 MPa at 7, 28, and 182 days, respectively, 30S20P showed increases of approximately 9, 3, and 7% at these intervals. This enhancement is attributed to the combined effects of the different cements and concrete grades. PSC contributes to long-term strength through its slag content, while PPC's pozzolanic material improves microstructure via secondary hydration, reducing porosity. The interface formed between the two layers in 30S20P plays a vital role in strength improvement, acting as a transition zone that blends the properties of both concretes. This zone likely distributes stress more evenly and serves as a barrier to crack propagation. The refined microstructure at the interface minimizes weak points and can arrest or redirect cracks as they move between layers, resulting in a more cohesive and durable structure.

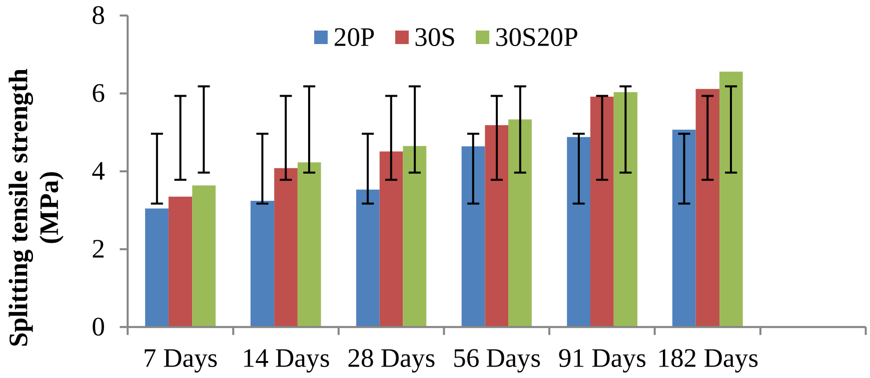

Fig. 4. Effect of layers on tensile strength

In addition to the strength enhancement from graded layering, this study explored further improvements by incorporating fly ash and lime into PSC. Graded concrete samples 30S620P, 30S520P, 30S420P, and 30S320P were tested at various curing ages. In the control sample 30S20P, the bottom layer used plain PSC. When PSC was partially replaced (40–70%) with FA and 7% lime, tensile strength gains were noted, especially at 14–91 days. At 14 days, samples showed a 2–13% increase in splitting tensile strength over 30S20P, indicating that FA and lime contribute to early strength via refined pore structure and pozzolanic reactions. However, strength development at 7 days was lower, likely due to FA's slower initial reactivity compared to PSC. Significant gains between 14 and 91 days are attributed to continued pozzolanic activity and lime's role in forming additional calcium silicate hydrate (C-S-H), which densifies the matrix and enhances bond strength. The 60% replacement level (53% FA and 7% lime) appears optimal, providing improved tensile strength without compromising integrity. However, strength gains plateaued at 182 days. This may result from the near-completion of pozzolanic reactions, as reactive silica from FA becomes fully consumed and microstructural development stabilizes. Beyond this point, additional FA and lime likely yield marginal benefits, indicating a saturation limit in their effectiveness. The results are presented in Figure 5.

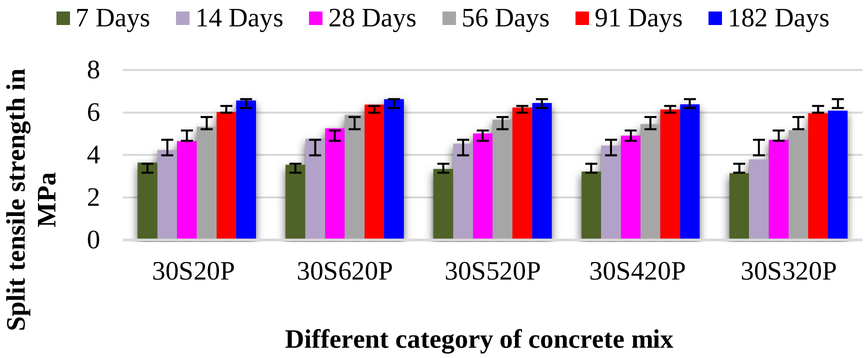

Fig. 5. Effect of replacement of PSC with fly ash on tensile strength

V.iii. Resistance against water sorption

Sorptivity is a key durability indicator of concrete, reflecting its ability to absorb water through capillary action. Higher sorptivity increases vulnerability to freeze-thaw cycles, chemical attack, and corrosion, while lower values enhance resistance in aggressive environments. In this study, sorptivity was measured for normal concretes (20P and 30S), and graded concretes (30S20P and 30S420P). The sample 30S420P, made with 53% FA and 7% lime on 60% PSC replacement, offered better properties than 30S and 30S20P, for which it was considered for the test of sorptivity. The water sorption percentages for 20P and 30S were 0.633% and 0.565%, respectively. When combined in a 1:1 thickness ratio to form graded concrete 30S20P, sorptivity dropped significantly to 0.141%, showing a 75% reduction compared to 30S. This improvement is attributed to a denser interface layer formed between M20 (PPC) and M30 (PSC) concretes, where finer particles from the lower-grade layer likely filled voids in the higher-grade one, reducing capillary porosity. Further enhancement was observed in the 30S420P mix, which had a water sorption of 0.135% representing a 76% and 4% improvement over 30S and 30S20P, respectively. The fly ash contributed to additional C-S-H gel formation through pozzolanic reactions, while lime improved matrix bonding. These modifications refined the microstructure and further reduced permeability. The results are presented in Figure 6.

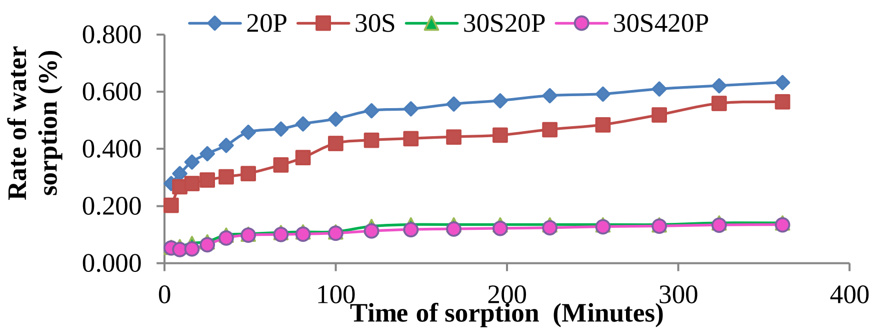

Fig. 6. Water sorption of normal and graded concrete

V.iv. Resistance against acidic environment

Acid resistance of concrete refers to its ability to withstand degradation in acidic environments, such as sulfuric acid, which attacks calcium hydroxide in the cement matrix, causing leaching, strength loss, and erosion. This study evaluated the acid resistance of normal concrete (20P and 30S) and graded concrete (30S20P and 30S420P) by measuring strength loss after exposure to a 1% sulfuric acid solution for 28, 91, and 182 days, compared to water-cured controls. Normal concrete 20P showed 5–6% strength loss over time, while the 30S experienced slightly lower losses of 4–5.23%. However, the layered 30S20P mix significantly improved acid resistance, with only 2–3% strength loss. Replacing 60% of PSC in the bottom layer of 30S with 53% fly ash (FA) and 7% lime in mix 30S420P further enhanced resistance, with losses below 3%. The results are presented in Figure 7.

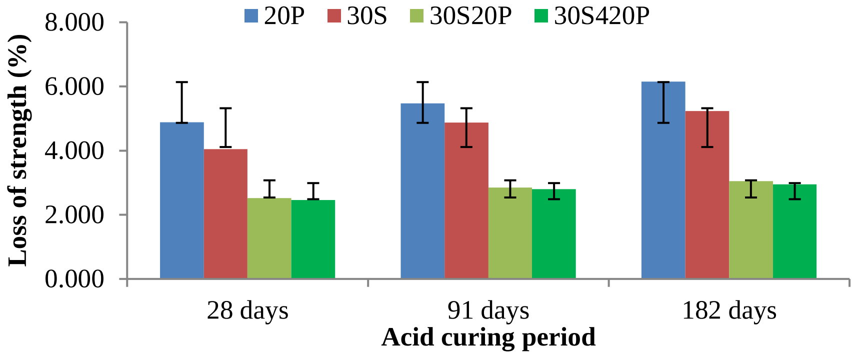

Fig. 7. Acid resistance of normal and graded concrete

Compared to 30S, 30S20P showed 38–42% reductions in strength loss, and 30S420P achieved 39–44% reductions over the same periods. The improved performance in graded concretes is attributed to the dense interfacial zone created by layering, which hinders acid penetration. In 30S20P, pozzolanic reactions from PPC increase C-S-H gel formation and reduce porosity. In 30S420P, FA fills microvoids and enhances secondary hydration, while lime helps neutralize acidic compounds, collectively improving durability under acidic exposure.

V.v. Microscopic analysis

The microscopic analysis of normal concrete samples and graded concrete samples was carried out through scanning electron microscopy (SEM). SEM is a powerful tool used to analyze the microstructure of concrete at high magnification. It provides detailed images of the concrete's surface, revealing the morphology of cement hydration products, voids, and cracks. SEM helps in identifying the distribution of aggregates, pore structures, and any potential defects like microcracks or voids. In the present study, normal concrete samples (20P and 30S) and graded samples (30S20P and 30S420P) were considered for SEM analysis. The micrographs are presented in Figure 8.

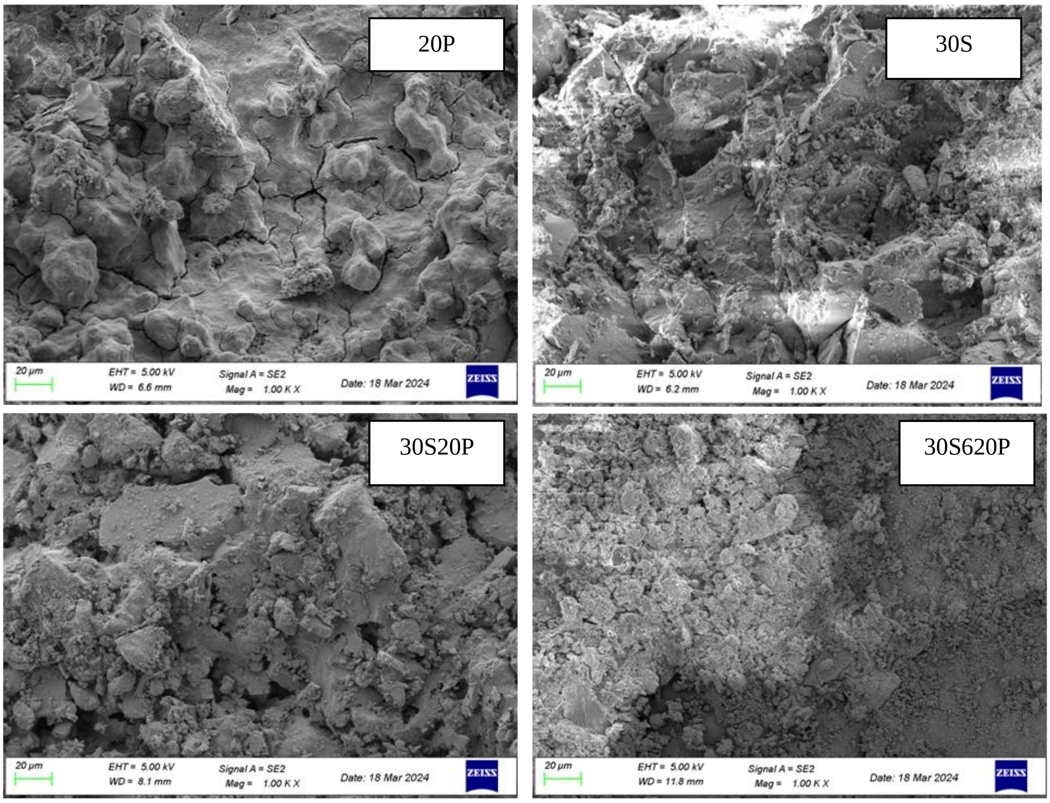

Fig. 8. Microstructure of normal and graded concrete

The micrograph of 20P shows a relatively porous structure, with visible voids and microcracks. The formation of calcium silicate hydrate (C-S-H) seems less dense, which correlates with the typical behavior of M20-grade concrete. The microstructure of 30S appears more refined, with fewer pores and microcracks compared to 20P. The increased density of the C-S-H gel and better particle packing in this sample likely contribute to the overall higher strength for the 30S. The micrograph of the graded concrete sample 30S20P shows a well-integrated interface. The top layer (20P) exhibits fewer voids compared to the single-layered 20P, indicating that the 30S bottom layer may have influenced the densification of the 20P top layer. This improved interfacial zone likely contributes to the properties of graded concrete as compared to the single-layered 30S, suggesting that the combination of different grades and binders improves microstructural packing. The SEM image of 30S420P reveals a dense microstructure, particularly in the bottom layer, where fly ash and lime have been added. The pozzolanic reaction of fly ash, combined with lime, appears to have further densified the C-S-H gel. The interface between the two layers is smooth, showing good adhesion and a refined microstructure.

V.vi. Embodied carbon

Embodied carbon in concrete refers to the total CO_2 emissions associated with its life cycle, from raw material extraction to construction. Cement, the main binder in concrete, is the largest contributor due to its energy-intensive production, accounting for a significant portion of global CO_2 emissions. Reducing concrete's embodied carbon is vital for sustainable construction and can be achieved by using supplementary cementitious materials, adopting alternative fuels, and improving construction methods.

In this study, the embodied carbon of normal and graded concrete mixes was assessed using data from Hammond et al. [XXXIII, XXXIV, XXXV], with results summarized in Table 5. All mixes used similar amounts of fine and coarse aggregates, which have relatively low embodied carbon. Therefore, differences in total emissions are mainly due to variations in cement content and replacement levels.

M30 concrete (30S), with 447 kg/m³ of cement, showed the highest embodied carbon at 334.893 $kgCO_2/m^3$, whereas M20 concrete (20P) had lower values due to reduced cement content. Notably, the double-layered samples (30S620P, 30S520P, 30S420P, 30S320P) demonstrated significant reductions in embodied carbon by partially replacing PSC with fly ash and lime. The greatest reduction was seen in 30S320P, which used 63% replacement and achieved a 38.02% reduction (207.560 $kgCO_2/m^3$) compared to 30S. The results are presented in Table 5.

Table 5: Embodied carbon of normal and graded concrete samples

	Coarse aggregate (Kg/m³)	**Fine aggregate (Kg/m³)**	**Cement (Kg/m³)**	**Fly ash (Kg/m³)**	**GGBFS (Kg/m³)**	**Ground lime stone (Kg/m³)**	**Water**	**Embodied carbon (KgCO²/m³)**	**% of benefit w.r.t. 30S**
Embodied carbon of materials ⇨	**0.0048**	**0.0048**	**0.73**	**0.008**	**0.083**	**0.032**	**0.001**	**Total**	
30S	614	1134	447	0	0	0	193	**334.893**	
20P	708	1283	405	0	0	0	183	305.389	
30S20P	661	1208.5	426	0	0	0	188	320.141	-4.40
30S620P	661	1208.5	336.6	73.75	0	15.65	188	255.970	-23.56
30S520P	661	1208.5	314.25	96.1	0	15.65	188	239.833	-28.38
30S420P	661	1208.5	291.9	118.45	0	15.65	188	223.697	-33.20
30S320P	661	1208.5	269.55	140.8	0	15.65	188	207.560	-38.02

VI. Conclusions

The following conclusions have been drawn from the recent study:

- The graded concrete (30S20P), made in two layers of equal height with M30 (30S) and M20 (20P) grades using PSC and PPC cements, exhibited 17, 5, 31, and 34% higher compressive strength than the higher-grade concrete (30S) at 7, 28, 91, and 182 days, respectively.

- Graded concretes (30S620P, 30S520P, and 30S420P), incorporating 40-60% cement replacement with 33-53% fly ash and 7% lime from 30S, showed 3-16% better compressive strength than 30S.
- The tensile strength of graded concrete 30S20P was 9, 3, 2 and 7% higher than 30S after 7, 28, 91, and 182 days of water curing, while 30S420P (with 60% cement replacement) showed a 4-9% improvement over 30S during the same period.
- After sulfuric acid exposure, 30S20P exhibited 38, 41, and 42% higher acid resistance at 28, 91, and 182 days, respectively, while 30S420P showed 39, 42, and 44% improvement over 30S.
- Both graded concretes demonstrated significantly reduced water sorption; 30S20P and 30S420P showed 75% and 76% lower sorption than 30S due to denser microstructure.
- Microstructural analysis confirmed a denser matrix in 30S20P and 30S420P compared to their parent concretes (30S and 20P).
- Embodied carbon was reduced by 4% in 30S20P and 33% in 30S420P compared to 30S.
- The graded concrete combining M20 and M30 through a layered system using PSC and PPC cements achieved strength nearing M45, with improved durability and sustainability benefits.
- Future work may incorporate detailed finite element simulations to visualize stress flow and interfacial behavior explicitly.

Conflict of Interest:

There was no relevant conflict of interest regarding this paper.

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