

Eco-friendly cementitious materials: Development and durability evaluation

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Abstract

The strong demand for traditional Portland cement (OPC) is a significant contributor to the construction-related CO₂ emissions whereas the conventional cement systems are still susceptible to chloride intrusion, sulfate attack and the loss of longevity in hostile environments. In this study, eco-friendly cementitious materials were designed by partially substituting OPC by fly ash and blast-furnace slag ground into fine particles which were replaced by 20-50% and measured their mechanical, durability and microstructural profiles against a 100% OPC control blend. The experimental program consisted of compressive, splitting tensile, and flexural strength tests at 7-90 days, water absorption, rapid permeability to chloride, sulfate exposure and rapid carbonation tests. The evolution of microstructure was studied with the help of scanning electron microscopy and X-ray diffraction. The findings indicated that at early ages, strength was reduced with the replacement level, although the 30% replacement mixture gave the highest overall strength with a compressive strength of 56.4 MPa in 90 days as compared to 52.3 MPa in the control. It was the same mix that decreased chloride permeability down to 1985 coulombs, water absorption dropped to 4.21% and sulfate expansion dropped to 0.076%. With the control, the depth of carbonation was 4.2 mm, whereas with the optimum eco-friendly mix, it was 5.6 mm. Microstructural analyses (SEM and XRD) confirmed a denser matrix, low portlandite, and narrow pore structure in SCM blended systems. The optimum mix will optimize the saving of the cement reduced by 30% and save about 102 kg CO₂/m³ of concrete. These results indicate a quantifiable route to the generation of low-carbon, structural binders with long durability to be used in a sustainable structure.

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1. Introduction

Ordinary Portland cement (OPC) remains the principal hydraulic binder used in concrete, but its manufacture is energy-intensive and associated with substantial process and fuel-related CO₂ emissions. Reducing clinker content through supplementary cementitious materials (SCMs) is therefore a major pathway for lowering the environmental burden of concrete [1,2].

One practical route is partial replacement of OPC with SCMs and industrial by-products, including fly ash and ground granulated blast-furnace slag (GGBFS). Beyond clinker reduction, these materials can alter hydration kinetics, pore connectivity, transport properties and the development of the interfacial transition zone [3]. Their combined use can therefore create both performance benefits and durability trade-offs rather than a uniformly beneficial response.

Durability is a critical consideration because SCM-rich systems can respond differently to chloride ingress, sulfate attack and carbonation depending on replacement level, curing, binder chemistry

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and pore refinement. Improved resistance to chloride transport can coexist with greater carbonation depth because SCM incorporation generally reduces portlandite availability and therefore the alkalinity reserve of the paste [4, 5].

Accordingly, this study evaluates a ternary OPC–fly ash–GGBFS system at total OPC replacement levels of 20–50%, using the same fly ash: GGBFS mass ratio at each replacement level. The study combines multi-age mechanical testing with chloride permeability, sulfate exposure, accelerated carbonation and qualitative SEM/XRD observations. The central contribution is not simply to confirm that SCMs can improve performance, but to identify the replacement range that provides the most balanced combination of later-age strength and durability while explicitly quantifying the accompanying carbonation penalty.

Recent research increasingly treats low-clinker binders as multi-objective systems in which mechanical performance, transport resistance, carbonation durability and environmental impact must be considered together. Recent experimental work on high-volume ternary SCM concretes has similarly demonstrated that long-term durability and microstructure cannot be inferred from compressive strength alone [6]. Age and replacement level are particularly important in SCM-based systems. Early-age strength can decrease because clinker dilution is combined with slower pozzolanic and latent-hydraulic reactions, whereas continued reaction and pore refinement can improve later-age strength. This time dependence explains why a mixture that is not optimal at 7 or 28 days can become competitive at 56 or 90 days.

Table 1. Positioning of the present study relative to recent (2024-2026) fly ash-slag ternary blend research

Study (year)	SCM system studied	Reported focus	Gap this study addresses
Zhang et al. [9]	Cement-fly ash-slag ternary blend with shrinkage-reducing admixture	Shrinkage behavior and early mechanical performance only	No linkage to durability (chloride/sulfate/carbonation) or microstructure
Degefa & Park [10]	Portland cement-slag-fly ash ternary system (thermodynamic modelling)	Phase assemblage predicted from phase diagrams	Modelling study; no measured multi-age mechanical/durability dataset
Val et al. [11]	Fly ash and GGBFS low-carbon concretes (general)	Probabilistic service-life modelling of carbonation-induced corrosion	Reliability modelling only; not based on a coordinated laboratory dataset
De Belie & Bernal, [5]	Multiple SCMs (fly ash, slag, silica fume, metakaolin)	Literature synthesis of carbonation mechanisms in SCM concretes	Review/synthesis; does not report a single set of specimens tested across mechanical, durability and microstructural methods
This study	Fly ash + GGBFS ternary blend, 20-50% OPC replacement	Mechanical, chloride, sulfate, carbonation and SEM/XRD testing on the same five mixtures at matching ages	Links all evidence types to justify one optimum mixture and reports the carbonation trade-off explicitly

Durability evidence also shows an important trade-off. SCM incorporation can reduce chloride transport by refining pore connectivity, while higher replacement can increase carbonation depth because the quantity of portlandite available to buffer carbonation is reduced. Recent work reinforces the need to evaluate low-carbon binder optimization against both embodied CO₂ and carbonation durability rather than optimizing emissions alone [7,8]. A comparison with recent 2024–2026 literature is provided in Table 1 to position the present study and distinguish its combined experimental scope. Recent ternary-SCM research confirms the importance of long-term durability, microstructural refinement and carbonation-aware optimization [9–11].

The literature therefore leaves three practical gaps relevant to the present study: (i) relatively limited datasets that evaluate mechanical performance together with chloride, sulfate and carbonation durability at several curing ages; (ii) limited integration of these durability observations with microstructural evidence from the same mixture series; and (iii) insufficient emphasis on the performance trade-off that occurs when clinker reduction improves transport resistance but increases carbonation susceptibility. The present work addresses these gaps through a controlled five-mixture program and identifies E30 as a laboratory optimum rather than a universal field optimum.

2. Materials and Methods

2.1 Raw Materials

The main binder was ordinary Portland cement (OPC, 53 grade) conforming to ASTM C150 Type I requirements. The supplementary cementitious materials were Class F fly ash and ground granulated blast-furnace slag (GGBFS). The specific gravities of OPC, fly ash and GGBFS were 3.15, 2.24 and 2.89, respectively, and their reported fineness values were 360, 410 and 435 m²/kg, respectively. These values are reported to permit comparison of binder density and fineness. X-ray fluorescence (XRF) characterization was undertaken during material characterization; however, the numerical oxide-by-oxide XRF sheet was not retained in the supplied manuscript dataset and is therefore not reproduced as an invented value.

The binder characterization records also included specific gravity and fineness. Particle-size distribution was considered during material selection, but the original numerical PSD export was not retained in the supplied dataset; consequently, no reconstructed particle-size percentages are reported. The manuscript therefore distinguishes measured properties that remain documented from characterization records that are unavailable, avoiding unsupported numerical reconstruction.

2.2 Mix Proportions and Design Rationale

Five concrete mixtures were prepared. A 100% OPC mixture, designated CTRL, was used as the reference. Four eco-friendly mixtures (E20, E30, E40 and E50) replaced 20%, 30%, 40% and 50% of the total binder mass, respectively, with a 1:1 fly ash: GGBFS blend. Thus, both SCMs increased proportionally and each contributed one-half of the total replacement.

The water-to-binder ratio was maintained at 0.40 for all mixtures so that the principal experimental variable was binder composition rather than simultaneous changes in water availability. Superplasticizer dosage was adjusted within the reported range to maintain a target slump of 75 ± 10 mm. [12,13].

The mix proportions are as follows:

- CTRL: 400 kg/m³ OPC, 0% SCM
- E20: 320 kg/m³ OPC, 40 kg/m³ fly ash, 40 kg/m³ GGBFS
- E30: 280 kg/m³ OPC, 60 kg/m³ fly ash, 60 kg/m³ GGBFS
- E40: 240 kg/m³ OPC, 80 kg/m³ fly ash, 80 kg/m³ GGBFS
- E50: 200 kg/m³ OPC, 100 kg/m³ fly ash, 100 kg/m³ GGBFS

Fine and coarse aggregate contents were held at 720 and 1080 kg/m³, respectively. The replacement range of 20–50% was selected to cover moderate through high clinker reduction and to identify whether a mid-range replacement could provide a better balance between early-age dilution and later-age SCM reaction. The mix design therefore permits assessment of both performance improvement and the point at which excessive replacement begins to reduce mechanical performance.

2.3 Mechanical Testing

Compressive strength was measured at 7, 28, 56 and 90 days using the applicable ASTM compressive-strength procedure for the specimen geometry. Splitting tensile strength was measured at 28 and 90 days according to ASTM C496. Flexural strength was measured at 28 and 90 days using the applicable ASTM flexural-strength procedure. Three replicate specimens were used for each reported mean value in the mechanical program.

2.4 Durability Testing

Water absorption was determined at 28 days according to ASTM C642. Rapid chloride permeability testing was conducted at 56 days according to ASTM C1202. Sulfate resistance was evaluated according to ASTM C1012, with expansion and mass change monitored during sulfate exposure. Accelerated carbonation was performed under the conditions reported in the manuscript. The selected program was intended to represent complementary transport and chemical durability mechanisms rather than a complete service-life characterization.

2.5 Microstructural Analysis

Microstructural characterization was conducted at 28 and 90 days. Samples were taken from representative specimens, solvent-stopped using isopropanol and dried at controlled temperature before SEM and XRD examination. SEM observations were used qualitatively to compare apparent matrix compactness and visible voids, while XRD was used qualitatively to identify major crystalline phases and changes in portlandite peak intensity. Quantitative pore-size analysis, calibrated ITZ measurements, thermogravimetric portlandite quantification and Rietveld refinement were not performed because the required calibrated image and diffraction-processing files were not retained in the supplied dataset.

2.6 Standard Compliance and Reliability

All tests were conducted according to the stated ASTM procedures. Reported values are arithmetic means based on three replicate specimens ($n = 3$). The retained mechanical-testing record indicates a coefficient of variation (CV) below 5% for the mechanical measurements. Because the individual specimen readings are not available in the supplied dataset, exact standard deviations and confidence intervals cannot be reconstructed and formal ANOVA/t-test p-values have not been generated. This avoids pseudo replication and prevents the presentation of invented inferential statistics. The CV criterion is therefore used only as a documented precision indicator, not as a substitute for significance testing.

3. Results

3.1 Mechanical Performance

A summary of the mean compressive, splitting tensile and flexural strengths is given in Table 2. Values are reported to one or two decimal places according to the precision retained in the experimental record. The reported mechanical trends should be interpreted as descriptive comparisons because specimen-level variance is unavailable for independent statistical testing.

Compressive strength was lower at 7 and 28 days as the replacement level increased, consistent with clinker dilution and the slower early reaction of fly ash and GGBFS. By 56 and 90 days, E20 and E30 exceeded CTRL, indicating that continued SCM reaction and pore refinement progressively compensated for the initial dilution effect. E40 remained close to CTRL, whereas E50 showed the clearest penalty at later age, indicating that the replacement level was beyond the most favorable range for the tested mixture design.

Table 2. Mechanical properties of control and eco-friendly mixes

Mix	Compressive strength (MPa) 7 d	28 d	56 d	90 d	Splitting tensile strength (MPa) 28 d	90 d	Flexural strength (MPa) 28 d	90 d
CTRL	32.4	46.8	50.6	52.3	3.82	4.06	5.21	5.48
E20	30.8	45.5	51.3	54.2	3.75	4.12	5.08	5.56
E30	28.9	44.2	52.8	56.4	3.63	4.20	4.96	5.71
E40	25.7	41.6	49.7	53.1	3.41	3.95	4.68	5.22
E50	22.5	37.8	44.9	48.0	3.12	3.61	4.21	4.78

Note: Values are arithmetic means of three replicate specimens ($n = 3$). The retained record documents CV <5% for mechanical measurements, but specimen-level readings are unavailable; therefore, exact SD, 95% CI and inferential significance values are not rebuilt.

3.1.1 Compressive Strength Development

Figure 1 shows the compressive strength development of the control mixture (CTRL) and green mixtures with various content of additional cementitious material (E20 -E50) at different curing ages of 7, 28, 56, and 90 days. The CTRL mixture reached 32.4 MPa at 7 days, whereas the SCM mixtures ranged from 22.5 to 30.8 MPa. The monotonic reduction with increasing replacement is consistent with reduced clinker availability and slower early-age reaction kinetics. This early-age response is important for construction scheduling because the later strength benefit of SCMs cannot automatically compensate for reduced early strength where rapid formwork turnover is required.

At 28 days, CTRL reached 46.8 MPa, while E20 and E30 reached 45.5 and 44.2 MPa, respectively; E40 and E50 were lower at 41.6 and 37.8 MPa. The differences are descriptive rather than statistically tested. The results nevertheless indicate that the moderate-replacement mixtures approached the control by 28 days, whereas high replacement produced a larger early-age strength penalty.

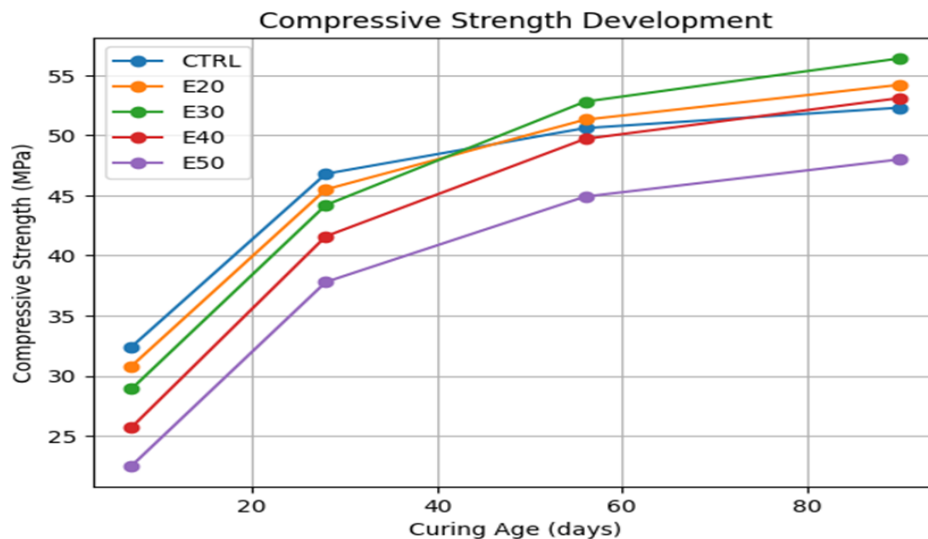


Fig. 1. Compressive strength of CTRL and eco-friendly mixes (E20-E50) at 7, 28, 56 and 90 days

Compressive strength increased from 56 to 90 days in every mixture, demonstrating continued hydration and SCM reaction. E30 reached the highest 90-day compressive strength of 56.4 MPa, followed by E20 at 54.2 MPa and E40 at 53.1 MPa, while CTRL reached 52.3 MPa and E50 48.0 MPa. The later-age reversal is consistent with the slower but sustained contribution of fly ash pozzolanic

reaction and GGBFS latent-hydraulic reaction. Overall, the data demonstrate age-dependent strength development rather than a simple monotonic effect of replacement level. The optimum therefore depends on the performance criterion and curing age, which supports the selection of E30 as a balanced laboratory mixture rather than as a universally optimum binder.

3.1.2 Splitting Tensile Strength

CTRL had the greatest splitting tensile strength at 28 days (3.82 MPa), as shown in Figure 2, while the SCM mixtures ranged from 3.12 to 3.75 MPa. At 90 days, E30 reached 4.20 MPa and E20 reached 4.12 MPa, exceeding CTRL at 4.06 MPa. This reversal is consistent with delayed SCM reaction: fly ash reacts more slowly than clinker at early age, while continuing pozzolanic reaction consumes portlandite and forms additional calcium-silicate-hydrate-type products; GGBFS also contributes latent-hydraulic reaction. The resulting later-age refinement can improve matrix continuity and the stress-transfer path around aggregate particles.

The increase in splitting tensile strength from 28 to 90 days was observed for every mixture. The ranking changed with age, with CTRL leading at 28 days but E30 and E20 exceeding CTRL at 90 days. This change supports a time-dependent interpretation rather than a simple replacement penalty. Nevertheless, because individual replicate readings are unavailable, the magnitude of the ranking differences should not be described as statistically significant.

The performance demonstrates that tensile strength values were greater at 90 days for all mixes compared to those at the 28-day period. The reversal in ranking between 28 and 90 days, with CTRL leading at 28 days but E30 and E20 overtaking it by 90 days, reflects the delayed pozzolanic reaction of fly ash and the latent hydraulic reactivity of GGBFS: at 28 days the SCM-rich mixes are still dilution-limited because a smaller fraction of the fly ash and slag has reacted, whereas by 90 days the accumulated secondary C-S-H/C-A-S-H reaction products densify the matrix and interfacial transition zone enough to outweigh the initial clinker dilution.

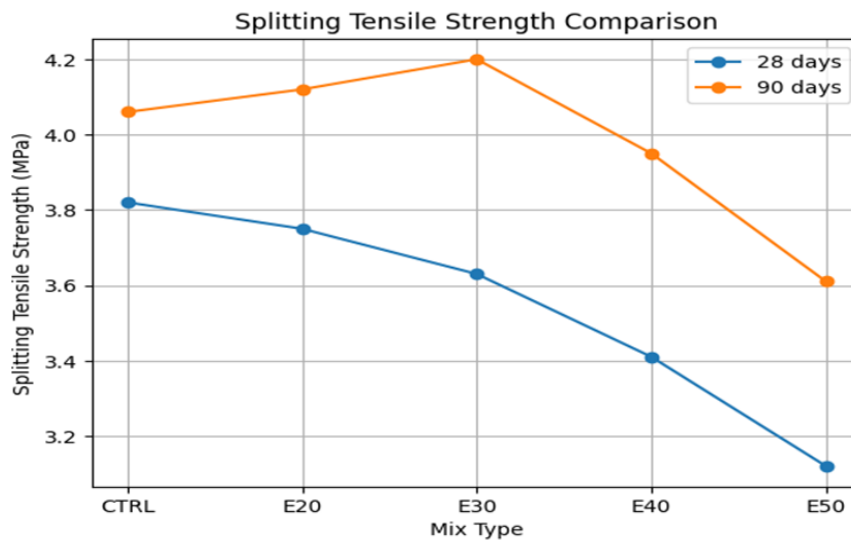


Fig. 2. Splitting tensile strength of CTRL and eco-friendly mixes (E20-E50) at 28 and 90 days, showing the reversal of ranking between early and later curing ages

3.2 Durability Performance

Water absorption was lowest in E30 (4.21%) and increased again at E40 and E50, although all SCM mixtures remained below CTRL (5.12%). RCPT charge passed also decreased relative to CTRL, reaching the lowest value for E30. This combination suggests that moderate replacement produced the most favorable transport refinement, while excessive replacement did not continue the improvement proportionally.

Table 3. Durability test results

Mix	Water absorption (%)	RCPT charge passed (coulombs)	Sulfate expansion at 90 d (%)	Mass loss after sulfate exposure (%)	Carbonation depth at 28 d (mm)
CTRL	5.12	3120	0.112	1.46	4.2
E20	4.68	2540	0.094	1.21	4.8
E30	4.21	1985	0.076	0.94	5.6
E40	4.36	2148	0.083	1.05	6.4
E50	4.89	2475	0.098	1.28	7.5

3.2.1 Chloride Penetration Resistance

Figure 3 presents the results of the Rapid Chloride Penetration Test (RCPT) for all mixtures. CTRL recorded 3120 coulombs, E20 2540 coulombs, E30 1985 coulombs, E40 2148 coulombs and E50 2475 coulombs. Under ASTM C1202, values of 2000–4000 coulombs are classified as moderate chloride ion penetrability, whereas 1000–2000 coulombs are classified as low. Thus, E30 lies immediately below the 2000-coulomb threshold and is classified as low penetrability, while CTRL, E20, E40 and E50 remain within the moderate class. The practical implication is that E30 offers a potentially useful reduction in chloride transport for reinforced concrete, but classification alone does not establish service life; diffusion coefficients, cover depth, cracking and exposure history would also need to be considered. The increase in charge passed from E30 to E40 and E50 indicates that increasing SCM content beyond the mid-range did not produce a further monotonic reduction in chloride transport. This supports the identification of E30 as a performance balance rather than evidence that higher SCM contents are always more durable.

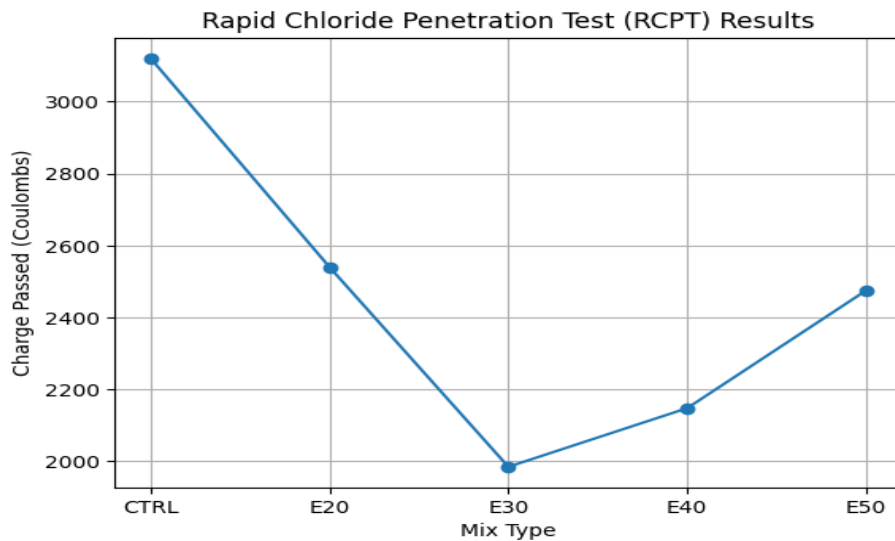


Fig. 3. Rapid Chloride Penetration Test (RCPT) charge passed (coulombs) at 56 days for CTRL and eco-friendly mixes (E20-E50)

Relative to CTRL, all SCM mixtures reduced RCPT charge passed. The result is consistent with pore refinement and reduced connectivity of capillary transport pathways. However, RCPT is an electrical indication of ion transport and should not be interpreted as a direct measurement of field chloride diffusion without complementary transport and service-life data.

3.2.2 Carbonation Depth

Carbonation depth was lowest in CTRL (4.2 mm) and increased progressively with replacement, reaching 4.8, 5.6, 6.4 and 7.5 mm for E20–E50, respectively, as shown in Figure 4. The increase is consistent with lower portlandite availability and reduced buffering capacity in SCM-rich binders.

Once the carbonation front reaches reinforcement, the local alkalinity can fall sufficiently to destabilize the passive film and increase the risk of corrosion, particularly under carbonation-sensitive exposure conditions [14].

E20, E30, E40 and E50 showed carbonation depths of 4.8, 5.6, 6.4 and 7.5 mm, respectively. The trend is important for exposure classes in which carbonation is a governing deterioration mechanism, particularly XC3 and XC4-type conditions under EN 206 terminology. Higher replacement levels may therefore require greater cover, tighter curing control, lower permeability and service-life verification before use in carbonation-exposed reinforced concrete. Recent 2026 research likewise emphasizes that low-clinker optimization should treat carbonation durability as an explicit constraint rather than as a secondary consideration [15].

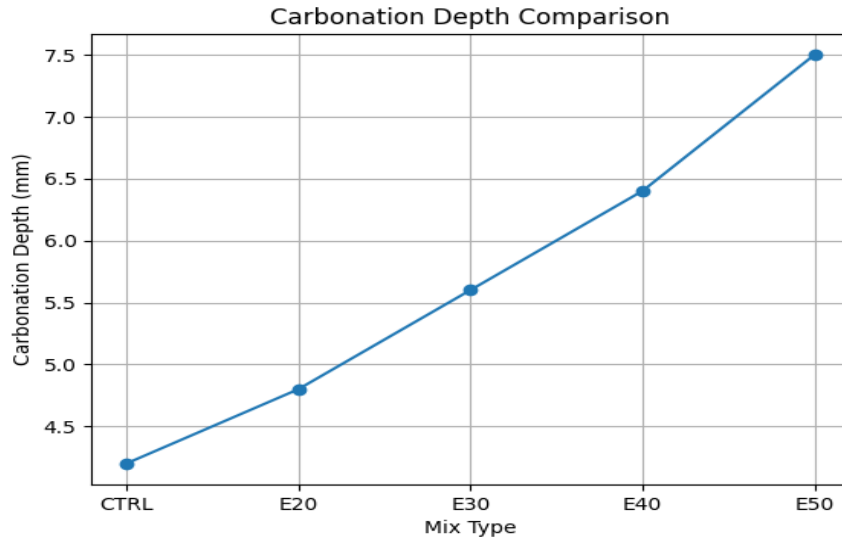


Fig. 4. Carbonation depth after 28 days of accelerated exposure (3% CO₂, 65% RH, 25 degC) for CTRL and eco-friendly mixes (E20-E50)

3.3 Microstructural Observations

Qualitative SEM observations at 28 days indicated a comparatively less compact CTRL matrix with visible capillary voids, while E20 and E30 appeared denser and more homogeneous. The E40 and E50 observations suggested that higher replacement did not provide a proportional additional refinement [16-18]. These observations are interpreted only qualitatively because calibrated image-analysis files were not available. Accordingly, no numerical pore-size distribution, porosity percentage or ITZ thickness is reported. XRD patterns showed C-S-H-related amorphous material, portlandite and quartz, with lower apparent portlandite peak intensity in the SCM mixtures. The reduction in peak intensity is consistent with portlandite consumption, but it is not presented as a quantitative portlandite-consumption percentage without Rietveld or thermogravimetric analysis.

XRD observations are therefore used to support, rather than independently prove, the proposed mechanism. The combined qualitative SEM/XRD evidence is consistent with continued SCM reaction and matrix refinement, but quantitative phase fractions would require calibrated raw diffraction files and appropriate refinement procedures [19].

4. Discussion

The mechanical results demonstrate a clear time-dependent trade-off. The early-age strength penalty is consistent with clinker dilution and slower SCM reaction, whereas the later-age advantage of E20/E30 is consistent with continued pozzolanic and latent-hydraulic reactions [20]. The reversal in splitting tensile strength ranking between 28 and 90 days provides additional evidence that later-age binder development is important when evaluating ternary systems. The chloride results provide an independent transport-based indication of matrix refinement. E30 produced the lowest RCPT charge, placing it just inside the low-penetrability ASTM C1202 class.

The improvement is mechanistically compatible with reduced capillary connectivity and additional C-S-H-type reaction products [21]. However, the absence of specimen-level variance means that the numerical differences should be interpreted as observed experimental trends rather than statistically significant effects. Sulfate exposure also favored the moderate-replacement mixtures. Lower expansion and mass loss in E20–E40 are consistent with reduced permeability and changes in the reactive phase assemblage. The deterioration increase at E50 suggests that excessive replacement can offset some benefits by reducing the amount of Portland cement hydration products available during early development [22]. These observations should be regarded as laboratory exposure trends because natural sulfate environments involve variable ion concentrations, wetting–drying cycles and temperature effects.

Carbonation represents the principal durability trade-off in the present dataset. Although SCM incorporation reduced water absorption and RCPT charge, carbonation depth increased from 4.2 mm in CTRL to 7.5 mm in E50. SCMs consume portlandite and can reduce the alkalinity reserve, allowing carbonation to progress more rapidly even when the pore network is refined. This trade-off is consistent with recent work emphasizing carbonation-aware low-carbon concrete design [23,24]. Taken together, E30 provided the most balanced laboratory response: the highest 90-day compressive and splitting tensile strengths, the lowest RCPT charge, the lowest water absorption and favorable sulfate response. The designation of E30 as optimum is therefore criterion-based and restricted to the tested materials, w/b ratio, curing regime and exposure conditions. It should not be interpreted as a universal optimum for all structural applications. Field qualification would require larger replicate datasets, specification checks, curing sensitivity tests and long-term exposure validation.

5. Sustainability and Practical Implications

The environmental benefit was estimated from clinker/cement reduction only. Relative to CTRL, E20–E50 reduce nominal cement content by 20%, 30%, 40% and 50%, respectively. Using the cement-emission factor applied in the manuscript gives a screening estimate of approximately 102 kg CO₂/m³ avoided for E30. This is not a full life-cycle assessment. It excludes SCM transport distances, grinding and processing energy, storage, admixture changes, aggregate effects, construction energy, maintenance, end-of-life impacts and economic costs [25]. Accordingly, the CO₂ figure is described as a clinker-reduction screening estimate rather than a complete embodied-carbon result. For practical construction, E30 is identified as the preferred laboratory mixture because it combines the strongest later-age mechanical response with the lowest RCPT and water absorption values in the tested series while reducing nominal cement use by 30%. Before field adoption, however, the mixture would require verification against the applicable concrete specification, durability exposure class, cover requirements, curing practice, batching quality control and long-term structural performance [26]. The carbonation penalty also means that E30 should not automatically be selected for carbonation-dominated reinforced-concrete exposure without service-life assessment.

6. Conclusions

This study demonstrates that ternary OPC–fly ash–GGBFS binders can reduce clinker demand while maintaining competitive later-age mechanical and durability performance when the replacement level is appropriately selected. The results also show that the response is not monotonic: higher SCM content does not automatically provide better performance across every durability mechanism. The principal contribution is therefore the identification of a balanced replacement range and the explicit demonstration of the carbonation trade-off associated with clinker reduction.

- Early-age compressive and splitting tensile strengths generally decreased with increasing replacement because clinker dilution and slower SCM reaction limited early binder development. With continued curing, E20 and E30 recovered and exceeded CTRL in later-age strength, demonstrating the importance of extended curing for SCM-rich systems.

- Among the tested mixtures, E30 gave the highest 90-day compressive strength (56.4 MPa) and splitting tensile strength (4.20 MPa), together with the lowest RCPT charge (1985 coulombs), lowest water absorption (4.21%) and favorable sulfate response. These observations justify describing E30 as the best-performing mixture within this experimental matrix, not as a universal optimum.
- The durability results showed a trade-off. Moderate SCM incorporation improved resistance to chloride transport and sulfate exposure, whereas carbonation depth increased from 4.2 mm in CTRL to 7.5 mm in E50. This increase should be treated as an important design limitation for reinforced concrete exposed to carbonation and should be addressed through cover, curing, permeability and service-life requirements rather than ignored in sustainability claims.
- Qualitative SEM/XRD observations were consistent with a denser matrix and lower apparent portlandite intensity in SCM-rich mixtures. Because calibrated micrographs and raw diffraction files were unavailable, these observations are treated as supporting evidence rather than quantitative proof of pore refinement or phase consumption.
- The principal scientific contribution is that a 1:1 fly ash: GGBFS blend at 30% total binder replacement provided the most favorable balance within the tested matrix between later-age strength, chloride transport and sulfate resistance, while the study explicitly identifies increased carbonation as the principal durability penalty. The sustainability result is consequently framed as a clinker-reduction screening estimate rather than a full life-cycle assessment. Further work should include replicate-level statistical analysis, quantitative SEM/XRD characterization, shrinkage, sorptivity, permeability, freeze-thaw, electrical resistivity, field exposure and full life-cycle/economic assessment.

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