


Reinventing concrete: exploring strength and durability with portland slag cement

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ABSTRACT

The potential of Portland Slag Cement (PSC) may increase mechanical strength and longevity, its application in concrete is becoming more and more popular. PSC-concrete qualities are examined in this work, with a particular emphasis on microstructure, strength, and durability. Compressive, split tensile, flexural, and modulus of elasticity tests were conducted using different curing techniques. The outcomes were contrasted with formulations of regular Portland cement (OPC). At various curing times, tests for durability such as porosity, acid resistance, sorptivity, water absorption, and chloride penetration were carried out. PSC-related microstructure alterations were examined using sophisticated methods including SEM and XRD. Results show that PSC enhances concrete performance over the short and long terms, especially in abrasive settings. Microstructural research reveals that the effect of slag is responsible for improved pozzolanic reactions, decreased porosity, and refined pore structure. The potential of PSC to improve the lifetime and durability of concrete is highlighted by this study.

Keywords: Portland slag cement; Mechanical; Durability; Micro analysis.

1. INTRODUCTION

The incorporation of metakaolin (MK) and ultra-fine slag into Portland cement (PC) has been shown to enrich the compressive strength and fluidity of the blended cement, suggesting that ultra-fine slag can enhance the physical and mechanical properties of MK blended cement [1]. Similarly, the use of blasted copper slag as a fine aggregate in Portland cement concrete has demonstrated an increase in workability and a reduction in water absorption capacity, although there is a reduction in compressive strength with higher replacement levels [2].

Studies into Portland-slag and composite cement concretes have shown that incorporating ground GGBS, along with silica fume (SF) and fly ash (FA), can improve engineering and durability characteristics. However, it's important to note that this enhancement may come at the expense of reduced resistance to carbonation [3–5]. The effect of slag cement on ultra-high performance concrete (UHPC) has been studied, showing that slag cement can improve flowability, reduce superplasticizer dosage, and influence shrinkage and durability properties [6, 7].

Chemical activation of SBPC using various chemical activators and quality enriches like Triisopropanolamine (TIPA) and Triethanolamine (TEA) has been found to improve the hydraulic properties and axial strength of the material [8, 9]. Alkali-activated Portland blast-furnace slag cement has exhibited significant increases in compressive strength and a dense microstructure when activated with NaOH and water glass [10, 11].

Slag Portland cement's carbonation durability has been thoroughly studied, and the results show that slag Portland cement-reinforced soil has a lower carbonation durability than regular Portland cement. Interestingly, though, carbonation has been proven to increase its potency [12–14]. Additionally, the development of an inner product that is continuously hydrated and an exterior product that is highly polymerized, low-Ca, and amorphous C-S-H have been related to the long-term performance of slag concretes, supporting durability. [15, 16]

The addition of natural pozzolanic additives like Rice Husk Ash (RHA) and Natural Steatite Powder (NSP) to Portland slag cement mortar has been shown to improve mechanical properties and durability, with the best results observed at lower replacement levels [17]. Lastly, thermal activation of OPC-slag mortars has been

explored, revealing that heating can significantly enhance early and ultimate strengths, which is particularly beneficial for the precast industry [18, 19].

The BIS specification IS 455:2015 lays out the rules and regulations that control of PSC in India. This extensive manual covers all facets of PSC production, features, and testing protocols, making it the go-to resource for guaranteeing PSC quality and consistency [20].

ASTM C595/C595M-20 is a commonly accepted standard specification for blended hydraulic cements, which includes PSC. This standard describes the composition, physical characteristics, and performance requirements of PSC and provides extensive instructions for its manufacturing and use in the United States [21, 22]. In a similar vein, the EN 197-1:2011 standard is well respected throughout Europe. It offers comprehensive details on the composition, specifications, and conformance standards that apply to popular cements, such as Portland Slag Cement (PSC). This document, which has been approved by the European Committee for Standardization (CEN), provides the fundamental guidelines that control the whole range of PSC manufacturing and application in European building practices. The comparison of Portland cement of grade 33 and Portland slag cement is lacking from the previous research.

2. MATERIALS AND METHODS

2.1. Cement

Portland Slag Cement properties relative density and fineness of the cement are 2.679 and 2%, respectively. With an initial setting time of 112 minutes and a final setting time of 248 minutes, the cement typically has a consistency of around 32%. The cement mortar's compressive strengths after the curing time are measured at three days, seven days, and twenty-eight days, and they are 12.07 MPa, 17.49 MPa, and 29.58 MPa, respectively. These characteristics give important information about the properties of the cement, which makes it a great choice for a range of building applications with different performance requirements across different periods [23].

2.2. Fine aggregate

The given river sand demonstrates the following characteristics: It is compact, as seen by its relative density of 2.648. The particle size distribution's fineness modulus, as indicated by sieve analysis, is 2.717. It's categorized as medium sand and is appropriate for building because it's in Zone II. It has a 4.05% water absorption rate, which allows it to hold moisture while being stable. Its density when loosely packed is indicated by its loose bulk density of 1668 kg/m³, while its density when compacted is shown by its dry rodded bulk density of 1833 kg/m³. Together, these characteristics offer vital information for choosing and applying this medium sand in construction, guaranteeing that it satisfies certain project specifications.

2.3. Coarse aggregate

The following fundamental qualities apply to the provided material: With a relative density of 2.989, it possesses a high degree of solidity and compactness. Its remarkably low water adsorption capacity (about 0.58%) suggests that it is resistant to absorbing moisture. Mass per unit volume, or volumetric density, is 1530 kg/m³. All of these qualities suggest that this material is best suited for applications that call for high density and little water absorption, which makes it helpful in industrial, engineering, and architectural settings where moisture resistance and durability are important considerations. The maximum size of coarse aggregate used in this research is 20 mm.

2.4. Curing

In the material processing and construction sectors, curing methods have a big impact on finished product efficacy and durability. Typical curing procedures involve preserving ideal moisture and temperature levels to enable the right hydration of cement in concrete. This process is essential for improving strength growth and preventing cracks from forming. The hydrochloric acid curing technique, on the other hand, is a specific technology used to speed up the curing process of goods made of precast concrete. By applying a diluted hydrochloric acid solution to the surface, this method efficiently increases the hardness of the surface. On the other hand, the production of acid-resistant materials, such as acid-resistant bricks, uses sulfuric acid curing. This process is vital for guaranteeing that the finished product will withstand corrosive conditions in the event that it is exposed to severe chemicals like sulfuric acid. This method creates a thick, impermeable covering that provides protection against the degradation of chemicals. The results of the various treatment modalities have been compared.

3. EXPERIMENTAL INVESTIGATION

A comprehensive experimental study is being planned to assess the workability, mechanical qualities, durability, and microstructural analysis of a specific building material, such as Portland Slag Cement (PSC) compared with OPC 33 grade in a comprehensive manner. Gaining important knowledge about this material's behavior in various building settings is the goal. The compaction factor test and slump test will be used to evaluate workability, with an emphasis on compaction and placement ease during construction. To monitor its evolution over time, mechanical characteristics such as axial, tensile, and flexural strengths will be assessed at different curing intervals. A variety of tests, including those for saturated water absorption, porosity, acid resistance, sorptivity, and fast chloride penetration, will be used to assess durability in order to determine how well it can handle environmental stresses while preserving structural integrity. The material's microstructure, phase composition, and pore structure will all be examined microscopic using X-ray diffraction (XRD) and scanning electron microscopy (SEM), which will provide insight into the material's inherent properties and any weak points.

This extensive experimental study is to improve our understanding of the material's adaptability in various building scenarios, enabling researchers and engineers to make well-informed choices about its suitability and practical performance.

4. RESULTS AND DISCUSSION

4.1. Slump cone test

The concrete mixes were made and their slump flow characteristics assessed as part of a mix design research. Mix M1, which is standard concrete, showed a 122 mm slump flow. Mix M2, which had an admixture, had a 128 mm slump flow and demonstrated better workability. In contrast, Mix M3, in the absence of any admixture, had a slump flow that was 121 mm less. These findings show how admixtures affect concrete workability, with Mix M2 showing the best flowability out of all the mixes put to the test. By adding admixture the workability have been increased and without adding admixture the workability of concrete have been reduced.

4.2. Compaction factor

As part of the mix design assessment procedure, we evaluated three different concrete mixes according to their compaction factor. The compaction factor of mix M1, which is standard concrete, was found to be 0.962. On the other hand, Mix M2, which included an admixture, demonstrated marginally improved compaction (factor of 0.969). On the other hand, Mix M3, which was not mixed, had a compaction factor of 0.964. These results emphasize the important impact of commixture on the workability of concrete; Mix M2 shows the greatest compaction factor of all the mixes tested, indicating that it is easier to compaction during construction. By adding admixture the workability have been increased and without adding admixture the workability of concrete have been reduced.

4.3. Compressive strength test

Figure 1 shows a visual representation of the compression strength data (in MPa) for different concrete mixes at different curing durations. The findings of the compression strength analysis show clear patterns in different mix designs and curing techniques. Mixtures including admixture showed the highest strengths during normal curing: M2 (28.89 MPa), M3 (27.83 MPa), and M1 (26.50 MPa), in that order. Concentric hydrochloric acid curing, on the other hand, produced somewhat lower strengths; the top three were M5 (28.24 MPa), M6 (27.26 MPa), and M4 (26.53 MPa). Similarly, decreasing strengths were shown in concentric sulfuric acid curing; the greatest values were found in M8 (27.26 MPa), M9 (26.74 MPa), and M7 (25.51 MPa). Notably, admixture's effectiveness in enhancing concrete performance is highlighted by the constant strength improvement seen with it across all curing techniques.

4.4. Split tensile strength

Figure 2 shows a visual representation of the split tensile strength data (in MPa) for different concrete mixes at different curing durations. The split tensile strength results depict varying trends across different mix designs and curing methods. Under normal curing, mixes with admixture exhibited the highest strengths: M2 (2.53 MPa), M3 (2.51 MPa), and M1 (2.47 MPa) at 28 days, respectively. Conversely, concentric hydrochloric acid curing yielded slightly lower strengths, with M5 (2.48 MPa), M6 (2.46 MPa), and M4 (2.44 MPa) leading the results. Similarly, concentric sulfuric acid curing displayed decreased strengths, with M8 (2.46 MPa), M9 (2.43 MPa), and M7 (2.41 MPa) exhibiting the highest values. The consistent strength enhancement observed with admixture across all curing methods highlights its efficacy in improving concrete performance.

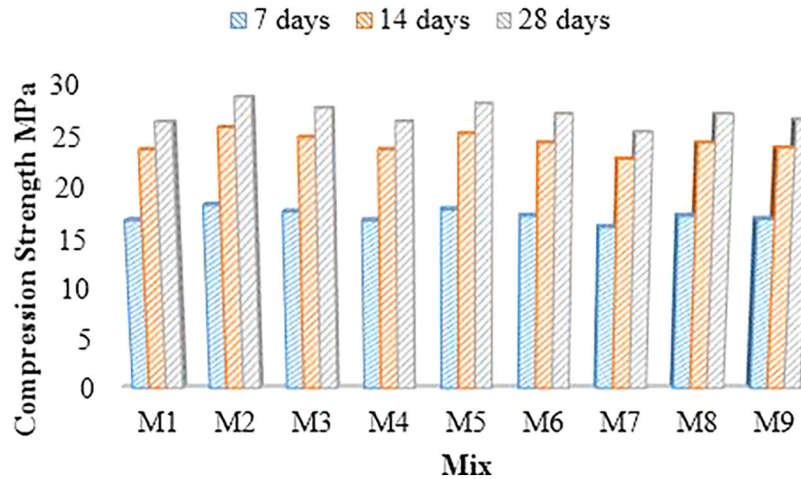


Figure 1: Shows the graphical representation of compressive strength test.

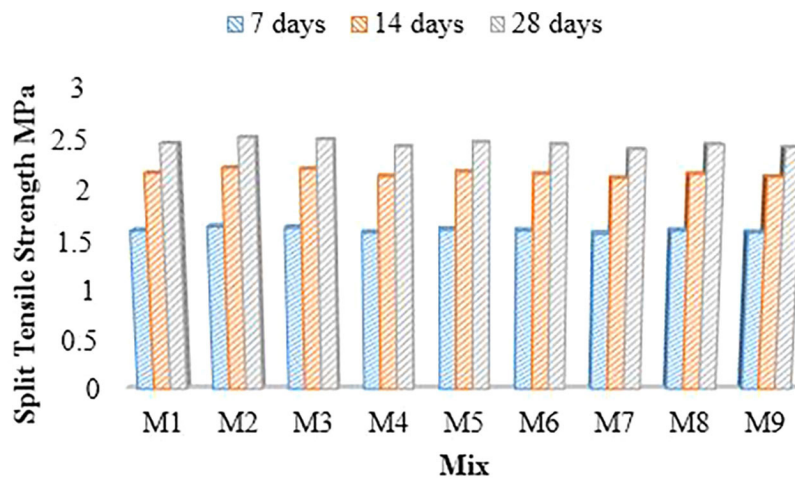


Figure 2: Shows the graphical representation of split tensile strength test.

4.5. Flexural strength test

Figure 3 shows a visual representation of the flexural strength data (in MPa) for different concrete mixes at different curing durations. The flexural strength results exhibit distinctive patterns across various mix designs and curing methods. Under normal curing, mixes with admixture displayed the highest strengths: M2 (3.76 MPa), M3 (3.62 MPa), and M1 (3.45 MPa) at 28 days, respectively. Conversely, concentric hydrochloric acid curing resulted in slightly lower strengths, with M5 (3.67 MPa), M6 (3.54 MPa), and M4 (3.45 MPa) leading the results. Similarly, concentric sulfuric acid curing demonstrated decreased strengths, with M8 (3.54 MPa), M9 (3.48 MPa), and M7 (3.32 MPa) exhibiting the highest values. The consistent strength enhancement observed with admixture across all curing methods highlights its efficacy in improving concrete performance.

4.6. Modulus of elasticity

The visual variation in the modulus of elasticity (abbreviated as “E”) values for different concrete mixes, expressed in megapascals (MPa), is displayed in Figure 4. The results reveal nuanced variations in the modulus of elasticity (E) among concrete mixes subjected to different curing methods and admixture compositions. Under normal curing conditions, mixes M1, M2, and M3 displayed E values of 21285 MPa, 21335 MPa, and 21306 MPa, respectively. Transitioning to concentric hydrochloric acid curing, mixes M4, M5, and M6 exhibited slightly lower E values, ranging from 21216 MPa to 21294 MPa. Interestingly, when exposed to concentric sulfuric acid curing, mixes M7, M8, and M9 demonstrated the lowest E values, spanning from 21203 MPa to

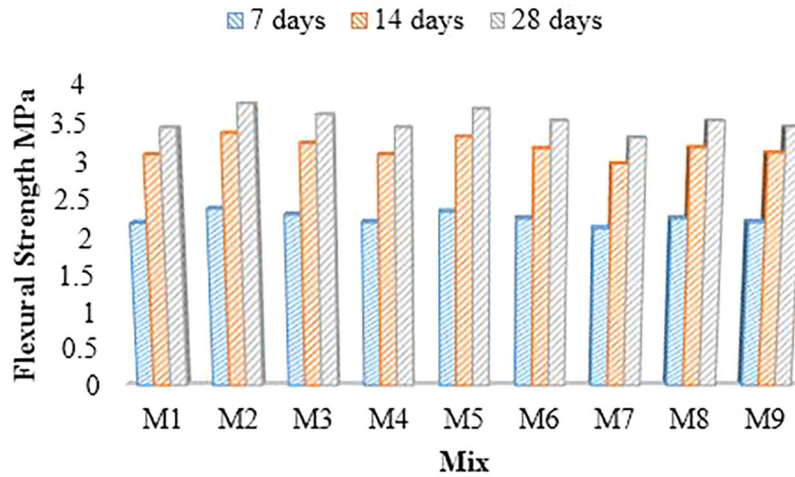


Figure 3: Shows the graphical representation of flexural strength test.

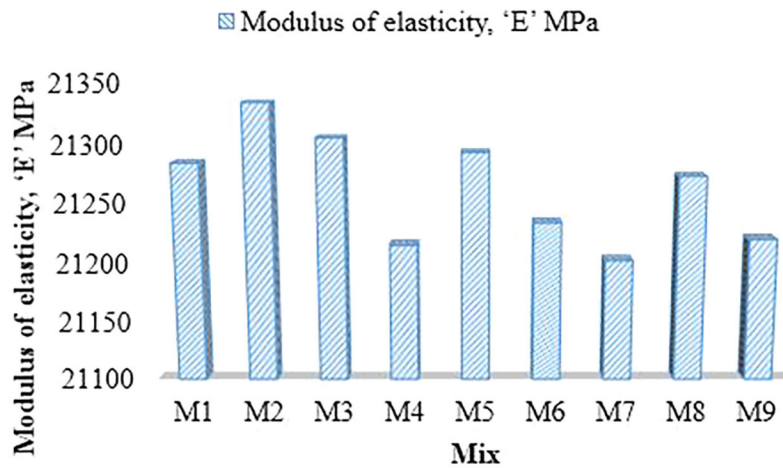


Figure 4: Shows the graphical representation of modulus of elasticity.

21274 MPa. These findings underscore the subtle influence of curing methods and admixture presence on the modulus of elasticity, highlighting the need for further investigation into their precise effects on concrete structural integrity.

4.7. Saturated water absorption

Figure 5 shows the percentage of saturated water absorbed by different concrete mixes at varying curing times. Longer curing times consistently show a tendency of saturation water absorption across all curing techniques—normal, concentric hydrochloric acid, and concentric sulfuric acid curing. For example, mixes M1, M2, and M3 showed, at 28 days, water absorption rates of 2.99%, 2.94%, and 2.96%, respectively, under typical curing conditions. Mixtures that were cured in sulfuric acid and concentric hydrochloric acid also had similar water absorption values. These findings highlight how additive compositions and curing techniques affect concrete’s ability to absorb water. For the purpose of creating resilient concrete buildings that can successfully survive climatic conditions, it is essential to comprehend these dynamics.

4.8. Porosity

The effective porosity (%) of many concrete mixes at varied cure times is shown in Figure 6. A steady trend of effective porosity is seen over time for all three types of curing techniques: normal, concentric sulfuric acid, and concentric hydrochloric acid. For example, mixes M1, M2, and M3 showed effective porosities of 5.82%, 5.76%, and 5.79%, respectively, at 28 days under standard curing conditions. Similar effective porosity values

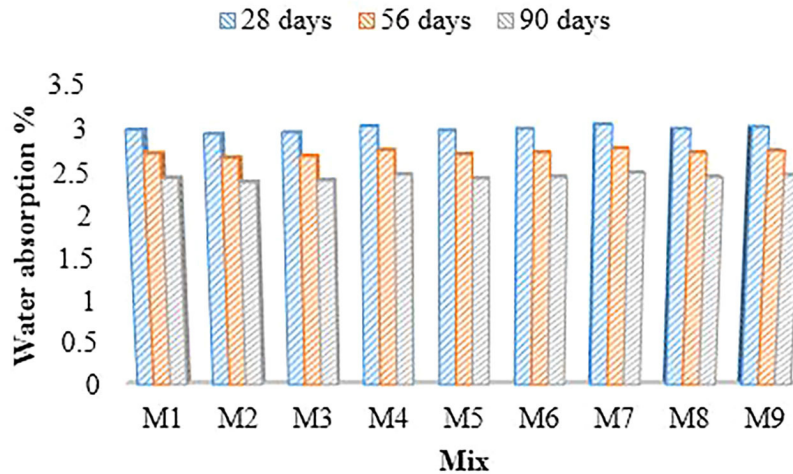


Figure 5: Shows the graphical representation of saturated water absorption.

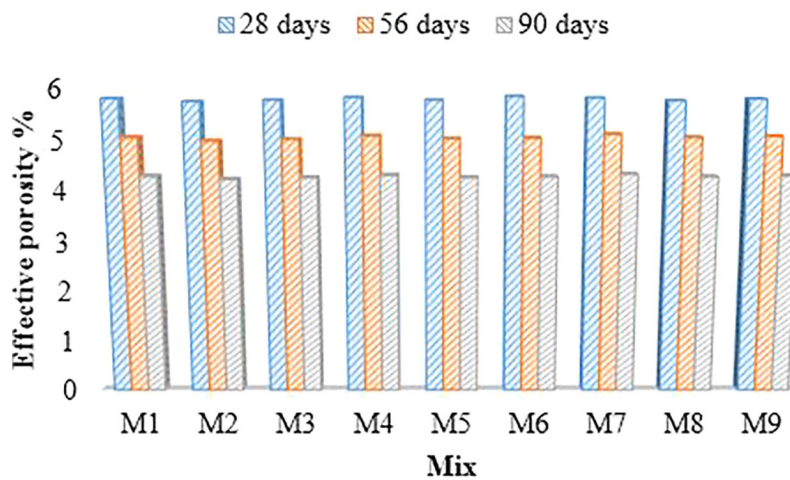


Figure 6: Shows the graphical representation of porosity.

were observed in mixtures that were cured in sulfuric acid and concentrated hydrochloric acid. These findings demonstrate how additive compositions and curing techniques affect the porosity properties of concrete.

4.9. Acid resistance test

The Figure 7 presents the percentage of weight loss from exposure to sulfuric acid for various concrete mixes at different curing durations. Across all curing methods—normal, concentrated hydrochloric acid, and concentrated sulfuric acid curing—a consistent trend of weight loss is observed over time. For instance, at 28 days, mixes M1, M2, and M3 under normal curing experienced weight losses of 4.66%, 4.59%, and 4.62%, respectively. Similarly, mixes subjected to concentrated hydrochloric acid and sulfuric acid curing showed comparable weight loss values. These findings highlight the influence of curing methods and admixture compositions on the durability of concrete in acidic environments.

4.10. Sorptivity test

The Figure 8 illustrates the sorptivity (in $10^{-5}10^{-5}$ (m/s^{1/2})) of various concrete mixes at different curing durations. Across all curing methods—normal, concentrated hydrochloric acid, and concentrated sulfuric acid curing—a consistent trend of sorptivity is observed over time. For instance, at 28 days, mixes M1, M2, and M3 under normal curing exhibited sorptivity values of 5.53×10^{-5} , 5.53×10^{-5} , 5.50×10^{-5} , 5.50×10^{-5} , and 5.52×10^{-5} , 5.52×10^{-5} (m/s^{1/2}) respectively. Similarly, mixes subjected to concentrated hydrochloric acid and sulfuric acid curing showed comparable sorptivity values. These results underscore the influence of curing

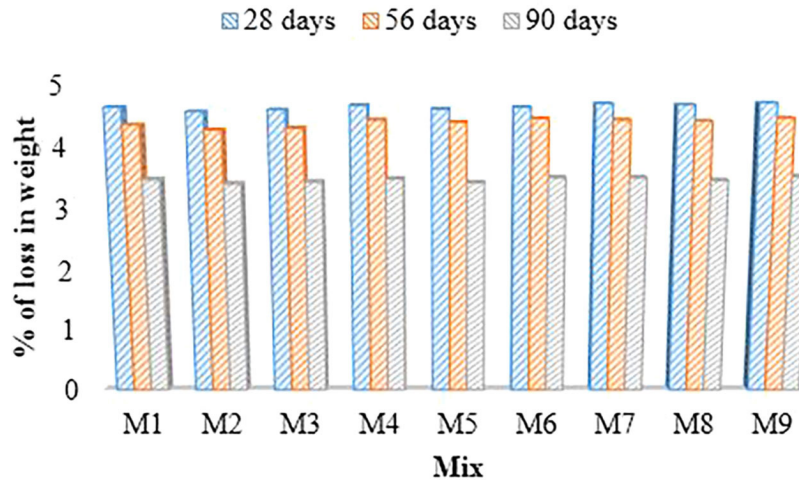


Figure 7: Shows the graphical representation of acid resistance test.

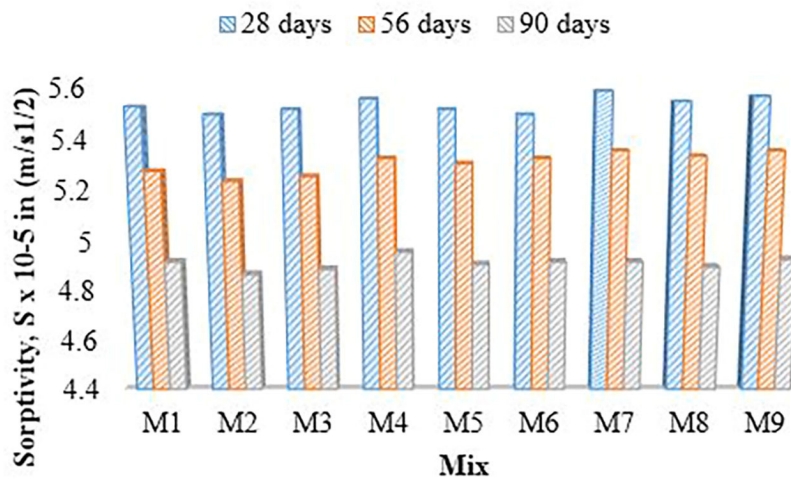


Figure 8: Shows the graphical representation of sorptivity test.

methods and admixture compositions on the water absorption characteristics of concrete. Understanding these variations is vital for designing concrete structures with optimal resistance to moisture ingress and related deterioration.

4.11. Rapid chloride penetration test

Figure 9 shows the total charge passed (measured in Coulombs) for a range of concrete mixtures at varying curing times. A steady trend of total charge buildup is shown over time for all curing techniques—normal, concentric sulfuric acid, and concentric hydrochloric acid. For example, mixes M1, M2, and M3 showed total charge values of 2157 C, 2136 C, and 2153 C, respectively, at 28 days under normal curing. Mixtures that were cured in sulfuric acid and concentric hydrochloric acid also had similar total charge values. These findings imply that the electrical characteristics of concrete are influenced by additive content and curing techniques.

4.12. SEM

The microstructure of concrete specimens was examined using scanning electron microscopy (SEM), which provided important information on composition, shape, and pore structure. Upon normal curing, SEM analysis of conventional concrete indicates an effective hydration process with a well-dispersed matrix of hydrated cement particles and few unhydrated ones. Admixture-treated concrete has a microstructure that is similar in terms of effective dispersion and pore distribution. The microstructure is similar when there is no mixing. On the

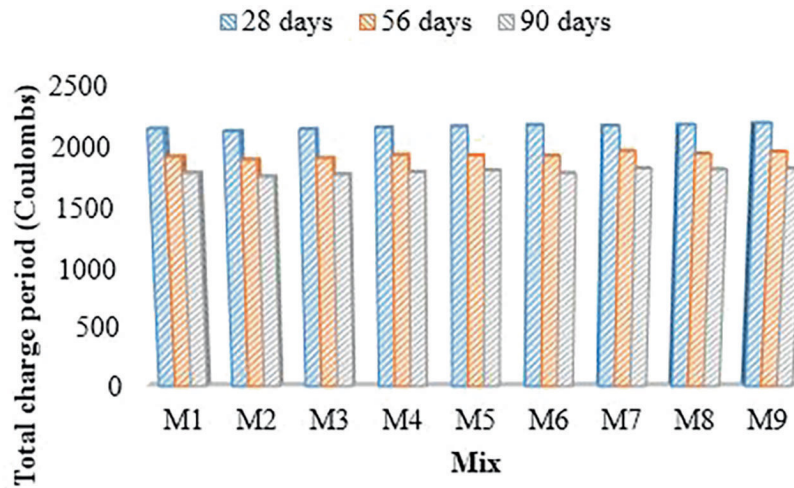


Figure 9: Shows the graphical representation of rapid chloride penetration test.

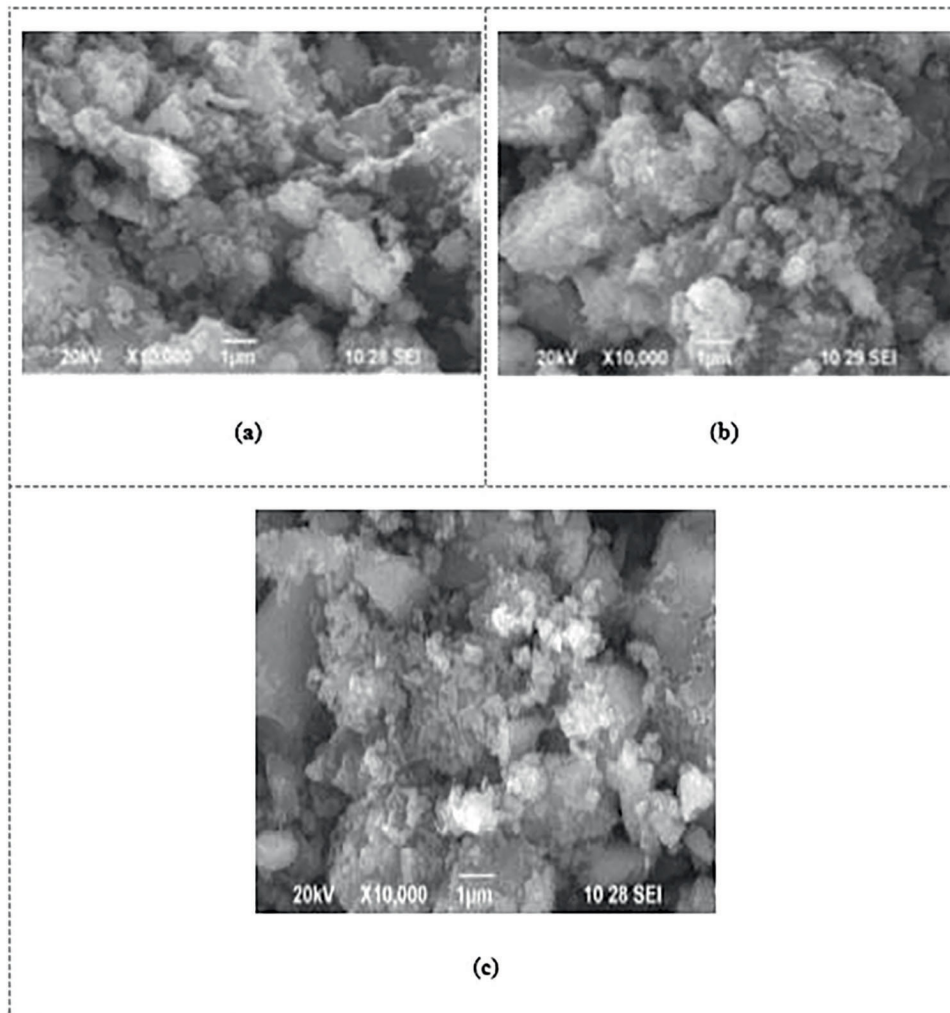


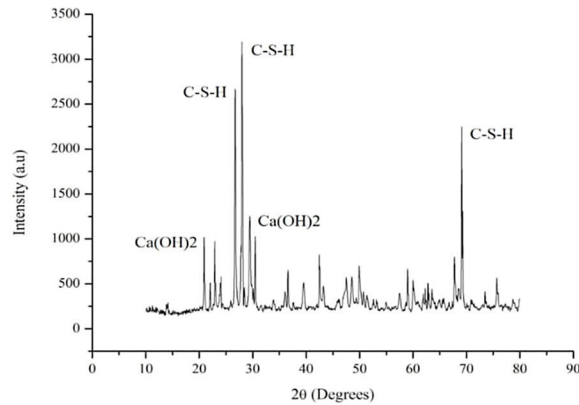
Figure 10: Shows the SEM images.

other hand, concrete surfaces exhibit etching, increased porosity, and cementitious material leaking during concentric hydrochloric acid curing, showing corrosive effects. Concentric sulfuric acid curing causes noticeable etching, large porosity, and substantial leaching in the microstructure of the concrete, which is indicative of the acid's corrosive effects. SEM analysis offers vital information on the microstructural alterations brought about

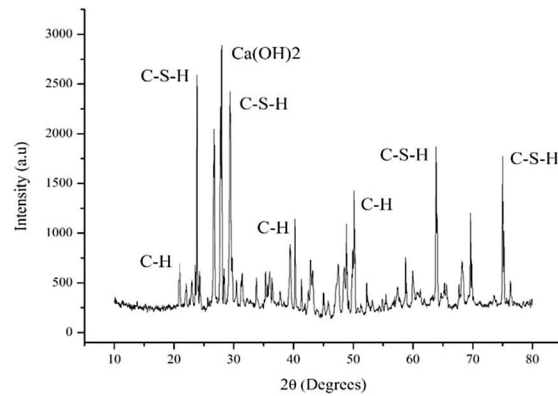
by curing techniques and the presence of admixtures, information that is critical for evaluating the durability and long-term performance of concrete in practical uses. The SEM images of mix M1, M4, and M6 are displayed in Figure 10(a)–(c).

4.13. XRD

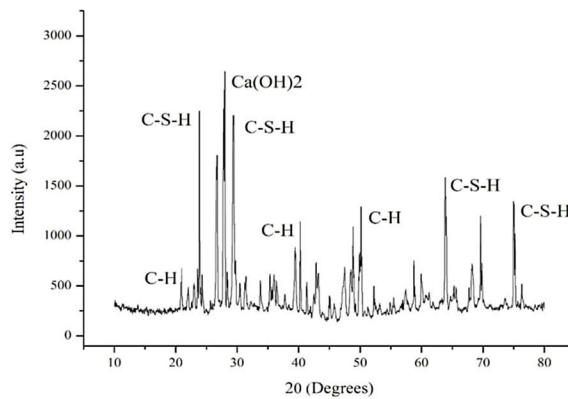
An essential technique for determining the minerals and crystalline components found in powdered concrete samples is X-ray diffraction (XRD). This technique offers comprehensive information on the sample composition, especially with regard to the phases of calcite and silica. A tiny quantity of the powdered sample is put



(a)



(b)



(c)

Figure 11: (a), (b) and (c) shows the XRD images of mix M1, M4 and M6.

into a container, its surface is smoothed, and it is then subjected to XRD examination. Cu-K α radiation is used at 40 kV/20 mA, with a scanning speed of 2°/min, a width of 2.5, and a CPS set at 1k during the analysis. Data is recorded in stepped increments of 0.04 degrees over a three-second interval, covering an angle of 2 θ ranging from 3 to 70° in the XRD scan. This all-encompassing strategy guarantees precise characterisation and identification of the crystalline components in the concrete samples.

XRD analysis was employed to investigate the crystalline phases and mineral content of concrete specimens derived from various mix designs and curing conditions. This NDT provides valuable insights into the mineralogical composition of concrete, facilitating the assessment of its long-term performance and durability. In the case of nominal concrete subjected to normal curing conditions, XRD examination revealed peaks hydrated Ca₂SiO₄ phases, including Ca(OH)₂ and Ca₂SiO₄ hydrate (C-S-H). These findings underscore the presence of key hydration products characteristic of well-hydrated cementitious systems, shedding light on the microstructural development and potential durability of the concrete. The production of solid crystalline phases and successful cement hydration are indicated by these peaks. Concrete with Admixture (Normal Curing): Similar dominating peaks linked to hydrated calcium silicate phases are visible in the XRD pattern of concrete with an admixture, indicating effective cement hydration. The crystalline constitution is mostly unaltered by the mixing.

Concrete specimens without admixture and subjected to normal curing conditions exhibited a mineralogical composition consistent with ordinary concrete. XRD analysis revealed distinct peaks corresponding to phases of hydrated calcium silicate, akin to those observed in conventional concrete. Conventional Concrete (Concentric Hydrochloric Acid Curing): The XRD study of concrete that has undergone this method shows a decrease in the peak intensity of the phases that correspond to hydrated calcium silicates. This decrease is a sign that the acid's corrosive properties are causing cementitious components to leach and dissolve. The XRD pictures of mix M1, M4, and M6 are displayed in Figure 11(a)–(c).

5. CONCLUSION

Extensive experimental research on a range of concrete mixtures with varying curing times and admixtures present has provided important new understandings of the materials' workability, mechanical qualities, durability traits, and microstructural alterations. The main conclusions are as follows:

- The use of an admixture typically made concrete more workable, simpler to handle and position during construction. For all combinations, extended curing times raised the concrete's tensile, flexural, and compressive strengths. Mechanical strength was positively impacted by the presence of the additive, albeit little.
- Concrete subjected to harsh curing conditions, such sulfuric and hydrochloric acid curing, showed signs of increased porosity, cementitious material leaching, and decreased durability. This highlights how vital it is to take precautions when facing challenging circumstances.
- Visual and mineralogical data on the microstructure of concrete were obtained by SEM and XRD studies. The lack of a substantial alteration in the microstructural alterations caused by the curing procedures when the addition was present emphasizes the importance of carefully selecting the curing environment.
- Aggressive curing of concrete resulted in greater sorptivity and electrical charge, suggesting enriched permeability and perhaps long-term durability issues.

In conclusion, this study has shown how important curing conditions and the presence of admixtures are in affecting the workability, mechanical qualities, longevity, and microstructural features of concrete. Based on particular building needs and climatic circumstances, these findings provide helpful recommendations for choosing appropriate mix designs and curing techniques, which will eventually aid in the production of more robust and long-lasting concrete structures.

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