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Microstructural and Strength Characterization of Acid-Resistant Cement Mortar Incorporating Crab Shell Powder and Recycled PET

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Microstructural and Strength Characterization of Acid-Resistant Cement Mortar Incorporating Crab Shell Powder and Recycled PET

Abstract - Environmental pollution caused by marine shell waste and plastic disposal, together with carbon dioxide emissions from cement production, has increased the demand for sustainable construction materials. This study investigates the microstructural characteristics and acid resistance of cement mortar incorporating crab shell powder (CSP) as a partial cement replacement and recycled polyethylene terephthalate (PET) plastic as a fine aggregate replacement. X-ray diffraction (XRD) analysis identified portlandite, quartz, belite, and tobermorite phases, providing insights into hydration and microstructural development. X-ray fluorescence (XRF) analysis revealed slight variations in the major oxide composition and clinker compounds, supporting the potential use of CSP as a supplementary cementitious material. Durability performance was evaluated by immersing mortar cubes in hydrochloric acid (HCl) and sulfuric acid (H_2SO_4) for 56 and 92 days. Weight loss and compressive strength were assessed to determine the effects of CSP and PET replacement levels. The results indicate that moderate CSP incorporation improves acid resistance and durability, whereas excessive replacement causes deterioration of the cementitious matrix. A CSP replacement level of up to 15% by weight of cement is identified as a promising option for sustainable mortar production. This approach offers potential benefits through waste valorization and reduced reliance on conventional cement and natural fine aggregates.

Keywords - Crab shell powder, PET plastic waste, Micro-Structural Characterization, Cement Mortar Mechanical Strength, Cement Mortar Durability.

1. INTRODUCTION

The rapid growth of urbanization and infrastructure development increases the demand for cement-based construction materials. However, the production of ordinary Portland cement is

associated with high energy consumption and considerable carbon dioxide emissions, which contribute significantly to global warming and environmental concerns [1]. Consequently, increasing attention has been directed toward the development of sustainable construction materials such as solid waste. The utilization of industrial, agricultural, and municipal wastes in cementitious systems not only reduces the consumption of natural resources but also promotes waste recycling and supports the principles of circular economy [2]. These materials may exhibit pozzolanic or filler effects, which contribute to the formation of additional calcium silicate hydrate (C-S-H) gel and refinement of the pore structure, thereby enhancing the long-term performance of cementitious composites [3].

Marine food wastes not only create environmental problems but also necessitate the development of sustainable recycling strategies for their effective utilization [4]. Among various shell wastes, crab shells are particularly attractive because they are predominantly composed of calcium carbonate and contain valuable mineral constituents that can be utilized in cementitious systems. These materials have been reported to contribute to hydration reactions, promote the formation of additional calcium silicate hydrate (C-S-H) gel, and improve the microstructural properties of cement-based composites [5].

Plastic waste, particularly polyethylene terephthalate (PET), has become one of the most persistent environmental pollutants owing to its non-biodegradable nature and continuously increasing consumption worldwide [6], [7]. The improper disposal of post-consumer PET bottles poses serious ecological and waste management challenges, thereby necessitating the development of effective recycling strategies [8]. Previous investigations have shown that PET particles can be used as partial replacements for fine aggregate in mortar and concrete without causing significant reductions in mechanical properties when incorporated at lower replacement levels [9].

PET-modified cementitious composites have been reported to exhibit improved toughness, enhanced crack resistance, and reduced permeability. These characteristics contribute to better resistance against aggressive environments and improved long-term durability performance [10]. However, excessive incorporation of PET particles may adversely affect compressive strength due to increased porosity and weaker interfacial bonding between the plastic particles and the cement matrix [11]. Previous researchers reported that PET-modified mortars and concretes exhibit satisfactory performance when incorporated at optimum replacement levels, thereby providing an effective approach for recycling plastic waste and reducing environmental pollution [12]. In addition, studies on PET-based mortar composites have demonstrated improved resistance against aggressive chemical environments due to reduced permeability and restricted penetration of harmful ions [13].

Similarly, investigations on chemically exposed mortar specimens have revealed that the severity of deterioration depends on the type of aggressive medium, exposure duration, and microstructural characteristics of the cementitious matrix [14]. The incorporation of suitable supplementary materials has shown to enhance matrix densification and improve resistance against acid and sulfate attack, thereby contributing to long-term durability performance [15].

Furthermore, advanced characterization techniques such as X-ray fluorescence (XRF), X-ray diffraction (XRD), scanning electron microscopy (SEM), and thermal analyses have been extensively employed to identify hydration products and evaluate changes in phase composition responsible for strength development and durability enhancement [16].

Objective

The objective of the experiment is to assess the microstructural composition of materials, and durability study of cement mortar cubes partially replaced with crab shell powder (CSP) and PET plastic waste for circular economy.

2. MATERIALS AND METHODS

2.1 Materials

Cement mortar specimens are prepared using Ordinary Portland Cement (OPC) that complied with IS 269:2015. Locally available river sand conforming to IS 383:2016 grading standards are utilized as fine aggregate. Potable water is used for preparation of mix as well as for curing.

2.1.1 Processing of Crab Shell Powder (CSP)

Crab shells are collected from Madurai fish market and washed in clean water thoroughly to remove dirt, mud and residual flesh. Sun dried cleaned shells are crushed and sieved with a 90 μm sieve to produce fine crab shell powder (CSP). There have been some previous studies on the preparation and utilization of crab shell waste in engineering and material applications such as soil improvement, bioplastic fabrication, and concrete mixtures [25 - 28]. These studies provide a literature basis to investigate the possible utilization of crab shell waste in cement-based materials.

The sieved crab shell powder is calcined in a muffle furnace at 800 °C for 5 h, then cooled to room temperature and re-sieved to obtain the final CSP as shown in Figure 1 in the present study. The experimental processing parameters in the present study are calcination temperature and time. The prepared CSP is then used as a component in cement mortar with recycled polyethylene terephthalate (PET) waste.



a) Crab shell waste generation



b) Plastic Waste generation



c) Cleaning the waste



d) Crushing and screening



e) Calcination Process

Fig 1. Processing of Crab Shell Powder (CSP)

2.1.2 Chemical Transformation during CSP Processing

Calcium carbonate ($CaCO_3$) is an important component of cement-based materials as mainly fine-grained filler. Its fine particle size helps to fill the voids between the cement grains thus enhancing the particle packing density and leads to more compacted microstructure. The physical effect of $CaCO_3$ can be supplemented by its participation in early-stage reactions, especially affecting the C_3A phase, which can accelerate the early hydration process. This leads to faster setting and helps in better early strength. In addition, the presence of calcium carbonate improves the workability of the mixture, making it smoother and easier to place.

Crab shells consist mainly of calcium carbonate ($CaCO_3$) as well as chitin, proteins, organic matter and some minor inorganic constituents. The calcium carbonate in the shell can be thermally decomposed to calcium oxide (CaO), a reactive calcium bearing phase, during calcination. The reaction of the thermal decomposition of calcium carbonate is written as follows: $CaCO_3 \rightarrow CaO + CO_2\uparrow$.

Calcination causes decomposition of calcium carbonate at high temperatures, usually in the range of 700-900 °C, depending on the conditions of heating, the characteristics of particles and purity of the material. The process yields carbon dioxide (CO_2) and leaves behind calcium oxide (CaO), also known as quicklime. The formation of CaO increases the chemical reactivity of the calcium bearing component of the crab shell and can influence its subsequent interaction with water and cementitious phases: $CaO + H_2O \rightarrow Ca(OH)_2$ + heat

The formation of calcium hydroxide is significant in cementitious systems because $Ca(OH)_2$ provides a highly alkaline environment and can participate in subsequent chemical reactions with reactive silica- and alumina-containing phases. In a cement mortar incorporating calcined crab shell powder, the calcium-rich phases may therefore contribute to the development of hydration products and modification of the cement matrix. In particular, the presence of calcium hydroxide can provide calcium ions and an alkaline environment that may facilitate pozzolanic or secondary reactions when reactive siliceous or aluminous constituents are

available. Therefore, the theoretical transformation of calcium carbonate in crab shell waste can be described as a two-stage process: thermal decomposition of $CaCO_3$ into CaO during calcination, followed by hydration of CaO to $Ca(OH)_2$ in the presence of water. These transformations provide a chemical basis for considering processed crab shell waste as a potential calcium-rich supplementary material in cementitious systems. However, the extent of these reactions depends on the calcination temperature, duration, particle size, mineralogical composition, and the presence of organic and other inorganic constituents in the crab shell powder.

3. MICRO STRUCTURAL CHARACTERIZATION STUDY OF MATERIALS

3.1 X-Ray Fluorescence (XRF) analysis

Crab shell powder, ordinary Portland cement, and blended cementitious systems are all subjected to X-ray fluorescence (XRF) examination to ascertain their chemical makeup. The main oxides are identified are SiO_2, AlO_3, FeO_3, CaO, MgO, KO, NaO, and SO_3. Additionally, the major clinker phases—tricalcium silicate (C_3S), dicalcium silicate (C_2S), tricalcium aluminate (C_3A), and tetracalcium aluminoferrite (C_4AF)—are estimated using the Bogue equations.

3.2 X-Ray Diffraction (XRD) analysis

Crystalline phases and hydration products formed during cement hydration are examined using X-ray diffraction (XRD). XRD analysis is performed on selected 28-day cured mortar specimens to identify crystalline phases and hydration products such as portlandite, quartz, belite, calcite, feldspar, mullite, and tobermorite.

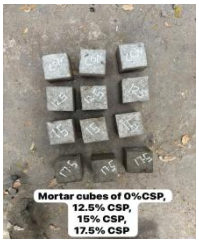
Major phases such portlandite, quartz, belite, feldspar, calcite, mullite, and tobermorite are found by analyzing the diffraction patterns. The microstructural development and correlation between the hydration products and the durability features of the mortar specimens are assessed using the acquired results.

3.3 Proportions and Cube preparation

The cement to sand mix proportion by volume used in this study was 1:3. The water/cement ratio was kept constant at 0.45 for all mortar mixes. The mix proportion was chosen according to the desired experimental requirements and the water to cement ratio was kept constant to ensure homogeneity in the preparation of the control and modified mortar specimens. A control mortar mix is made for comparison with partial replacement of CSP and Plastic as shown in Figure 2. The Mix ID and its various replacement proportions are given in Table 1. Three specimens for each Mix ID are cast and tested. Visual observations of surface deterioration and failure patterns were also recorded. All tests were conducted in accordance with IS 456:2000 and IS 516:2021.



a) Cement, CSP, Plastic & FA



b) CSP Mixed Mortar Cubes



c) Plastic Mixed Mortar Cubes

Fig 2. Casting of Mortar Cubes

Table 1. Mix ID's of CSP and PET plastic

Mix ID	CSP (%)	PET Plastic (%)
C0	0	0
C10	10	0

C12.5	12.5	0
C15	15	0
C17.5	17.5	0
C20	20	0
PC2.5	0	2.5
PC5	0	5

After 28 days of water curing, mortar cube specimens were immersed in H_2SO_4 and HCl solutions for exposure periods of 56 and 92 days. Acid solutions are renewed every 7 days to maintain constant concentration. After exposure, specimens were cleaned, surface dried, and tested for weight loss and residual compressive strength.

The percentage weight loss is calculated using Eqs. (1) :

$$\frac{(\text{Initial Weight} - \text{Final Weight})}{\text{Initial Weight}} * 100 \qquad (1)$$

3.4 Compressive Strength

Compressive strength is measured using a 3000 kN Compression Testing Machine (CTM) at a loading rate of 1.25 kN/s in accordance with IS 4031 (Part 6).The mortar cubes are taken out of the acid solutions and let to dry in the open after the durability exposure period. Each cast specimen's maximum load is noted, and the related compressive strength values are calculated.

Strength Retention (%) is calculated using equation 2

$$\frac{\text{Compressive Strength of Acid Cured Specimen}}{\text{Compressive Strength of Water Cured Specimen}} * 100 \qquad (2)$$

Cast specimens failure and cracking patterns are recorded during and after loading. A visual

evaluation of the mortar specimens' structural integrity and manner of failure is provided by Figure 3, which shows the compression testing process and the accompanying failure patterns of the specimens following durability exposure.

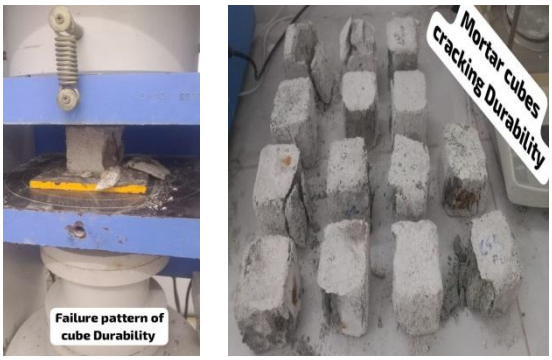


Fig. 3 Compression testing and failure patterns

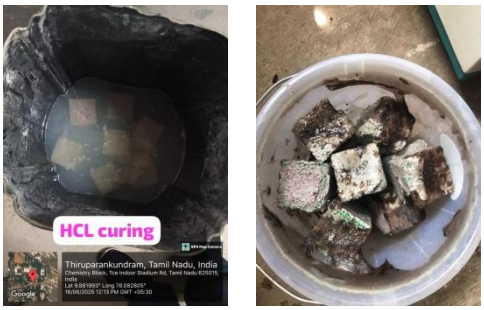


Fig. 4. HCl exposed specimens

Visual determination shows the degree of deterioration brought on by acidic attack, the mortar cubes are visually examined after being submerged in a hydrochloric acid (HCl) solution. After extended exposure times, alterations in surface roughness, material loss, and general appearance are noted. The state of the mortar specimens following 56 and 92 days of HCl curing is shown in Figure 4, demonstrating the impact of acid exposure on the durability properties of the changed mortar mixes

4. RESULTS AND DISCUSSION

4.1 Materials XRF analysis and bogue compounds

The chemical composition of Ordinary Portland Cement (OPC), Crab Shell Powder (CSP), and the respective mixed cementitious systems is ascertained by X-ray fluorescence (XRF) analysis. Bogue equations are used to estimate the main clinker phases—tricalcium silicate (C_3S), dicalcium silicate (C_2S), tricalcium aluminate (C_3A), and tetracalcium aluminoferrite (C_4AF).

The blended cementitious systems' chemical composition is marginally affected by the addition of Crab Shell Powder (CSP) as seen in the XRF data shown in Table 2. CSP replacement levels increased, the SiO_2 content while CaO content decreases marginally. Al_2O_3, Fe_2O_3, and SO_3 concentrations are also found to decrease marginally as CSP proportion increases. Overall oxide compositions are within the permissible limits, suggesting that CSP is a suitable additional cementitious material for mortar application. CSP cannot entirely replace Portland cement because of its lower silicate content, its calcium-rich composition contributes to hydration reactions and matrix densification.

Table 2. Chemical composition of OPC, CSP, and CSP-blended cementitious systems (wt. %) determined by XRF analysis

Oxide	**OPC**	**CSP**	**CSP10**	**CSP12.5**	**CSP15**	**CSP17.5**	**CSP20**
SiO_2	23.21	**26.12**	23.50	23.57	23.64	23.72	23.79
Al_2O_3	4.52	4.12	4.48	4.47	4.46	4.45	4.44
Fe_2O_3	3.86	3.21	3.80	3.78	3.77	3.75	3.74
CaO	65.26	64.96	64.55	64.37	64.20	64.02	63.85

MgO	1.80	1.30	1.75	1.74	1.73	1.71	1.70
K_2O	1.30	1.00	1.27	1.26	1.25	1.25	1.24
Na_2O	0.62	0.34	0.59	0.58	0.58	0.57	0.56
SO_3	1.64	0.05	1.48	1.44	1.40	1.36	1.32
TiO_2	–	0.19	0.02	0.02	0.03	0.03	0.04
P_2O_5	–	0.19	0.02	0.02	0.03	0.03	0.04
Mn_2O_3	–	0.02	0.00	0.00	0.00	0.00	0.00
LOI	0.56	1.69	0.67	0.70	0.73	0.76	0.79

The Bogue equations are used to estimate the primary clinker phases based on the oxide compositions determined by XRF analysis. Table 3 and Figure 5 show the computed phase compositions of the OPC-CSP blended systems, which shed light on how CSP integration affects the relative amounts of alite, belite, aluminate, and ferrite phases.

Tricalcium silicate (C_3S) concentration decreases gradually from 48.8% in OPC to 45.9% after 20% CSP replacement and dicalcium silicate (C_2S) content increases from 29.7% to 31.9% as calculated from Bogue models using oxide compositions acquired from XRF analysis. Tetracalcium aluminoferrite (C_4AF) and tricalcium aluminate (C_3A) are almost having equal proportion. An increase in C_2S is advantageous for later-age strength growth and durability performance, a decrease in early hydration activity is indicated by a drop in C_3S.

The gradual reduction in C_3S together with the increase in C_2S observed in the present study is consistent with previous investigations on shell-derived cementitious materials reported by Hasan et al. [3], Rux et al. [6], and Nwaeju et al. [1].

Table 3. Final estimated bogue compounds (wt.%)

Mix ID	C_3S	C_2S	C_3A	C_4AF
OPC	48.8	29.7	5.5	11.7
CSP10	47.6	30.7	5.4	11.6
CSP12.5	47.2	31.0	5.3	11.5
CSP15	46.8	31.3	5.3	11.5
CSP17.5	46.3	31.6	5.2	11.4
CSP20	45.9	31.9	5.1	11.4

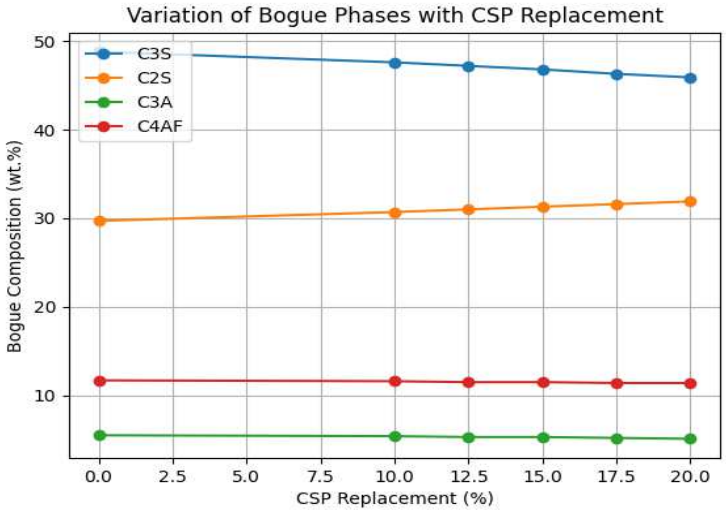


Fig. 5. Variation of bogue phase composition with CSP replacement level

XRF and Bogue compound analyses show that the addition of crab shell powder composition varies slightly the cementitious system's chemical and mineralogical composition, and confirming its potential as a sustainable replacement material for the creation of long-lasting cement mortar.

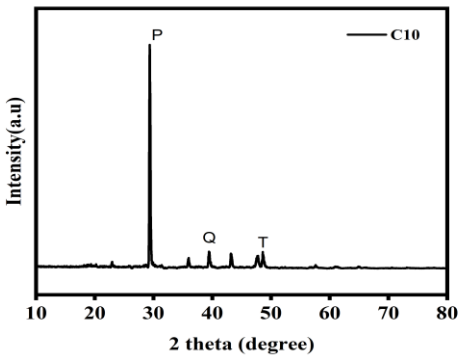
4.2 XRD analysis

Ccrystalline phases and hydration products found in the mortar specimens after curing are determined using X-ray diffraction (XRD) analysis. The mineralogical makeup and microstructural evolution of the cement matrix can be inferred from the XRD patterns.

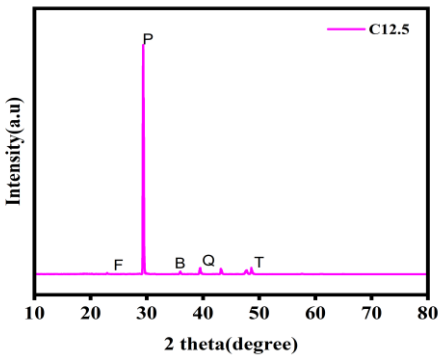
The increased intensity of tobermorite-related peaks observed in the C15 specimen is consistent with previous XRD investigations on shell-derived cementitious composites, which reported enhanced C–S–H formation and improved hydration characteristics at moderate shell powder replacement levels. Similar hydration behaviour has been reported by Hasan et al. [3] and Dananjaya et al. [5]. The present study further demonstrates that combining crab shell powder with recycled PET maintains these beneficial hydration products even after prolonged exposure to aggressive acidic environments.

The higher intensity of portlandite and tobermorite peaks in the optimum mixture confirms enhanced hydration and matrix densification, explaining the improved resistance to acid attack. These observations support the widely accepted theory that improved C–S–H development reduces permeability and enhances long-term durability of blended cementitious systems. Therefore, the present XRD results provide microstructural evidence supporting the observed mechanical performance.

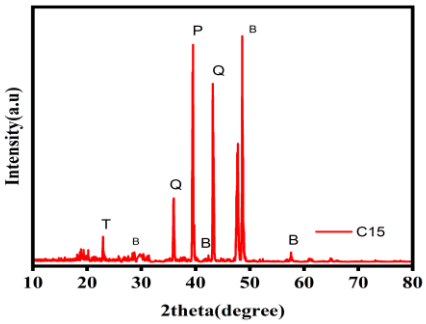
Figures 6 show the XRD patterns for the chosen mortar mixes. The impact of different CSP replacement levels on the hydration products and microstructural features of the cement mortar is evaluated by identifying and comparing the diffraction peaks corresponding to the primary crystalline phases.



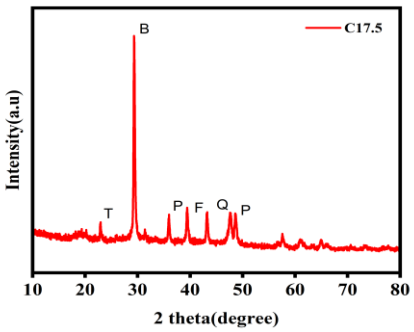
a) XRD pattern of C10



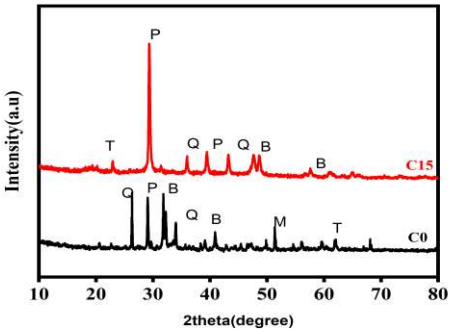
b) XRD pattern of C12.5



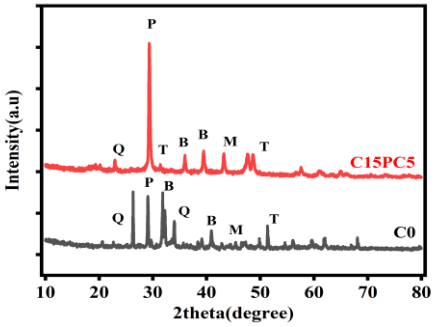
c) XRD pattern of C15



d) XRD pattern of C17.5



e) XRD pattern of C0 and C15



f) Comparison of XRD patterns of control and optimum mixes

Fig. 6. XRD patterns of C10, C12.5, C15 and C17.5 mortar cubes

Several crystalline phases, including portlandite (P), quartz (Q), belite (B), tobermorite (T), calcite (C), feldspar (F), and mullite (M), are seen in the XRD patterns of the chosen mortar specimens. The presence of portlandite verifies that the cement has hydrated and that calcium hydroxide has formed throughout the curing process. The silica-rich components found in the fine aggregate are primarily linked to the quartz peaks seen in the diffraction patterns, which support the mortar matrix's overall stability.

All the specimens contained belite (C_2S), demonstrating its role in long-term hydration and strength development. The creation of calcium silicate hydrate (C-S-H) gel, which is principally in charge of strength development and enhanced durability qualities, is represented by the presence of tobermorite, which is very important. While feldspar and mullite phases show the presence of aluminosilicate minerals and crystalline components within the system, calcite peaks can be linked to the carbonation of hydration products.

The C15 specimen show relatively higher concentrations of portlandite and tobermorite peaks among the mixtures examined, indicating superior microstructural development and increased hydration activity. In order to improve resistance against acid penetration and deterioration, more hydration products are formed, which led to matrix densification and decreased pore connectivity. On the other hand, excessive CSP replacement levels might have led to increased porosity and decreased hydration efficiency, which would have negatively impacted the mortar specimens' mechanical and durability properties. As a result, the XRD analysis verifies that a moderate use of crab shell powder encourages the formation of stable hydration products and helps cement mortar perform better in harsh environmental circumstances.

The presence of portlandite, tobermorite, and calcite confirms active hydration within the blended cement system. These observations support the established hydration mechanism of Portland cement, in which calcium silicate phases react with water to produce calcium silicate

hydrate (C–S–H) and calcium hydroxide. The increased intensity of hydration-related phases in the C15PC7.5 mixture explains its improved durability performance.

Overall, the XRD results are consistent with the durability observations, indicating that the optimal mix including 15% crab shell powder performs better due to enhanced hydration and matrix densification

Durability of Cement Mortar

Percentage weight loss of cement mortar cubes after exposure to acidic environment for Mix IDs' is shown in the figure 7. CSP replacements till 15% of cement show decrease in weight loss and increases to a peak more than the control.

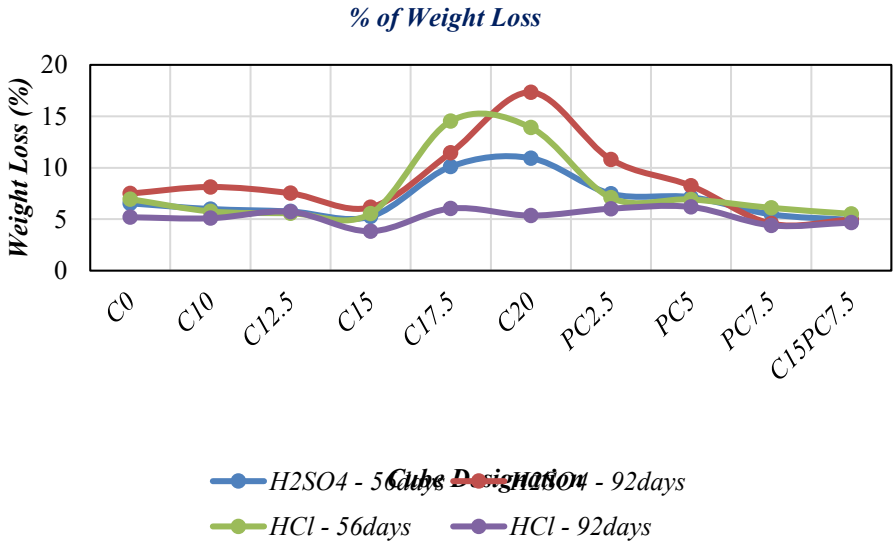


Fig.7. Comparison of % of weight loss

Compressive Strength of Cement Mortar

Compressive strength of cement mortar cubes after exposure to acidic environment exposure for Mix IDs' is shown in the figure 8. CSP replacement upto 15% of cement show decrease in weight loss and increases to a peak more than the control.

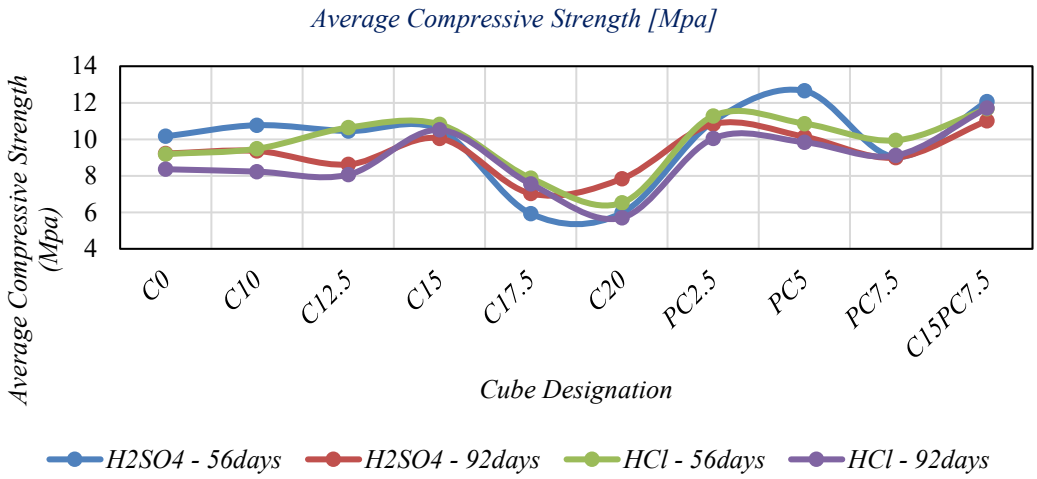


Fig. 8. Comparison of average compressive strength (Mpa)

4.3 Relative Weight loss analysis – H_2SO_4 and HCl exposure

C10 and C12.5 show an 8.54% increase in weight loss than control mix C0. Mix C15 demonstrated better acid resistance by 17.89% reduction in weight loss. At higher levels of CSP replacement; C17.5 and C20 showed notable increases in weight loss of 53.00% and 131.38%, respectively, indicating serious degradation under extended acid exposure. PC2.5 and PC5 demonstrated weight loss increase by 44.33% and 10.01%, respectively. Mix PC7.5 show a significant 38.99% drop in weight loss when compared to the control mix. Due to the synergistic effect of CSP and plastic replacement, the combined mix C15PC7.5 showed improved performance with a 33.78% reduction in weight loss, showing enhanced resistance against sulfuric acid attack as shown in Figure 6.

The improved durability of the C15 and C15PC7.5 mixtures after prolonged acid exposure can be attributed to the refinement of the cement matrix and reduced permeability resulting from the combined effects of crab shell powder and recycled PET. The calcium-rich nature of CSP promotes the formation of additional hydration products, while PET particles help bridge microcracks and restrict the penetration of aggressive ions. Consequently, acid ingress and

dissolution of hydration products are reduced, leading to lower weight loss compared with the control mix.

Similar improvements in durability have been reported for shell-derived cementitious materials by Hasan et al. [3] and Rux et al. [6], which states that the observed that moderate shell powder replacement enhances resistance to aggressive environments through improved particle packing and matrix densification. The present study further extends these findings by demonstrating that the simultaneous incorporation of recycled PET provides additional protection during long-term H_2SO_4 exposure, indicating a synergistic interaction between the two waste materials.

Similar trends were observed under hydrochloric acid exposure, although the degree of deterioration was comparatively lower than under sulfuric acid attack. Hydrochloric acid primarily removes calcium ions through decalcification, whereas sulfuric acid additionally forms expansive gypsum and ettringite, accelerating surface deterioration and internal cracking. The present observations therefore support the established mechanisms of acid attack on cementitious materials and are consistent with the findings of Benosman et al. [12] and Atabey et al. [14]. Furthermore, the optimum performance of the C15PC7.5 mixture confirms that the combined use of CSP and PET effectively improves long-term acid resistance beyond that achieved by either material individually.

4.4 Relative Compressive Strength Retention – under H_2SO_4 and HCl exposure

Mix C10 showed a slight 1.52% increase in compressive strength compared to the control mix, whereas C15 shown a more noticeable 9.00% improvement over control mix. Compressive strength improvements by 17.46% and 9.98% are attained by PC2.5 and PC5 among the plastic replacement mixtures. With a 19.41% increase in compressive strength over C0, the combined mix C15PC7.5 show the greatest improvement, demonstrating outstanding strength

preservation in acidic environments.. The significant decline seen for C17.5 and C20 indicates that the mechanical stability of mortar subjected to extended sulfuric acid attack is adversely affected by excessive CSP replacement. Overall, the optimum compromise between durability and strength retention is achieved with moderate levels of CSP and plastic inclusion, especially the C15PC7.5 mix.

Mix C15PC7.5 mixture demonstrates that moderate replacement levels effectively preserve the integrity of the hydrated cement matrix during prolonged acid exposure. Enhanced performance is attributed to improved particle packing, additional nucleation sites for hydration products, and reduced pore connectivity, which collectively minimize internal deterioration.

PC2.5 and PC5 show gains in compressive strength while having greater weight losses Because of the plastic particles' ability to bridge cracks. Overall, the findings indicate that, an ideal ratio of 15% CSP and 7.5% plastic replacement offers the best compromise between mechanical performance and durability by creating a compact and less permeable microstructure as shown in Figure 6.

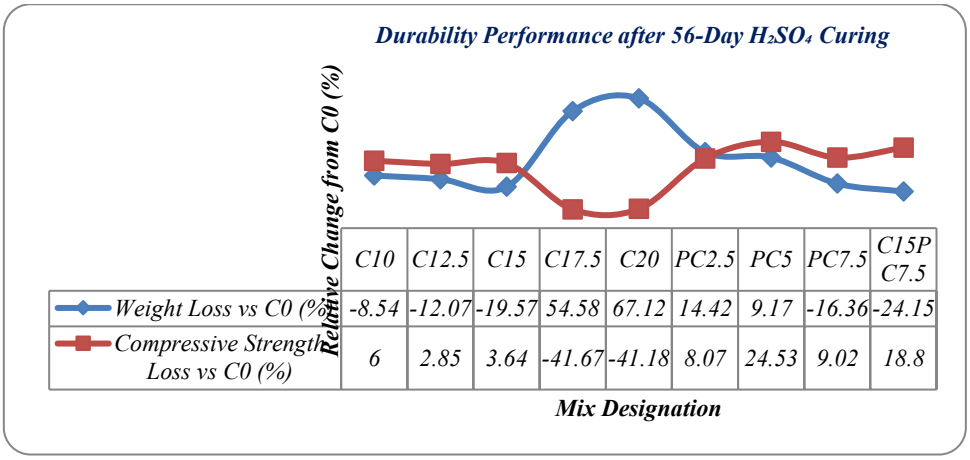
In contrast, replacement levels exceeding 15% CSP resulted in a noticeable reduction in residual strength because of cement dilution, reduced clinker availability, and increased porosity. Excessive replacement, limits the formation of calcium silicate hydrate (C–S–H) gel, thereby weakening the mortar matrix and increasing susceptibility to acid attack. This behaviour is in accordance with previous investigations on shell-derived supplementary cementitious materials, which consistently reported that durability improvements are achieved only within an optimum replacement range. Therefore, the present findings support the established theory that supplementary cementitious materials improve performance only when incorporated at appropriate dosages.

4.5 Relative Durability performance under H_2SO_4 and HCl exposure at 56days

The percentage weight loss of cast mortar cubes is as shown in Figure 9 & 10 immersed under sulfuric acid and hydrochloro acid. The cement matrix gradually deteriorates as a result of primary breakdown and leaching of calcium-bearing chemicals.

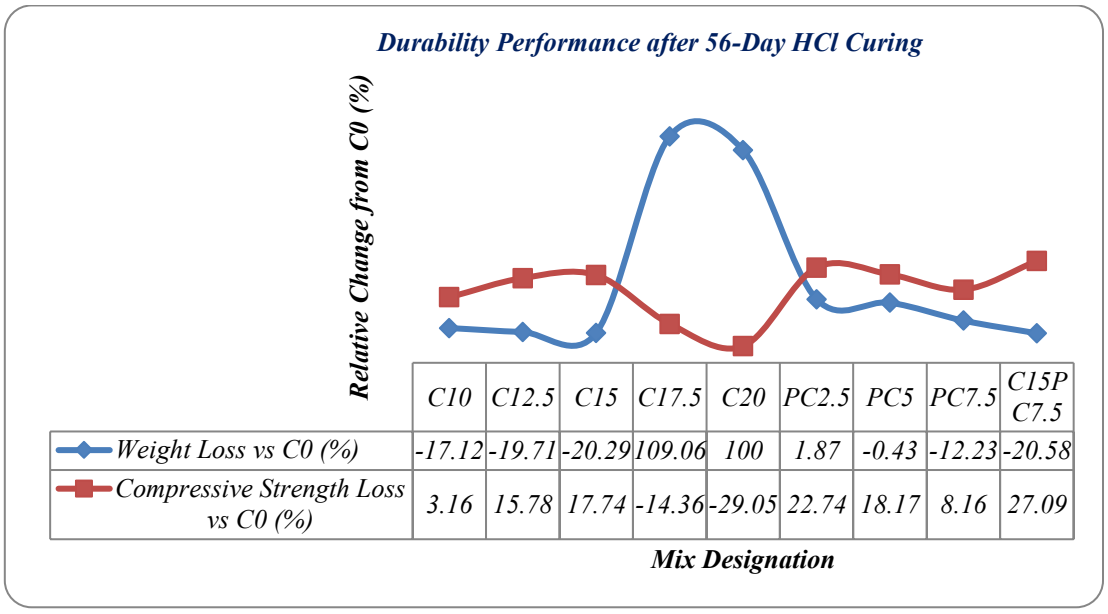
The mortar specimens exposed to H_2SO_4 exhibited greater deterioration than those immersed in HCl because sulfuric acid reacts with calcium hydroxide and C–S–H gel to produce gypsum and ettringite, resulting in expansion, cracking, and surface scaling. Hydrochloric acid primarily causes decalcification without generating expansive products. Similar observations have been reported by Benosman et al. [12] for PET-modified mortar composites and Atabey et al. [14] for mortars containing industrial waste powders. The present results further demonstrate that incorporating 15% crab shell powder with PET waste reduces acid-induced degradation by promoting a denser microstructure, extending the findings of Hasan et al. [3] and Rux et al. [6], who reported improved durability with shell-derived calcium carbonate materials.

CSP mix of C10 and C12.5 showed enhanced resistance with weight losses decreased by 8.40% and 12.07%, respectively than control mix C0. Mix C15 showed the greatest resistance with a weight loss reduction of 19.57% than C0. However, durability is negatively impacted by additional CSP content, as C17.5 and C20 demonstrated significant weight loss increases of 54.58% and 67.12%, respectively, indicating serious deterioration under sulfuric acid exposure. PC2.5 and PC5 mix show increase in weight loss of 14.42% and 9.17%, respectively, while PC7.5 did better in the plastic replacement series with a 16.36% decrease. The combined mix C15PC7.5 performed the best, exhibiting a 24.15% reduction in weight loss compared to C0. This suggests that the synergistic effect of 15% CSP and 7.5% plastic substitution improved resistance against acid



	C10	C12.5	C15	C17.5	C20	PC2.5	PC5	PC7.5	C15P C7.5
Weight Loss vs C0 (%)	-8.54	-12.07	-19.57	54.58	67.12	14.42	9.17	-16.36	-24.15
Compressive Strength Loss vs C0 (%)	6	2.85	3.64	-41.67	-41.18	8.07	24.53	9.02	18.8

Fig. 9. Variation in Weight Loss and Compressive Strength of Mortar Cubes H2SO4 curing at 56 days (Reference: Control Mix C0).



	C10	C12.5	C15	C17.5	C20	PC2.5	PC5	PC7.5	C15P C7.5
Weight Loss vs C0 (%)	-17.12	-19.71	-20.29	109.06	100	1.87	-0.43	-12.23	-20.58
Compressive Strength Loss vs C0 (%)	3.16	15.78	17.74	-14.36	-29.05	22.74	18.17	8.16	27.09

Fig. 10. Variation in Weight Loss and Compressive Strength of Mortar Cubes HCl at 56days (Reference: Control Mix C0)

The weight loss characteristics of mortar cubes after 56 days of HCl curing showed that the addition of CSP and plastic waste had a major impact on acid resistance. C10, C12.5, and C15 performed better than the control mix (C0), with weight loss reductions of 17.12%, 19.71%, and 20.29%, respectively. C15 showed the least amount of weight loss, suggesting improved resistance to attack by hydrochloric acid. Higher replacement levels of CSP, on the other hand,

had a negative impact on durability; in comparison to the control specimen, C17.5 and C20 showed increases in weight loss of 109.06% and 100.00%, respectively. PC2.5 showed a slight rise in weight loss of 1.87% in the plastic replacement series, whereas PC5 and PC7.5 showed reductions of 0.43% and 12.23%, respectively. The combined mix C15PC7.5 showed the best performance, with a 20.58% reduction in weight loss compared to C0. This suggests that the synergistic action of CSP and plastic replacement improved the mortar cubes' resistance against HCl attack.

The performance of the C15PC7.5 mixture is consistent with previous studies on shell-derived supplementary cementitious materials. Hasan et al. [3] reported that mortar containing seashell powder exhibited optimum durability at moderate replacement levels, while Rux et al. [6] demonstrated that shell waste can effectively function as a limestone alternative in cementitious materials. Similarly, previous investigations on oyster shell and other marine shell powders generally identified optimum replacement levels between 10% and 15%. The present study extends these findings by demonstrating that 15% crab shell powder combined with 7.5% recycled PET provides superior resistance against both H_2SO_4 and HCl attack, indicating a beneficial synergistic effect between the two waste materials.

4.6 Relative Durability performance under H_2SO_4 and HCl exposure at 92days

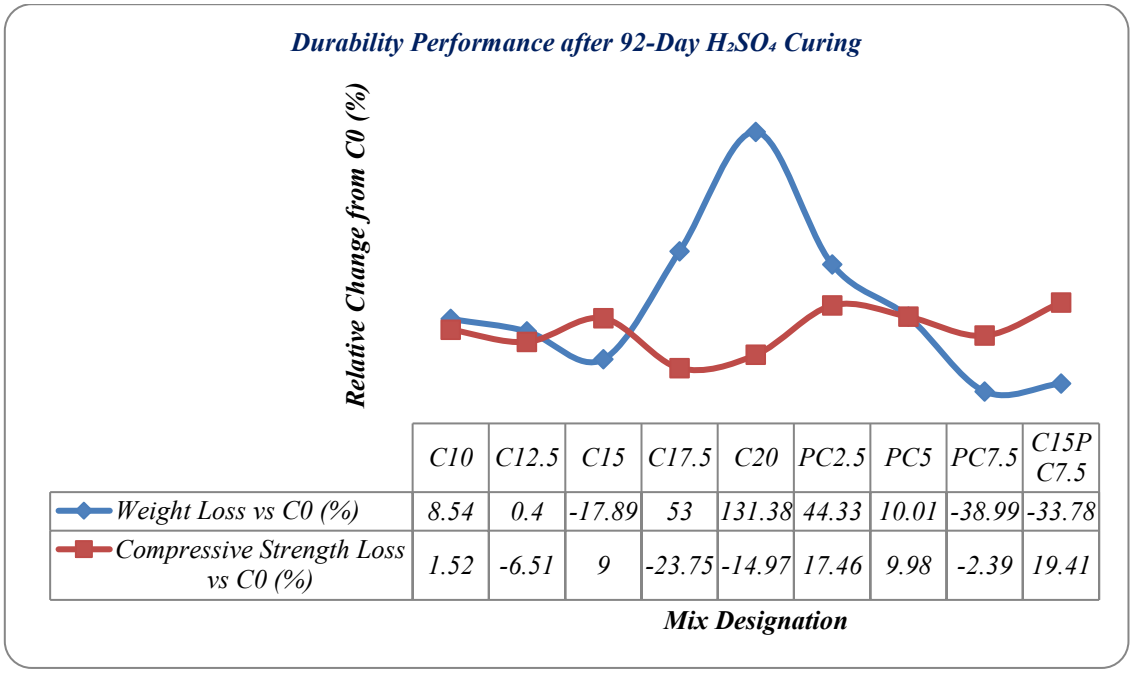
Compressive strength retention of mix C10, C12.5, and C15 increases by 6.00%, 2.85%, and 3.64% than control. On the other hand, substantial degradation is caused by higher CSP levels of 17.5% and 20%, which resulted in strength losses that are 41.67% and 41.18% more than C0. Plastic replacement mix PC2.5, PC5, and PC7.5 show decreases in compressive strength loss of 8.07%, 24.53%, and 9.02%, respectively than control. Mix PC5 notably showed the increase in compressive strength. Mix C15PC7.5 show 18.80% increase in compressive strength loss compared to C0. This suggests that the durability and mechanical integrity of

mortar cubes exposed to sulfuric acid for 56 days are effectively improved by the combined incorporation of CSP and plastic at optimal levels.

Compressive strength increases by 3.16% in C10 compared to the control mix, but increases are more noticeable in C12.5 and C15 is 15.78% and 17.74%, respectively. Strength is significantly reduced by extensive CSP inclusion, with C17.5 and C20 showing losses of 14.36% and 29.05%, respectively. PC2.5 and PC5 show significant increases in compressive strength of 22.74% and 18.17%, respectively. Mix PC7.5 shows a moderate increase of 8.16%. Mix C15PC7.5 demonstrated the highest increase in residual strength of 27.09% over control. These results imply that the mechanical stability and acid resistance of mortar cubes exposed to hydrochloric acid are successfully improved by optimal replacement quantities of CSP and plastic.

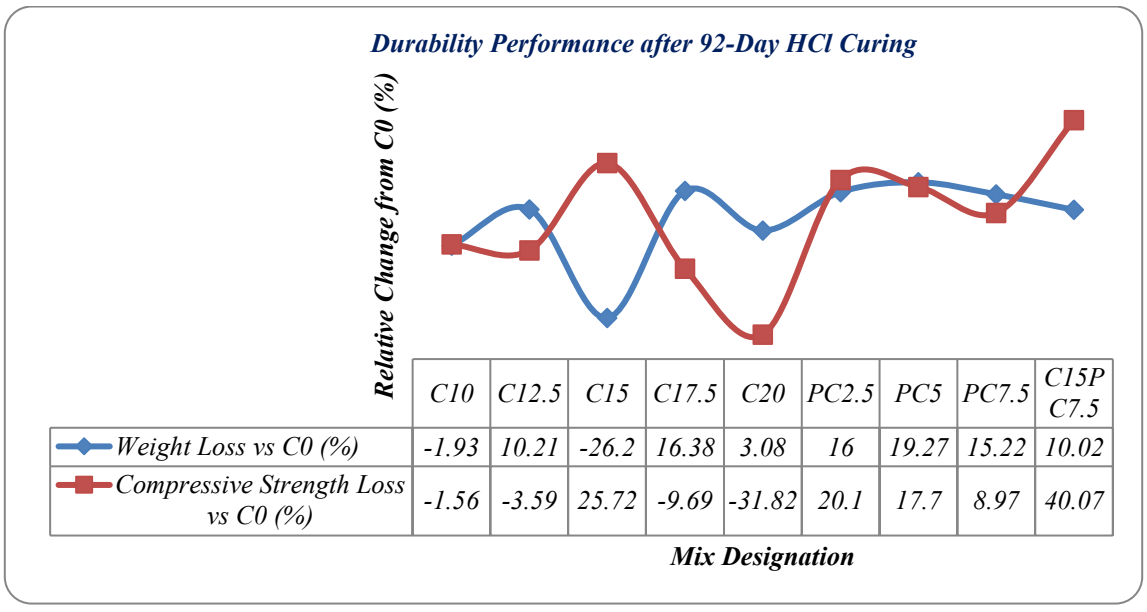
Crab shell powder enhances particle packing and provides nucleation sites for hydration products while maintaining sufficient clinker content. Similar optimum replacement levels have been reported for seashell-derived supplementary cementitious materials by Hasan et al. [3] and Rux et al. [6]. However, replacement levels beyond 15% resulted in strength reduction because of cement dilution, reduced calcium silicate hydration, and increased matrix porosity, consistent with previous findings on shell-based cementitious composites.

Percentage weight loss and relative compressive strength after 92 days of H_2SO_4 and HCL exposure are shown in Figure 11 & 12.



	C10	C12.5	C15	C17.5	C20	PC2.5	PC5	PC7.5	C15P C7.5
Weight Loss vs C0 (%)	8.54	0.4	-17.89	53	131.38	44.33	10.01	-38.99	-33.78
Compressive Strength Loss vs C0 (%)	1.52	-6.51	9	-23.75	-14.97	17.46	9.98	-2.39	19.41

Fig. 11. Variation in Weight Loss and Compressive Strength of Mortar Cubes H2SO4 curing at 92 days (Reference: Control Mix C0)



	C10	C12.5	C15	C17.5	C20	PC2.5	PC5	PC7.5	C15P C7.5
Weight Loss vs C0 (%)	-1.93	10.21	-26.2	16.38	3.08	16	19.27	15.22	10.02
Compressive Strength Loss vs C0 (%)	-1.56	-3.59	25.72	-9.69	-31.82	20.1	17.7	8.97	40.07

Fig. 12. Variation in Weight Loss and Compressive Strength of Mortar Cubes HCl at 92days (Reference: Control Mix C0)

5. CONCLUSION

Based on the experimental investigation into the durability performance and microstructural characteristics of cement mortar incorporating crab shell powder (CSP) and recycled PET plastic, the following conclusions are drawn:

1. Moderate replacement levels of crab shell powder and recycled PET plastic significantly enhanced durability and mechanical performance of cement mortar as well as resistance to acid-induced deterioration.

2. Sulfuric acid (H_2SO_4) exposure caused substantially greater deterioration than hydrochloric acid (HCl) exposure due to the formation of expansive gypsum and ettringite phases, resulting in higher weight loss and lower compressive strength retention.

3. Increasing the duration of acid exposure from 56 to 92 days intensified material degradation under both HCl and H_2SO_4 environments, demonstrating that prolonged acid attack progressively weakens the cement matrix through continuous decalcification and dissolution of hydration products.

4. Among all mixtures investigated, the mortar containing 15% crab shell powder and 7.5% recycled PET plastic (C15PC7.5) exhibited the best overall durability performance, showing the lowest weight loss and the highest compressive strength retention after prolonged acid exposure.

5. XRF analysis revealed only minor variations in the major oxide compositions of the blended cement systems. However, the calculated Bogue compound composition indicated a slight reduction in tricalcium silicate (C_3S) and a corresponding increase in dicalcium silicate (C_2S) with increasing CSP content, suggesting enhanced later-age hydration characteristics and improved long-term durability.

6. XRD analysis confirmed the presence of hydration and crystalline phases, including portlandite, quartz, belite, calcite, feldspar, mullite, and tobermorite. The enhanced intensity

of hydration-related phases in the optimum mixtures indicates improved hydration reactions, matrix densification, and the development of a more stable microstructure capable of resisting acid penetration.

7. The combined interpretation of durability, XRF, and XRD results establishes a clear relationship between microstructural evolution and durability performance.

6. FUTURE SCOPE OF WORK

Future research may concentrate on the other microstructural characterization and real time mortar analysis that incorporates PET plastic and crab shell powder (CSP). In order to promote ecologically friendly and resource-efficient building techniques, the created material may also be expanded to concrete applications and used in sustainable construction goods like masonry units, plastering works, paving blocks, and precast parts.

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