Experimental Studies on the Effect of SCMs and Waste Foundry Sand on the Durability of High-Performance Concrete

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Abstract

The pursuit of sustainable construction has intensified the search for durable concrete incorporating industrial by-products. This study comprehensively evaluates the durability performance of High-Performance Concrete (HPC) where cement is partially replaced with Supplementary Cementitious Materials (SCMs)—20% fly ash and 10% Alccofine—and natural fine aggregate is substituted with Waste Foundry Sand (WFS) at 10–40% levels. Critical durability parameters, including Ultrasonic Pulse Velocity (USPV), water absorption, sorptivity, and resistance to acid attack (5% H_2SO_4 and HCl), were rigorously assessed after 28 and 90 days of curing. The results demonstrate that the mix with 20% WFS (M3) exhibits superior durability, characterized by excellent internal densification (USPV: 4.8 km/s), low water absorption (~2%), and outstanding acid resistance with over 90% compressive strength retention. Conversely, mixes with higher WFS content (≥30%) showed increased porosity and reduced chemical resistance. These findings conclusively establish that the synergistic use of fly ash, Alccofine, and 20% WFS produces an eco-friendly HPC with significantly enhanced durability, making it highly suitable for modern infrastructure exposed to aggressive environments.

Keywords: High-Performance Concrete, Durability, Supplementary Cementitious Materials, Waste Foundry Sand, Acid Attack, Sorptivity, Ultrasonic Pulse Velocity.

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1. Introduction

Concrete is the cornerstone of global infrastructure, but its conventional production relies on cement and natural river sand, materials whose extraction and processing incur substantial environmental costs, including high carbon emissions and ecological degradation. A promising pathway toward sustainable development in the construction sector lies in the Utilization of industrial by-products. Supplementary Cementitious Materials (SCMs) like fly ash and Alccofine, and aggregate substitutes such as Waste Foundry Sand (WFS), offer a dual advantage: they reduce the environmental footprint of concrete and enhance its technical performance.

2. The incorporation of SCMs is known to fundamentally improve the durability of concrete. Fly ash, a pozzolanic material, contributes to long-term strength development and pore refinement through secondary hydration reactions. Alccofine, with its ultra-fine particle size, significantly

enhances the packing density of the cementitious matrix, leading to reduced permeability and improved resistance against aggressive agents. Simultaneously, WFS, a silica-rich by-product from the metal casting industry, presents a viable alternative to natural sand, helping to conserve river ecosystems and reduce landfill waste.

3. While numerous studies have investigated the mechanical properties of concrete containing these materials, a critical knowledge gap remains regarding their combined effect on long-term durability, especially under chemically aggressive conditions. Durability—the ability of concrete to resist weathering, chemical attack, and abrasion while maintaining its desired engineering properties—is paramount for ensuring the long-term service life and sustainability of structures.

4. This study is therefore designed to systematically investigate the effect of combining SCMs (20% fly ash, 10% Alccofine) and varying percentages of WFS (0% to 40%) on the durability characteristics of M40 grade High-Performance Concrete. The research focuses on key durability indicators: internal microstructure density via Ultrasonic Pulse Velocity (USPV), water absorption and sorptivity as measures of permeability, and performance in acidic environments. The findings aim to identify an optimal mix design that maximizes durability and sustainability, providing crucial data for engineers seeking to specify eco-friendly concrete for demanding applications.

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5. MATERIALS

2.1 Cement: Ordinary Portland Cement (OPC 53 grade, IS 12269:2013)

2.2 Fly Ash: Class F, replacing 20% of cement

2.3 Alccofine 1203: Micro-fine GGBS-based material, 10% cement replacement

2.4 Fine Aggregate: Natural river sand (Zone II, IS 383:2016)

2.5 Waste Foundry Sand (WFS): Industrial by-product used as fine aggregate **replacement** at 10%, 20%, 30%, and 40% levels

2.6 Coarse Aggregate: 20 mm crushed stone

2.7 Water: Potable, as per IS 456:2000

2.8 Superplasticizer: 0.5% of binder weight

3. Mix Design and Casting

Concrete was designed for M40 grade in accordance with IS 10262:2019, using a water-to-cement ratio (w/c) of 0.35. Five mixes were prepared:

- M1: Control mix
- Fine aggregate replacement by 3.025WFS: 10%, 20%, 30%, and 40%

- Mix proportion: 1:1.625:3.025:0.35

Table:01 Mix Proportion	
Material	Quantity
Cement	400 kg/m³
Fine aggregate	650 kg/m³
Coarse aggregate	1210 kg/m³
Water	140 lit/m³
Super Plasticizer	2.0 kg/m³
W/C ratio	0.35

Table: 02 Mix Composition					
Nomenclature of Mixes					
Mix Proportion (%)					
Mix	C	FY	AC	FA	WFS
M1	100	0	0	100	0
M2	70	20	10	90	10
M3	70	20	10	80	20
M4	70	20	10	70	30
M5	70	20	10	60	40

C= cement, FY=Fly ash, Ac= Alccofine FA= Fine aggregate, WFS= Waste foundry sand

EXPERIMENTAL INVESTIGATIO

Cube size: 150 × 150 × 150 mm

Curing: 28 days in water at 27 ± 2°C

Testing Procedures

1. **Ultrasonic Pulse Velocity (USPV):** IS 13311:1992
2. **Acid Resistance Test:** (ASTM C267) Specimens immersed in 5% H_2SO_4 and 5% HCl, tested at 28 & 90 days for **weight loss** and **compressive strength loss**.
3. **Water Absorption Test:** (ASTM C642) Mass difference between oven-dried and water-immersed specimens.
4. **Sorptivity Test:** (ASTM C1585) Capillary suction measured; sorptivity coefficient calculated.

4. RESULTS AND DISCUSSIONS

Ultrasonic Pulse Velocity (USPV)

The USPV results (Table 3) show a clear trend: values increase from M1 to M3, peak at M3 (20% WFS), and then decline for M4 and M5. M3 achieved the highest values, classified as "Excellent" quality (4.6 km/s at 28 days and 4.8 km/s at 90 days).

Table 3 USPV Results			
Ultrasonic Pulse Velocity (USPV)			
Mixes	**28 days (km/s)**	**90 days (km/s)**	**Quality Grade***
M1	4.4	4.6	Good
M2	4.5	4.7	Good to Excellent
M3	4.6	4.8	Excellent
M4	4.3	4.5	Good
M5	4.1	4.3	Medium to Good

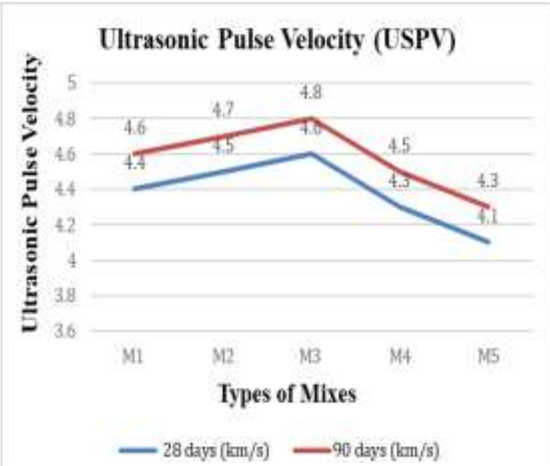

Figure 1 Ultrasonic Pulse Velocity Test Result

The USPV is directly correlated to the density and homogeneity of the concrete's internal microstructure. The superior performance of mix M3 (20% WFS) is attributed to a synergistic densification effect. The pozzolanic reactions from the SCMs (fly ash and Alccofine) generate additional calcium silicate hydrate (C-S-H) gel, which refines pore structure and reduces capillary porosity. Concurrently, the well-graded WFS at this optimal percentage integrates seamlessly with the natural sand, creating a denser and more cohesive aggregate skeleton. This results in a highly compact matrix with fewer internal flaws, allowing sound waves to travel faster.

The decline in USPV for M4 and M5 (30-40% WFS) is due to a dilution effect. The higher water absorption of WFS (1.2% vs. 0.85% for natural sand) creates a more porous Interfacial Transition Zone (ITZ) around each particle when used in high volumes. The increased number of these weaker, more porous micro-zones scatters and attenuates the ultrasonic pulses, reducing the measured velocity and indicating lower internal density.

Water Absorption

Mix M3 consistently demonstrated the lowest water absorption (1.05% at 24 hrs) and lowest sorptivity coefficient, indicating superior resistance to fluid ingress. The control mix (M1) and mixes with high WFS content (M4, M5) showed significantly higher absorption and sorptivity.

TABLE 4 WATER ABSORPTION

MIXES	INITIAL WEIGHT	TIME(HOURS) & WATER ABSORPTION (%)		
	W(kg)	24	48	72
M1	2.69	1.15 %	1.54 %	2.05 %
M2	2.64	1.25 %	1.72 %	2.15 %
M3	2.71	1.05 %	1.45 %	2.02 %
M4	2.68	1.35 %	1.86 %	2.35 %
M5	2.62	1.45 %	2.05 %	2.65 %

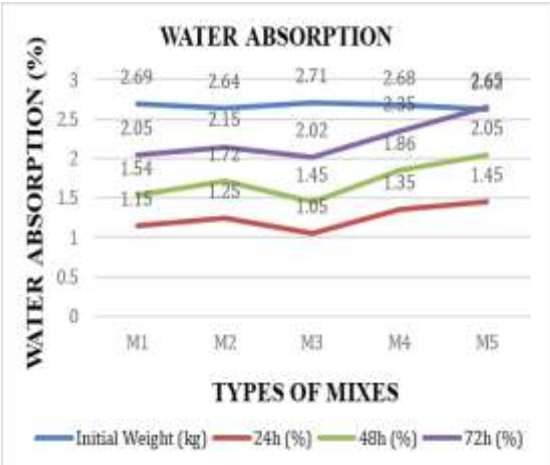

Figure 2 Water Absorption Test Results

Water absorption is a direct indicator of the concrete's capillary porosity and permeability. The low absorption of mix M3 is a direct consequence of the clogged and refined pore network from the SCMs' pozzolanic reactions. The ultra-fine particles of Alccofine are particularly effective in blocking capillary pores, making the path for water ingress more

tortuous and difficult. The optimal amount of WFS does not disrupt this dense matrix. Conversely, the higher absorption in M4 and M5 is caused by the Above-mentioned porous ITZs around the excess WFS particles. These zones act as interconnected channels, facilitating the easy entry and movement of water through the concrete matrix by capillary action. This increased permeability directly compromises durability by allowing easier entry for deleterious substances.
higher absorption in M4 and M5 is directly linked to the increased micro-porosity at the ITZ surrounding the WFS particles. The greater the number of these porous zones, the more interconnected the capillary network becomes, facilitating easier water ingress and reducing the concrete's overall durability.

Acid Resistance

The mix with 20% WFS (M3) exhibited remarkable acid resistance, retaining over 90% of its compressive strength after 90 days of exposure to both 5% HCl and 5% H_2SO_4 solutions. It also showed the least weight loss. The control mix (M1) was the most vulnerable, while higher WFS mixes (M4, M5) showed increased degradation compared to M3.

The superior acid resistance of the optimal mix M3, containing 20% fly ash, 10% Alccofine, and 20% waste foundry sand (WFS), stems from a dual protective mechanism: firstly, the pozzolanic reactions of the supplementary cementitious materials effectively consume the soluble calcium hydroxide (CH)—a primary target for acid attack—converting it into additional stable calcium silicate hydrate (C-S-H) gel; and secondly, the significantly refined pore structure and reduced permeability of the matrix, as evidenced by low water absorption and sorptivity, create a formidable barrier that drastically slows the ingress of acidic solutions (HCl and H_2SO_4), thereby hindering their destructive interaction with the cementitious components. Conversely, the observed decline in acid resistance at higher WFS replacements (≥30%) is directly attributable to an increase in overall porosity and weaker interfacial zones, which facilitate more rapid acid penetration and consequently accelerate the deterioration process through enhanced leaching of CH and decomposition of the C-S-H gel.

Table 5: Weight Loss (%) of HPC Specimens After Acid Attack					
Mix	**WFS (%)**	**HCl (28 Days)**	**HCl (90Days)**	**H_2SO_4 (28 Days)**	**H_2SO_4 (90Days)**
M1	0	2.50%	3.20%	3.80%	4.50%
M2	10	1.80%	2.40%	3.00%	3.60%
M3	20	1.50%	1.90%	2.50%	2.90%
M4	30	2.20%	2.80%	3.50%	4.10%
M5	40	2.70%	3.50%	4.20%	5.00%

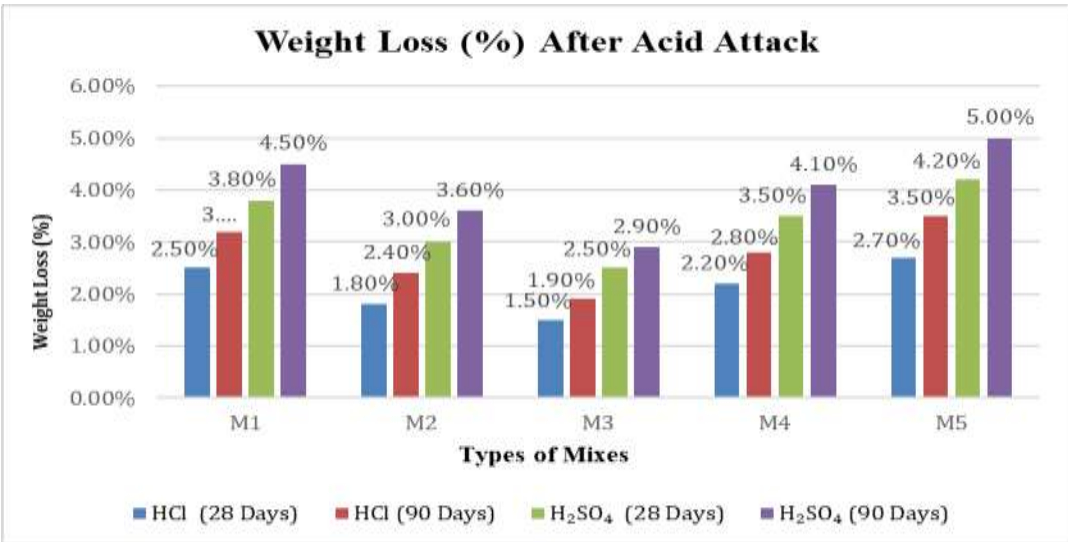

Table 6: Compressive Strength Retention (%) of HPC After Acid Attack					
Mix	**WFS (%)**	**HCl (28 Days)**	**HCl (90Days)**	**H_2SO_4 (28 Days)**	**H_2SO_4 (90 Days)**
M1	0	90.00%	88.00%	86.00%	84.00%
M2	10	93.00%	91.00%	90.00%	88.00%
M3	20	95.50%	93.80%	93.20%	90.50%
M4	30	91.50%	88.50%	87.50%	85.00%
M5	40	88.00%	85.00%	84.00%	80.50%

Sorptivity of Concrete Test

The sorptivity test, which measures the rate of water uptake through capillary action, showed that M3 had the lowest absorption values over time, while the control mix (M1) absorbed the most.

Sorptivity is a more sensitive measure of surface permeability than total absorption. The excellent performance of M3 (low sorptivity coefficient) confirms that the combination of SCMs and optimal WFS not only reduces total porosity but also significantly alters the pore structure, converting interconnected capillaries into discontinuous, finer pores. This drastically reduces the capillary suction force, which is the primary driver for water and aggressive ion penetration in concrete. This is a critical finding for durability, as it indicates a heightened resistance to corrosion, freeze-thaw cycles, and chemical attack.

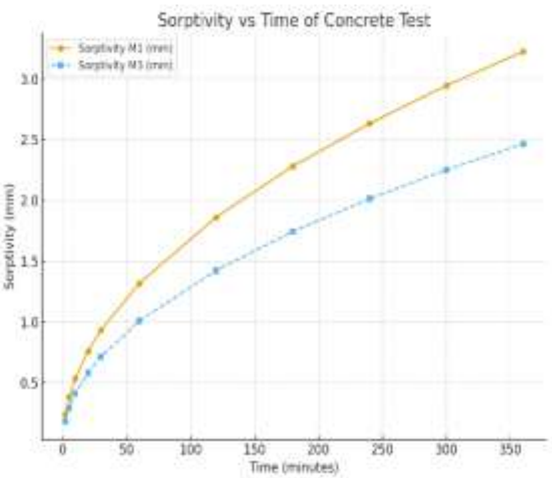

Figure 3 Sorptivity Test Result

Table 5 Sorptivity of Concrete Test

Time (min)	Sqrt(t) (min^0.5)	Sorptivity M1 (mm)	Sorptivity M3 (mm)
2	1.41	0.239	0.183
5	2.24	0.381	0.292
10	3.16	0.537	0.411
20	4.47	0.76	0.581
30	5.48	0.932	0.713
60	7.75	1.318	1.008
120	10.95	1.862	1.424
180	13.42	2.282	1.744
240	15.49	2.634	2.014
300	17.32	2.945	2.252
360	18.97	3.225	2.466

5. Conclusion

Based on the comprehensive experimental investigation into the durability of High-Performance Concrete (HPC) incorporating Supplementary Cementitious Materials (SCMs) and Waste Foundry Sand (WFS), the following conclusions are drawn:

Optimal Durability Performance: The mix **M3**, with 20% cement replacement by SCMs (20% fly ash + 10% Alccofine) and 20% fine aggregate replacement by WFS, was identified as the optimal composition. It demonstrated superior performance across all durability parameters tested, achieving an "Excellent" USPV rating (4.8 km/s), the lowest water absorption and sorptivity, and exceptional acid resistance with over 90% strength retention after 90 days of exposure.

Synergistic Microstructural Densification: The enhanced durability is attributed to a synergistic effect. The SCMs effectively consume calcium hydroxide and reduce porosity through pozzolanic reactions, while the optimal amount of WFS contributes to a well-graded aggregate matrix. This combination results in a denser, less permeable microstructure that impedes the penetration of water and aggressive chemicals.

Influence of High WFS Content: Replacements beyond 20% WFS (M4, M5) led to a progressive decline in durability. This is directly linked to the higher water absorption of WFS, which, in excess, increases the porosity and number of weaker interfacial transition zones (ITZs) within the concrete, facilitating the ingress of deleterious substances.

Sustainable HPC Solution: This study conclusively proves that the strategic incorporation of 20% WFS with a blend of fly ash and Alccofine produces a sustainable, eco-friendly High-Performance Concrete that does not merely match but significantly exceeds the durability performance of conventional concrete. This approach offers a technically sound and environmentally responsible solution for constructing durable infrastructure, especially in environments prone to chemical aggression.

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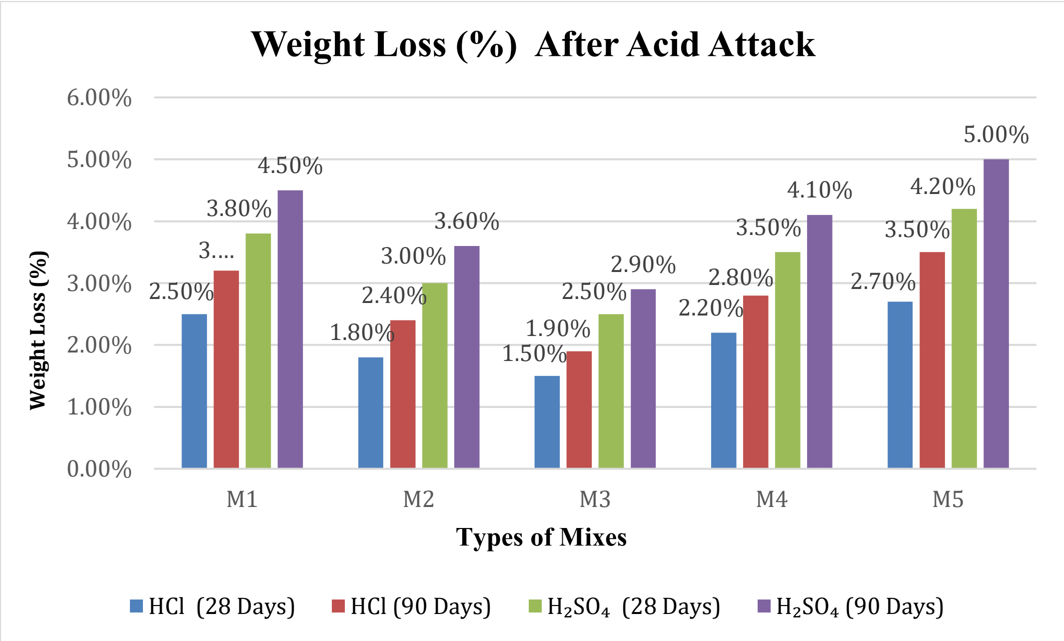
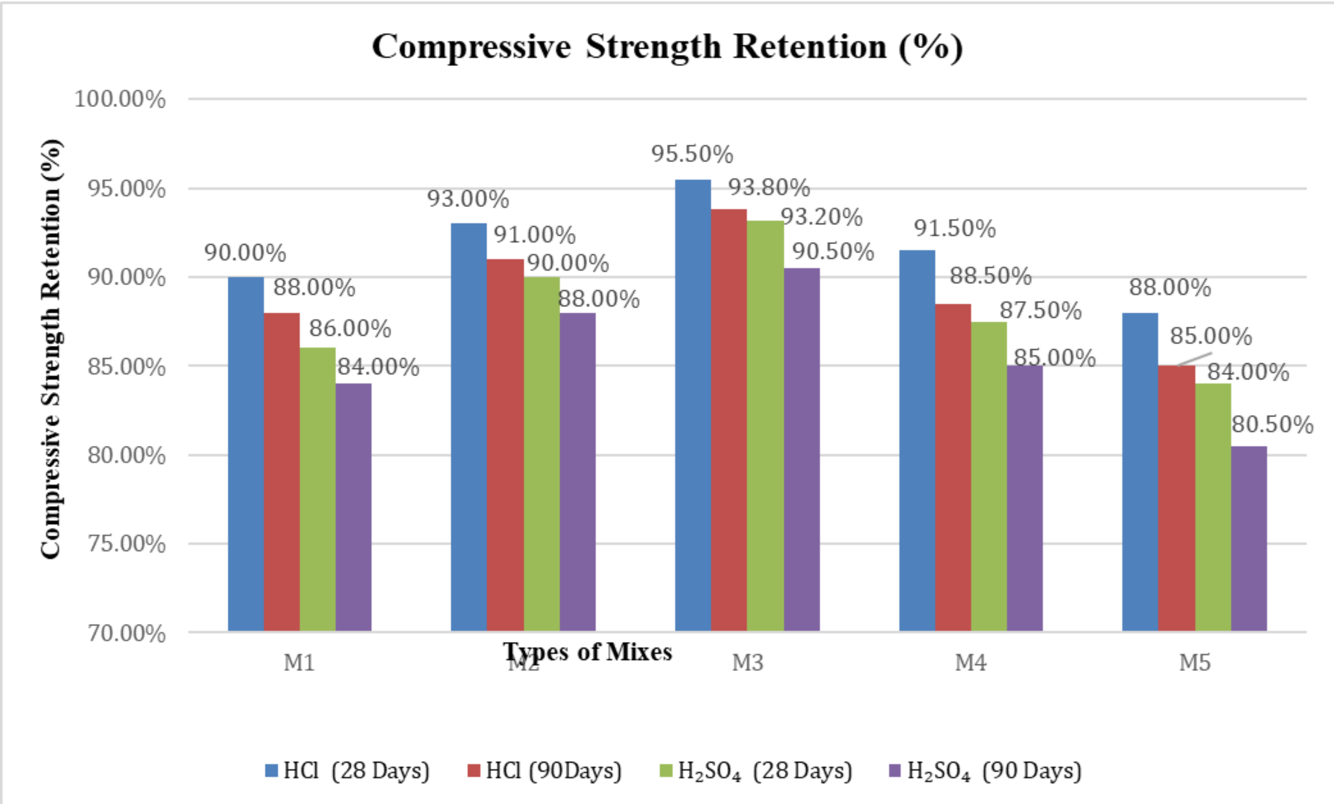

Weight Loss (%) After Acid Attack
Weight Loss (%)
6.00%
5.00%
4.00%
3.00%
2.00%
1.00%
0.00%
2.50%
3....
3.80%
4.50%
1.80%
2.40%
3.00%
3.60%
1.50%
1.90%
2.50%
2.90%
2.20%
2.80%
3.50%
4.10%
2.70%
3.50%
4.20%
5.00%
M1
M2
M3
M4
M5
Types of Mixes
HCl (28 Days)
HCl (90 Days)
H_2SO_4 (28 Days)
H_2SO_4 (90 Days)


Compressive Strength Retention (%)
Compressive Strength Retention (%)
100.00%
95.00%
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93.80%
93.20%
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88.50%
87.50%
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85.00%
84.00%
80.50%
M1
M2
M3
M4
M5
Types of Mixes
HCl (28 Days)
HCl (90Days)
H_2SO_4 (28 Days)
H_2SO_4 (90 Days)