Original Article

Assessment Of Mechanical And Durability Properties Of Concrete Containing GGBFS And Silica Fume Under HCL Exposure

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Abstract

In recent decades, global warming and CO_2 emissions have made sustainable development a priority. Diverse industrial sectors are rapidly developing innovative technology while coping with waste disposal concerns. Waste management issues in numerous areas contribute to pollution in the environment. Concrete can be manufactured by substituting various industrial wastes for cement, and attempts are undertaken to reduce environmental emissions and waste management principles. Industrial waste is now being used in concrete to provide the best choice for the environment and the construction industry to generate sustainable concrete. In the current investigation, various percentages of industrial waste, such as ground granulated blast furnace slag (GGBFS) up to 50% and Silica Fume up to 20%, were employed for concrete preparation. The compressive strength of hardened concrete was evaluated after a 28-day curing period. After that, concrete was exposed to HCL for 90 days and 180 days to assess deterioration in an aggressive environment. Concrete was also subjected to some non-destructive testing (NDT) to assess strength degradation. Microstructure and regression analysis were also performed. The results of this study were positive, demonstrating that concrete with optimal waste replacement enhances physical qualities.

Keywords: Ground granulated blast furnace Slag (GGBFS), Silica Fume, HCL Exposure, Weight Reduction, Microstructure, Non-destructive testing (NDT)

1. INTRODUCTION

The most significant component of the construction business is concrete. Because durability has become one of the most important issues in the building of reinforced concrete structures with long service lives and the development of construction technologies in recent years, it is necessary to manufacture well-designed concrete as a durable construction material. Concrete, on the other hand, uses a lot of natural resources including gravel, sand, water and cement. Furthermore, each year 3 billion tons of raw materials are utilized in cement production around the world [1, 2] and cement manufacturing accounts for around 2.5 percent of total global CO2 emissions from industrial sources. [3,4]. The growing consumption of natural resources, the large generation of industrial wastes and environmental contamination necessitate the development of new solutions for a sustainable future. Mineral admixtures such as pulverized granulated blast furnace slag, fly ash and silica fume, when used as a partial cement replacement, are one of the most effective strategies to reduce environmental impact. The pozzolanic reaction, which is attributed to the use of mineral admixtures in concrete production, improves the compressive strength, pore structure and permeability of mortars and concretes [3-6]. This strategy has the potential to minimize costs, conserve energy, reduce waste [3-7] and the lesser cement required also leads to a reduction in CO2 emissions from cement manufacture [8,9]. Compressive strength is improved when ground granulated blast furnace slag is used as a cement replacement due to the fineness of the ground granulated blast furnace slag and chemical hydration [10,11]. Partially replacing slag by weight may reduce early strength, but it considerably improves later strength, microstructure properties and durability of hardened Portland cement and concrete [12,13]. An artificial neural network was used to forecast compressive strength using varying W/C ratios, cement content, and GGBFS replacement ratios [14].

Silica fume (SF) is well known for improving the connection between paste and aggregate [15–17]. For decades, silica fume has been used as a supplemental cementitious material (SCM).Concrete characteristics have been claimed to be influenced by this by-product of the elemental silicon or ferrosilicon industries. Because of its high specific surface area, silica fume is known to reduce the workability of OPC concrete [18]. It has been proven that adding up to 20% silica fume to OPC concrete improves its mechanical qualities. One of the causes of Portland cement concrete deterioration is the aggressive attack of sulphate ions [19]. Sulphate ions react with some cement paste constituents to form sulphoaluminate hydrates (ettringite or monosulphate) and gypsum, which cause concrete to expand and crack. The chemical resistance to sulphate attack is increased in supersulphated Portland blast-furnace slag or pozzolanic cements, which also have impermeability and a lower heat of hydration [20]. The resistance of silica fume-sulphate blended cement pastes to sulphate attack displays promising results [21]. Because of the fine pore structure and low lime concentration, these blended cements are resistant to sulphate attack. Replacement of silica fume has a considerable impact on the mechanical properties and in particularly, the durability of high-performance concretes [22]. The mechanical and durability of alkali activated slag (AAS) mortars were investigated by replacing ground granulated blast furnace slag (GGBFS) with Nano silica at 2% and 4% and silica fume at 5%, 7.5% and 10% in mortar mixtures. The GGBFS was activated with a mixture of sodium hydroxide (NaOH) or potassium hydroxide (KOH) and sodium silicate (Na2SiO3). Single, binary and ternary blended AAS mortars were subjected to a variety of fresh concrete and hardened concrete tests in order to determine the impact of the factors on the mechanical, durability and bond strength of the AAS mortars. The results showed that adding Nano silica to AAS mortars improved performance significantly, whereas adding more than 5% silica fume did not [23]. Up to 100% substitution and up to 12 months, the effect of silica fume or granulated slag as high alumina cement (HAC) substitutes on sulphate attack of regular Portland and alumina cement blends was evaluated [24]. The results indicate that cement pastes containing silica fume contain more combined water and less free lime than those containing granulated slag. The aggressive attack of sulphate ions on hardened cement pastes is reduced when HAC is replaced by silica fume or granulated slag in the OPC–HAC blend, however granulated slag is more effective than silica fume.

2. MATERIALS AND METHODS

2.1. Cement, GGBFS & Silica Fume

Ordinary Portland cement 53 grade conforming to IS 269: 2015[25] was used in the investigation. GGBFS and silica fume were given by Stallion Energy Pvt. Ltd., Rajkot, Gujarat, India. The essential components of the OPC Cement, GGBFS, and Silica Fume used in this study are shown in Table 1.

Table 1 Basic Component of OPC Cement, GGBFS and Silica Fume

Basic Components	OPC Cement	GGBFS	Silica Fume
Silica as SiO_2	21.47 %	35.47%	92.80%
Aluminium Oxide as Al_2O_3	4.91%	14.27%	0.6%
Iron Oxide as Fe_2O_3	3.43 %	2.41%	0.3%
Calcium Oxide as CaO	62.75 %	35.89%	----
Magnesium Oxide as MgO	1.63 %	8.06%	0.6%
Sulphur Trioxide as SO_3	2.33 %	1.58%	0.1%
Sodium Oxide as Na_2 +Potassium Oxide as K_2O	0.65 %	0.2%	1.17%

2.2. Fine Aggregates

Fine aggregate from the Surendranagar region of the Bhogavo river was utilized in concrete that fulfilled IS 383: 2016[26] and IS 2386 -1963 standards (Part-I-III) [27-29]. Tables 2 and 3 depicted fine aggregate grading and various parameters, respectively.

Table 2 Sieve Analysis of Fine Aggregate

Sieve Size	% Passing
10 mm	100.0
4.75 mm	97.0
2.36 mm	85.7
1.18 mm	68.4
600 microns	46.5
300 microns	21.5
150 microns	7.6
< 150 microns	---

Table 3 Different Parameters of Fine Aggregate

Tests	Results
Fineness Modulus	2.73
Specific Gravity	2.68
Bulk Density (kg/m3)	1718
Silt Content (%)	1.56
Grading Zone	II
Water Absorption (%)	1.2

2.3. Coarse Aggregates

The Coarse aggregate locally available in sayla taluka of Surendranagar district was used in concrete fulfilling to IS 383: 2016[26] and IS 2386 -1963 (Part-I-III) [27-29]. Table 4 and 5 depicted coarse aggregate grading and various parameters, respectively.

2.4. Concrete Mix Design

In this study, M-40 concrete was made according to IS 10262-2019 [31]. 10%, 20%, 30%, 40%, and 50% GGBFS were employed as partial cement replacements in concrete, with 5%, 10%, 15% and 20% silica fume, as illustrated in Figure 1 designated by mixes M1 to M20, respectively. For this investigation, a total of 21 mixes, including a control mix were created. To determine the effect of GGBFS and Silica Fume on the compressive strength of concrete, the pozzolanic strength index was measured for 7 and 28 days, with the control concrete compressive strength serving as a reference. The best replacement percentage for concrete mix preparation was found to be 30% GGBFS and 5% silica fume based on the pozzolanic strength index.

Table 4 Sieve Analysis of Coarse Aggregate For 20 mm & 10 mm Size

IS: Sieve Size	% Passing (20 mm)	Specification as per IS 383-2016 (20 mm)	% Passing (10 mm)	Specification as per IS 383-2016 (10 mm)
80 mm	100.00	100.00	100.00	100.00
40 mm	100.00	100.00	100.00	100.00
20 mm	95.66	85 to 100	100.00	100.00
10 mm	4.60	0 to 20	94.98	85 to 100
4.75 mm	0.00	0 to 5	9.12	0 to 20
2.36 mm	0.00	---	0.00	0 to 5
1.18 mm	0.00	---	0.00	---
600 microns	0.00	---	0.00	---
300 microns	0.00	---	0.00	---
150 microns	0.00	---	0.00	---
< 150 microns	--	---	--	---

Table 5 Different Parameters of Coarse Aggregate for 20 mm & 10 mm Size

Tests	Results (20 mm)	Results (10 mm)
Specific Gravity	2.78	2.75
Water Absorption %	0.60	0.70
Bulk Density (kg/m^3)	1587	1577
Aggregate Impact Value (%)	6.64	12.13
Aggregate Crushing Value (%)	7.12	13.82
Aggregate Flakiness Index	11.83	12.97
Aggregate Elongation Index	9.46	11.09

The following Table 6 shows the concrete mix design for M-40 grade control mix and with partial cement replacement.

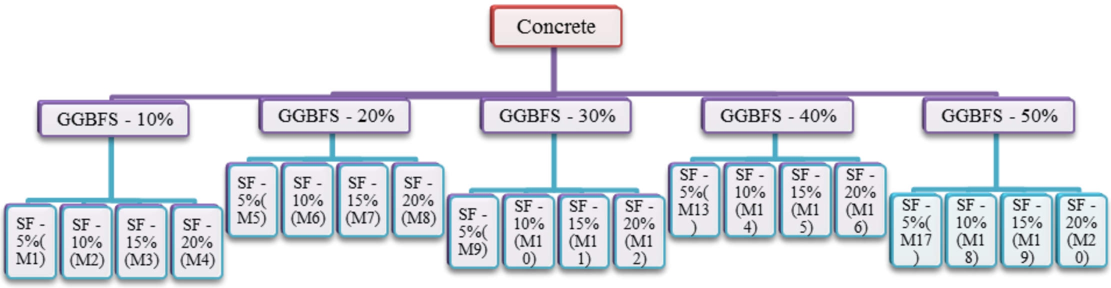


Figure 1 Different percentage of GGBFS and silica fume used for all mixes

Table 6 Concrete Mix Design for M-40 Grade

Material	PC40	PC40GSF35
Cement OPC (kg)	440	286
GGBS (kg)	-	132
Silica Fume (kg)	-	22
Sand (kg)	645	645
20 mm Aggregate (kg)	711	711
10 mm Aggregate (kg)	471	471
Water (kg)	176	176
Admixture (%)	0.15%	0.20%
W/C Ratio	0.4	0.4
Slump (mm)	59	75
Compaction Factor	0.93	0.86

2.5. HCL Exposure

Portland cement concrete is more vulnerable to acid attack due to its alkaline nature. The behaviour of concrete exposed to harsh environmental conditions was examined by exposing it to 5% hydrochloric acid (HCL). The appearance, weight loss and compressive strength deterioration of the designated acidic solutions were investigated. The compressive strength tests were carried out on cube specimens in line with IS 516: 1959 [34]. SEM investigations were also used to analyse the concrete's microstructural characteristics. Every week, the solution was checked to ensure that the concentration remained consistent throughout the test period. Typically, damage starts at the edges and corners and continues to racking and spalling. The use of pozzolanas boosts acid resistance as well. After 28 days of conventional curing, specimens were immersed in HCL solution for 90 days and 180 days of exposure.

2.6. Non-Destructive Testing – Rebound Hammer

According to IS 13311 (Part 2): 1992 [32], all specimens were subjected to a rebound hammer test, with 9 readings collected on each of the cubes' two faces. After 28 days of water curing, the test results were obtained followed by 90 and 180 days of HCL exposure. As a result, concrete mix surface hardness is assumed to be proportional to compressive strength. The rebound value, often known as the rebound or rebound index, is determined by the grading. By glancing at the graph on the hammer, you may figure out the compressive strength.

2.7. Non-Destructive Testing – Ultrasonic Pulse Velocity

The test involves measuring the travel time T of an ultrasonic pulse generated by an electro acoustic transducer in touch with one surface of the concrete mixes component under test and receiving it at the other end by a comparable contact sensor Surface. In the laboratory, ultrasonic pulse velocity tests on cubes were done in accordance with IS 13311 (Part 1): 1992 [31], resulting in a concrete quality rating based on pulse velocity. The test findings were obtained after 28 days of water curing, followed by 90, and 180 days of HCL exposure.

3. RESULTS AND DISCUSSION

3.1. Compressive Strength

After 7 days and 28 days of curing, 150 mm x 150 mm concrete cubes were evaluated for compressive strength according to IS 516: 1959 [34]. Figure 2 shows concrete compressive strength after 7 and 28 days, with M-40 control concrete specimens designated by PC40 and concrete specimens with 35% waste replacement (30% GGBFS + 5% Silica Fume) marked by PC40GSF35. Figure 1 indicates that concrete's compressive strength increased from 30.52 MPa to 33.43 MPa after 7 days of curing and from 48.98 to 49.99 MPa after 28 days of curing. It was discovered that when the curing period lengthens, compressive strength increases. The addition of GGBFS and silica fume to the matrix increases the binding between the cement paste and aggregate particles while also raising the cement paste's density, which improves the concrete's compressive strength significantly. This is due to the filler effect of GGBFS and the use of silica fume to produce dense concrete. Because of the pozzolanic characteristics of GGBFS and silica fume, strength was also improved. At 28 days, a combined replacement of 35% (GGBFS and silica fume) in total cementitious materials was used to achieve a strength superior to that of conventional concrete.

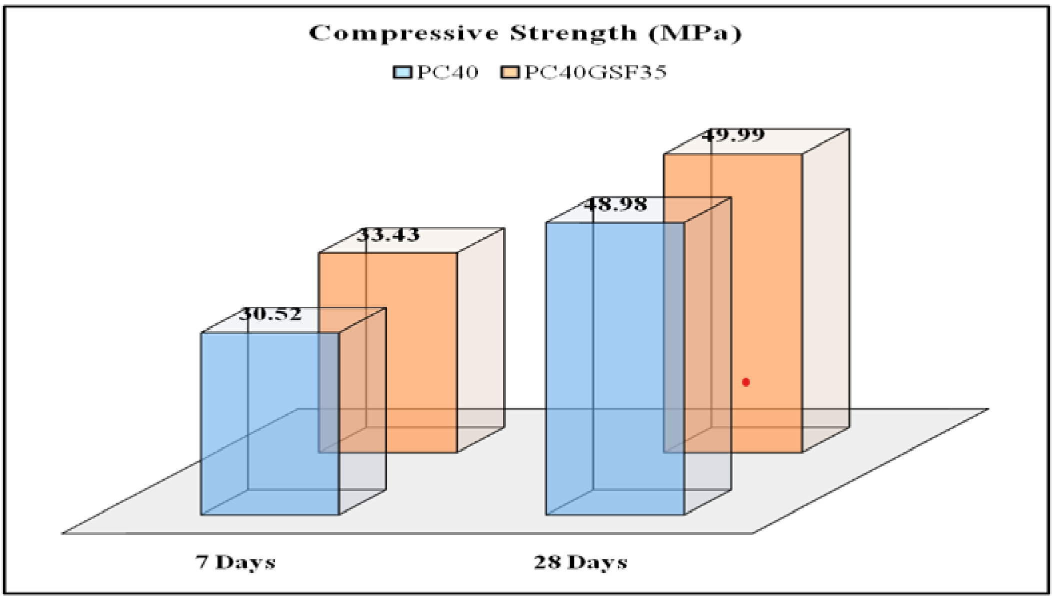
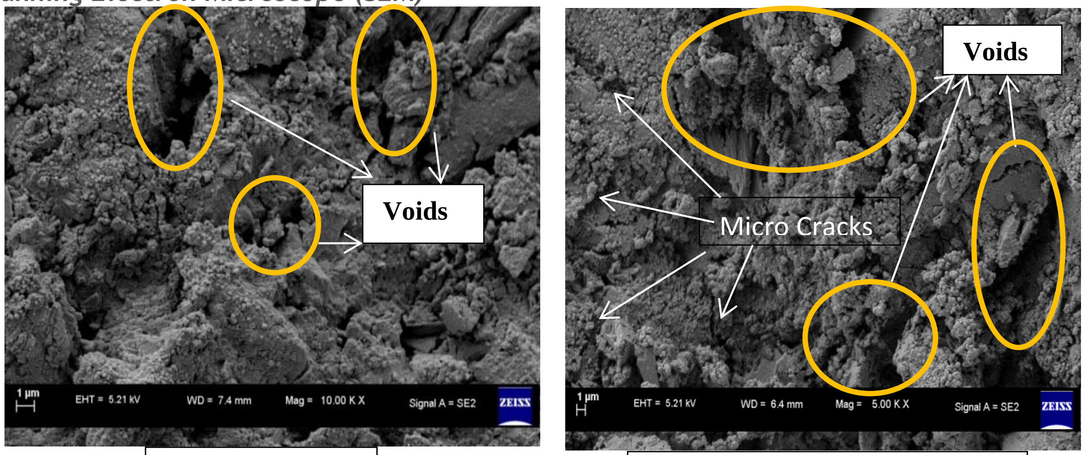


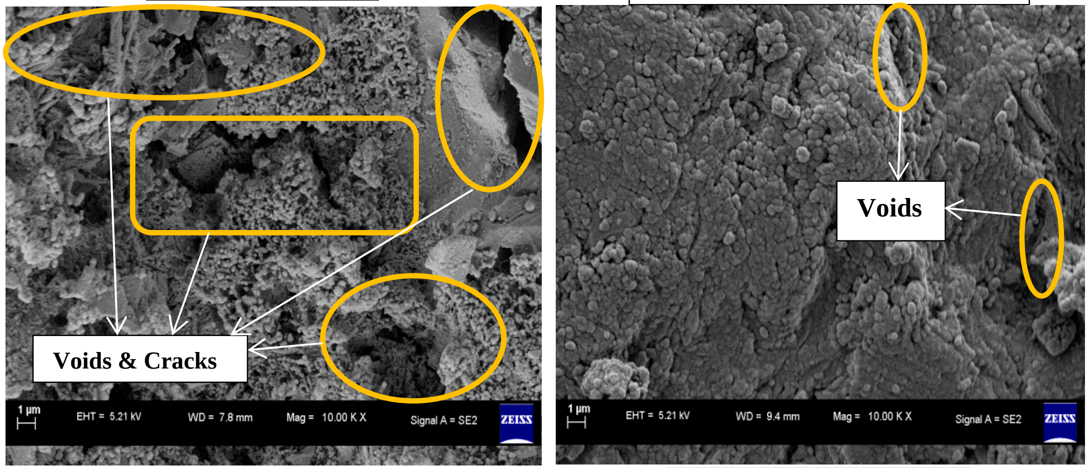
Figure 2 Compressive Strength of Concrete for 7 days and 28 days

3.2. Scanning Electron Microscope (SEM)



PC40 – 28 Days

PC40 - 90 Days (HCL Exposure)



PC40 - 180 Days (HCL Exposure)

PC40GSF35 - 28 Days

Figure 3 Microstructure of PC40 (28 days water curing, 90 days & 180 days HCL Exposure) concrete and PC40GSF35 (28 days water curing) Concrete

Figure 3 shows the microstructure of control concrete after 28 days of water curing, 90 days of HCL exposure, 180 days of HCL exposure and concrete with combined 35% (GGBFS and silica fume) replacement after 28 days of water curing denoted by PC40 – 28 Days, PC40 – 90 Days (HCL Exposure), PC40 – 180 Days (HCL Exposure) and PC40GSF35 – 28 Days.

Figure 4 shows the microstructure of concrete with combined 35% (GGBFS and silica fume) replacement after 28 days of water curing followed by 90 days and 180 days HCL exposure, denoted by, PC40GSF35 – 90 Days (HCL Exposure) and PC40GSF35 – 180 Days (HCL Exposure). GGBFS can be used to efficiently minimize pore size in concrete. GGFBS content increases, resulting in a denser structure that resists water penetration [35]. In addition, coarse pores in GGBS concrete were significantly reduced and the pore structure of OPC concrete was dramatically improved when GGFBS was added to the mix [36]. Fewer cracks were found due to the high pozzolanic reactivity and the physical filler effect of silica fume. The addition of more than 5% silica fume did not necessarily increase the compressive strength of the mixes [23]. Figure 3 shows that after 28 days of curing, there were few and small voids in the PC40 concrete mix. After 90 days of HCL exposure followed by 28 days of water curing, there were more voids and micro cracks observed in the PC40 concrete mix. Large voids and disintegration were detected after 180 days of HCL exposure to PC40 concrete.

Figure **3** demonstrates that after 28 days of curing, PC40GSF35 Concrete with combined 35% (GGBFS and silica fume) replacement had very few and small voids compared to PC40 concrete mix due to dense particle packing effect of GGBFS and silica fume. There were fewer voids observed in the PC40GSF35 concrete mix after 90 and 180 days of HCL exposure followed by 28 days of water curing than in the PC40 concrete mix.

PC40GSF35 - 90 Days (HCL Exposure)

PC40GSF35 - 180 Days (HCL Exposure)

Figure 4 Microstructure of PC40GSF35 (90 days & 180 days HCL Exposure) Concrete

3.3. Effect of HCL Exposure

After being soaked in HCL solution for 90 and 180 days, followed by 28 days of water curing, M-40 grade concrete cubes were evaluated. Figure 5 shows the test results for the same. Figure 5 shows that the compressive strength of PC40 specimens dropped from 48.98 MPa after 28 days of water curing to 41.42 MPa and 37.28 MPa after 90 and 180 days of HCL exposure. PC40GSF35 specimens' compressive strength dropped from 49.99 MPa after 28 days of water curing to 42.29 MPa and 39.24 MPa after 90 and 180 days of HCL exposure, respectively.

Figure 6 shows that after 90 and 180 days of HCL exposure, the percentage drop in compressive strength of PC40 specimens was 84.57% and 76.11%, respectively, compared to 100% after 28 days of water curing. Compressive strength of PC40GSF35 specimens was reduced by 84.59% and 78.49% after 90 and 180 days of HCL exposure, respectively, compared to 100% after 28 days of water curing. After 180 days of HCL exposure, compressive strength was nearer to 40 MPa for PC40GSF35 mix, indicating that the harsh acidic environment had no effect on the compressive strength.

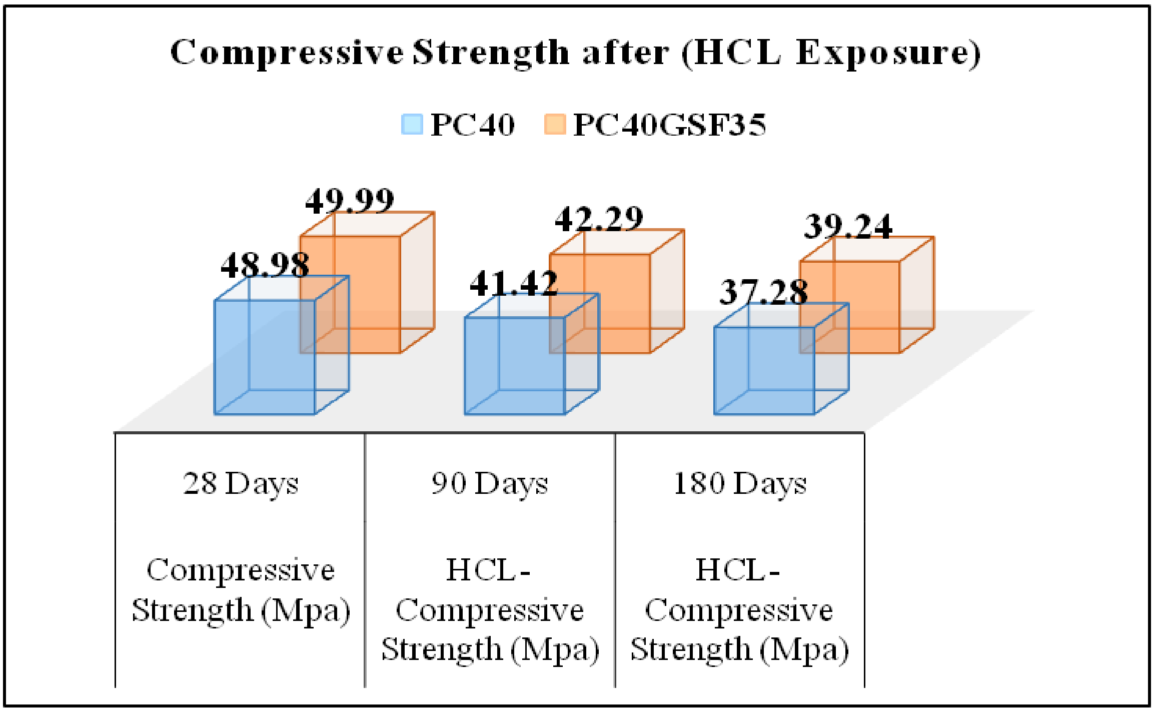


Figure 5 Compressive Strength Results for HCL Exposure of 90 days & 180 days

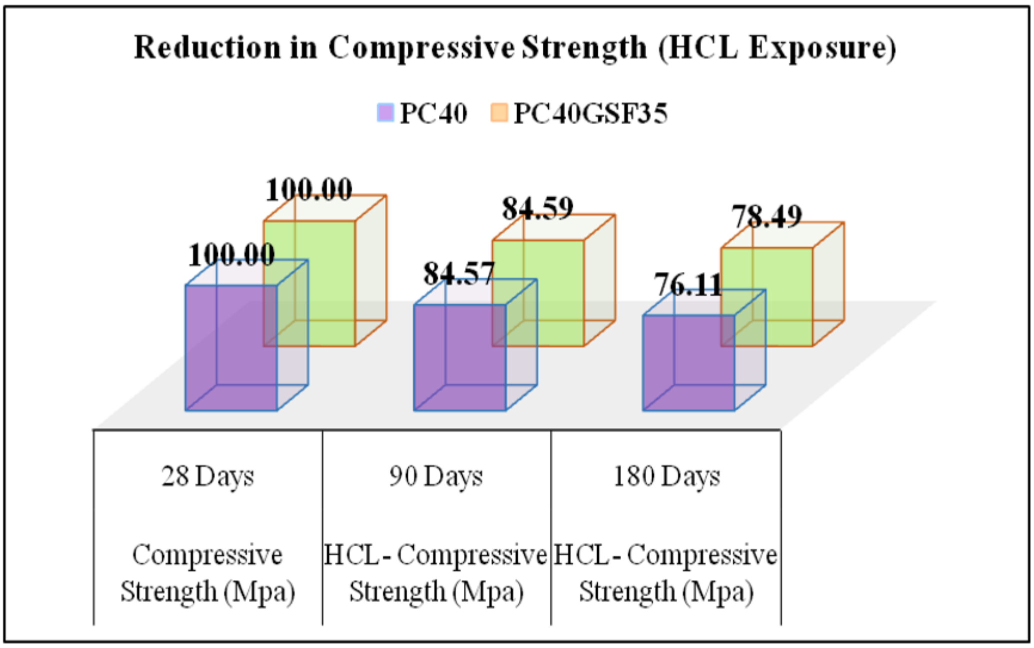


Figure 6 Percentage Reductions in Compressive Strength after HCL Exposure

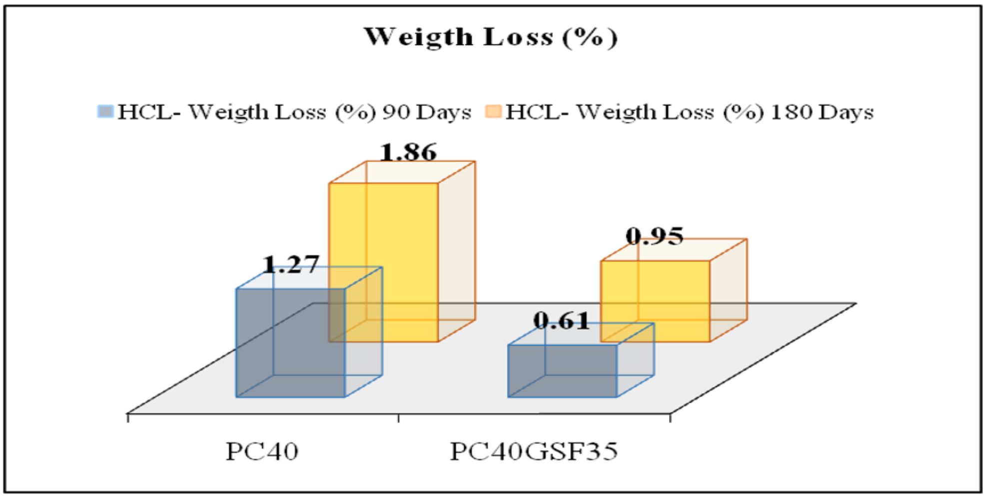


Figure 7 Concrete weight loss percentages after HCL Exposure

From below figure 7 it was observed, reduction in weight of PC40 cube specimens were found from 1.27% and 1.86% after 90 and 180 days HCL exposure respectively compared to 28 days water curing. Reduction in weight of PC40GSF35 cube specimens were found from 0.61% and 0.95% after 90 and 180 days HCL exposure respectively compared to 28 days water curing. Figure 8 shows appearance of HCL exposed cubes after 90 days and 180 days.

Figure 8 PC40 Concrete Surface after 90 days (A) and 180 days (B) of HCL Exposure

Figure 9 PC40GSF35 Concrete Surface after 90 days (A) and 180 days (B) of HCL Exposure

After 90 days of HCL exposure, the edges of PC40 concrete were degraded, as shown in Figure 8(A). On the concrete surface, little pits were discovered along with the edge. Figure 8(B) shows significant edge and surface erosion after 180 days of HCL exposure. All coarse aggregate was exposed as the outside surface eroded due to the hard environment. Figure 9(A) shows that after 90 days of HCL exposure, there was no degradation to the edges and surface of PC40GSF35 concrete when compared to PC40 control concrete (Figure 8(A)). After 180 days of HCL exposure, edges of PC40GSF35 concrete were observed to decay much less than edges of PC40 control concrete (Figure 9(B)). Similarly, when compared to PC40 concrete specimens, the exterior surface of PC40GSF35 concrete was not much harmed.

3.4. Non-Destructive Testing – Rebound Hammer

All HCL-exposed cube specimens were subjected to a rebound hammer test, followed by 28 days of water curing. Figure 10 illustrates the results of the rebound hammer test in terms of compressive strength. After 28 days of water curing, compressive strengths of 48.98 MPa and 49.99 MPa were found for PC40 and PC40GSF35 mixes, respectively. For the same curing period, the rebound hammer compressive strength of PC40 and PC40GSF35 mix was 50 MPa and 52 MPa, respectively. Compressive strength measured by rebound hammer test after 90 days of HCL exposure was 37 MPa for PC40 and 39 MPa for PC40GSF35 mix, respectively. After 180 days of HCL exposure, the PC40 and PC40GSF35 mix showed 36 MPa and 38 MPa of compressive strength, respectively. As the HCL exposure length was extended, this drop in compressive strength was noticed due to the development of micro cracks and an increase in the amount of voids in concrete, as illustrated in Figures 3 and 4.

Figure 11 shows the percentage change in compressive strength as a result of the rebound hammer test. Rebound hammer testing revealed a reduction in compressive strength of PC40 control mix from 74% to 72% after 90 and 180 days of HCL exposure respectively, compared to 100% after 28 days of water curing. By rebound hammer test, the compressive strength of the PC40GSF35 mix decreased from 75% to 73.08% after 90 and 180 days of HCL exposure respectively, compared to 100% after 28 days of water curing.

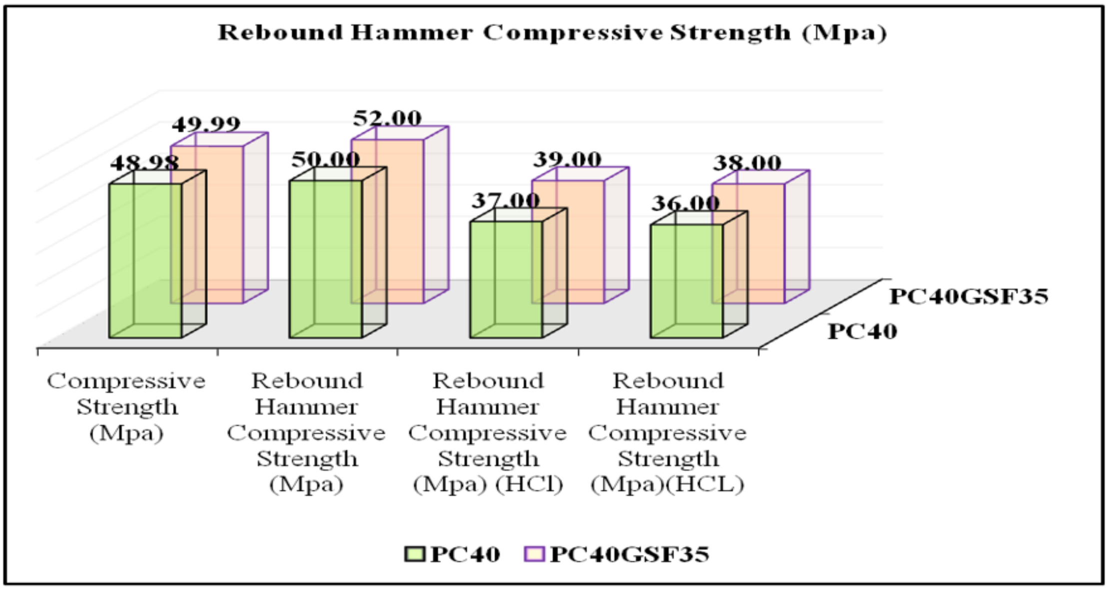


Figure 10 Rebound hammer test results

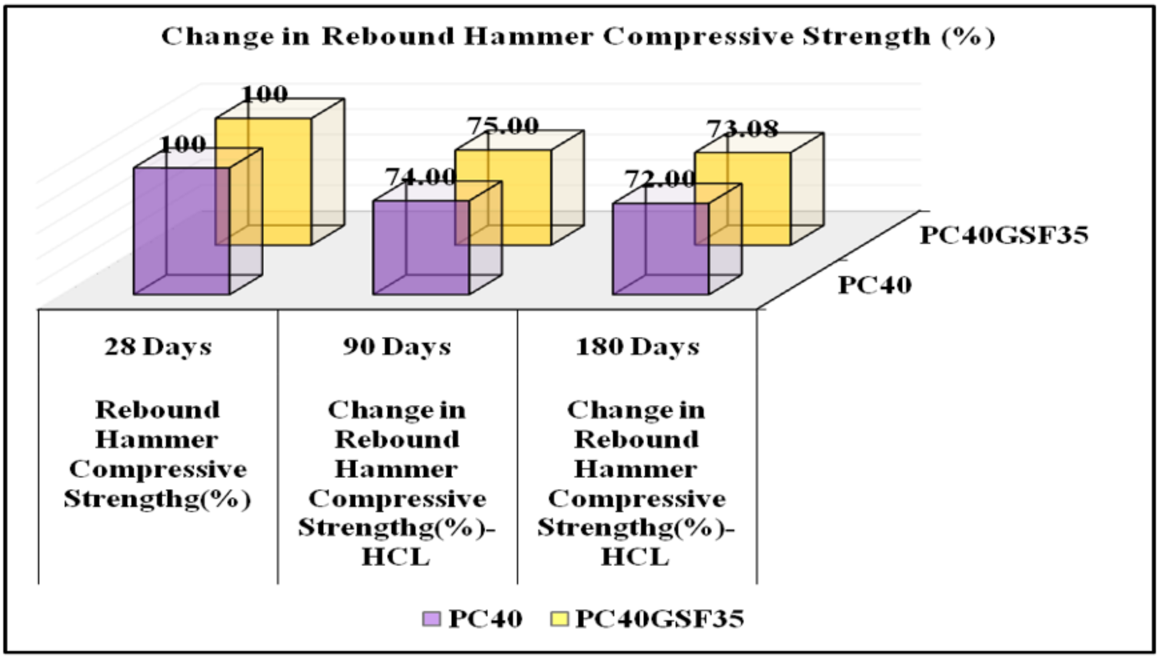


Figure 11 Percentage change in rebound hammer compressive strength

3.5. Non-Destructive Testing - Ultrasonic Pulse Velocity

All HCL-exposed cube specimens were subjected to an ultrasonic pulse velocity test, which was followed by a 28-day water curing period. Figure 12 depicts the quality of concrete as a function of pulse velocity.

Figure 12 show that when the HCL exposure time increased, the ultrasonic pulse velocity decreased. PC40 mix pulse velocity lags from 4.59 km/s, 4.23 km/s to 3.29 km/s were reported after 28 days of curing, 90 days and 180 days of HCL exposure respectively. Also Postponement in pulse velocity was observed for PC40 GSF35 mix from 4.79 km/s, 4.35 km/s to 3.40 km/s for 28 days curing, 90 days and 180 days HCL exposure respectively. The decrease in pulse velocity was detected as a result of concrete degradation in an aggressive environment and due to development of voids and cracks.

3.6. Regression Analysis

Figure 13 shows the relationship between concrete cube compressive strength and rebound hammer test compressive strength after 28 days of water curing, 90 days and 180 days of HCL exposure with R^2 coefficient for PC40 mix. With an R^2 of 0.9168, it reveals a decrease in compressive strength following HCL exposure.

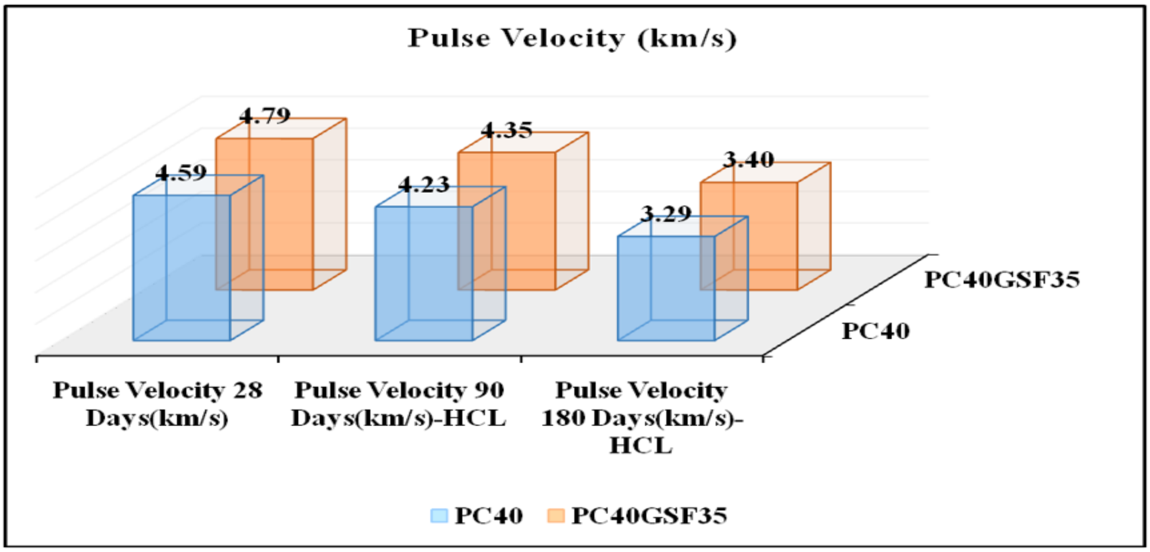


Figure 12 Ultrasonic Pulse Velocity Test Results

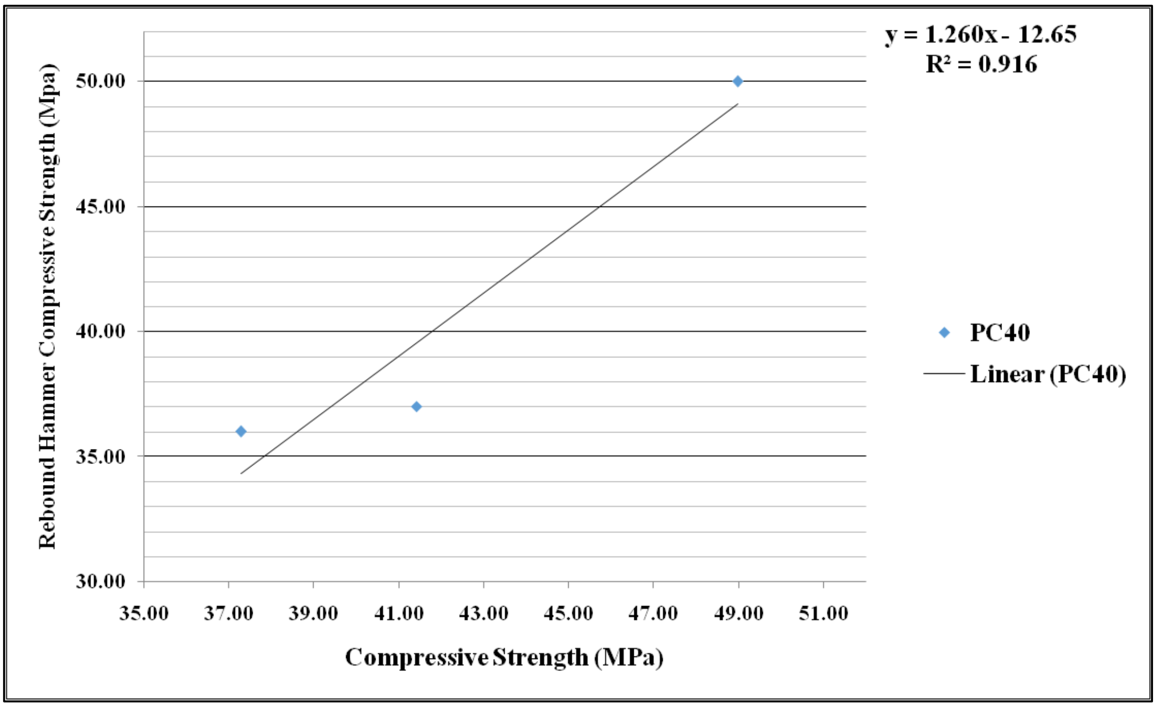


Figure 13 Relationship between compressive strength and rebound hammer test of PC40 mix

Figure 14 below demonstrates the R^2 coefficient for PC40GSF35 mix and the relationship between concrete cube compressive strength and rebound hammer test compressive strength after 28 days of water curing, 90 days and 180 days of HCL exposure. The same pattern was observed with R^2 of 0.9545 with the decrease in compressive strength following HCL exposure. In comparison to PC40 concrete mix, PC40GSF35 concrete has a greater R^2.

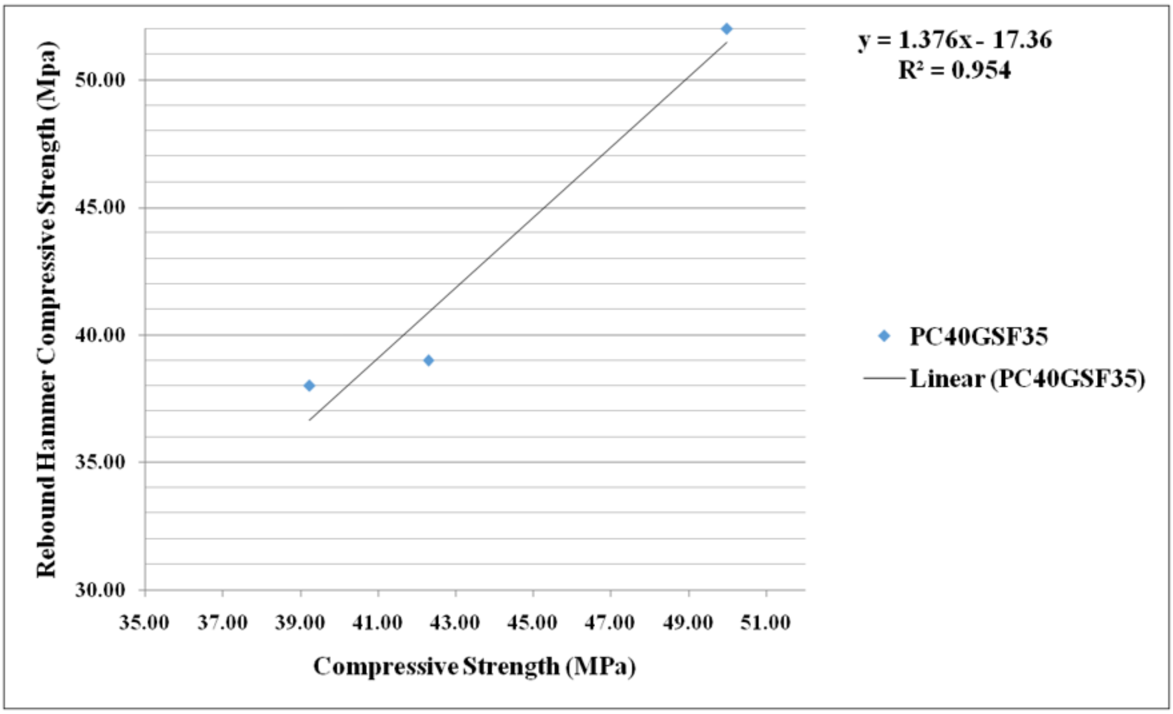


Figure 14 Relationship between compressive strength and rebound hammer test of PC40GSF35 mix

CONCLUSION

Hardened concrete testing, durability testing, microstructure analysis and non-destructive testing were used to assess the effectiveness of partial replacement of GGBFS and silica fume with cement in concrete manufacturing. Based on the findings of this study, the following key conclusions may be drawn:

1. Comparing 28 days of water curing to 90 days and 180 days of HCL exposure, there was a reduction in compressive strength of PC40 specimens ranging from 84.57% to 76.11%.

2. For 90 days and 180 days of HCL exposure, compressive strength of PC40GSF35 specimens was reduced between 84.59% and 78.49% compared to 28 days water curing, indicating a small marginal reduction in concrete strength after combined use of GGBFS and silica fume in concrete compared to control concrete.
3. In comparison to 28 days of water curing, weight loss of PC40 specimens ranged from 1.27% to 1.86% after 90 and 180 days of HCL exposure.
4. Weight loss of PC40GSF35 specimens ranged from 0.61 to 0.95% after 90 and 180 days of HCL exposure respectively, when compared to 28 days of water curing, indicating that PC40GSF35 concrete mix has stronger densification and particle packing than PC40 control mix.
5. Due to the good pozzolanic nature of GGBFS and silica fume, SEM pictures of PC40GSF35 concrete mix show very little voids and micro fractures development following HCL exposure compared to PC40 concrete mix.
6. Surface hardness test results were analyzed using a non-destructive test, which revealed that PC40GSF35 has a superior surface quality than reference mix PC40 after 90 and 180 days of HCL exposure.
7. After 90 days and 180 days of HCL exposure, ultrasonic pulse velocity tests revealed that concrete made with 35% waste, namely PC40GSF35, was dense and homogeneous, with better pulse velocity compared to control mix PC40 concrete mix.
8. Cement manufacturing's carbon emissions in the atmosphere can be reduced to some extent by using industrial waste instead of cement in concrete preparation, making the environment more sustainable.

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