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Research Article

Effect on Sulfuric Acid Resistance and Shrinkage of Concrete Incorporating Processed Bagasse Ash and Silica Fume

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Using ordinary Portland cement (OPC) in concrete has significant environmental and sustainability concerns. Notably, in the production of OPC, large volumes of greenhouse gases are produced, which contribute to global warming, and large amounts of natural raw materials are used, which can lead to the depletion of nonrenewable resources with time. In addition, OPC production is highly energy-intensive. To mitigate these concerns, it has become common practice to reduce the amount of OPC used in concrete production by partially replacing OPC with a supplementary cementitious material (SCM). Most of the SCMs used have pozzolanic properties and react with free lime in OPC to provide more cementitious material, which increases the long-term strength of concrete and also densifies the pore structure, resulting in improved durability in harsh environments. This study explored the effect of OPC on the resistance to sulfuric acid attack and drying shrinkage when OPC is partially replaced by processed bagasse ash (PBA) at dosages of up to 50%, together with 5% silica fume. Both materials are pozzolanic and are expected to react with free lime in OPC concrete to increase the strength and densify the concrete; however, with increased PBA dosage, the cement is diluted, and a reduction in strength can be expected. This study explores the benefits that can be realized, focusing primarily on sulfuric acid resistance and the reduction of drying shrinkage.

1. Introduction

The global population is experiencing a rapid increase accompanied by significant advancements in high-rise construction and the associated infrastructure development [1–3], and there is an increasing demand for concrete, a versatile material used in construction [4, 5]. Ordinary Portland cement (OPC) is a widely used binder in concrete production, including broad application and widespread acceptance [6–9]. However, the production process of OPC consumes a lot of natural resources (e.g., limestone and clay) and requires a significant amount of energy. In addition, it produces a considerable amount of greenhouse gases and contributes to global warming [10–13]. To address these issues, it is vital to explore materials that can reduce the amount of OPC used to make concrete, such as reusing wastes from industrial and agricultural industries as partial substitution materials for OPC in concrete [14, 15]. Among wastes from the industrial sector commonly used are slag, fly ash [16], coal ash [17], metakaolin [18], and oil shale ash [19]. Similarly, rice husk ash [20] and bagasse ash (BA) have been used in agriculture. In particular, silica fume (SF) and BA are highly effective pozzolanic substances that enhance concrete characteristics [21].

Sugarcane is a very significant product in developing nations. Its cultivation needs sufficient sunlight, water, and warmth, limiting its growth in semitropical areas [22]. Sugarcane production in 2019 was 1.9 billion metric tons worldwide [23]. Sugar is completely extracted from sugarcane, and the remaining waste is bagasse. This material generates steam in sugar mills to produce electricity. The bagasse is generally burned at 600–900°C, resulting in waste called BA [24]. There currently needs to be an appropriate use of BA waste

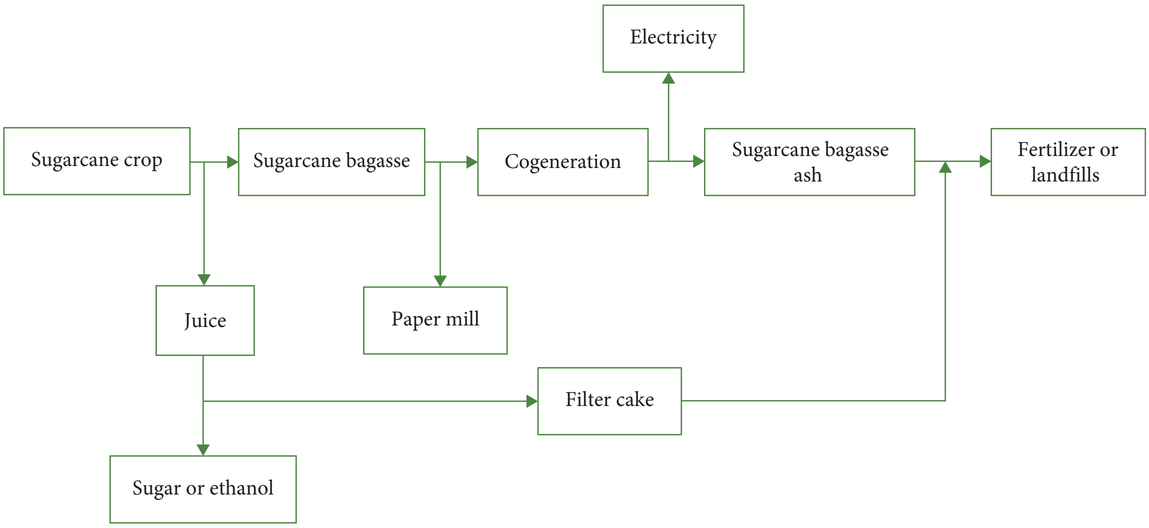


Figure 1: Bagasse cogeneration process [27].

due to the eco-hazardous nature of BA and the shortage of dumping sites in the recent population boom. Therefore, improper disposal of the small particles from BA could lead to environmental risks such as air pollution and surrounding land and water pollution, resulting in detrimental environmental alterations [25, 26]. Figure 1 presents the BA generation process.

Concrete is generally considered one of the primary building materials used in construction projects, with an average use of 1 m^3 per person globally every year [28, 29]. The durability of concrete is one of the most critical performance properties, particularly in the context of concrete used in coastal areas or aggressive environments [30–32]. Generally, the environment of areas along the seas and ocean shores is saturated with salt, among which sulfate is relatively high. The sulfate salt in this environment typically weakens the hydration bonds of concrete, leading to a significant destructive effect and impacting its durability [33, 34]. However, the concrete must be strong enough to prolong the life span of any construction project while surviving weathering, chemical attack, abrasion, and other forms of degradation and maintaining its intended functionality [35]. OPC concrete is susceptible to chemical attacks from acids and sulfates, which is of great concern. It is widely known that the alkaline characteristic of OPC concrete makes it sensitive to acid attacks such that when exposed to acids, the cement paste constituent parts disintegrate [36].

Indeed, acid degradation alone poses a significant obstacle in the long term to the durability of concrete in structures such as biogas and water treatment [37, 38]. The sulfate attack is a widespread cause of harm to the durability of concrete. The reaction between the cement particles on the concrete surface produces AFt, gypsum, and other corroded products [39]. When the concrete comes in contact with sulfuric acid, it starts deteriorating, and the deterioration process can be roughly divided into two phases. The first phase occurs upon interaction with calcium hydroxide, and the second phase occurs through its reaction with calcium silicate hydrates, as demonstrated in Equations (1) and (2) [40]. These chemical reactions instigate alterations in both concrete and mortar's weight, strength, and microstructure, consequently influencing their physical and chemical characteristics. These must be considered during construction, especially in coastal areas [41]. Thus, the phenomenon of sulfate attack is regarded as a pivotal subject of investigation within the field of structural engineering, which attracts considerable research attention on a global scale [33].

$$\mathrm{Ca(OH)_2 + H_2SO_4 = CaSO_4.2H_2O(gypsum)} \tag{1}$$

$$\mathrm{3CaO.SiO_2 + H_2SO_4 = CaSO_4.2H_2O + Si(OH)_4} \tag{2}$$

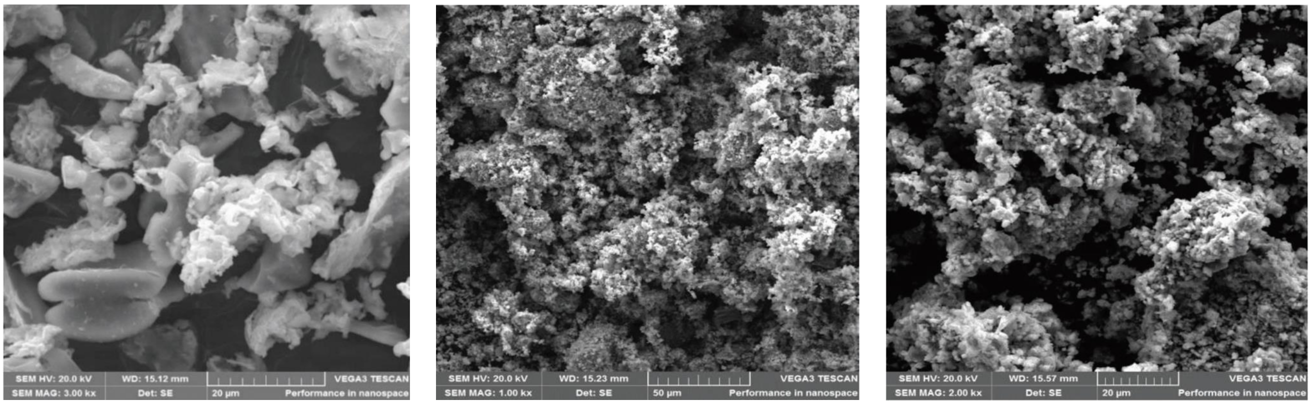
In addition to the above challenges, a substantial amount of heat is generated during the initial phase of OPC concrete hydration, leading to uneven thermal energy dissipation. The temperature loss is higher on the surface of the concrete than on the inside. Therefore, temperature gradients or variations will arise, leading to stress development and deformation in the concrete [42]. At the start of the drying, the thermal evaporation of unbound water leads to the shrinking of the concrete. In addition, drying shrinkage of hardened cement paste induces cracking around the aggregates. These cracks reduce the elastic modulus and strength of concrete [43]. Concrete shrinkage occurs in two phases: the initial stage, which spans the first 24 hr after pouring, and the subsequent stage, which occurs with the setting and hardening of concrete. The practical forms of shrinkage occurring at both stages are thermal shrinkage, autogenous shrinkage, and drying shrinkage; these types have similar effects but different mechanisms [44].

Previous researchers examined whether sulfuric acid affected the properties of concrete. For instance, Arif et al. [45] explored the impact of incorporating BA as a supplementary cementitious material in concrete, partially replacing OPC. The authors concluded that BA increased concrete-to-acid resistance because of decreased permeability and

Table 1: The chemical compositions of processed bagasse ash, silica fume, and cement.

Oxide (%)	SiO_2	Al_2O_3	Fe_2O_3	CaO	K_2O	MgO	P_2O_5	TiO_2	MnO	SO_3	LOI	$\sum P^*$
PBA	76.18	3.62	8.71	2.88	5.495	—	1.422	0.937	0.456	—	5.82	88.51
Silica fume	97.99	—	0.099	0.664	0.123	0.001	0.615	0.018	0.021	0.394	—	—
Cement	24.62	5.454	2.741	62.74	0.607	—	0.439	0.193	0.025	2.964	—	—

$\sum P^* = SiO_2 + Al_2O_3 + Fe_2O_3$.



(a) (b) (c)

Figure 2: SEM analysis of processed bagasse ash, silica fume, and cement: (a) processed bagasse ash; (b) silica fume; (c) cement.

pore filling and reduced drying shrinkage. Also, Chindaprasirt et al. [46] reported that sulfuric acid causes weight loss in OPC concrete, which increases with immersion time. In a study by Arif et al. [47], the effect on cement paste and mortar of replacing cement with BA at 5%, 10%, 15%, and 20% of the weight of cement was investigated. The authors reported that adding BA enhanced sulfuric acid resistance by measuring weight and compressive strength loss. In another study by Siqueira et al. [48], replacing part of OPC with 7% BA and 14% limestone filler was recommended for durability, as both maintained the respective properties of the reference cement. Also, a study by Sothornchaiwit et al. [49] used 50 mm cubic specimens to analyze the mass loss of alkali-activated mortar containing SF over a 28-day subjected to 3% sulfuric acid solution. They concluded that the weight loss reduced as the SF content and curing temperature increased. Joshaghani and Moeini [50] measured the effect of sulfuric acid on the weight and strength loss of mortar containing bagasse and rice husk ashes. They found that these ashes improved the mortar's acid resistance.

In summary, combining alternative materials into concrete production presents an economic strategy to reduce dependence on OPC, nonrenewable resources, CO_2 emissions, and their contribution to global warming. For example, using alternative materials to replace OPC promises substantial cost savings. However, despite the vast research in this area, studies on using BA combined with SF on concrete durability regarding sulfuric acid attack and drying shrinkage have not been given due attention. Given this scenario, the present study sought to examine the impact of partially replacing cement with a combination of processed bagasse ash (PBA) at varying dosages (0%, 10%, 20%, 30%, 40%, and 50%) and SF (5%) on the durability of concrete against sulfuric acid attack and the control of drying shrinkage.

2. Materials and Methods

2.1. Materials. In this research, the concrete specimens were made using OPC CEM I as per EN 197; fine powders of SF conformed to ASTM C1240; PBA, which was tested to ASTM C 311 and classified as satisfying ASTM C618; and superplasticizer, and aggregates conforming to ASTM C136. X-ray fluorescence techniques were applied to investigate the mineral composition of PBA, SF, and cement. In addition, the samples were subjected to scanning electron microscope (SEM) analysis to reveal their morphology, which is given in Table 1 and Figure 2(a)–2(c), respectively. In Table 1, the combination of iron (III) oxide (Fe_2O_3), aluminum oxide (Al_2O_3), and silicon oxide (SiO_2) in PBA accounted for 88.51% of the total content, with a loss of ignition of 5.82%; this percentage fell within the specified limit of 6%, thus meeting the requirements of ASTM C618, as a results PBA was categorized as a Class F pozzolan. The primary component of the SF was SiO_2, which constituted 97.99% of its composition. The binding material's physical properties and aggregates are presented in Table 2. X-ray diffraction of PBA is shown in Figure 3. It was observed that the main component was quartz.

Local coarse aggregates (CA) and fine aggregates (FAs), with respective maximum particle sizes of 12.5 mm and 4.75 mm, were used. Grading curves for fine and coarse aggregates were plotted on a semilogarithmic graph, showing the cumulative percentage passing, as illustrated in Figure 4. This indicates

Table 2: The physical properties of cement, processed bagasse ash, and silica fume.

Physical test	Portland cement	Processed bagasse ash	Silica fume	Coarse aggregates	Fine aggregates	Aggregate crushing value (ACV) (%)	Aggregate impact value (AIV) (%)
Specific gravity	3.1	2.1	2.2	2.66	2.61	17.6	6.2
Fineness modulus	—	—	—	—	2.7	—	—
Density (kg/m^3)	—	—	—	1,468	1,677	—	—
Water absorption (%)	—	—	—	3.5	7.61	—	—
Voids ratio (%)	—	—	—	42	28	—	—

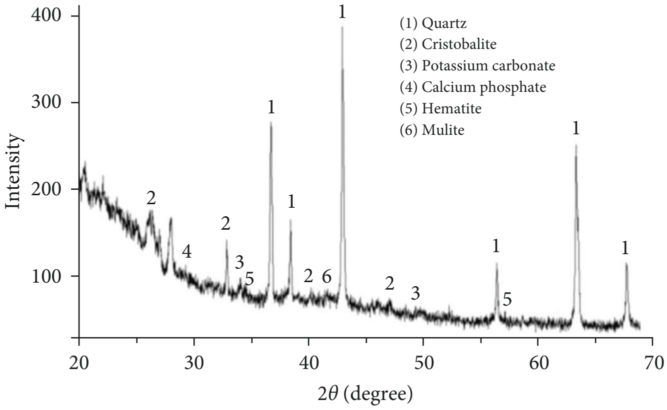


Figure 3: XRD of the processed bagasse ash.

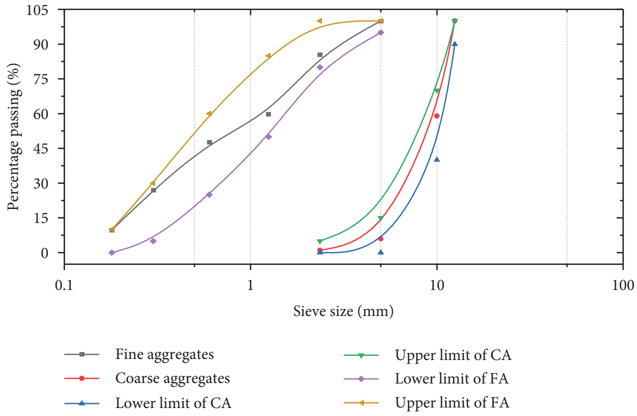


Figure 4: Aggregates of particle size distribution.

that the curves for the aggregates were within the specified range according to ASTM C33. The concrete mixtures were prepared using SF (5%) mixed with PBA at either 0%, 10%, 20%, 30%, 40%, or 50% to achieve high-strength concrete (>60 MPa). The details of the mix proportions and designation are presented in Table 3. For concrete mixing, a rotating drum mixer was employed: water was introduced first, followed by cement, PBA, and SF, ensuring a homogeneous paste. FA was subsequently incorporated into the paste, and continued mixing was done to achieve uniform mortar. The coarse aggregates were then mixed to attain a consistent concrete blend. Throughout the process, SP was consistently included to sustain a manageable mixture.

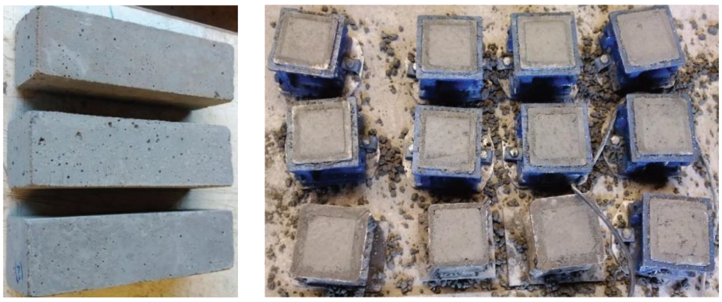
2.2. The Experimental Program. The sulfuric acid solution employed in concrete tests could be viewed as a "simulating" sewer environment," as reported by Arif et al. [45], Chindaprasirt et al. [46], and Arif et al. [47]. In this study, ASTM C267 was used to carry out the sulfuric acid resistance test. The cube samples of size 100 mm × 100 mm × 100 mm were cast and cured in ordinary tap water. Subsequently, the samples were submerged in a 3% sulfuric acid solution to maintain a reasonably constant acid concentration; the solution was renewed once after the first week of exposure and then every 2 weeks. After removing the acid, the specimens were cleaned with a cloth to remove surface debris. Visual appearance was observed, and specimens were weighed before and after immersion to determine the weight loss percentage. In addition, compressive strength loss was evaluated. Three samples were tested for each record, and the mean was recorded.

On the other hand, ASTM C157 was used to investigate the drying shrinkage of concrete. Prisms of 75 × 75 × 270 mm^3 were cast, and after the first 24 hr of casting, they were cured in water for 24 hr. Then, all specimens were taken out of the water, and their surfaces were dried using damp clothing. The specimen's initial length was recorded and kept at 232°C with a relative humidity of 50.4%. Consecutive length measurements were taken after each period of up to 16 weeks. The length difference at each period was divided by

Table 3: Mix proportions and designation (kg/m^3).

Mix	SCBA (%)	SCBA	SF	Cement	Water	w/b ratio	SP	CA	FA
1	0	0	25	475	175	0.35	3.0	1,000	700
2	10	48	25	428	175	0.35	6.0	1,000	700
3	20	95	25	380	175	0.35	9.0	1,000	700
4	30	143	25	333	225	0.45	6.0	1,000	700
5	40	190	25	285	225	0.45	7.5	1,000	700
6	50	237.5	25	237.5	225	0.45	9.5	1,000	700

SF, silica fume; SP, superplasticizer; FA, fine aggregate; CA, coarse aggregate; w/b, water/binder.



(a) (b)

Figure 5: The experimental program: (a) cuboid prisms; (b) the cube specimens.

Table 4: Test and specimen details of the concrete.

Experimental	Specimen type	Age of test	Specimen size	Standard
Sulfuric acid	Cube	90 days of normal curing, followed by 28 and 56 days immersed in sulfuric acid	$100 \times 100 \times 100\,\text{mm}^3$	ASTM C267
Drying shrinkage	Prism	4, 7, 14, and 28 days, then 8 and 16 weeks	$75 \times 75 \times 270\,\text{mm}^3$	ASTM C157

the initial length to obtain drying shrinkage. All data on drying shrinkage was computed as an average measurement on three prismatic cubic specimens. Figures 5(a) and 5(b) and Table 4 summarize the experimental results of the study.

3. Results and Discussions

3.1. Sulfuric Acid Resistance

3.1.1. Visual Appearance. Deterioration of concrete can occur when it is exposed to a sulfate-rich environment. Sulfuric acid chemically reacts to form gypsum ($CaSO_4.2H_2O$), which then reacts with tricalcium aluminate (C_3A) in the paste to produce an expansive product called ettringite, which causes concrete spalling, cracking, expansion, and weight loss, and strength loss [41, 51]. Calcium silicate hydrates (C—S—H) may also undergo decalcification due to sulfuric acid. In the end, it will convert the C—S—H into amorphous hydrous silica, which results in a loss of cohesiveness and strength of the paste matrix [52]. Figures 6(a) and 6(b) illustrate the visual appearance of OPC and PBA concrete specimens at 28 and 56 days, respectively. Notably, from the first week of exposure to sulfuric acid, the specimens developed a white layer on their surfaces. It is assumed that this white layer consisted mainly of gypsum. Nnadi and Lizarazo-Marriaga [40] found a similar observation. It was also observed that there was negligible surface deterioration from 40% to 50% PBA replacement level. In contrast, specimens with up to 20% replacement level were significantly eroded, which could be attributed to the presence of unreacted $Ca(OH)_2$. Although the extent of degradation among the specimens was not easily distinguished through visual examination, the surface's degradation increased with time. Utilization of $Ca(OH)_2$ during the pozzolanic reaction and the enhanced pore-filling effect from the remaining unreacted PBA may clarify the heightened resistance to sulfuric acid corrosion observed with higher PBA substitution levels [47]. Simlar observation was made by Joshaghani and Moeini [50].

3.1.2. Weight Change after Exposure to Sulfuric Acid. Sulfuric acid can cause damage to concrete due to its combination of acid and sulfate attack. The mass changes and percentage loss results are presented in Figures 7 and 8, respectively, over 56 days of immersion. It can be seen that the weight of all concrete specimens continuously decreased in comparison to specimens that were cured in normal water. A significant reduction in the dry density was observed at 28 and 56 days of acid immersion with up to a 20% replacement level. At the same time, negligible reduction occurred with a 40% and 50% PBA replacement level. For example, at 28 days with 0% PBA replacement level, dry density changed from

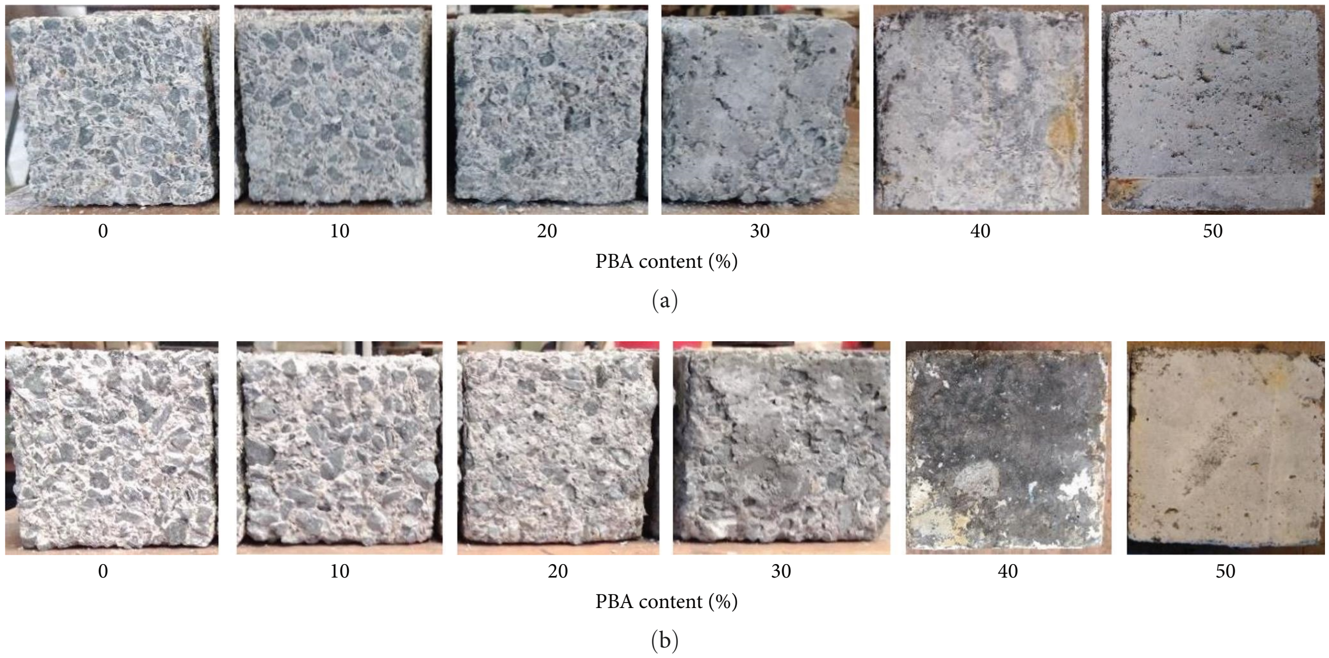


Figure 6: Concrete specimens immersed in sulfuric acid: (a) 28 days; (b) 56 days.

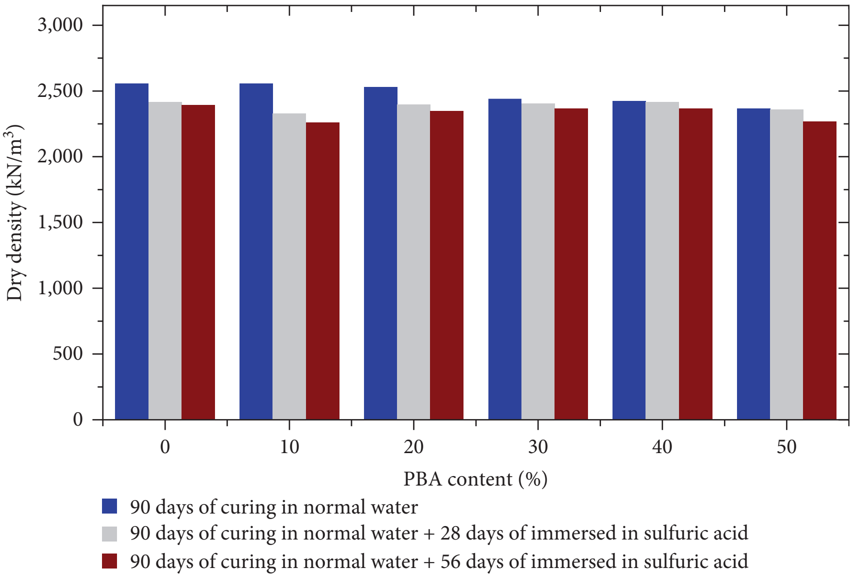


Figure 7: Effects of sulfuric acid on the dry density of concrete.

2,555 to 2,414 kg/m^3, an 8.67% loss, whereas with 20% density changed from 2,531 to 2,329 kg/m^3, a 6.34% loss. In contrast, with 40%, it varied from 2,424 to 2,415 kg/m^3, a 2.5% loss, and with 50%, the change was from 2,365 to 2,357 kg/m^3, a loss of only 1.11%. After that, at 56 days, the highest and lowest losses were observed with 10% PBA and 50%, which were 10.09% and 1.85%, respectively. The reduction in weight loss was attributed to the pozzolanic reaction caused by substituting OPC with PBA. This substitution decreased Ca(OH)$_2$ and increased fine filler material, thereby enhancing resistance to weight loss in acidic environments [45, 46]. These findings are comparable with those observed in other investigations on the use of BA in mortar and concrete, which were carried out by Arif et al. [47], Sothornchaiwit et al. [49], Chusilp et al. [53], Khan et al. [48], and Chindaprasirt et al. [46]. The weight loss percentage is recorded, as shown in Equation (3).

$$\text{Weight loss percentage} = \frac{M_o - M_\mathrm{i}}{M_o} \times 100, \qquad (3)$$

where M_o and M_i are the mean weight of the air-dried sample before submersion and the average weight of the surface-dried sample after submersion, respectively.

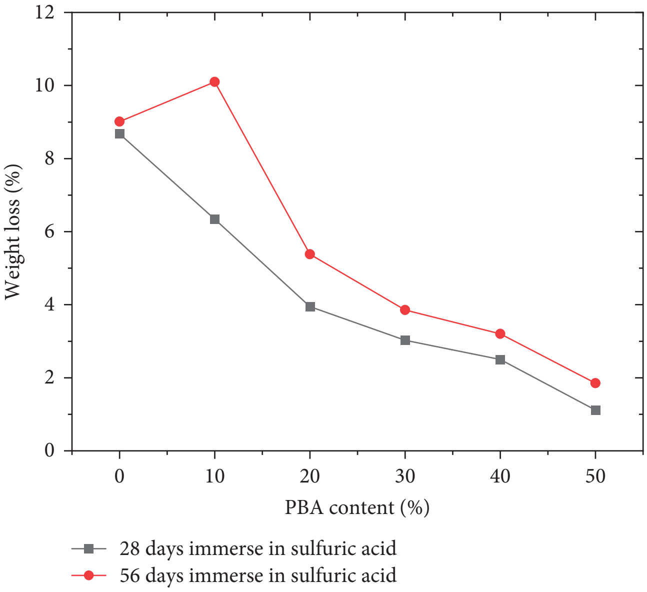


Figure 8: Weight loss after placing in sulfuric acid.

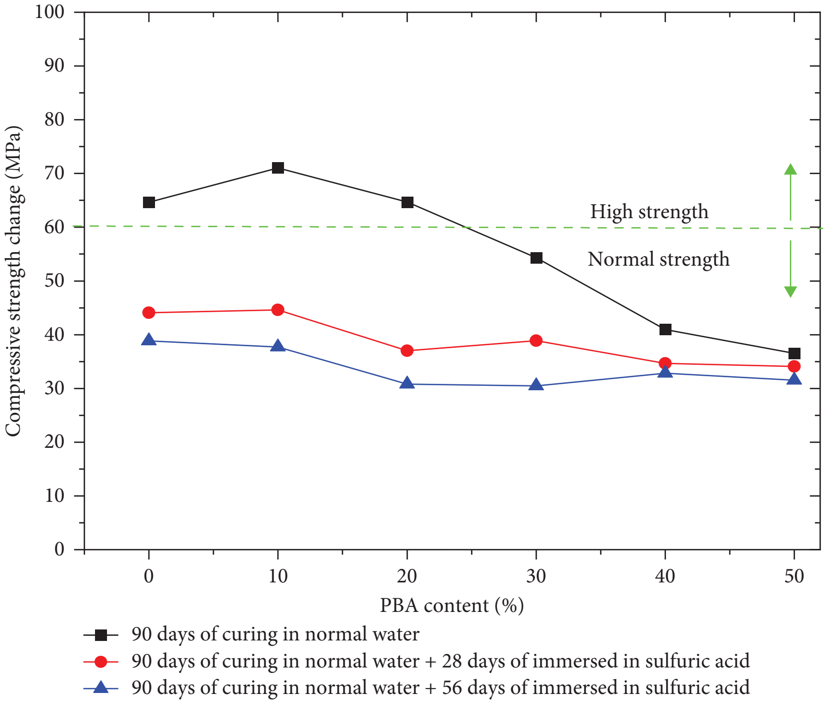


Figure 9: Effect of sulfuric acid on compressive strength.

3.1.3. Compressive Strength Changes after Exposure to Sulfuric Acid. Changes in compressive strength and percentage of compressive strength loss of PBA concrete cured in normal water and subsequently exposed to a sulfuric acid solution for 28 and 56 days are presented in Figures 9 and 10, respectively. For specimens cured in normal water, it can be observed that the obtained compressive strength can be considered as high-strength concrete (>60 MPa) with up to 20% replacement level. Moreover, from 30% to 50% replacement level, the strength can be considered normal structural concrete (>25 MPa). After being exposed to sulfuric acid, the strength changed, and with up to 20% PBA replacement level, there was a dramatic compressive strength reduction. For example, at 28 days of immersion with 0% dosage, the strength changed from 65 to 44.1 MPa, which is a 32% loss. With 10%, it was altered from 71 to 44.6 MPa, a 37% loss, while with 20%, it was changed from 64 to 37 MPa, a 43% loss. At the 40% PBA replacement level, strength altered from 41 to 32.8 MPa, a 19.8% loss, and strength was changed at the 50% level from 36.54 to 31.5 MPa, a 13.7% loss. The

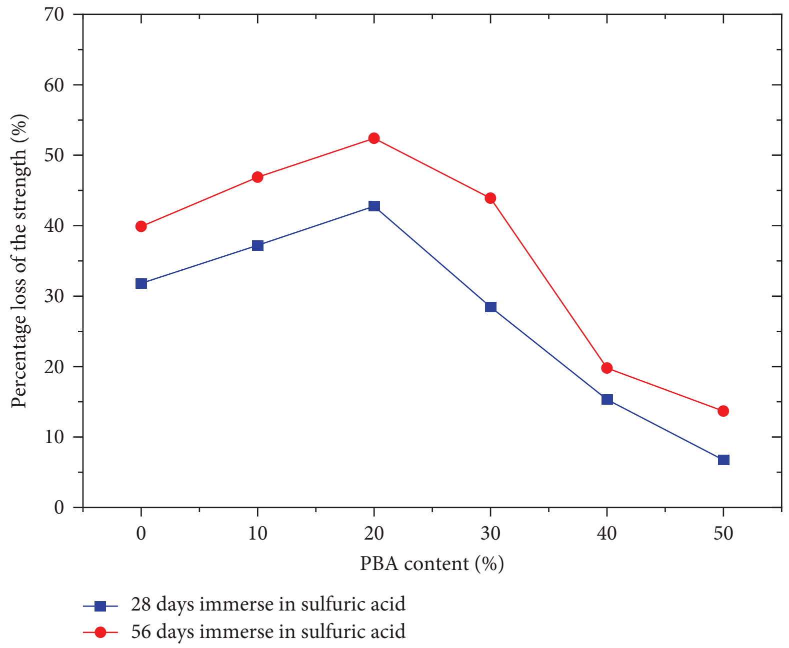


FIGURE 10: Percentage loss of the compressive strength due to sulfuric acid.

highest loss of strength of 52.4% was observed with a 20% PBA replacement level. Several research conducted by Arif et al. [45, 47], Sothornchaiwit et al. [49], and Jha et al. [54] also found similar findings. In addition, research conducted by Al-Sodani et al. [55] reported that the most significant resilience against acid attacks was witnessed when employing a substantial quantity of natural pozzolan. The calculation of percentage loss in compressive strength by Equation (4).

$$\text{Loss in compressive strength ls} = \frac{f_{ti} - f_{t0}}{f_{ti}} \times 100, \tag{4}$$

where f_{ti} and f_{to} are the average compressive strength of samples cured in normal water and the average compressive strength after submerging in sulfuric acid, respectively.

3.2. Concrete Drying Shrinkage. Shrinkage of concrete occurs when moisture is lost to the atmosphere. Both ambient temperature and humidity influence the evaporation process, which is primarily responsible for causing this effect. The decrease in shrinkage is, therefore, a reflection of the reduced loss of free water from the pores of the concrete [56]. As PBA is added to concrete, it uses the free water in the pores of concrete in pozzolanic reactions, which bind the water in the molecular structure of cement paste, thereby reducing the amount that can be lost through evaporation. Moreover, the additional cementitious products formed from pozzolanic reactions densify the concrete pores and seal the avenues through which moisture can be lost [57, 58]. In this study, Figure 11 presents the length change due to drying shrinkage of the concrete samples for up to 16 weeks. The result shows that drying shrinkage increased with time. At 16 weeks, the OPC concrete had the highest drying shrinkage of 0.132%, while the PBA concrete with different PBA replacement levels had fewer reductions. As observed, the drying shrinkage values for 10%, 20%, 30%, 40%, and 50% SCBA concrete were 0.124%, 0.121%, 0.120%, 0.117%, and 0.112%, respectively. This shows a progressive decrease in shrinkage with increasing PBA content.

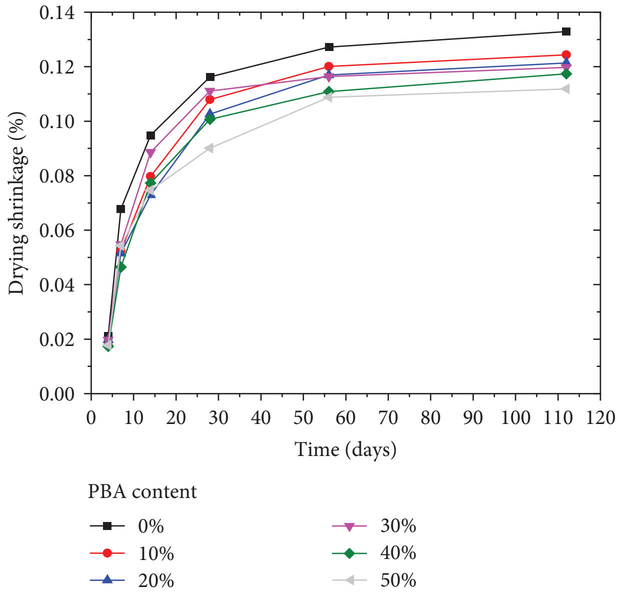


FIGURE 11: Drying shrinkage of PBA concrete.

4. Conclusions and Future Recommendations

4.1. Conclusions. This study demonstrated the benefits of high-volume cement replacement with PBA and SF. The research holds significance as it has shown that treated concrete can have better performance and enhanced life in an environment of high acidity caused by industrial and domestic effluents or acidic ground conditions. The following conclusions can be made:

(i) Visual degradation of concrete decreases significantly as cement with PBA at 40%–50% dosages, showcasing its efficacy in enhancing concrete structures' durability and esthetic appeal over time.
(ii) The highest and lowest weight losses were observed with 10% PBA and 50%, respectively, which were 10% and 1.85%, highlighting the significant variation in performance based on the dosage of PBA incorporated.
(iii) The highest loss of compressive strength of 52.4% was observed with a 20% PBA replacement level, and the lowest loss of compressive strength of 13.7% was observed with a 50% PBA replacement level, which indicates that PBA enhanced the durability against sulfuric acid.

5. Future Recommendations

Recommendations for further study may be summarized as follows:

(i) Further investigation should broaden the examination of concrete resistance to acids by considering other varieties of acids, such as carbonic and hydrochloric acids.
(ii) Further exploration of the acid resistance of concrete derived from different aluminosilicate sources, such as volcanic ash, low-grade clay, wood ash, etc., could yield valuable insights.

Data Availability

The article includes the data supporting the findings of the study.

Conflicts of Interest

The authors confirm that no known conflicts of interest, either financial or personal, could have influenced the findings presented in this paper.

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