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Investigation on Mechanical and Durability Properties of Concrete Mixed with Silica Fume as Cementitious Material and Coal Bottom Ash as Fine Aggregate Replacement Material

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Abstract: Cement production produces a high amount of carbon dioxide, which has a negative impact on the environment. By utilizing waste products instead of cement, environmental degradation can be reduced. The current study was undertaken to study the mechanical and durability performance of concrete by replacing 7.5%, 10%, and 12.5% silica fume (SF) of cement weight. Additionally, coal bottom ash (CBA) was also substituted as fine aggregates with 10%, 20%, and 30%. Compressive strength and indirect tensile strength were the major parameters regarding mechanical properties, while corrosion analysis and sulfate attack were set for durability performance. Sixteen mixes were prepared including a control mix. Out of these, three mixes contained SF, three mixes contained CBA, and eight mixes contained both SF and CBA with 1:2:4 ratio at 0.5 w/b ratio. The results concluded that the addition of 12.5% SF and 30% CBA gives optimum compressive strength and tensile strength. Furthermore, using the SF and CBA reduces the workability of concrete. Furthermore, the use of these byproducts increased the durability in terms of corrosion and sulfate attack.

Keywords: coal bottom ash; silica fume; partial replacement; mechanical performance; durability performance

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1. Introduction

Concrete is one of the materials mostly used in the construction of buildings and other infrastructure projects. By 2050, it is expected that the demand for concrete will have increased to nearly 7.5 billion m^3 (roughly 18 billion tons) [1]. Because of this huge demand for concrete in the construction industry, it will also cause 10% Co_2 emission in the natural environment. This release of Co_2 results in the rising of temperatures on the earth, and thus the occurrence of problems like global warming and climate change. It is understood that concrete is essential for the construction of large structures, but on the other hand, it also increases the energy cost for manufacturing cement, thus utilizing the natural resources that are needed for cement production [2–4]. Such extensive use of concrete, increases the use of natural aggregates and cement, putting a strain on the environment. Coarse and fine aggregates occupy around 60–75% volume of the concrete, and because of the extensive use of both these natural materials, there will be a shortage of these materials in near future [5]. As a result, in the present environment of the scarcity of river sand

and increased infrastructure growth, it is more important than ever to find a replacement material for river sand in concrete [6].

In electricity power generation plants, which produce a huge amount of CBA and FA as waste products of around about 20–80%, using both the materials in the making of concrete can surely reduce the problem of not only disposal, but also in saving the environment [1]. The particle size of CBA can vary from fine sand to fine gravel. Chemical composition shows that the main ingredients of CBA include silica, iron, alumina, and a small quantity of calcium and magnesium sulfate [6]. Since ash is considered waste, it is disposed of in landfills or ponds. In some power plants, bottom ash is combined with fly ash before being cleared [7]. In reality, dumping coal bottom ash in the open air endangers people and the environment [8]. Singh et al. described how the presence of coal bottom ash increases the risk of health problems such as skin, lung, and bladder cancer [9]. As a result, developing concrete products that use this material as one of the mix ingredients will save landfill space, time, resources, and energy. This method would lower manufacturing costs while still protecting the environment from waste's negative landfilling and human health effects [10].

It was observed from the available literature that the CBA had very little effect on compressive strength when it was replaced with fine sand. However, when the replacement level increased, the flexural strength and modulus of elasticity decreased. [11]. Literature reports that when CBA was used as a replacement of fine sand, the compressive strength obtained was lower than the control concrete mix at shorter curing durations. Moreover, the improvement in strength was found to be equal or higher than the control concrete mix when longer curing duration was selected [12,13]. Another study shows that by using CBA as a replacement of sand keeping w/c ratio fixed, the slump of concrete increased while the compressive strength decreased [14]. A similar study indicates that by increasing CBA content, the compressive strength decreased when a constant w/c ratio was adopted [15].

SF in concrete as a pozzolanic material provides better bonding on the interface zone of cement paste-aggregate, which is usually weaker. Generally, SF in concrete is used for the pozzolanic effect (chemical effect) because the rapid pozzolanic reaction, which generates the C-S-H gel during the early age of concrete results in early strength gain when SF is added to the concrete mix as reported by [16,17]. In the early days of curing, such as at 7 days, SF shows very fast pozzolanic behavior, and it was observed that the major cause of such a fast hydration process in SF concrete was due to compounds such as $Ca(OH)_2$ and C–S–H gel, as described by [18]. SF is mostly used as a substitute of cement in conventional as well as of high-performance concrete (HPC) because of its much finer surface area as described by [19]. In another study, it was concluded that high-strength concrete with 10% SF by the mass of cement, and w/b ratios of 0.22, 0.25, and 0.28, exhibited increased drying shrinkage strain up to 610×10^{-6}, whereas for the normal-strength concrete (w/b = 0.57), it was about 50% lower [20]. It was also suggested by different authors that when SF is used, the workability of concrete reduces so as to achieve workable as well high-strength concrete; a small amount of superplasticizer is used in concrete, this is because the finer particles of SF need a little extra water for the proper hydration mechanism [21,22]. A few investigations found that the typical replacement level of SF in concrete can vary between 20 and 30% [23]. It affects the properties of concrete like porosity and CH content, which increases both the compressive and flexural strength of concrete. Previous investigations have indicated the typical silica fume content used in the concrete mixture is approximately 20% to 30%, by the mass of cementitious materials. In contrast, other research has found that the dosage levels of 5–15% were used for obtaining higher strength values [24].

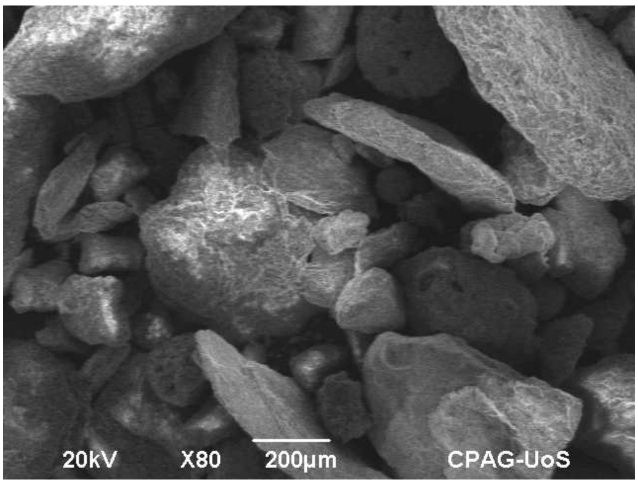
The mechanism of concrete considering mechanical and durability performance incorporating various industrial by-products was investigated by many researchers; however, the standard method, which is being used to quantify the mechanical and durability performance keeping SF dosage level fix and varying dosage levels of CBA at different curing ages, was not touched by many researchers. So, the present study was carried out to determine both the mechanical and durability performance of concrete containing CBA and SF as a partial replacement of sand and cement, respectively.

Hence, the main purpose of this study was to evaluate the effect of using CBA as a substitute for sand (10–30%), combined with silica fume as a cement replacement with various percentages (7.5–12.5%). For mechanical properties, the compressive strength and split tensile strength properties of concrete were determined at 28- and 90-day water curing. In the end, the test results of normal conventional concrete were compared with those of concrete containing both CBA and silica fume. Moreover, SEM and EDS were performed to check the characteristics of materials and chemical composition of CBA and silica used in this study. Furthermore, the influence of CBA on durability properties, especially the effect of corrosion and sulphur attack, was also investigated in this study.

2. Experimental Program

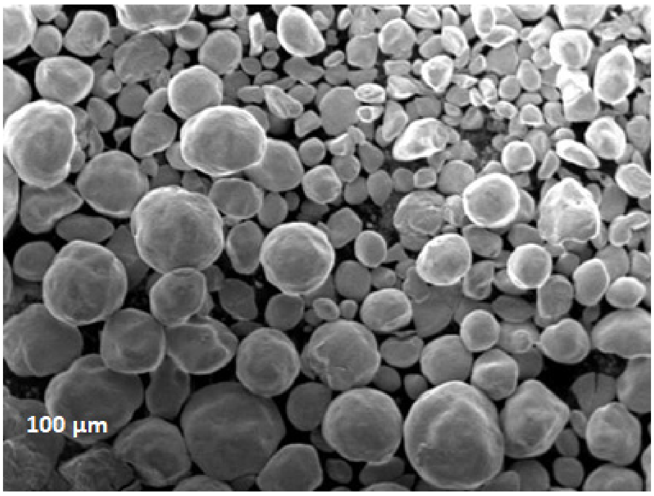
2.1. Materials and Mix Proportions

Ordinary Portland cement (OPC) of Type-I was used as a binder, which complies with ASTM C150-05 (2005) and BS 12 (1991). The crushed aggregate of 20 mm maximum size was used as a coarse aggregate in the concrete. The hill sand was used as a fine aggregate after sieving through standard sieve No.4 (4.75 mm). The aggregates were washed before use in the mix to separate the silt, clay, organic impurities, or any undesired sticky material that adversely affects the quality of concrete. After washing, the wet aggregates were left at room temperature to get the saturated surface dry condition. The coal bottom ash (CBA) was used as a partial replacement material for sand. The samples of CBA were collected from the Lakhra coal power plant, district Jamshoro. Coal bottom ash was sieved from sieve No.4. The SF was obtained from a local supplier located in Karachi, Pakistan. Silica fume is an amorphous polymorph of silicon dioxide (SiO_2) [25] and is an ultrafine powder collected as a by-product of the manufacturing of silicon and ferrosilicon alloys, having a particle size of $\leq$0.15 µm. SEM images of both CBA and SF are shown in Figure 1 for more clear understanding. The replacement of sand with coal bottom ash was carried out at 0 to 30% by weight with an increment of 10% while the cement was replaced with silica fume ranging from 7.5% to 12.5% with an increment of 2.5%. The chemical composition of materials used in this research is given in Table 1. The sum of SiO_2, $Al2O_3$, and $Fe2O_3$ can be calculated according to ASTM C 618 [26]. A concrete mix ratio of 1:2:4 as per Table 2 with a w/c ratio of 0.5 was used throughout the study.



(**a**)

Figure 1. *Cont.*



(**b**)

Figure 1. SEM images of (**a**) Coal Bottom Ash; (**b**) Silica Fume.

Table 1. Properties of cement and coal bottom ash.

Material	Physical Properties		Chemical Analysis (% Age)						
	Blaine (cm^2/g)	Specific Gravity	SiO_2	CaO	Al_2O_3	MgO	K_2O	Fe_2O_3	LOI
Cement	3008	3.14	20.78	60.89	5.11	3.00	0.00	3.17	1.71
CBA	-	2.30	35.37	3.307	28.18	1.956	0.976	20.64	-
Silica Fume	-	2.22	93.28	0.23	0.49	0.9	0.98	1.3	-

Table 2. Concrete mix proportion.

S.No	Mix Type	OPC (kg)	Sand (kg)	CBA (kg)	SF (kg)	C.A (kg)	Water (kg)	W/C (kg)
01	Plain	20	40	0	0	80	10	0.5
02	10CBA	20	38	2	0	80	10	0.5
03	20CBA	20	36	4	0	80	10	0.5
04	30CBA	20	34	6	0	80	10	0.5
05	7.5SF	18.5	32	0	1.5	80	10	0.5
06	10SF	18	30	0	2	80	10	0.5
07	12.5SF	17.5	28	0	2.5	80	10	0.5
08	7.5SF10CBA	18.5	38	2	1.5	80	10	0.5
09	7.5SF20CBA	18.5	36	4	1.5	80	10	0.5
10	7.5SF30CBA	18.5	34	6	1.5	80	10	0.5
11	10SF10CBA	18	38	2	2	80	10	0.5
12	10SF20CBA	18	36	4	2	80	10	0.5
13	10SF20CBA	18	34	6	2	80	10	0.5
14	12.5SF10CBA	17.5	38	2	2.5	80	10	0.5
15	12.5SF20CBA	17.5	36	4	2.5	80	10	0.5
16	12.5SF20CBA	17.5	34	6	2.5	80	10	0.5

2.2. Specimen Preparations and Test Method

The standard size of 150 mm × 300 mm cylindrical specimens were cast for the determination of compressive strength and splitting tensile strength of concrete. Abram's cone apparatus was used to measure the workability (slump test) of each concrete mix. After 24 h, the concrete specimens were demolded and placed in clean water to cure for 28 and 90 days, respectively. The compressive strength of concrete samples was assessed by an automatic Tecno-Test compression testing machine, having a load capacity of 3000 KN. The tensile strength of concrete specimens was assessed using a Universal Testing Machine (UTM) having a load capacity of 1800 KN.

For the corrosion analysis test, cylindrical specimens of 100 × 200 mm were cast. A bar of 12 mm diameter, and 300 mm in length was placed in the center of all specimens. The samples were first immersed in water for 28 days after demolding. After 28 day curing period, specimens were then immersed into the water tank containing a solution of 3% NaCl for 14 days. After 14 days, the samples were removed from the water tank and allowed to air dry. This wet and air-dry curing cycle continued for 90 days. Corrosion potential was determined according to ASTM C-876 [27]. The average of three specimens was used to calculate a specimen's corrosion potential.

The length variations of prism specimens measuring 25 mm × 25 mm × 285 mm were used to calculate the sulfate resistance of concrete. These specimens were prepared as specified in ASTM C1012 [28]. The prisms were demolded, and then placed in sodium sulfate solution for 28 days. The lengths of the samples were again recorded. Change in length was recorded with the help of a digital meter.

3. Results and Discussions

3.1. Workability

The slump test was conducted to check the workability of each concrete mix. Figure 2 depicts the workability of the mixtures containing CBA of 10, 20, and 30%. Replaced with fine aggregate. Figure 2 indicates that with increments in CBA percentage the slump decreased. This trend of decreasing slump values validates the findings of Bheel et al. [25]. The higher value 110 mm was achieved in the plain mixture, while the lowest value of 85 mm was achieved in the 30CBA mixture. The addition of CBA in the concrete affects its workability because CBA is porous and granular material having high porosity and a rough surface. It absorbs a higher amount of water from the mixed concrete matrix. The slump of the concrete mix continued to decrease as the amount of CBA was increased. This trend is also suggested in the literature [29–31].

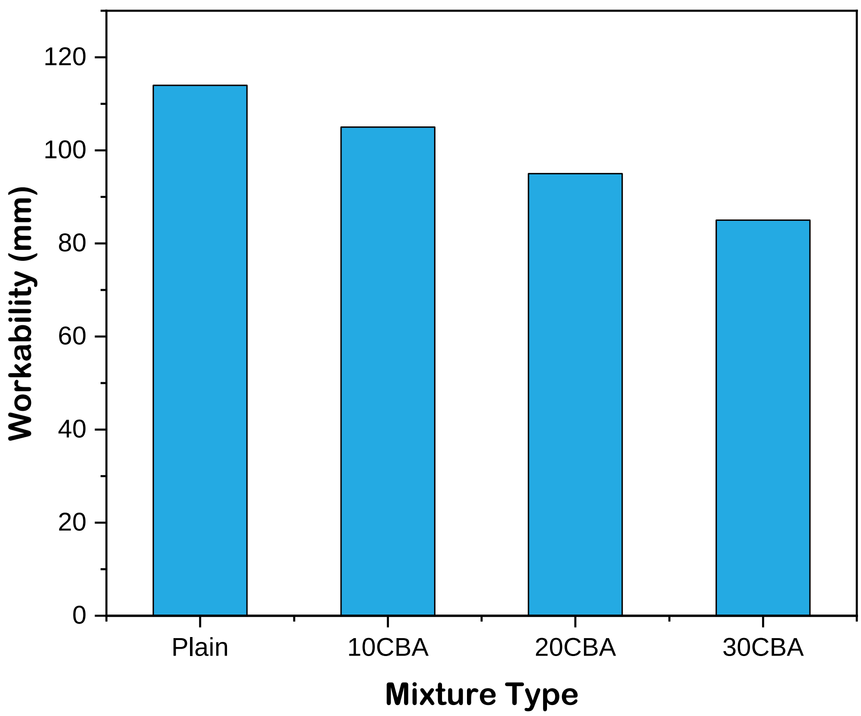


Figure 2. Workability of the mixture blended with CBA.

Furthermore, Figure 3 illustrates the workability of various mixtures containing different percentages of SF and CBA. From the figure, it can be seen that the highest workability recorded was 114 mm, which represents plain concrete, while the smallest workability was recorded at 34 mm when using 15% silica fume as cement replacement and 30% coal bottom ash as fine aggregate replacement. From the results, it can be concluded that workability decreases as the percentage of SF and CBA increases. Abidin et al. [32] also found that due to the porous nature of CBA, the workability reduces as CBA absorbs higher amounts of water during mixing. As validated by Keerio et al. [33], who found that as the dosage of silica fume increased, the workability decreased, because of the porous nature of CBA and SF. Furthermore, Figure 4 shows the workability of mixes containing silica fume as cement replacement with 5, 10, and 15%. From the Figure 4, it can be seen that as the percentage of SF increases, the workability decreases.

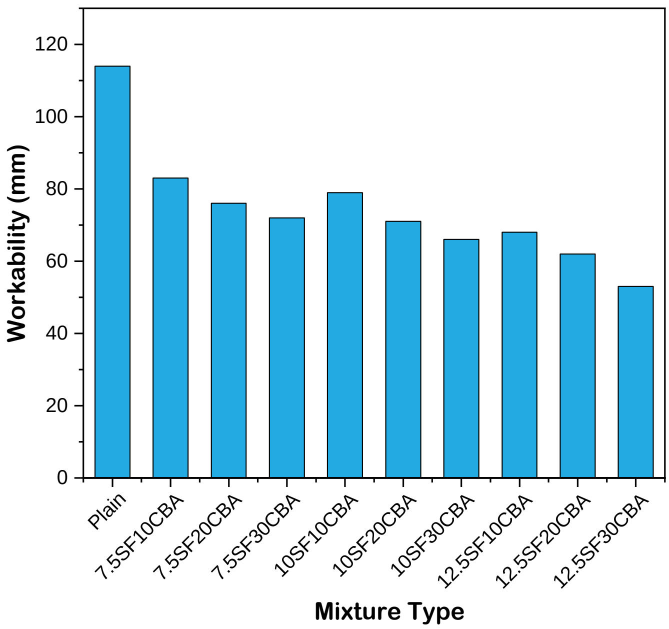


Figure 3. Workability of mixture blended with different percentages of CBA and SF.

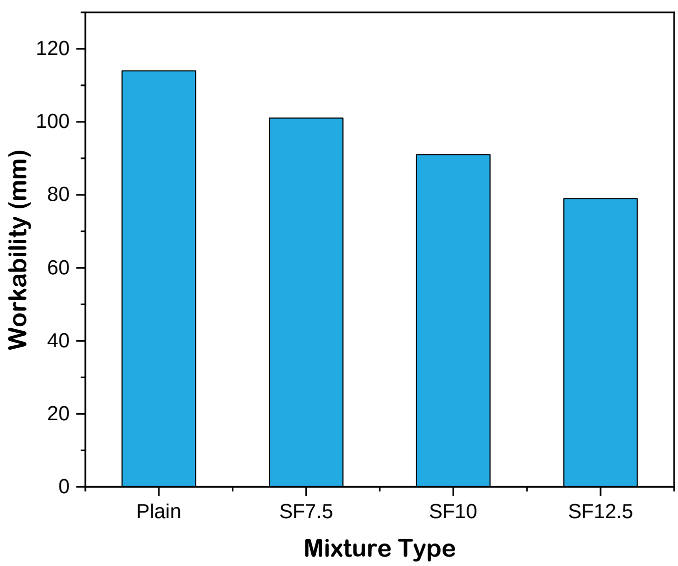


Figure 4. Workability of mixture blended with SF.

3.2. Compressive Strength

The compressive strength of concrete containing various percentages of silica fume is illustrated in Figure 5. The Maximum strength after 28- and 90-day curing was achieved for the mixture containing 12.5% silica fume. An increment of 15.76% and 11.98% could be noted after 28- and 90-day water curing, respectively. Furthermore, Figure 5 is clear evidence that as the percentage of silica fume increases, the strength of concrete increases.

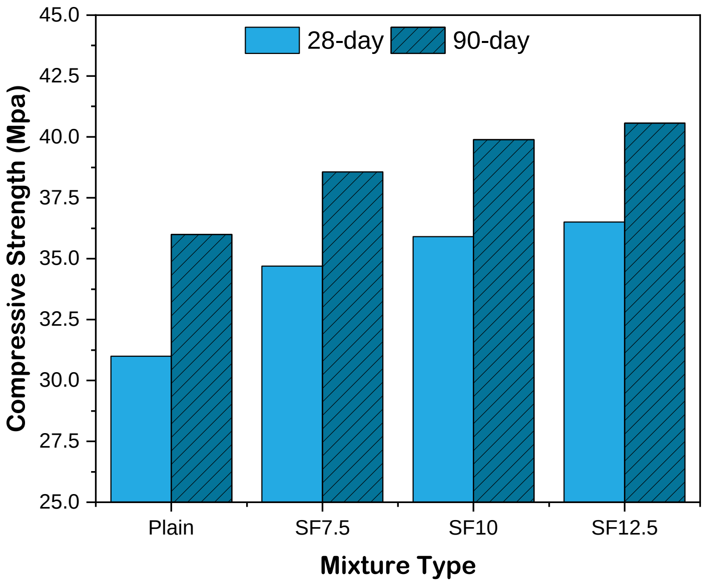


Figure 5. Compressive strength of concrete with Silica Fume.

The pozzolanic reaction between silica fume and calcium hydroxide results in the creation of calcium silicate hydrate. However, Almusallam et al. [34], in their study, revealed that an increase in strength of up to 10% of silica fume was recorded. Moreover, Bhemood and Ziari [35], in their study, found that an increment of 25% in compressive strength was achieved at 10% silica fume dosage after 28-day water curing. Figure 6 presents the cylindrical compressive strength of the specimens containing CBA as replacement for fine aggregates after 28- and 90-day water curing.

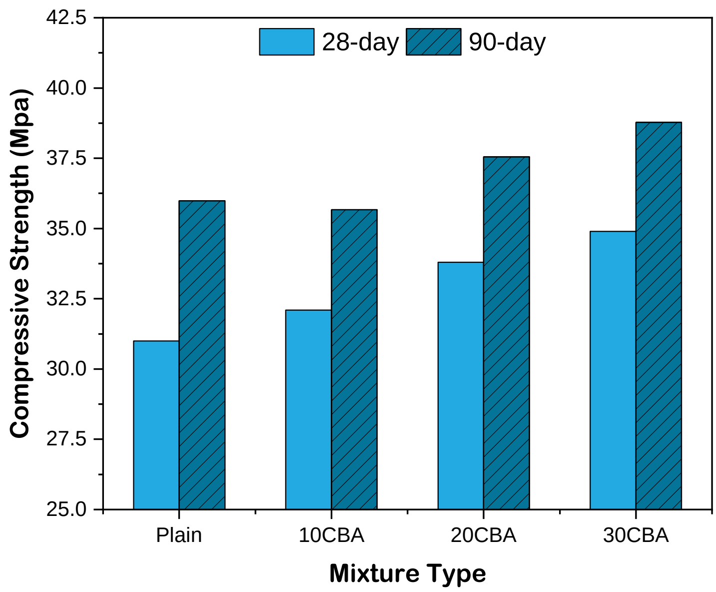


Figure 6. Compressive strength of concrete mixed with CBA.

The maximum strength of 34.9 MPa and 38.78 MPa after 28- and 90-day water curing, respectively, was achieved at 30% replacement of sand with CBA, while the minimum strength of 32.1 MPa and 35.67 MPa was achieved after 28 and 90-day water curing, respectively, when 10% of CBA was utilized as replacement for sand. From Figure 5, it can be assessed that maximum compressive strength was attained when 30% of CBA was substituted for fine aggregates. [25]. In their study, Mangi et al. [30] concluded that the optimum strength of concrete was achieved when 30% CBA was consumed. Beyond this percentage, the strength decreased. The major cause of this reduction in strength is the CBA content, which generates the permeable concrete with additional holes distributed across the surface of CBA in concrete. Moreover, this reduction is also due to the highwater absorption and porosity of CBA particles [30]. Additionally, Figure 7 represents the compressive strength of concrete with various mixtures containing CBA and SF. It can be seen from Figure 7 that the maximum compressive strength was achieved when the 12.5% SF was replaced with cement, along with different CBA percentages (10–30%) replaced with fine aggregate. The minimum strength was achieved when 7.5% and 10% SF were blended with various CBA ratios (10–30%) and substituted as fine aggregates. The optimal compressive strength, however, was attained by 38.45 MPa by utilizing 12.5 percent silica fume and 30 percent CBA in concrete, which is approximately 20% greater than conventional mixes after 28-days curing. According to the current study's findings, when the SF and CBA were mixed together, the compressive strength enhanced. Because of the high silica content present in SF and CBA, the compressive strength was increased. The fineness of the SF and CBA particles could also have contributed to the higher compressive strength. Because the fineness of SF and CBA improves the transition zone of concrete, this helps in gaining the compressive strength. Furthermore, the strength enhancement might be due to the additional pozzolanic reaction from tiny CBA particles, which enhances this unprecedented rise in aggregate interfacial bonding [33,36].

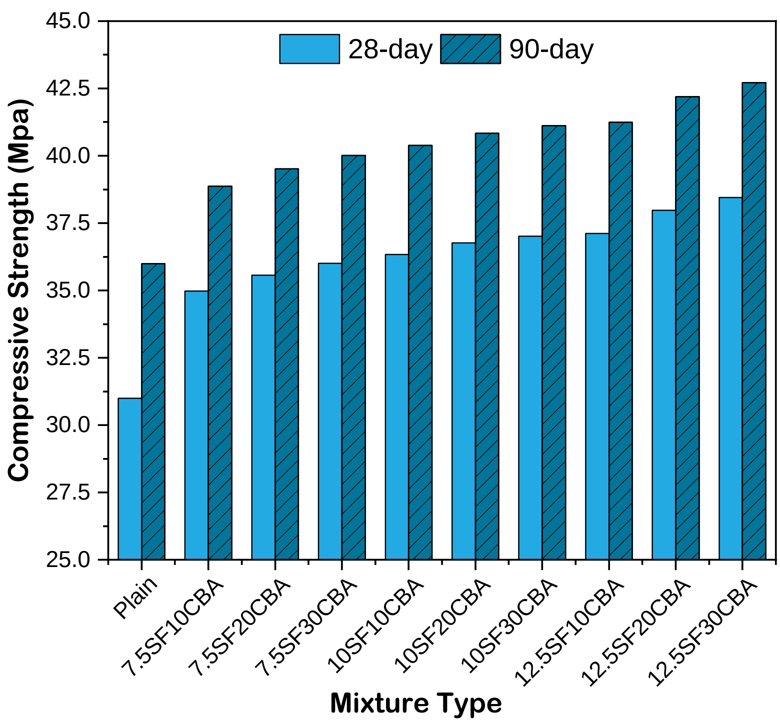


Figure 7. Compressive strength of concrete mixed CBA and SF.

3.3. Split Tensile Strength

The tensile strength of concrete containing silica fume after 28- and 90-day water curing is illustrated in Figure 8. When 12.5% SF was substituted with cement, the maximum strength was 4.29 Mpa and 4.66 Mpa after 28 and 90 days of water curing, respectively.

Similarly, for the same curing periods, the minimum strength was found to be 3.63 Mpa and 3.64 Mpa, respectively, when 7.5% SF was replaced with cement. However, a marginal increment of almost 4% could be seen for the 12.5 SF mix when compared with 10 SF. Roy et al. [37] and Hanumesh et al. [38], in their study, concluded that the strength of concrete starts decreasing when the amount of SF exceeds by 10% cement replacement. Moreover, Keereio et al. [33], in their study, mentioned a decrease in the strength of SF beyond 10% replacement of cement. The maximum amount of SF added in the current study was 12.5%, which was not used in the previous investigations [38–40]. Though a very marginal increment of 3.96% after 28-day water curing could be seen from Figure 8 for 12.5 SF when compared with 10 SF. Furthermore, Figure 9 shows the tensile strength of concrete having various percentages of CBA replaced with fine aggregate. In this case, the maximum strength was achieved when 30% CBA was replaced with fine aggregates, while the minimum was achieved at 10% replacement of fine aggregates after 28- and 90-day water curing. While comparing 30 CBA with plain concrete after 28 days of curing, an increase in nearly 18 percent was found, while the same was only 2.96 percent for 10 CBA when compared to conventional concrete. Moreover, from the literature, it is evident that the maximum strength could be achieved by replacing 30%CBA with the fine aggregates [25,29].

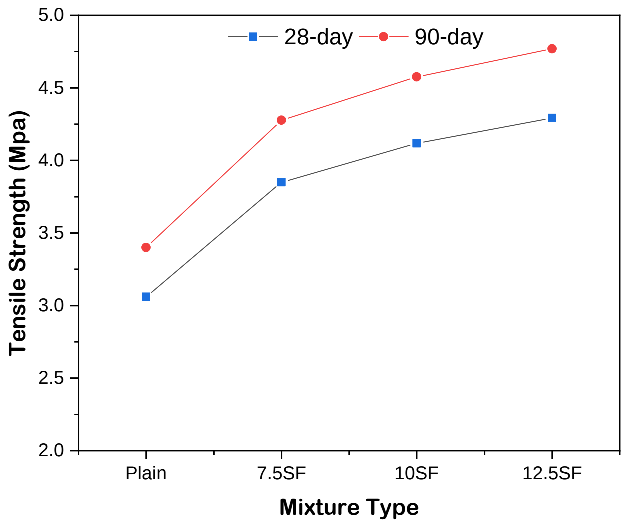


Figure 8. Tensile Strength of concrete mixed with SF.

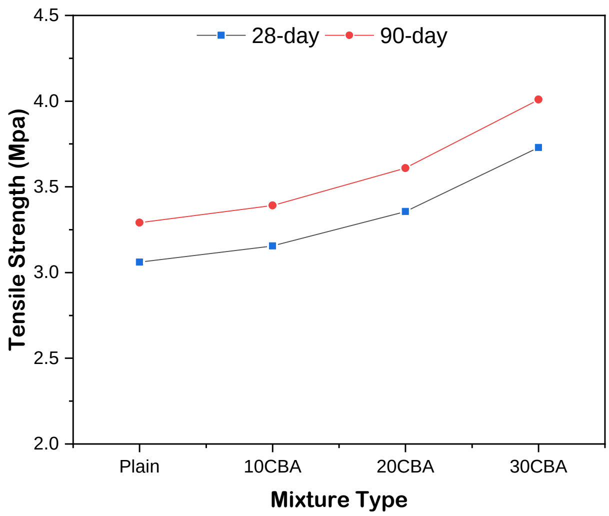


Figure 9. Tensile Strength of concrete mixed with CBA.

Figure 10 illustrates the split tensile strength of concrete mixed with various amounts of silica fume (7.5–12.5%) replaced with cement and CBA (10–30%) substituted with fine aggregates. From the figure, it could be finalized that the mixture containing 30% CBA and 12.5% SF has the maximum tensile strength. The optimum tensile strength was found to be 4.74 Mpa and 5.21 Mpa after 28- and 90-day water curing, respectively. Tensile strength was raised by up to 35.44% and 36.85% after 28- and 90-day curing, respectively, as compared to ordinary concrete. However, the minimum tensile strength of 3.45 Mpa and 3.79 Mpa was found under mixture 7.5 SF10 CBA after 28- and 90-day curing. The increase in tensile strength could be attributed to the surface area of silica fume and CBA [25,33].

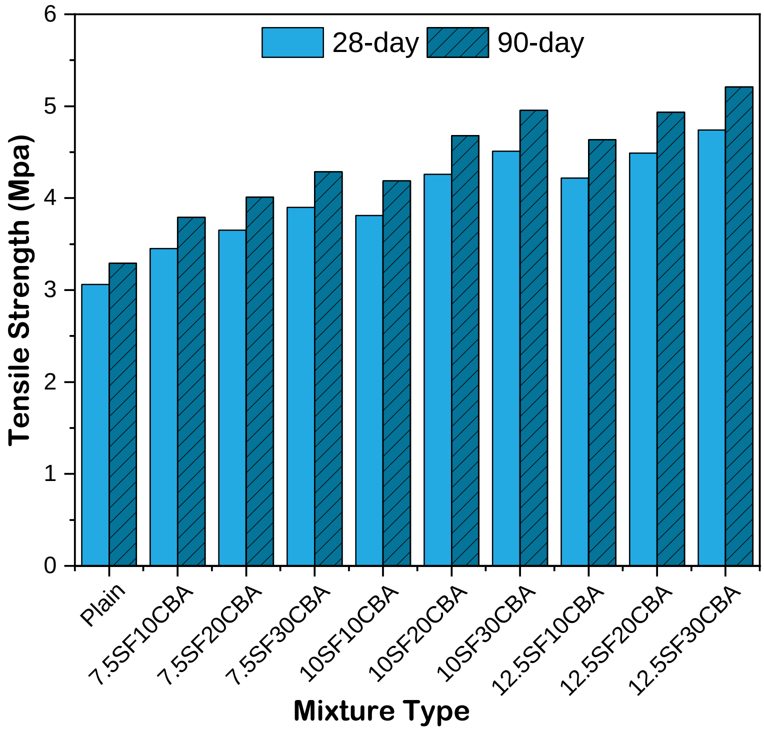


Figure 10. Tensile Strength of concrete mixed with CBA and SF.

3.4. Corrosion Analysis

It is a fact that corrosion of steel is caused by the chloride inclusion in concrete, which seriously affects RCC structures. It was observed from this study as well as from available research that [15,41–44] the addition of CBA and SF decreases the chloride penetration inside the concrete mass and enhances the internal resistance of concrete. Table 3 and Figure 11 show that as the percentage of CBA was increased, the resistance to chloride ions was also increased. Mix M1 with 12.5 S.F and 0 CBA gives −287 mV and mix M4 with 12.5 SF30 CBA gives −211 mV. The obtained results clearly showed that silica fume SF and coal bottom ash CBA are very effective in terms of corrosion resistance in concrete. Saadoun and Gahtani [41] studied that blending of plain cement with 10% or 20% SF significantly increase the resistance against corrosion. Berke [42] found that using silica fume significantly increased the long term corrosion resistance. The effectiveness of SF concrete in resisting damage caused by embedded steel corrosion was reported by Khedr and Idriss [43]. They discovered that combining plain concrete with 10–20% silica fume significantly increased corrosion resistance. Kou and Poon [15] investigated whether the use of bottom ash in concrete increases the resistance to the chloride-ion penetration. Coal bottom ash gives concrete better resistance to chloride-ion penetration, according to Singh and Siddique [44]. Halit Yazici [39] determined that by using Fly ash and silica fume in self-compacted concrete resistance to chloride-ion, penetration increased. Moreover, Detwiler et al. [40] used various supplementary cementitious materials to find the influence of these materials in enhancing the chloride resistance of cured concrete. These studies verify the results of the current study. All these by-products show better performance as compared to the normal concrete mix and improve the durability performance of the concrete.

Table 3. Corrosion analysis of 90-Day's sodium chloride solution.

Sr.	CBA and SF % Replacement	Corrosion Potential (mV)
M 1	12.5 SF 0 CBA	−287
M 2	12.5 SF 10 CBA	−261
M 3	12.5 SF 20 CBA	−234
M 4	12.5 SF 30 CBA	−211

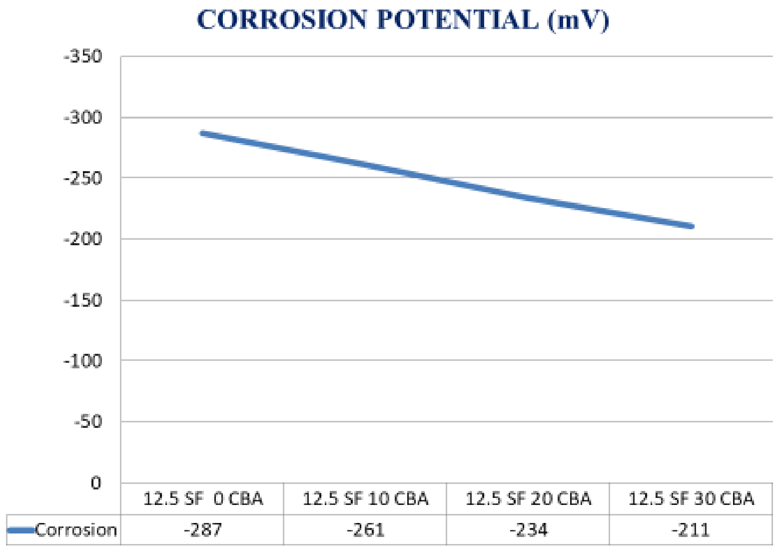


Figure 11. Corrosion Potential mV.

3.5. Sulfate Attack

Use of silica fume and coal bottom ash in the concrete matrix gives excellent resistance to sulfate attack. As seen in Table 4, the increasing amount of CBA enhances resistance to sulfate attack. For the sulfate resistance test, all the specimens were immersed in a Na_2SO_4 solution. The change in length of each specimen was measured with the help of a digital meter. It can be observed that after exposure to Na_2SO_4 mix M1 with 12.5 SF 0 CBA gives a 0.52% increment and mix M4 with 12.5 SF 30 CBA gives 0.32% increment. Many researchers have described the same trend. Ghafoori and Cai [45,46] studied the effect of bottom ash in concrete. From their investigation, it is observed that bottom ash gives excellent resistance to sulfate attack. Mangat and Khatib [47] conducted a study that shows the effect of silica fume on durability performance and concluded that an optimum level of 5–15% of silica fume as a substitute for cement improved concrete sulfate resistance. Cohen and Bentur [48] studied the effects of substituting 15% silica fume with cement. Sulfate resistance was confirmed in silica fume samples. According to Sajjad et al. [49], using CBA in concrete minimizes the negative effects of sulphate and chloride in concrete.

Table 4. Sulfate Attack of 28-Days in sodium sulfate solution (Na_2SO_4).

Sr.No	CBA % Replacement	Initial Length (mm)	Final Length (mm)	% Increment
M 1	12.5 SF 0 CBA	285.2 ± 0.03	286.7 ± 0.04	0.52
M 2	12.5 SF 10 CBA	285.4 ± 0.04	286.5 ± 0.05	0.39
M 3	12.5 SF 20 CBA	285.7 ± 0.02	286.7 ± 0.04	0.35
M 4	12.5 SF 30 CBA	285.0 ± 0.05	285.9 ± 0.05	0.32

4. Conclusions

Based on conducted study, it can be concluded that Coal Bottom Ash (CBA) can be a suitable substitute material of fine aggregate in concrete mix combined with silica fume. The use of CBA material in the concrete preparation is a viable invention and technology for manufacturing green concrete with high performance in the construction area. To fully comprehend the characteristics of CBA concrete, further long-term experimental work will be required in the future. The effective use of a large volume of coal bottom ash as a sand and gravel substitute will minimize the use of natural fine and coarse aggregate while also reducing the amount of coal waste disposed of in landfills. Furthermore, it will be very beneficial to use the industrial waste by-product from an economic and environmental point of view.

The workability of the resulting concrete decreased with the increase in the CBA and SF contents because the water absorption of CBA is higher than the sand. It is suggested that, while preparing CBA concrete, rather than selecting a constant water/binder ratio a constant slump should be considered.

CBA has the potential to be employed in the production of medium-strength concrete as a coarse and fine aggregate alternative. A 30% CBA replacement as a fine aggregate along with 12.5% SF as a cement replacement achieved the maximum compressive strength 38.45 Mpa, which is almost 21% greater than the conventional concrete. As a result, in order to improve its use as a construction element, CBA concrete must be developed using contemporary design methodologies and the right mix design to provide high strength, durability, and serviceability.

The splitting tensile strength of all those concrete mixtures containing CBA was improved when 12.5% SF was used as a partial replacement of cement. The maximum tensile strength of 38.45 Mpa was achieved at 12.5SF30CBA. SF has a low carbon content which is quite helpful to generate good quality pozzolanic reaction and functions as an extra binder component in the concrete hardening process.

The test results indicate that with 12.5% SF and 30% CBA replacement, with cement and sand respectively in concrete mixtures show good mechanical and durability properties. Moreover, these mixtures have also great environmental and economic benefits.

The durability properties i.e. chloride penetration resistance and sulfate attack resistance of the concrete by using SF and CBA, especially 12.5% SF replacement, is improved when combined with 30% CBA.

The use of a high percentage of CBA with the incorporation of FA as a cementitious material in concrete preparation is a realistic innovation and strategy for producing a green construction industry while also assisting with waste management of combustion products at power plants.

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