

Optimizing Coal Ash as a Sustainable Substitute of Cement and Aggregate in Structural Concrete

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ABSTRACT

The manufacture of concrete for constructing the structures like highways, bridges, and buildings requires large amounts of cement and aggregates. This high concrete production depletes natural resources like sand and gravel for the construction industry. It also negatively impacts the environment due to cement usage. This study looked at using waste materials like coal bottom ash (CBA) and fly ash (FA) in concrete as substitutes for some of the typical aggregates and cement. The goal was to reduce the environmental impact and preserve natural resources. The study made concrete with regular Portland cement, sand, 10mm coarse aggregate, locally available CBA, and FA. 15% fly ash was selected as an optimal level from initial testing. The CBA was used to replace 0-35% of the fine aggregate sand. Test cubes and cylinders were made with different mixes. Compressive strength, tensile strength, carbonation, and sulfate attack tests were done after curing. Results showed 25% CBA improved the concrete's mechanical performance. The compressive and tensile strengths increased but not above conventional concrete. This is because CBA needs more moisture for full hydration over longer curing times. Also, the concrete's durability improved in terms of resistance to carbonation and sulfate attack.

Keywords: Mechanical properties; Fly Ash (FA); durability properties; Coal Bottom Ash (CBA)

INTRODUCTION

Concrete is widely used in construction material in today's era due to its ease of use, good performance, and long lifespan. It's even called an artificial rock because of its durability in extreme weather. However, the high demand for concrete is depleting natural resources like sand and

gravel. Studies show the major issues are the large amounts of industrial waste and environmental pollution from concrete production. This points to the need for more sustainable solutions. The key is improving resource efficiency by decreasing energy and material usage. Considering industrial wastes like coal bottom ash, fly ash, silica fume and waste glass in concrete could be a possible

solution. These materials are low cost, very durable and eco-friendly. They can help address the economic and environmental problems of the concrete industry. Numerous studies have examined the influence of coal bottom ash (CBA) on concrete performance. One study by (Topçu et al. 2014) produced durable geopolymer concrete with CBA replacing sand, without any cement. They tested different parameters at various curing ages. (Ghafoori & Buchole 1997) found that high-calcium CBA yielded more sustainable and durable concrete. They observed increased workability when CBA replaced sand at the same slump. The split tensile strength was equal or higher with a 50/50 mix of sand and CBA. Compressive strength was comparable to conventional concrete.

(Aggarwal et al. 2007) found compressive strength with CBA was not higher than normal concrete, but declined less over time, especially at 28 days. (Kim & Lee, 2011) saw a large drop in elastic modulus with CBA as fine aggregate in high strength concrete, but strength was similar. (Andrade et al. 2009) confirmed the reduced modulus with CBA addition.

Several studies (Aramraks 2006; Singh & Siddique 2015) found abrasion resistance decreased using CBA as fine aggregate. (Siddique 2003b, 2003a) saw improved compressive strength but poorer abrasion with fly ash as fine aggregate. (Ghafoori & Buchole 1997) determined water-reducing admixtures significantly increased compressive and tensile strength of concrete with partial CBA sand replacement.

Coal-fired power plants produce massive amounts of ash waste, primarily fly ash with about 20% bottom ash. Bottom ash's granular texture allows its use as concrete sand replacement. In recent years, fly ash has gained popularity as a partial substitution for cement in concrete. The replacement of some cement with fly ash can result in slower early strength development, as fly ash has a low calcium content compared to cement. So, cement replacement is typically limited to around 30% to minimize this effect. Overall, fly ash is used less than bottom ash in concrete. Cement makes up only ~20% of concrete's volume, while fine aggregate is 50-100% more. Since the goal is maximizing utilization of coal ash waste, full replacement of fine aggregate makes more sense than partial cement substitution. Though fly ash benefits concrete's later strength and durability, its low calcium content slows early strength development. Given the proportion of ingredients, replacing fine aggregate allows higher volumes of ash utilization. Testing different replacement levels is needed to optimize fly ash and bottom ash utilization while maintaining acceptable concrete performance.

Studies show that as the replacement of fly ash increases, the consistency of the concrete also increases. In addition to enhancing strength development over time

(Siddique 2003a) (Ali et al. 2022; Siddique, 2003b), fly ash improves the long-term corrosion resistance of concrete structures due to its pozzolanic properties (Maslehuddin et al. 1989) (Maslehuddin et al. 1989). However, concrete with very high fly ash content tends to have reduced workability and abrasion resistance (Buller, Abro, et al. 2019; Siddique 2003a).

Based on these findings, most researchers conclude that the maximum fly ash replacement level should be around 50% of the fine aggregate volume (Bilir et al. 2015; Buller, Abro et al. 2021). Though some studies found fly ash could replace 60-70% of sand in mortars before significantly impacting properties. The pozzolanic reactivity of fly ash contributes to concrete strength and durability, but too much can negatively affect workability and wear resistance. Further research is needed to optimize fly ash utilization while maintaining acceptable concrete performance.

Only a handful of studies have examined concrete containing both coal bottom ash (CBA) and fly ash (FA) as replacements for cement and sand. Limited studies are available in literature who have used high volumes of both materials. (Buller, Lee, et al. 2019; Rafieizonooz et al. 2016) found 75% CBA and 20% FA improved compressive, flexural, and tensile strengths as well as drying shrinkage compared to conventional concrete. Furthermore, enhancements in strength along with increased sulfate and acid resistance with CBA and FA were also noticed by (Buller et al. 2019; Rafieizonooz et al. 2016).

Given the limited research using high volumes of FA and CBA and in concrete, this study seeks to expand on prior work by experimentally evaluating concrete containing both materials to determine the effects on mechanical properties and durability. Most prior research has not considered using high amounts of CBA and FA together. This comprehensive testing will provide new insights into the effects on concrete properties when maximizing use of these coal combustion products.

Only a handful of studies have looked at concrete containing both coal bottom ash (CBA) and fly ash (FA) replacing sand and cement. Very few have utilized high volumes of both materials. One study (Buller, Lee, et al. 2019; Rafieizonooz et al. 2016) found 75% CBA and 20% FA improved compressive, flexural, and tensile strengths as well as drying shrinkage compared to conventional concrete. Another study (Buller, et al. 2021; Rafieizonooz et al. 2017) saw enhancements in strength along with increased sulfate and acid resistance with CBA and FA.

This study aims to build on that limited work by testing concrete with FA and CBA to practically determine mechanical and durability performance. Most prior research has not considered using high amounts of CBA and FA together. This comprehensive testing will provide new insights into the effects on

concrete properties when maximizing use of these coal combustion by-products. That's the reason why the dual fold objectives were considered for the current study. The first objective is to evaluate strength with 0-35% CBA as fine aggregate and 15% FA replacing cement. The first objective was to evaluate strength properties by testing density, compressive strength, and split tensile strength after 7 and 28 days of water curing. The 2nd goal was to determine durability characteristics using coal bottom ash (CBA) and fly ash (FA) by conducting carbonation and sulfate attack tests. This extensive testing regime will provide valuable insights into the impacts of high volumes of coal combustion products on various concrete performance aspects.

METHODOLOGY

MATERIALS

Type I ordinary Portland cement (OPC) conforming to ASTM C150-05 and BS 12 specifications was used. It was taken from the local Nawabshah market under the brand Lucky Cement. For collecting the sand, locally available sand passing the 4.75mm sieve was utilized as fine aggregate. It was cleaned and dried to saturated surface dry (SSD) condition before mixing. The coarse aggregate of 10-15mm sized was used for the current study. Sieves were employed to grade the coarse aggregate as per standards. The aggregates were cleaned, dried to SSD condition, and sieved before use.

The coal bottom ash was sourced from the Lakhra coal power plant in Jamshoro district. It was sieved through the #4 sieve before use as partial sand replacement. And the Fly Ash, (FA) was obtained from a supplier in Karachi, Pakistan. An optimal 15% FA (by weight) was used to partially replace cement, based on the DOE mix design method.

Eight concrete batches were prepared with varying percentages of CBA and the decided 15% FA dosage.

Details of the mix proportions and material dosages are provided in Table 3.1.

SPECIMEN PREPARATION

To determine the mechanical and durability performance, 100mm×100mm cubes were cast for concrete compressive strength testing and cylinders of 100mm × 200mm for tensile strength testing. The concrete ingredients including cement, sand, and water were weighed before mixing. Hand mixing was done to combine the materials. To ensure uniform fly ash dispersion. To ensure thorough dispersion of the fly ash, the sand and binder materials (OPC and fly ash) were first mixed vigorously together for 3-5 minutes. Water was then slowly incorporated into the dry mix and blending continued for approximately 3 minutes to obtain a consistent and homogeneous concrete mixture. Specimens were cast in standard molds. After 24 hours, they were removed from the molds. Before the testing the specimens were cleaned with the microfiber cloth to get away with any kind of particles. They were checked for defects like cracks or broken edges. The tests were conducted in the Civil Engineering department's structures laboratory at the QUEST Nawabshah campus. Standard procedures were followed for sample preparation, casting, curing, and testing.

TEST METHOD

Density: The day after casting and before demolding, the density of all cylinder specimens was measured. Density was calculated by dividing the specimen's weight by its volume as per standard (C138/C138M-17a, 2017).

Compressive strength: The compression test is key for evaluating concrete's mechanical properties. It was performed as per ASTM C39/C39M on 150mm cubes after 28 days of curing. Compressive strength was calculated using the equation:

$$f_{cu} = \frac{P}{A} \quad (1)$$

TABLE 1. Details of the mix proportions

Batch	Type	Cement (%)	FA (%)	CA (%)	CBA (%)	W/B
C	Control	100	100	100	---	0.5
FC05	FA and BA	100	95	100	5	0.5
FC10	FA and BA	100	90	100	10	0.5
FC15	FA and BA	100	85	100	15	0.5
FC20	FA and BA	100	80	100	20	0.5
FC25	FA and BA	100	75	100	25	0.5
FC30	FA and BA	100	70	100	30	0.5
FC35	FA and BA	100	65	100	35	0.5

Where f_{cu} is the compressive strength, P is the maximum load sustained, and A is the specimen cross-sectional area.

Split tensile strength: The tensile strength test was done on cylinder specimens after 28 days of curing using a Universal Testing Machine (UTM) with constant loading rate as per standard test method. The following equation was used:

$$f_t = \frac{2P}{\pi LD} \quad (2)$$

Where f_t is the tensile strength, P is the maximum load, D is the cylinder diameter, and L is the length.

Corrosion analysis: 100mm × 200mm cylindrical specimens with 12mm diameter 300mm long bar inserted centrally were cast. After 28-day water curing, they were immersed in 3% NaCl solution for 14 days. This 90-day wet-dry cycle was repeated as per ASTM C876 (ASTM Standard C-876, 1999). Corrosion potential was measured on 3 specimens and averaged.

Sulphate attack: 25x25x285 mm prism specimens were prepared per ASTM C1012 (C1012, 2013). After 28-day curing, they were immersed in sodium sulfate solution. The length change of the specimens was quantified using a digital meter, by comparing the measurements taken before and after immersion in the sulfate solution.

RESULTS AND DISCUSSION

DENSITY OF CONCRETE

Density is a valuable factor influencing concrete strength and permeability. Figure 2 shows the density values obtained in the laboratory for the different CBA dosage mixes with optimum 15% fly ash. Density decreased as CBA content increased up to 25% sand replacement (Bhutto & Buller, 2020; Mastoi et al. 2020). Average density of the control mix (0.50 w/c ratio, no CBA) was 2345 kg/m³. The mixes with CBA had lower density than the normal concrete without CBA. The maximum 5% density reduction occurred at 25% CBA content. This is attributed to the higher porosity of CBA compared to natural sand, which lowers the unit weight of CBA concrete. Summarizing the results, density declined with increasing CBA dosage up to 25% replacement, beyond which it started to improve again. The decreased density is due to the porous nature of CBA versus normal sand. Optimizing CBA content is necessary to limit density reduction while improving sustainability.

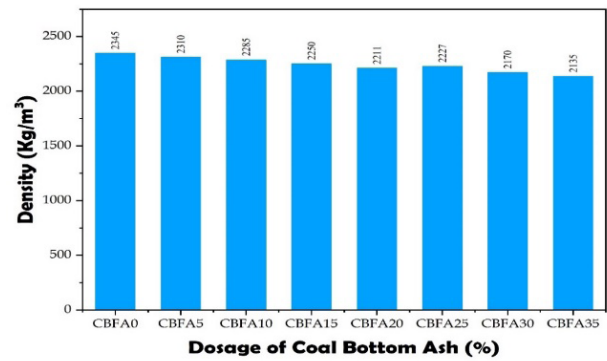


FIGURE 1. Concrete density of different mixes with and without CBA+FA

COMPRESSIVE STRENGTH

Figure 3 shows the compressive strength results for the CBA concrete mixes under 7- and 28-day water curing. Overall, CBA had a minor effect on compressive strength. As CBA increased from 0% to 35%, strength decreased slightly for all specimens. The control mix had 55.44 MPa at 28 days, while the CBA mixes were marginally lower. This aligns with other studies like (Buller, Abro, et al. 2021; Buller, Tunio, et al. 2019; Memon et al. 2019; Rafeizonooz et al. 2016; Tunio et al. 2019) that showed a small drop in strength with CBA. (Buller, Ali, et al. 2021; Cheriaf et al. 1999). found the pozzolanic reaction of CBA accelerates after 28 days, partially offsetting the strength loss from CBA as fine aggregate. Here, the 25% CBA mix had a 5.6% strength reduction at 28 days versus the control. Curing conditions significantly affected compressive strength. Oven drying decreased strength across all CBA contents, with a maximum 5.6% reduction. This may be from dehydration of C-S-H gel at 105°C damaging the cement paste, as noted by (Hager, 2013). Additionally, water evaporation increased porosity, also reducing strength.

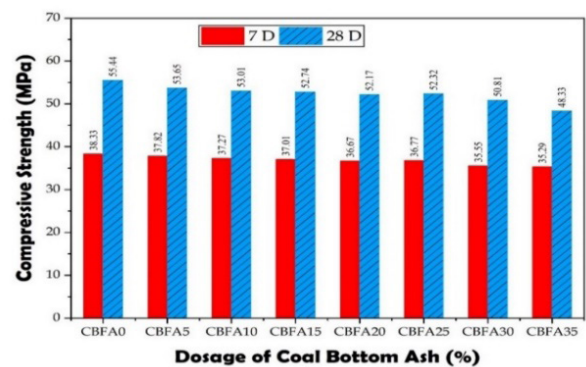


FIGURE 2. Details of compressive strength for different mixes

SPLIT TENSILE STRENGTH

Figure 4 shows the split tensile strengths after 7- and 28-day curing, for both saturated surface dry (SSD) and oven-dried conditions. The results showed decreasing tensile strength with higher CBA levels. The 20% and 25% CBA mixes had 3.1% and 2.7% lower tensile strength versus the control concrete.

Singh and Siddique found 25% CBA had the best tensile strength (Singh & Siddique 2015), though it declined steadily beyond 28 days. The lower density and more porous structure of CBA particles is believed to cause internal cracks under load, reducing tensile strength. Further testing is needed to better understand the impacts of CBA on concrete tensile performance.

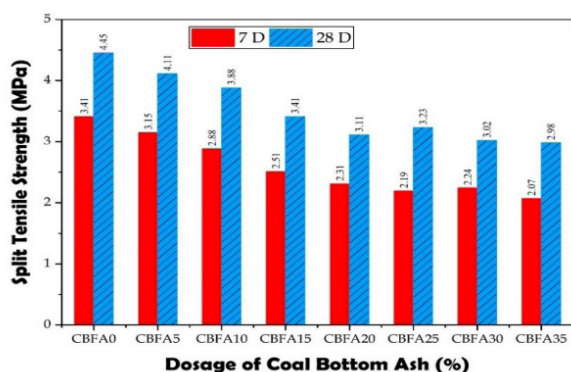


FIGURE 3. Details of compressive strength of different mixes

The test results showed a significant decrease in splitting tensile strength as CBA content increased. Compared to the control concrete, the mixes with 20% and 25% CBA had 3.1% and 2.7% lower tensile strengths respectively, as CBA increased from 0% to 35%. This reduction in tensile performance with higher CBA levels may be attributed to the lower density and more porous structure of CBA particles versus natural sand. Further testing is required to better understand the impact of coal bottom ash on the tensile properties of concrete.

CORROSION ANALYSIS

It is known that chloride ingress causes corrosion of steel reinforcement, negatively impacting reinforced concrete structures. The findings here and in other studies (Al-Saadoun & Al-Gahtani, 1992; Berke, 1989; Khedr & Idriss, 1995; S.-C. Kou & Poon, 2009; Singh & Siddique, 2014)

show that adding fly ash (FA) and coal bottom ash (CBA) enhances resistance to chloride penetration in concrete. Figure 5 illustrates that increasing CBA dosage improved chloride resistance. The control mix with 15% FA and 0% CBA had -290 mV, while the mix with 15% FA and 35% CBA measured -197 mV. This clearly demonstrates the beneficial effect of FA and CBA on concrete's corrosion protection.

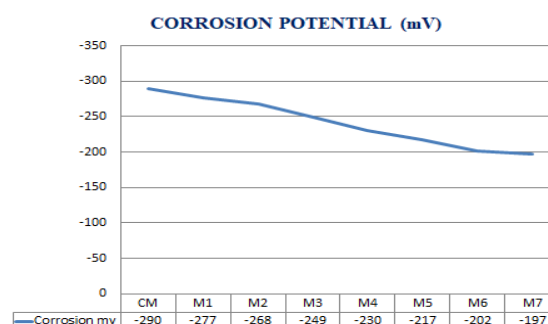


FIGURE 4. depiction of corrosion potential

As explained by Singh and Siddique (Singh & Siddique, 2014), CBA is more resistant to chloride ingress than regular aggregates. Other researchers like (Yazıcı, 2008), (S. C. Kou & Poon, 2009), and Detwiler (Detwiler et al. 1994) also found FA and CBA boost chloride resistance in concrete. The industrial byproducts outperform standard concrete and enhance durability against chloride exposure.

SULPHATE ATTACK

Table 2 shows the sulfate attack results. Resistance improved with higher CBA percentages. The samples were immersed in Na₂SO₄ solution and length change measured. The control mix had 0.56% expansion, while the 35% CBA mix only expanded 0.18% after sulfate exposure.

Other studies confirm these findings Mangi et al (Mangi et al. 2019) found CBA reduces the effects of sulfates in concrete. Moreover, they showed optimum silica fume dosage (5-15%) as cement replacement boosted concrete's sulfate resistance. Ghafoori and Cai (Ghafoori & Cai, 1998b, 1998a) demonstrated the benefits of bottom ash against sulfate attack. The collective results clearly show fly ash and bottom ash enhance concrete durability against detrimental sulfate exposure.

TABLE 2. Details of the sulphate attack results immersed in Sodium sulphate solution at 28-days

Mix	%	Initial Length (mm)	Final Length (mm)	% Increment
Control Mix	CM0%	286.2 ± 0.03	287.1 ± 0.04	0.55
Mix 1	FC5	284.8 ± 0.02	285.1 ± 0.04	0.41
Mix 2	FC10	284.7 ± 0.01	286.2 ± 0.04	0.34
Mix 3	FC15	286.1 ± 0.05	285.9 ± 0.04	0.33
Mix 4	FC20	284.1 ± 0.05	285.9 ± 0.04	0.29
Mix 5	FC25	284.6 ± 0.03	285.9 ± 0.04	0.24
Mix 6	FC30	286.4 ± 0.01	287.1 ± 0.04	0.22
Mix 7	FC35	286.7 ± 0.02	285.9 ± 0.04	0.17

CONCLUSION

This study examined the effects of coal bottom ash (CBA) and fly ash (FA) on the mechanical and durability properties of concrete. Based on the results following conclusions could be drawn from the current study:

1. This study used an optimal 15% fly ash dosage combined with 0-35% coal bottom ash (CBA) as fine aggregate substitution. Cylinder and cubes were tested after 7 and 28 days of water curing.
2. The results revealed that the decreasing compressive and tensile strengths with higher CBA content, with maximum reductions of 12.8% and 33% respectively at 28 days versus control concrete. This is attributed to the porous CBA particles causing internal cracks under load.
3. The results showed decreasing compressive and tensile strengths with higher CBA content, with maximum reductions of 12.8% and 33% respectively at 28 days versus control concrete. This is attributed to the porous CBA particles causing internal cracks under load.

In summary, coal combustion products enhance durability but can reduce strength if curing is insufficient. Adequate hydration time allows strength development by densifying the porous CBA microstructure. Optimizing curing and fly ash and CBA levels is key to maximizing strength, durability, and sustainability.

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DECLARATION OF COMPETING INTEREST

None.

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