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Resistance to Wear, Durability and Micro Structural Properties of CBA as Sand Replacement in Mortar

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Abstract: This study investigated the effects of coal bottom ash (CBA) as a replacement for natural sand on the properties of mortar. The compressive strength, flexural strength, tensile strength, abrasion resistance, SEM analysis and durability of mortar were studied. Natural sand was replaced with coal bottom ash by 10 percentage increment up to 100 percentages by weight at a fixed water-cement ratio 0.47. The test specimens were maintained in a solution of Sodium chloride and magnesium sulphate for 180 days with a normality of 1.58 and 0.58, respectively, and their effects on the compressive strength and weight were studied. The results showed that the compressive strength, flexural strength and modulus of elasticity increased when the percentage of replacement of CBA increased up to 20 percentages, but decreased when the percentage replacement of CBA increased beyond 20% whereas density linear decreased. The tensile strength was increased up to the 30 percentage replacement and decreased for further replacements, whereas loss on abrasion was less up to 30 percentage replacement and increased for further replacement. When the specimens were maintained in a solution of Sodium chloride and Magnesium sulphate for 180 days, loss of compressive strength and weight was observed.

Keywords: *Compressive strength, Flexural strength, Density, Abrasion, tensile strength, Modulus of elasticity, Durability.*

1. Introduction

In many countries, the construction industry is rapidly growing, and uses natural resources, such as sand, to develop the infrastructure. This growth is affected by the lack of available good-quality natural resources. Natural resources are being depleted worldwide, and the amount of generated wastes from industry is considerably increasing. Sustainable development for construction involves using non-conventional materials such as copper slag and bottom ash to compensate for the lack of natural resources and find alternative methods to conserve the environment. In concrete construction, the prime source of fine aggregate is normally naturally available river sand, which is not widely available during floods and rainy seasons because of the huge demand of the construction industry. To solve this problem, a reliable source and continuous supply of an alternative material for these ingredients should be found, and their use is recommended. It is essential that this recommended alternative material is eco-friendly and easily available at a low cost without an intervallic supply. In India, thermal power plants are the main source of power generation. These plants have been generating approximately two-thirds of the power demand of the country. Many studies have shown the potential use of ash in concrete as well as mortar. Nadeem et al. (2013) demonstrated the performance of fly ash and metaka-olin (MK) mortar at elevated temperatures by partially replacing cement with 5%–20% MK and 20%–60% fly ash at temperatures from 27oC to 800oC ,whereas Rao studied the effect of water binder ratio, varying from 0.35 to 0.5 at constant increment of 0.005, at various ages of mortar with different percentage of silica fume on its compressive strength(Rao. 2001). Cultrone et al.(2005) examined the carbonation process in different types of mortars with and without pozzolana and compared the results with those of similar naturally carbonated mortars, and concluded that the mineralogy and texture of mortars vary depending on the type of additive used. Sajedi (2012) reported that the mortar-containing OPC and OPC-slag had higher strength with lower binder ratio, which was cured in water. Herve et al. (2010) studied the influence of the microstructure of mortar on its mechanical behavior based on three variable parameters, namely, the thickness of the interfacial transition zone, porosity gradient in the cement paste matrix, and nature of the constituents of the Interfacial Transition Zone. Furthermore, Jo (2008) studied the mechanical properties of epoxy cement mortars without hardener exposed to outdoor condition, while Islam and Islam (2010) conducted experimental investigation to study the effects of fly ash on the strength development of mortar and the optimum use of fly ash in mortar as a cement replacement at different ages. Modolo et al. (2013) examined the effect of bottom bed ash generated from the combustion of forest biomass residues as a sand replacement in mortar, while Ballester et al.(2007) studied the mechanical and structural properties of mortar using quarry limestone aggregate obtained as a byproduct from the waste of mussel cannery industries. Chakraborty et al. (2013) demonstrated that the physical characteristics and mechanical properties of cement mortar are significantly improved by jute fiber reinforcement. Reddy and Gupta (2008) reported that sand grading can influence the characteristics of mortar and showed that for a given consistency, mortar with fine sand requires 25%–30% more water. The rheology of fresh mortar such as mixing procedure, testing procedure and proportions of constituent material was studied (Banfill 1991). However, there are limited numbers of studies focused on CBA as a sand replacement in mortar. The present study was conducted to evaluate the mechanical properties , loss on abrasion of mortar, SEM images analysis and the effect of NaCl and magnesium sulphate(180 days) on mortar prepared with CBA as a sand replacement at 0 (Control mortar), 10%, 20%, 30%, 40%, 50%, 60%, 70%, 80%, 90%, and 100%. The results obtained are compared with control mortar prepared with natural sand.

2. Experimental Programs

2.1. Materials

Ultra Tech Grade 53 OPC was used in this study, in compliance with BIS: 269-1998. The natural sand of the river bed was obtained from the Tapi River, Nandurbar, Maharashtra, India. CBA was obtained from the Eklahare Thermal Power Plant, Nashik city, Maharashtra, India. BV Plastizers were used as directed by the manufacturer. Potable water was used for casting and curing processes of the mortar specimens. After casting, all cubic and beam specimens were maintained for curing in the curing tank. While curing the specimens, water was replaced every week.

2.2. Physical and Chemical Properties

To determine the fineness modulus of sand and bottom ash details were analyzed according to IS:383-1970. In the present study, the particle size distribution of sand and CBA was as shown in Figure 1.

The specific gravity and water absorption tests were performed as per BIS:2386-1963. The specific gravity of the sand and CBA was determined by using pycnometer. The fineness modulus, specific gravity, and water absorption of sand and CBA are presented in Table 1. The chemical composition of CBA and cement were presented in Table 2

Table 1: *Physical properties of the aggregates*

Material	Sand	CBA
Fineness modulus	3.75	3.092
Specific gravity	2.62	1.93
Water absorption	1.01	10.062

2.3. Mix proportion

The mix proportion selected for this study (cement – sand ratio) was 1:3 throughout the study with fixed water cement ratio of 0.47. Eleven mixes were prepared by CBA, which was substituted in place of sand from 10 to 100% with increment of 10%.

2.4 Casting of Coal Bottom Ash Mortar Specimens

The mortar constituents were mixed in a concrete mixer for 4–5 min to obtain a homogeneous consistency. When the percentage of CBA increased in the mortar, additional mixing time was required to obtain the desired consistency. After mixing, the cube and beam molds were filled in three layers and compacted using a tamping rod as well as a vibrating table to remove any entrapped air. Freshly poured mortar specimens were stored in laboratories on a leveled surface for 24 h at 27 ± 2°C. Then, the specimens were demolded and placed in potable water tank for curing for up to 7, 28, 56, and 180 days.

Table 2 *Chemical composition of cement, CBA*

Chemical constituents	OPC	CBA
SiO2	21.25	60.63
Al2O3	4.65	24.73
Fe2O3	3.86	6.96
CaO	62.67	-
MgO	2.79	0.44
SO3	2.62	0.58
K2O	0.93	-
Na2O	0.23	0.45
LOI	1.04	6.14

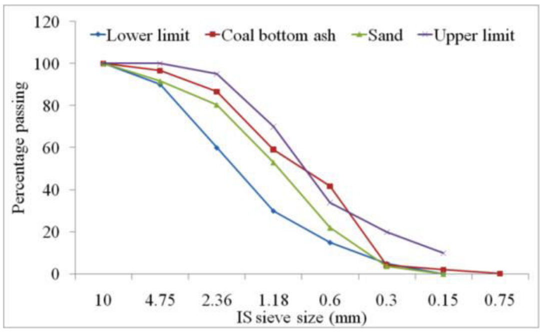

Figure 1 *Particle size distribution of sand and CBA in zone –I*

3. Test methods

The compression test conforming to BIS: 516-1959(R-1999) was performed on the specimens of size 70.7 × 70.7 × 70.7 mm using a 3000 kN capacity digital hydraulic uniaxial compression testing machine. The compressive load was applied continuously at a constant pace rate of 1.3 kN/s until the resistance of the specimen to increasing load collapsed and no greater load could be sustained. The maximum load applied to the specimen was recorded. The compressive strength of the specimen was calculated by dividing the maximum load applied to the specimen during the test by the cross-sectional area. The flexural test conforming BIS: 516-1959 was performed on the specimens of size 100 × 100 × 500 mm using a 1000-kN capacity digital hydraulic universal testing machine for two-point load. The flexural strength was calculated by using BIS: 516-1959. The tensile test conforming BIS: 269-1958 was performed on the briquette specimen having minimum cross section 25.4 mm x 25.4 mm. The maximum failure load was recorded and tensile strength was calculated by maximum load by minimum cross sectional area. Abrasion resistance test was conducted according to BIS: 1237(2012) and BIS: 9284(1997 R 1993) on the specimen size of 70.7 x 70.7 x 70.7 mm at 7 days and 28 days curing ages by using digital abrasion testing machine. The loss of thickness was calculated by using following relation (W1 - W2) x V / (W1 x A) where. Similar kind of method was adopted by many researches and consistent results were obtained (Turk, 2011; Arslan, 2001). Durability studies were conducted by immersing 70.7 × 70.7 × 70.7 mm mortar cube specimens after 28 days of curing in two different solutions of MgSO4 and NaCl, respectively, to evaluate the effect of sulfate and chloride for up to 180 days. Specimens of the same size were also kept for curing in portable water for 180 days.

4. Results and Discussion

4.1. Workability of Coal Bottom Ash Mortar (Consistency through flow table test)

The workability of CBA mortar was measured by flow table test for all mortar mixes as shown in table 3. The results shows the workability of CBA mortar was reduced as the percentage of CBA increased because of high water absorption of CBA as compared to natural sand. The porous particle of CBA absorbed faster and more water internally than sand particles so that availability of free water for lubrication of particle reduced.

To achieve the required workability of CBA mortar the plastizers was used silmlar method was addopted by Ghafoori and Bucholc (1997). The percentage of CBA increase in mortar the specific surface area of fine aggregate also increases. The uneven texture and complex shape of CBA also played important role in increasing the inter particle friction. The flow was observed for controlled mortar 165 mm, whereas for mix BA10 and BA20 the flow was observed 168 and 165 mm respectively which is closer to the controlled mortar but for mixes from BA30 to BA100 the flow was reduced by 13.79, 26.92, 32, 35.24, 43.47, 47.32, 57.14 and 73.68 percentages with compared to controlled mortar, similar trends of reduction in slump was observed by Aggarwal et al. (2007) and Malkit et al. (2014).

4.2. Compressive Strength of CBA Mortar

The compressive strength of mortar mixed with CBA with10%–100% replacements of sand and without CM (control mortar) is presented in figure 2. The compressive strength of control mortar was found to be 22.54 N/mm2, 39.35 N/mm2, 44.28 N/mm2, and 46.17 N/mm2 at 7, 28, 56, and 112 days, respectively. As expected, the compressive strength increased with increasing curing time.

However, the strength improvement at early curing ages (7 days) was slow due to pore filling effect. The CBA initially acted similar to pore filler and only after 7 days, its hydration liberated sufficient amount of lime for starting the secondary pozzolanic reaction. This reaction led to the formation of more amount of C-S-H gel; however, due to the porous nature of CBA, strength improvement was not significant. The compressive strength of mortar when sand was replaced by 10%–20% CBA was considerably increased, when compared with control mortar; this increase in strength was due to better particle size distribution and CBA acted as gap filler between the sand particles. When the replacement was increased from 30% to 100%, the compressive strength reduced, when compared with the control mortar at all curing ages. The lowest compressive strength was observed for mix BA100, which was 9.07, 18.67, 20.81 and 22.28 N/mm2 at 7, 28, 56, and 112 days, respectively; this decreased compressive strength may be due to the low specific gravity and porous particle of CBA. The water absorption of CBA was higher than that of sand used in the present study, and the higher water absorption indicated that the CBA particle had more pores so that adequate C-S-H gel was not available to bind the CBA particles.

As a result, compressive strength reduced as the percentage of CBA increased in the mortar. Figure 3(a) shows the SEM images of mortar when only natural sand was used, which revealed dense structure with sufficient C-S-H gel available to bind the sand particles together. Figure 3 (b) and (c) shows the SEM images of 10% and 20% CBA, which indicated the dense structure of mortar with sufficient C-S-H gel to bind the sand and CBA particle together, so that the compressive strength of mortar increased, when compared with the control mortar. Figures 3(d)–(f) and figures 4 (a)–(d) show the SEM images indicating some micropores with microcracks in the mortar with insufficient C-S-H gel; as a result, the hardened properties of the CBA mortar were decreased, when compared with those of the control mortar.

Table 3 *Slump flow of CBA mortar with and without plastizers*

Mix	Flow without plastizers	Flow with plastizers
CM	165	No plastizers
BA10	168	No plastizers
BA20	165	No plastizers
BA30	145	175
BA40	130	175
BA50	125	172

BA60	122	170
BA70	115	170
BA80	112	169
BA90	105	169
BA100	95	168

4.3. Flexural Strength of CBA Mortar

The flexural strength of control mortar was found to be 1.57, 2.26, 2.31, and 2.38 N/mm^2 at 7, 28, 56, and 112 days, respectively. The flexural strength was increased for mix BA10 and BA20, when compared with that of control mortar at all ages of curing. When the replacement was increased from 30 to 100, for the mix BA30 to BA100, the flexural strength was found to decrease at all ages of curing. When the replacement up to 50 percentages, the flexural strength was lesser but closer, when compared with the control mortar; however, when the replacement was more than 50 percentage, the flexural strength was considerably reduced. The lowest flexural strength was observed to be 0.52 N/mm^2 of mix BA100. The CBA mortar gained flexural strength with age, but it was lesser than that of the control mortar when the replacement was more than 20% because of poor interlocking among the CBA particles due to their spherical in nature. Figure 5 shows the variation in the flexural strength for different replacements with respect to the control mortar for 7, 28, 56, and 112 days of curing.

4.4 Effect of CBA on abrasion resistance of mortar

The abrasion resistance of CBA mortar was determined at curing age of 7 and 28 days and measured in terms of depth of wear. It was found that depth of wear increased with increased percentage of CBA at all curing ages excluding 10, 20 and 30 percentages replacement. Table 4 shows variation of depth of wear with increase in percentages replacement of sand by CBA in mortar from 10 percentages to 100 percentages. The loss on wear of controlled mortar was found to be 2.36 and 2.02 mm at 7 and 28 days respectively which indicate that as the age of curing increased the loss on wear deceased. For BA10 mix the percentage loss on wear was decreased by 37.2 and 39.31 whereas for BA20 mix percentages loss on wear was observed to be decreased by 20.41 and 30.32 and for BA30 mix loss on wear was decreased by 14.56 and 25.47 as compared to controlled mortar at 7 and 28 days of curing age respectively. This decrease in loss on wear may be due to the better particle size distribution up to 30 percentage replacements and dense structure of mortar which is observed in SEM images of these specimens (figures 3 (a),(b) and (c) . The percentages loss on wear was observed to decrease for all mixes from BA 40 to BA100 by 2.48, 5.98, 15.11, 20.81, 23.87, 29.77 and 31.59 at 7 days curing age and 1.94, 4.72, 11.79, 16.53, 22.61, 27.34 and 29.86 at 28 days curing age respectively, similar kind of results were obtained by Rafat(2003). From the above evidence of results analysis, as the curing age of CBA mortar increases the loss on wear was also decreased, this indicate that at early age bottom ash mortar gain strength slowly with respect to controlled mortar as well as the compressive strength increased the loss on wear was also decreased. The relation between the compressive strength and loss on wear is presented in figure 6. The linear relation between compressive strength and loss on wear variation is by the equation fc = 12.96 T + 62.17 and polynomial expression of CBA mortar is obtained as fc = - 1.872 T2 – 4.125 T + 52.65, where fc Compressive strength at 28 days in (N/mm^2) and T – Loss on wear in (mm^3/mm^2)

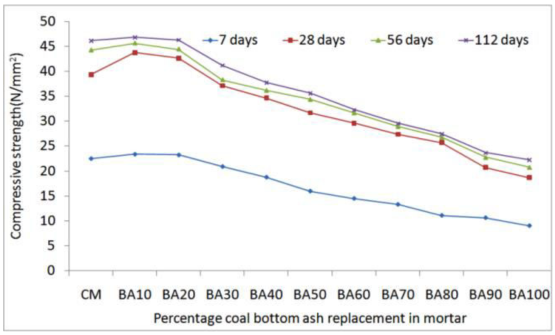

***Figure 2** Compressive strength gain of mortar with age*

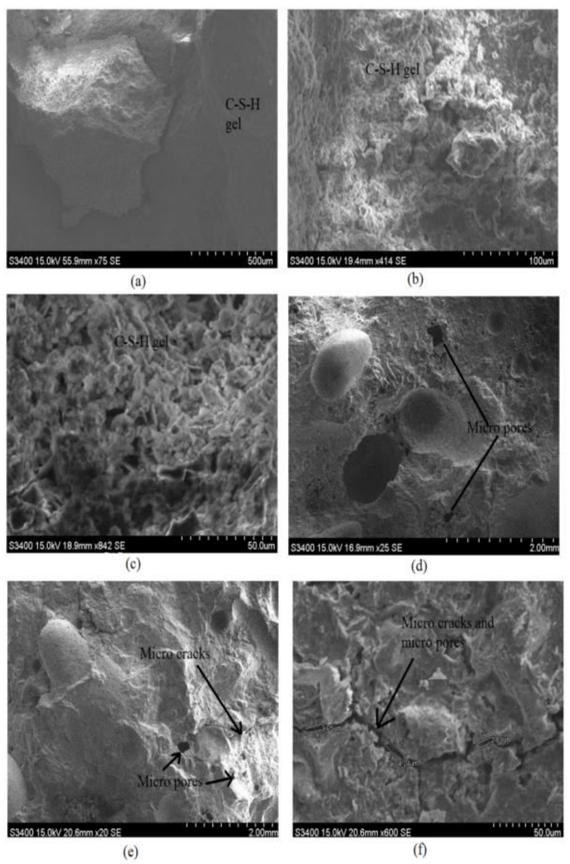

***Figure 3** SEM images of the control mortar and other mixes CM (a), BA10 (b), BA20 (c), BA40 (d), BA50 (e), and BA60 (f)*

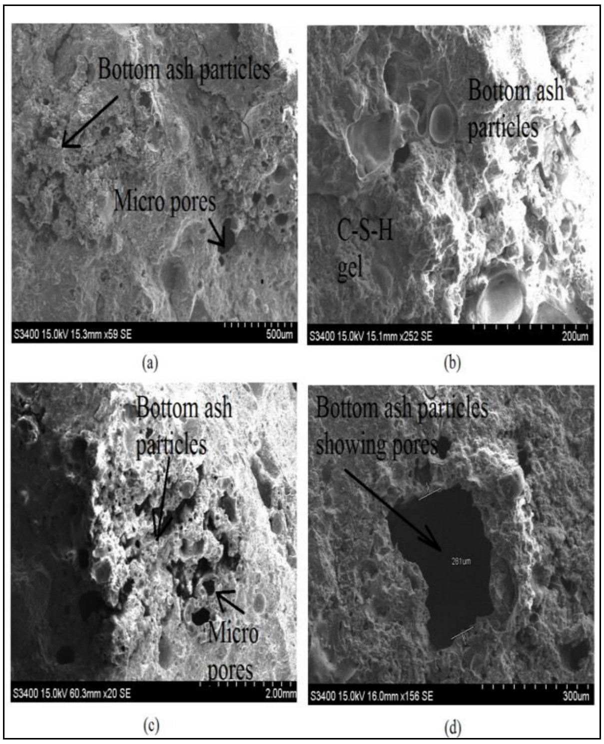

Figure 4 *SEM images of mix BA70 (a), BA80 (b), BA90(c), and BA100 (d)*

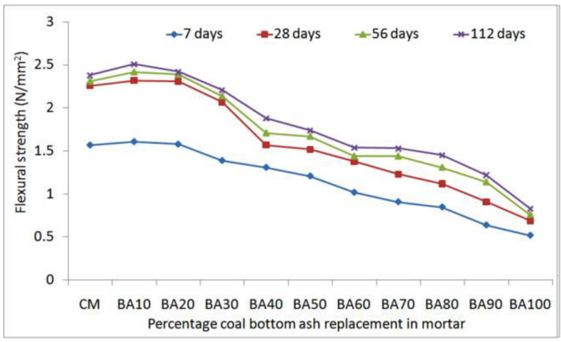

Figure 5 *Flexural strength gain of CBA mortar with age*

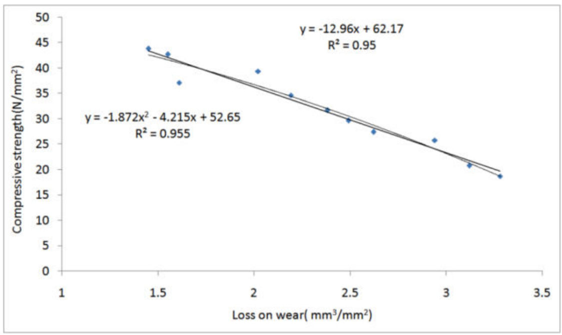

Figure 6 *Relation between the compressive strength and loss on wear of CBA mortar*

Table 4 *Mechanical properties and loss on wear of CBA mortar*

Mix	Compressive strength(N/mm^2)		Flexural strength (N/mm^2)		Tensile strength (N/mm^2)		Loss on wear (mm^3/mm^2)	
	7 days	28 days	7 days	28 days	7 days	28 days	7 days	28 days
CM	22.54	39.35	1.57	2.26	3.03	3.89	2.36	2.02
BA10	23.41	43.82	1.61	2.32	3.33	4.22	1.72	1.45
BA20	23.27	42.68	1.58	2.31	3.21	4.02	1.96	1.55
BA30	20.94	37.15	1.39	2.07	3.01	3.85	2.06	1.61
BA40	18.81	34.68	1.31	1.57	2.93	3.57	2.42	2.19
BA50	16.01	31.68	1.21	1.52	2.75	3.35	2.51	2.38
BA60	14.54	29.63	1.02	1.38	2.57	3.22	2.88	2.49
BA70	13.34	27.38	0.91	1.23	2.43	3.01	3.04	2.62
BA80	11.14	25.75	0.85	1.01	2.25	2.91	3.12	2.94
BA90	10.67	20.74	0.64	0.91	2.13	2.51	3.36	3.12
BA100	9.07	18.67	0.52	0.69	1.98	2.35	3.45	3.28

4.5 Effect of CBA on tensile strength of mortar

The tensile strength of CBA mortar results are presented in table 4. The test results of tensile strength shows that as the percentage of CBA increases, there was improved in the tensile strength at all curing ages. The tensile strength of mix BA10 was highest and followed by the mix BA20 at all age of curing. The tensile strength of controlled mortar was found to be 3.03 and 3.89 at 7 and 28 days respectively. The percentage tensile strength of mix BA10 and BA20 were increased by 9.01, 5.91 at 7 days curing whereas at 28 days increased by 7.85 and 3.33 with reference to controlled mortar. The tensile strength of mix BA30 was found to closer to the controlled mortar. It was observed that the compressive strength increased, the tensile strength also increased but with decreasing rate. Figure 7 shows the linear relationship between compressive strength and tensile strength. The ratio of compressive strength to tensile strength was found to be 10.12 for controlled mortar whereas for BA10 and BA100 were 10.38 and 4.94 respectively. From the above analysis it was found that the ratio of compressive to the tensile was decreased as the percentage of replacement increased similar results observed by Singh and Rafat (2014). The percentage tensile strength of BA40 to BA100 was decreased by 3.41, 10.18, 17.89, 24.69, 34.67, 42.25 and 53.03 at 7 days curing age whereas 8.96, 16.11, 20.81, 29.23, 33.67, 54.98 and 65.53 at 28 days curing ages. The results of tensile strength and compressive strength of CBA mortar are increased with increase in curing time as that of conventional mortar. The relation between compressive strength and tensile strength for CBA mortar derived by the authors in this study is compared with other studies proposed by Raphale (1984), Oluokun (1991) and BS 8007:1987 as shown in figure 7. The relation derived from results analysis is $f_t = 0.33(f_c)^{0.67}$ which is very close to the Garden and Poon(1976), where f_t = Tensile strength

4.6. Effect of Sodium chloride on CBA mortar

Figures 8 and 9 shows the effect of NaCl on loss in compressive strength and weight loss of controlled mortar and with CBA with respect to mortar specimens cured in water for 180 days. The access of salt into the cementitious materials through capillary suction can lead to crystallization of the salts in the pores of the mortar, causing expansion and exerting pressure on the capillaries. The salts show aggression only when they penetrate into the mortar. The percentage loss in compressive strength and weight of controlled mortar was found to be 1.97 and 1.76 with compared with cured in water. The percentage loss in compressive strength of mix BA10 to BA100 was found to be 1.52, 1.86, 1.80, 1.94, 1.724, 1.73, 1.94, 1.92, 2.16 and 2.78 whereas the percentage loss in weight was found to be 1.39, 1.16, 1.26, 1.50, 1.53, 1.54, 1.57, 1.63, 1.55, 1.69 and 1.82 with reference to specimens cured in water for 180 days respectively. With respect to the mortar prepared with sand, considerable weight loss with decreased compressive strength was observed. With regard to mortar prepared with CBA, the weight loss and reduction in the compressive strength were lower, when compared with the control mortar, indicating that CBA as a fine aggregate improved the chemical resistance and enhanced the durability of mortar. Manso reported that the presence of ladle furnace slag had no damaging effect when subjected to saline water (Manso et al. 2011).These results also suggest that CBA as fine aggregates in mortar could withstand adverse environments appropriately.

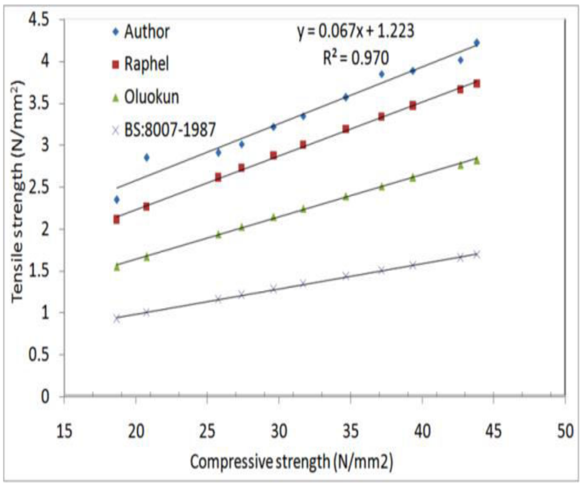

Figure 7 *Relation between compressive strength and tensile strength at 28 days curing age*

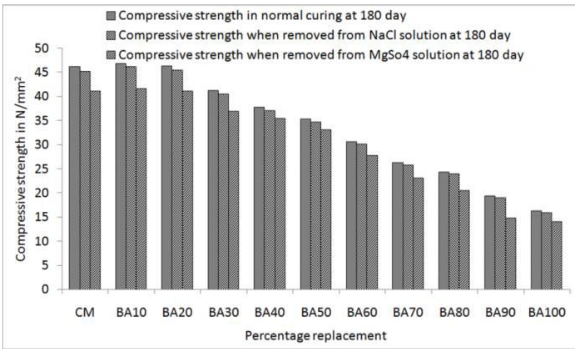

Figure 8 *Effect of NaCl and MgSO4on the compressive strength of the CBA mortar*

4.7. Effect of magnesium sulphate on CBA mortar

The loss in compressive strength and weight loss of mortar specimens when immersed in $MgSO_4$ solution after 180 days with respect to mortar specimens cured in water with same days was shown in figures 8 and 9 respectively. The percentage losses in weight were less in most of the CBA-added mortar specimens. Karatasios et al. reported that barium hydroxide increased the durability of hardened mixture against sulfate attacks (Karatasios et al. 2008). Although the effects of $MgSO_4$are cracking, swelling, expansion, weight loss, and loss in compressive strength, in the present study, only loss in the compressive strength and weight loss were studied. Solid salts do not severely affect mortar, but when they are in solution, they find access into the pores of the mortar and react with the hydrated cement product. The percentage loss in compressive strength and weight of controlled mortar was found to be 12. 23 and 1.77 with compared with specimen cured in water for 180 days. The percentage loss in compressive strength of mix BA10 to BA100 was found to be 11.94, 11.76, 11.81, 12.01, 12.10, 12.15, 12.26, 15.68, 15.72 and 16. 37 whereas loss in weight was 2.59, 2.30, 2.53, 2.55, 2.61, 2.84, 3.02, 3.26, 3.95 and 4.04 as compared with specimen cured in water after 180 days respectively. The percentage loss in compressive strength and weight was less as compared with controlled mortar. It was observed that the surface of the mortar specimen turned whitish after immersion in MgSO4solution, which indicated sulfate attack. In addition, the deterioration of mortar specimens was also noted on the surfaces and corners of specimens. Other sulfates have been reported to produce less damaging effects, when compared with Magnesium sulphate, due to the disintegration of hydrated calcium silicates, hydrated C_3A, and $Ca(OH)_2$. Furthermore, hydrated magnesium silicate has no binding properties. With regard to CBA mortar, CBA initially filled up larger pores with water and, subsequently, sufficient Ca $(OH)_2$ was liberated from primary hydration to react with silica present in the CBA, producing more C-S-H gel; as a result, the loss in the compressive strength of the CBA mortar was less, when compared with that of the control mortar.

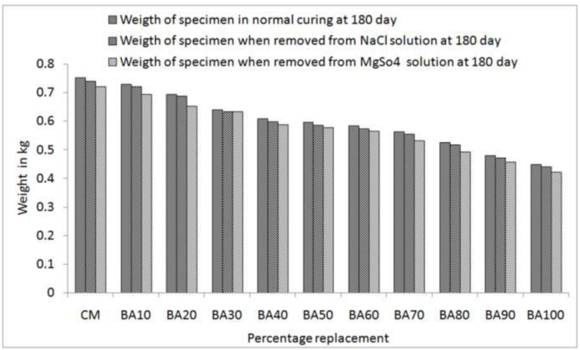

Figure 9 *Effect of NaCl and $MgSO_4$ on the weight of the CBA mortar*

5. Conclusion

From the present experimental work and the results obtained, the following conclusions can be drawn:

- From the flow table analysis of CBA mortar, the workability of mortar decreased as the percentage of CBA increased, this is due to the high water absorption, uneven surface and complex shape of CBA as compared to natural sand.
- The compressive strength CBA mortar for mix BA10, BA20 and BA30 was higher than the reference mortar, although at each percentage replacement level of sand by CBA, there is an increase in strength with increase in curing age.
- The flexural strength of CBA mortar for mix BA10 and BA20 series results are higher than the reference mortar and found to be decreasing from mix BA 30 to BA100 with controlled mortar. This indicates that up to 20 percentages substitution of sand by CBA is possible.
- The tensile strength of mix BA10 and BA20 was increased by 9.01 and 5.91 percentages as compared with controlled mortar and as the compressive strength increased the tensile strength also increased with increase in curing time. The ratio of compressive strength to tensile strength was decreased as the replacement level increased.
- From the abrasion test analysis, loss on wear for mix BA10, BA20 and BA30 was higher than that in controlled mortar; this increase in abrasion resistance of bottom ash mortar was due to well particle size distribution and dense structure of mortar. As the compressive strength increased the loss on wear was decreased.
- When the mortar specimens were immersed in NaCl and MgSO4 solutions for 180 days, loss in compressive strength and weight was observed; however, this loss was less, when compared with that noted in the control mortar, which showed the ability of the test specimens to withstand adverse environments
- From the SEM observation of controlled mortar, BA10, BA20 and BA30, the dense and compact structure was seen. it was also observed from the SEM images of mix BA40 to BA100 as the percentage of CBA increased the pores and micro cracks was also increased, this was due to the more porous particle of CBA.

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