Use of Unprocessed Coal Bottom Ash as Partial Fine Aggregate Replacement in Concrete

A S Cadersa
Faculty of Engineering
University of Mauritius
Réduit
E-mail: a.cadersa@uom.ac.mu

I Auckburally
Faculty of Engineering
University of Mauritius
Réduit
E-mail: IRFAAN@LIVE.COM

Paper accepted on 02 July 2014

Abstract

This paper investigates the use of unprocessed coal bottom ash as fine aggregate replacement in structural concrete in an attempt to contribute to a sound management of coal ash on the island of Mauritius. The coal bottom ash was obtained from FUEL thermal power station and had a loss of ignition of 11%. Experiments were conducted by replacing fine aggregate with bottom ash by weight in varying percentages (20%, 30%, 40%, 60%, and 80% respectively). The results showed that an increase in bottom ash content causes workability and plastic density to decrease and bleeding to increase. Moreover, above 40% replacement of bottom ash, compressive strength, flexural strength, and modulus of elasticity decreased sharply. In addition, an increase in bottom ash content improved the drying shrinkage performance of the concrete. The research also shows that 20% is the optimum percentage replacement to achieve favorable strength and good strength development pattern as a normal concrete mix with time. Unprocessed bottom ash from FUEL power station can thus be used as fine aggregate replacement in concrete for that specific percentage replacement. However, investigation should be carried out on the durability of the concrete.

Keywords: unprocessed bottom ash, fine aggregate replacement, structural concrete

**For correspondences and reprints*

1. INTRODUCTION

Bottom ash is formed in coal furnaces. Bottom ash, the solid residue from electric power generation process, represents the coarser size fraction that falls to the bottom of the combustion boiler. Parisa (2007) identified that characteristics of the ash residue are known to be highly variable. They differ from one plant to another and differences can be due to coal source, degree of pulverization, design of boiler, firing conditions, storage and handling methods.

According to the American Coal Ash Association (2006) statistics on bottom ash usage, just over 45 percent of all bottom ash produced is used, mainly in transportation applications such as structural fill, road base material, and as snow and ice control products. Bottom ash is also used as aggregate in lightweight concrete masonry units and raw feed material for the production of Portland cement (ACAA, 2011).Using coal combustion products (CCPs) in an environmentally safe manner saves virgin resources, and reduces energy consumption and greenhouse gas emissions (GHG). In addition, it helps reduce the need for landfill space and new landfills. Using CCPs also makes good economic sense; they are often less costly than the materials they replace (American Coal Ash Association Educational Foundation, n.d).

Bottom ash can be introduced as an aggregate, as a partial natural sand replacement, according to the grain-size distribution of the material for utilization in structural concrete (Andrade, 2004; Andrade et al. 2003).

The bottom ash will influence many parameters, namely; (1) water demand, as a function of the amount of fine particles, unburned material, and the natural water content which is removed internally from the ash particles; (2) the filler effect, with an improvement in the filling role (Odler and Röbler, 1985) and (3) mechanical properties, due also to the pozzolanic effect promoting the consumption of calcium hydroxide for the formation of calcium silicate hydrate, with a better filling of voids (Chengzi et al. 1996; Ravina, 1997; Cheriaf et al. 1999).

Experimental investigations by Ghafoori and Bucholc (1997) and Andrade et al. (2007) showed that compressive strength decreases with increasing percentage replacement of fine aggregates by bottom ash. In addition, Andrade et al. (2007) and Kim and Lee (2011), observed a decrease in density due to the low specific gravity of the ash. Since bottom ash particles are less stiff and less dense that normal fine particles resulting in weak porous paste, modulus of elasticity is decreased (Ghafoori and Bucholc, 1996). Bai et al. (2005) observed that at fixed W/C ratio of 0.45 and 0.55, drying shrinkage values of all bottom ash concrete were lower than the control mix. It was deduced that the bottom ash particles slowly release the moisture during drying phase of concrete.

Experimental investigations carried out by the Mauritius Research Council in 2001 concluded that both fly ash and bottom ash generated by local power producers on the island were not suitable for use in cement blending or in concrete due to their high loss of ignition of 29%. The investigators recommended that the ash be processed to reduce the amount of un-burnt carbon to 7% i.e to the percentage stipulated by British Codes; in order to make the ash appropriate for mixing with cement and for use in concrete (MTESRT, 2010). Presently in Mauritius, there is no best practice or legislations regarding the disposal of the coal ash generated. In addition, since there is no market value for the ash, most of the ash produced are either used for the leveling of sugarcane field tracks, or simply dumped on private land or dumping ground, thereby creating a potential risk of groundwater contamination. Only a little is used for agricultural purposes (MESD, 2009).

With the operation of more recent cyclone boilers, FUEL power plant has been able to bring down the un-burnt carbon content of bottom ash to 11%. In an attempt to address disposal problems, the use of bottom ash generated at FUEL power plant as partial fine aggregate replacement in structural concrete has been investigated in this research. Mechanical properties such as such as compressive strength, flexural strength, modulus of elasticity, hardened density, and drying shrinkage were evaluated. Durability of the bottom ash concrete will be evaluated at a later stage if the aforementioned mechanical properties are satisfactory.

2. MATERIALS AND METHODOLOGY

The bottom ash used was collected from FUEL thermoelectric power station in Mauritius. The bottom ash was in an oven dry state before batching the concrete mixes. The Portland cement used was OPC CM1 CEM 42.5 according to BS EN 197/1.The experimental study deals with investigating five different mixes compared to a control mix. The labels and description of the mixes are given in Table 1. To determine the effect of bottom ash on concrete, 20%, 30%, 40%, 60%, and 80% fine aggregate replacement by weight with unprocessed bottom ash.

Bottom ash based concrete produced in this study is given in Table 1 along with their descriptions.

Table 1: Concrete labels in the study

Concrete label	Description
BA0	Normal concrete with no bottom ash replacement
BA20	Bottom ash based concrete including 20% by mass replacement of fine aggregate
BA30	Bottom ash based concrete including 30% by mass replacement of fine aggregate
BA40	Bottom ash based concrete including 40% by mass replacement of fine aggregate
BA60	Bottom ash based concrete including 60% by mass replacement of fine aggregate
BA80	Bottom ash based concrete including 80% by mass replacement of fine aggregate

2.1 SAMPLE PREPARATION AND TESTING

2.1.1 Bottom Ash

Screening was carried out on the bottom ash sample obtained from the thermal power station to remove the coarse particles. The sample was therefore sieved manually using the 4.75mm sieve complying with the BS 410 and only the particles passing through the 4.75mm sieve was retained for use in the research.

Dry sieving method prescribed as per BS 812: Part 103:1985 was adopted during the whole process. Since the main aim of this study was to investigate the substitution of fine aggregates with bottom ash in concrete, it was necessary to meet the grading size of the fine aggregates. Figure 1 summarizes the procedure discussed above.

Figure 1: Screening Process of Bottom ash

2.1.2 Preliminary Investigations

In the first place, the bottom ash and the aggregates were analyzed in order to obtain data to devise the mixture proportions from the relevant mix design. Since bottom ash is a relatively new material employed in civil engineering applications, there are no such standards for testing. Therefore, the British Standards that were used to carry out the preliminary test on both the fine and coarse aggregates were adopted for the bottom ash as well. The sampling of the materials during the whole project was carried out by the quartering method as described in BS 812.

2.1.3 Concrete Mix Design

The mix design was prepared using data obtained from the preliminary investigations, and was based on the British Cement Association (BCA). The DOE mix design method was adopted for all the mixes. Grade 40MPa concrete mixes with mean target strength of 45MPa were designed. The amount of fine aggregates for each mix was the main variable parameter. Fine aggregate was replaced with bottom ash in increasing percentages from 20% to 80% by weight respectively while fixing the w/c ratio at 0.54. The free water and the absorbed water by the aggregates and the bottom ash were added to get the total water content. The targeted slump was 100 mm and no further addition of water was done during mixing.

Table 2: Mixture Proportioning

Mix	Fine aggregate (kg/m^3)	Bottom ash (kg/m^3)	Coarse aggregate (kg/m^3)	Cement (kg/m^3)	Free water (L/m^3)	Absorbed water (L/m^3)	Total water (L/m^3)
BA0	850	0	959	417	225	44	269
BA20	680	170	959	417	225	88	313
BA30	595	255	959	417	225	110	335
BA40	510	340	959	417	225	132	357
BA60	340	510	959	417	225	174	399
BA80	170	680	959	417	225	221	446

2.2 MATERIAL PROPERTIES

2.2.1 Particle size distribution

Table 3: Sieve analysis of Fine aggregate and Bottom ash

	Aggregate Type			
BS sieve size (mm)	**Fine**		**Bottom ash**	
	% Retained	**Cumulative % passing**	**% Retained**	**Cumulative % passing**
4.750	0.09	99.91	0	100
2.360	21.30	78.61	23.35	76.65
1.180	25.14	53.47	26.15	50.50
0.600	15.64	37.83	16.87	33.63
0.425	5.75	32.08	6.05	27.58
0.300	5.72	26.36	4.97	22.61

Figure 2 below shows that the particle size distribution of basaltic fine aggregates and bottom ash were almost similar. The fineness modulus of bottom ash was 3.72 compared to 3.55 for fine aggregate, which showed bottom ash to be a coarser material than normal crushed fine aggregate.

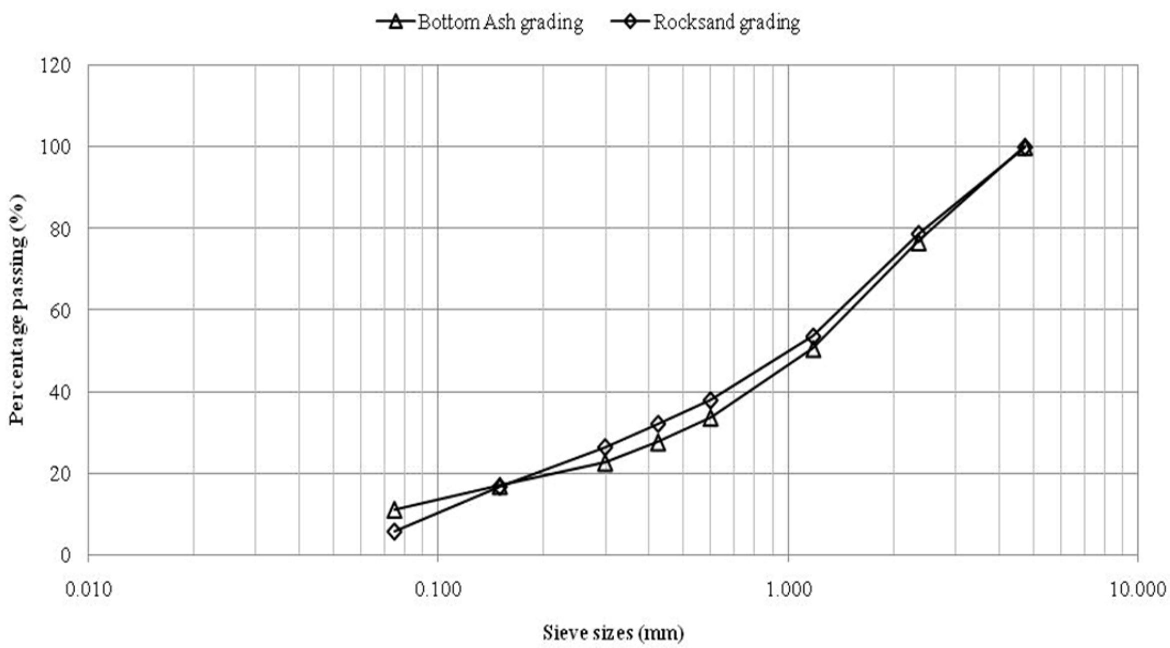

Figure 2: Cumulative passing vs. sieve sizes

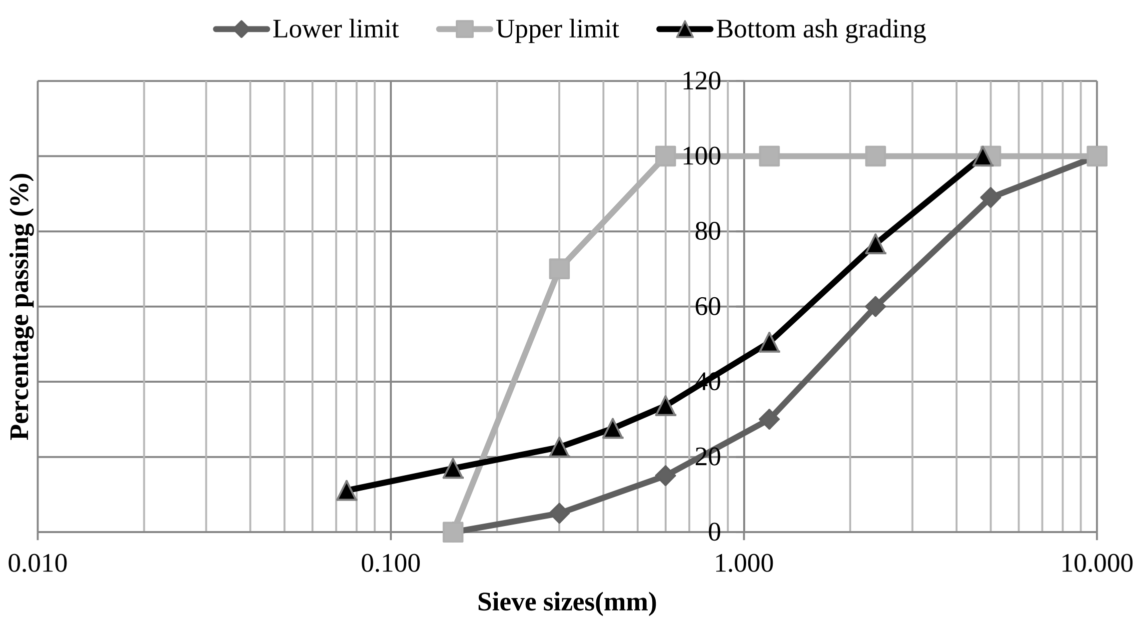

Figure 3: Bottom ash grading vs. overall limit in BS 882: 1992

Figure 3 shows that bottom ash grading is in full compliance with the overall limit mention in BS 882:1992.

2.2.2 Shapes and Texture of bottom ash

Figure 4(a) and 4(b) show that the bottom ash particles are porous, glassy, grayish and consist mostly of irregular shape particles with very few angular ones. In contrast, normal fine aggregates are granular and consist mainly of angular particles.

4(a) **4(b)**

Figures 2(a) & 4(b): Bottom ash after sieving after sieving through the 4.75mm sieve and microscopic view of bottom ash particles respectively

2.2.3 Specific gravity and Water absorption

Table 4: Densities and water absorption for aggregates and bottom ash

	Bottom ash	Fine aggregate	Coarse aggregate
Water absorption (%)	26	2.47	2.37
RD oven dried	1.21	2.82	2.66
RD saturated surface dry	1.53	2.92	2.74
Apparent RD	1.77	3.00	2.90

From Table 4, it is observed that the water absorption for bottom ash was very high compared to the fine aggregate. Moreover, the specific gravity of bottom ash was 1.77, which clearly indicated bottom ash to be a very light material compared to the normal fine aggregate.

3. RESULTS AND DISCUSSIONS

3.1 Workability

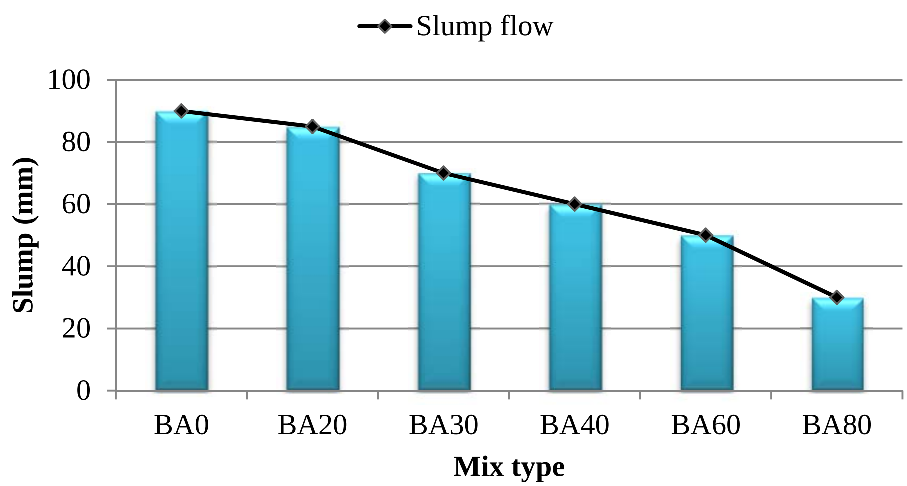

Figure 3: Effect of bottom ash replacement on workability

Figure 5 presents the flow characteristics of fresh concrete with different percentage of bottom ash replacement. The slump values decreased from 90 to 30 mm, which shows that an increase in bottom ash replacement strongly affects workability. The variation from 20% to 80% of bottom ash replacement decreased workability by 5.56% to 60% respectively compared to the control mix. Highly cohesive and sticky mixes were obtained at 60% and 80% replacement, with low workability. As replacement of bottom ash was increased, the amount of cement past to coat the bottom ash particles decreased, therefore augmenting friction between the bottom ash particles. Similar results were found by Shi-Cong and Chi- Sun (2009). The latter observed that the slump values increased with an increase in bottom ash content in the concrete mix, due to the fact that bottom ash has higher water absorption values than river sand. Aramraks (2006) observed that mixes with 50% and 100% bottom ash replacement required approximately 25-50% more mixing water content that normal concrete to obtain suitable workability.

3.2 Plastic density

The plastic density was carried out on fresh concrete just after the batching. Figure 6 shows that plastic density decreases with increasing bottom ash content due to the very low specific gravity of the material.

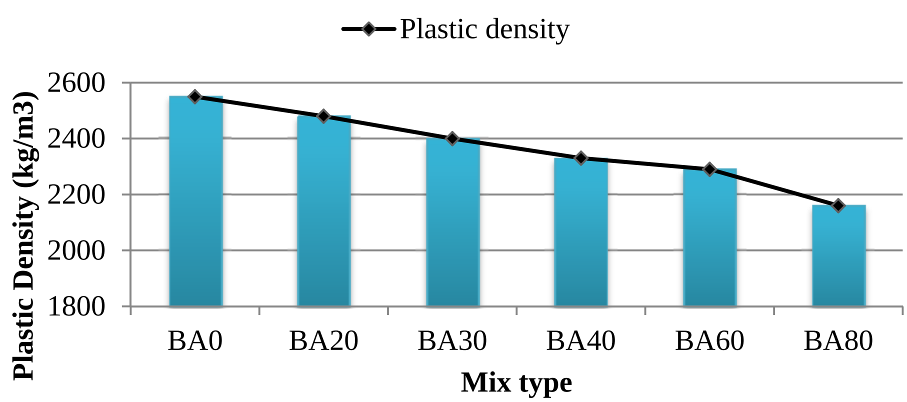

Figure 6: Effect of bottom ash replacement on plastic density

3.3 Bleeding

Figure 7 shows that both the bleeding capacity and bleeding time decrease with an increase in the bottom ash content. At 20% replacement of fine aggregates by bottom ash, the bleeding capacity was approximately the same as the control mix; while at 80% replacement, the bleeding capacity dropped to 1.94% of free water, i.e a 28.1% decrease compared to that of the control mix.

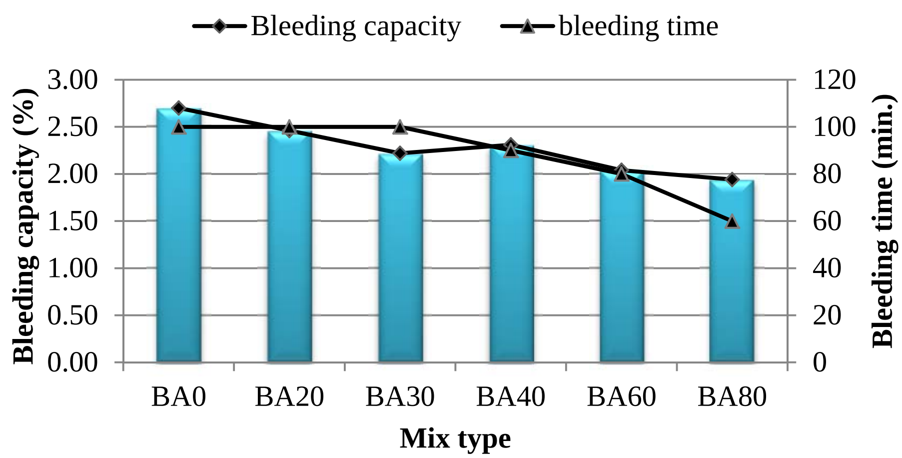

Figure 7: Effect of bottom ash replacement on bleeding capacity with respect to time of bleeding

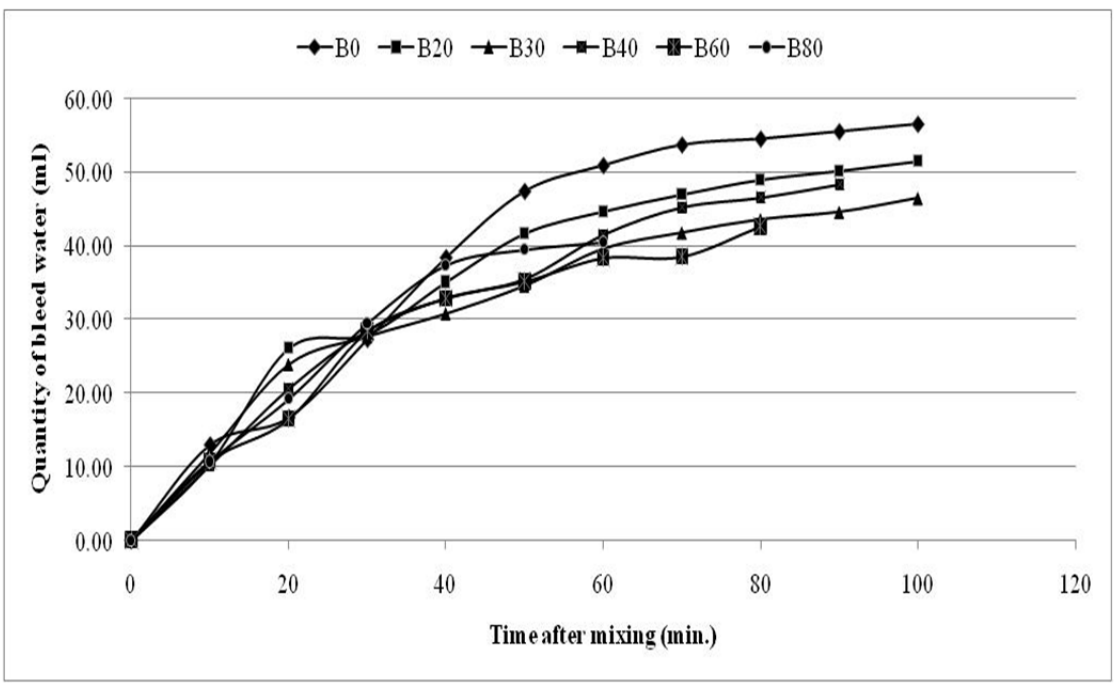

Figure 8: Water loss through bleeding

As seen in Figure 8, most water is lost after 40 minutes for all the mixes except for mix B20. Mix with higher bottom ash content lost more water by bleeding.
In this study, this decrease in bleeding can be associated with the low specific gravity of bottom ash. As the bottom ash content increases, the amount of binder coating the bottom ash particles decreases. Therefore, some bottom ash particles do not have a coating of binder such that the latter have to draw water from the mix, resulting in a decrease in the bleeding capacity.

However, Andrade et al. (2009) found that the presence of bottom ash increased the quantity of water loss by bleeding, the bleeding time and also the water release rate. The higher the bottom ash content, the greater were the effects. Ghafoori and Bucholc (1996) demonstrated that because of increased water demand of mixing water, the bottom ash mixtures displayed higher degree of bleeding that the control mixture.

3.4 Compressive strength

The compressive strength of each mix was determined at 3, 7, and 28 days of curing according to BS 1881: Part 116: 1983. The average compressive strengths of the 100mm cubes for each mix are displayed in Table 5. Satisfactory failures were observed for all compressive strength tests**.**

Table 5: Average compressive strength results for each mix

Days	**3**	**7**	**28**
Mix Type	**Average compressive strength(N/mm^2)**		
B0 (control)	22.85	29.72	43.03
B20	22.53	26.56	39.38
B30	17.17	24.38	36.28
B40	16.11	23.67	34.22
B60	9.80	12.25	17.56
B80	8.17	10.34	14.64

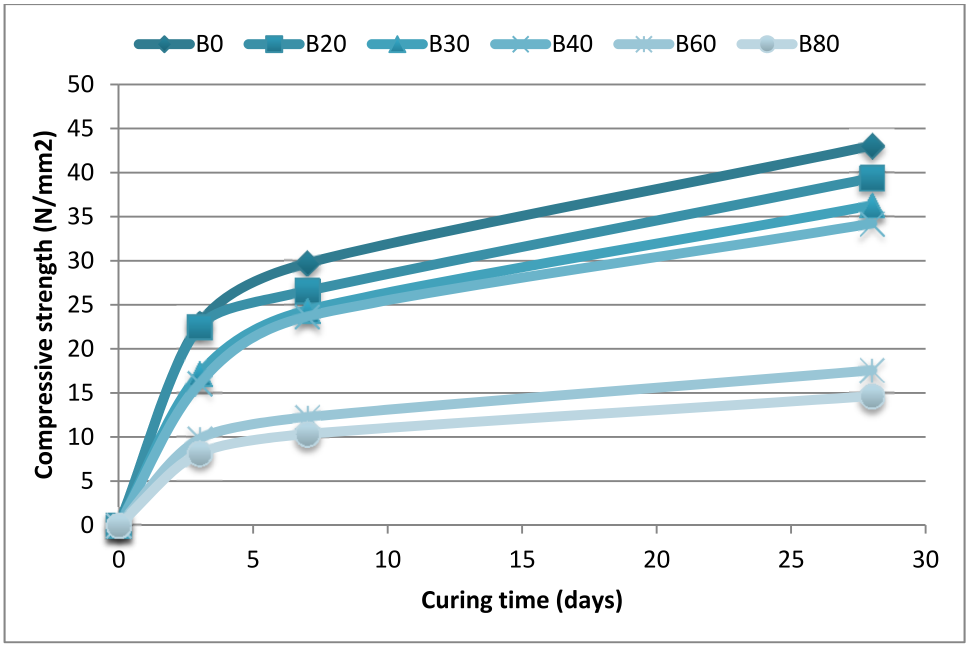

Figure 9: Compressive strength with Bottom Ash Content

Figure 9 clearly show that the compressive strengths of concrete mixes containing bottom ash are lower than the control mix at all tested days.

The concrete mixes containing bottom ash showed good strength development pattern with increasing age. Moreover, the 7 day strength of all the mixes reached two-third of the 28 day compressive strength.

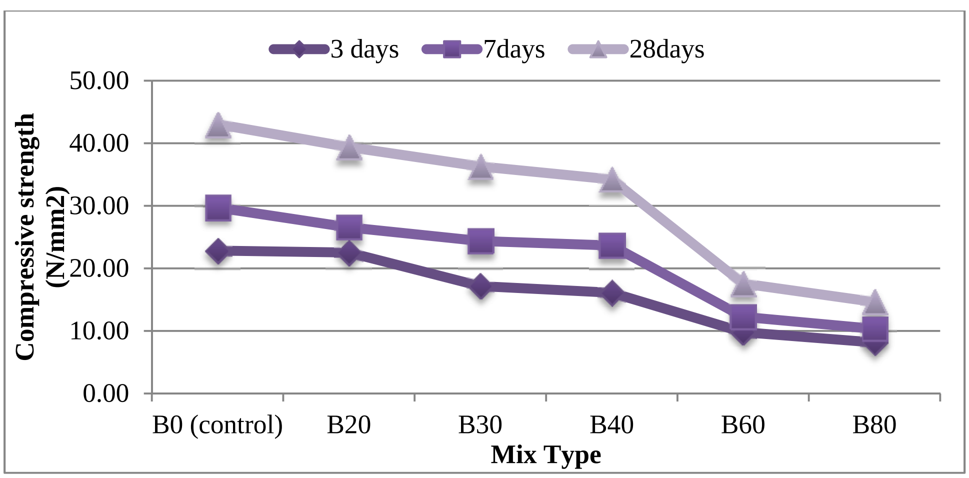

Figure 10: Relationship between compressive strength and percentage of bottom ash replacement

Figure 10 illustrates the achievement of compressive strength of all mixes at 3, 7, and 28 days. The 28 day compressive strength for B20, B30, B40, B60 and B80 decrease by 8.48%, 15.45%, 20.47%, 59.19%, and 65.98% respectively compared to the control mix B0. In addition B20 recorded the highest compressive strength at 28 days. The 28 day compressive strength of B60 and B80 mixes were significantly reduced as compared to that of the other mixes.

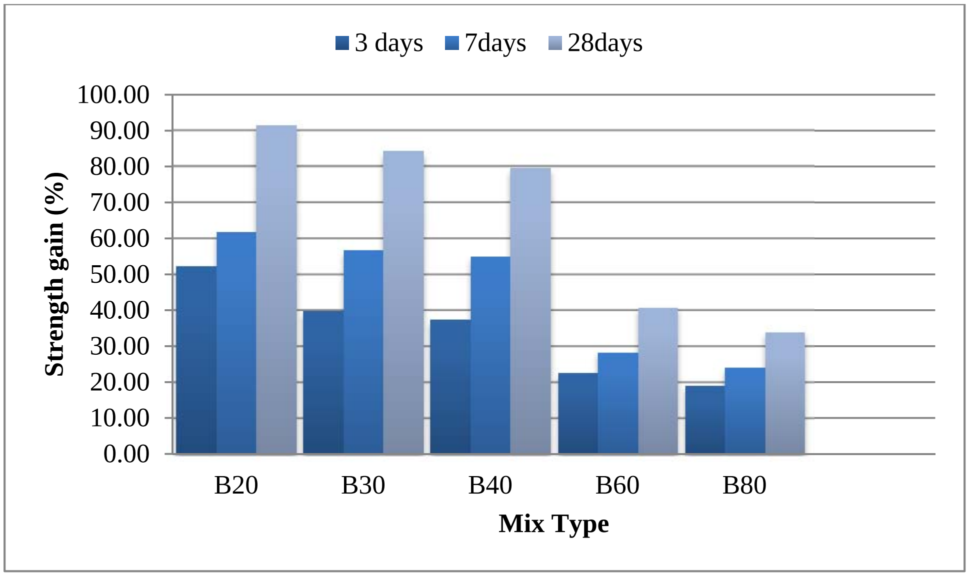

Figure 11: Relationship between strength gains with percentage of bottom replacement

Figure 11 shows that bottom ash concrete gains strength at a lower rate than the control mix. As replacement level of bottom ash is increased, the gain in compressive strength decreased further.

The decrease in compressive strength observed is due to the physical nature of the ash particles. Due to the porous surface structure and high absorptivity nature of the material, hydration of all cement particles may not have occurred, such that less paste is available for bonding. In addition, as water penetrates through the bottom ash, expulsion of air bubbles may cause voids between the interface of the cement paste and the coarse aggregates resulting in lower bond strength. At 60% and 80% replacement, this latter effect is pronounced. Similar results were also found by Ghafoori and Bucholc (1997) who observed that compressive strength of concrete mixtures containing bottom ash were lower than that of the control mix. The average differences in compressive strength at the age of 3 days and 7 days were 12.5% and 14.5% respectively. Shi- Cong and Chi- Sun (2009) demonstrated that at a fixed W/C the compressive strength decreased with an increase in the bottom ash content at all the ages. Aramraks (2006) demonstrated that the compressive strength of 50% and 100% replacement bottom ash concrete were approximately 20%-40% lower than that of the control mix.

3.5 Flexural strength

The flexural strength of each mix was determined at 44 days after casting according to BS 1881: Part 118:1983.

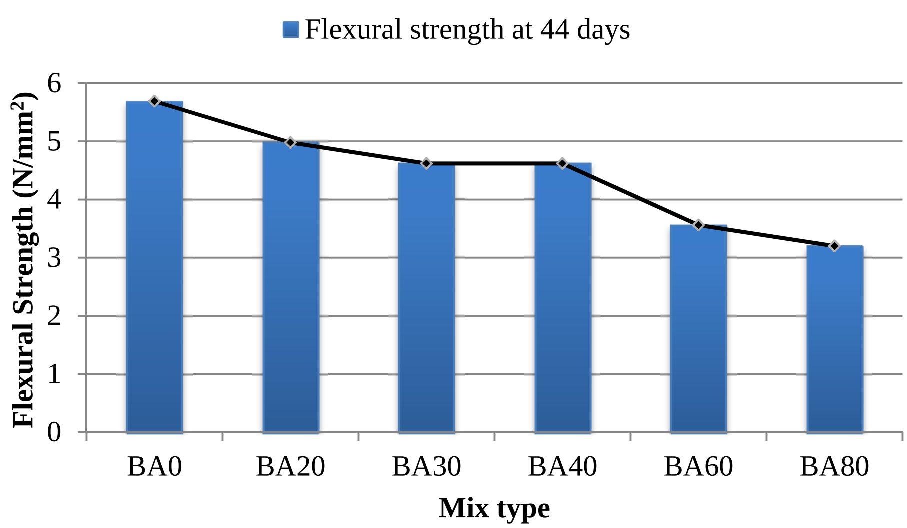

Figure 12: Effect of bottom ash on Flexural strength

Figure 12 shows a general decrease in flexural strength with an increase in bottom ash replacement. For the mix B20 and B80, a decrease of 12.48% and 43.7% respectively was noted compared to the control mix. The flexural strength decreased in a similar way to that of compressive strength. However, the same value for flexural strength was observed for mixes with 30% and 40% bottom ash replacement. The high porosity of the bottom ash contributed to an increase in the interfacial transition zone and hence prevented the full hydration of cement particles. At higher replacement level of bottom ash, the interface zone increased, thereby increasing the risk of micro cracks propagation and interface fracture under stress. Flexural strength is therefore reduced. Moreover, bottom ash being a porous material, upon its use as sand replacement, the paste becomes weak and porous. Since the volume of pores in concrete is increased, flexural strength decreases. Ghafoori and Bucholc (1996) found that flexural strength of bottom ash mixtures was lower than that of reference samples. When a super plasticizer admixture was incorporated into the bottom ash concrete, flexural strength equalled or slightly exceeded that of control concrete. Flexural strength of bottom ash concrete decreased with increase in bottom ash content but with the addition of super plasticizer, it slightly improved at almost all the curing ages.

3.6 Modulus of Elasticity

The modulus of elasticity for each mix was determined at 28 days according to BS 1881: Part 5: 1983.

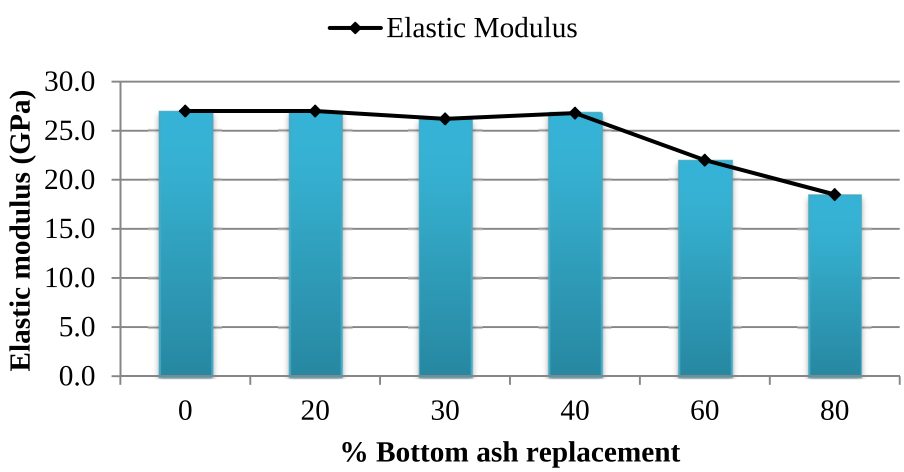

Figure 13: Effect of bottom ash on Modulus of Elasticity

It can be seen from Figure 13 that in general, the greater the bottom ash content, the lower the elastic modulus. However, the elastic modulus values at 20%, 30%, and 40% replacement were also close to the control mix and were within the typical range of 28 days static modulus of elasticity for a Grade 40 normal concrete (22 to 34 GPa) as per BS 8110: Part 2: 1985. Only at 60% and 80% replacement respectively was the elastic modulus significantly reduced. This decrease in elastic modulus above 40% replacement of bottom ash can be linked with the ascending bottom ash to cement ratio. The amount of binder for total volume of bottom ash beyond 40% bottom ash replacement is significantly reduced resulting in much lower bond strength and lower elastic modulus values. Ghafoori and Bucholc (1996) found that bottom ash concrete mixtures with all unit weights of cement displayed lower modulus of elasticity than that of reference sample. Kim and Lee (2011) found that the modulus of elasticity decreased with the increase in replacement of fine and coarse bottom ash aggregates.

3.7 Hardened density

The hardened density was determined at 3, 7, and 28 days from casting date. The mean value is displayed in Table 13 and represented in Figure 14.

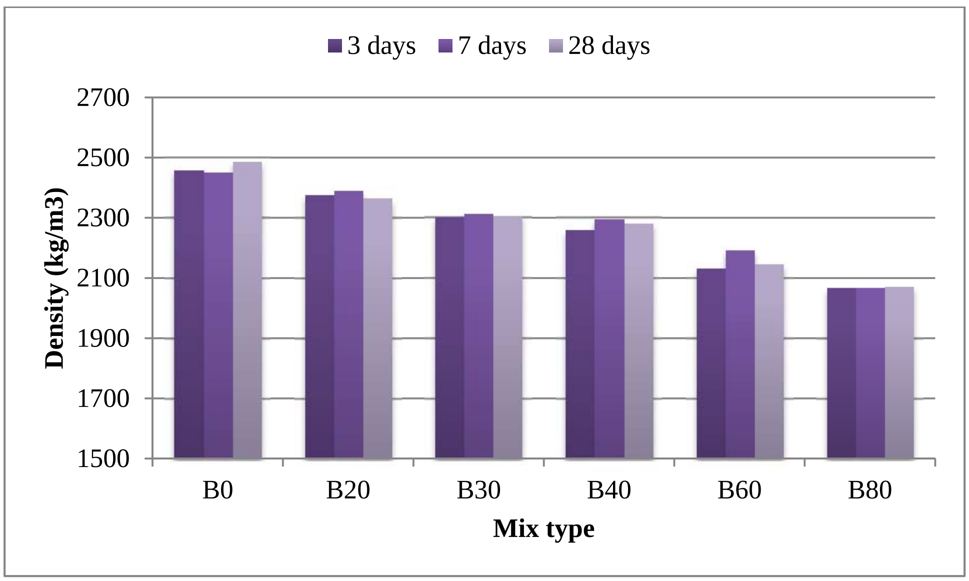

Figure 14: Effect of bottom ash replacement on hardened density

Figure 14 show that the densities of hardened concrete specimens with different percentage of bottom ash replacement decreases as replacement level increases. The density of individual mixes did not change much with age except for the control mix which increased slightly. However, a general decrease in density with respect to an increase in percentage of fine aggregate replacement is noted with curing age. The lowest density recorded was 2073 kg/m^3 at 80% replacement, which implied a net reduction of 415 kg/m^3 compared to the control specimen. Therefore based on the results obtained, the low specific gravity of bottom ash is the parameter that produces a decrease in density of bottom ash based concrete. Topcu and Bilir (2010) investigated the effect of bottom ash on 7 days and 28 days densities of mortars having proportions of fixed quantities of cement (500 kg/m^3), high range water reducing admixtures (3 kg/m^3) and varying percentages of bottom ash (specific gravity of 1.39 g/cm^3) as natural sand replacement in all the specimens. They observed that the weight of specimens decreased with increase in bottom ash content. The unit weight at the age of 7 days and 28 days ranged between 1.23 kg/dm^3 and 2.23 kg/dm^3 and 1.35 kg/dm^3 and 2.28 kg/dm^3 respectively.

3.8 Drying Shrinkage

Drying shrinkage test was done on three prisms for different percentage of bottom ash replacement and an average value was used for representation on Figure 15.

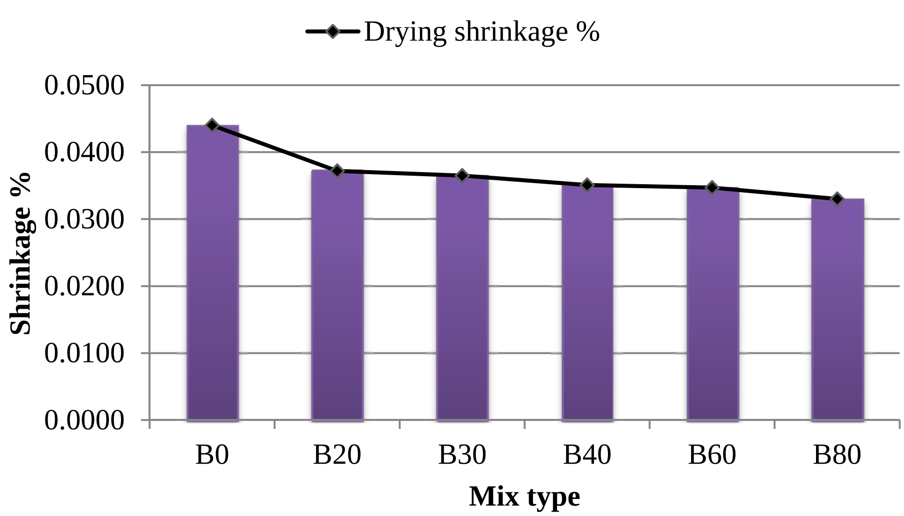

Figure 15: Effect of bottom ash on drying shrinkage

From Figure 15, a general linear decrease in drying shrinkage was noted with an increase in percentage replacement of bottom ash. It is observed that bottom ash concretes shrink less than the control mix. The difference in drying shrinkage between 20% to 80% replacement of bottom ash and the control mix was found to be 15.45% to 25% respectively. This decrease in shrinkage can be associated with the porous structure and high absorptivity of fine particles of bottom ash. Bai et al. (2005) observed that at fixed W/C ratio of 0.45 and 0.55 respectively, drying shrinkage values of all bottom ash concrete were lower than that of control concrete. However, at fixed workability, the drying shrinkage values were higher. At fixed slump range, with the increase in bottom ash content, they found that drying shrinkage increased contrary to the decrease in drying shrinkage observed on reduction of free water content.

4. CONCLUSIONS AND RECOMMENDATIONS

The aim of this research was to investigate the use of unprocessed bottom ash obtained at FUEL power station as partial fine aggregate replacement in concrete. The results show that inclusion of bottom ash influences the workability, loss of water through bleeding, bleeding rate, plastic density of fresh concrete and hardened density, compressive strength, flexural strength, modulus of elasticity, and drying shrinkage of hardened concrete.

20% by weight replacement of fine aggregate replacement by bottom ash is the optimum percentage replacement to achieve favourable strength and good strength development pattern as a normal concrete mix over increasing age. The introduction of bottom ash as fine aggregate in concrete improved drying shrinkage. Unprocessed bottom ash from FUEL power station can thus be used as fine aggregate replacement in concrete.

However, due to the high un-burnt carbon content of the ash, the durability of concrete needs to be investigated for that percentage replacement.

5. REFERENCES

ARAMRAKS, T. (2006). Experimental study of concrete mix with bottom ash as fine aggregate in Thailand. In: *Symposium on infrastructure development and the environment*, 1–5.

ANDRADE, L.B. (2004). Metodologia de Avaliac¸a˜o para Uso de Cinzas Pesadas de Termele tricas como Agregado Natural para Concreto (Methodology of assessment to use of bottom ash of thermoelectricpower plants as aggregate in concrete), Dissertac¸a˜o de mestrado, Departamento de Engenharia Civil, Universidade Federal de SantaCatarina, Brasil. (in Portuguese).

ANDRADE, L.B., ROCHA J.C, CHERIAF M., (2003). Avaliac¸a˜o do Comportamentono Estado Fresco de Argamassas de Concreto com Incorporac¸a˜o de Cinzas Pesadas em Substituic¸a˜o ao Agregado Miu´do (Investigation of concrete containing bottom ashes. In: Proceedings of the VI Symposium on Sustainable Development and Recycling of Buildings Materials). VI Semina´rio de Desenvolvimento Sustenta´vel ea Reciclagem na Construc¸a˜o Civil – Materiais Reciclados e suasAplicac¸o˜ es. Anais. Ibracon – Comiteˆ Te´cnico 206, Sa˜o Paulo. (in Portuguese).

ANDRADE, L.B, ROCHA, J.C, CHERIAF, M. (2009). Influence of coal bottom ash as fine aggregate on fresh properties of concrete. *Construction and Building Materials* (23), 609–14.

ACAA (AMERICAN COAL ASH ASSOCIATION) (2011). Coal Combustion Products (CCP) Production & Use Survey Report (Online). Country Club Drive, Farmington Hills. Available at http://www.acaa-usa.org/associations/8003/files/fina2o11CCPSurvey.pdf. (Accessed 03 September 2013)

AMERICAN COAL ASH ASSOCIATION EDUCATIONAL FOUNDATION (n.d). Coal Ash Facts (Online). Available At http://www.coalashfacts.org/CCP%20Fact%20Sheet%203%20-%20Environmentally%20&%20Socially%20Beneficial_FINAL.pdf. (Accessed 03 September 2013)

BAI, Y., DARCY, F., BASHEER, P.A.M (2005). Strength and drying shrinkage properties of concrete containing furnace bottom ash as fine aggregate. *Construction and Building Materials* (19):691–7.

CHENGZI, Z., AIQIN, W., MINGSHU, T., XIAOYU, L.1(996). The filling role of pozzolanic material. *Cement and Concrete Research* 26, 943–947.

CHERIAF, M., PE´RA, J., ROCHA, J.C. (1999). Pozzolanic properties of pulverized coal combustion bottom ash. *Cement and Concrete Research* 29, 1387–1391.

GHAFOORI, N., BUCHOLC, J. (1996). Investigation of lignite based bottom ash for structural concrete. *Journal of Materials in Civil Engineering* 8(3):128–37.

GHAFOORI, N., BUCHOLC, J. (1997). Properties of high-calcium dry bottom ash concrete. *ACI Materials Journal* 94 (2), 90–101.

KIM, H.K, LEE, H.K. (2011). Use of power plant bottom ash as fine and coarse aggregate in high-strength concrete. *Construction and Building Materials* 25,1115–22.

MESD (MINISTRY OF ENVIRONMENT & SUSTAINABLE DEVELOPMENT) (2009). Technical Advisory Committee on Coal Ash Management, Final Report, 39-41

MTESRT (MINISTRY OF TERTIARY EDUCATION, SCIENTIFIC RESEARCH & TECHNOLOGY) (2010).Status Report on Research on Coal Ash Management in Mauritius, Summary of Completed Research, 10-11.

ODLER, I., ROBLER, M. (1985). Investigations on the relationship between porosity, structure and strength of hydrated portland cement pastes. II–Effect of pore structure and of degree of hydration. *Cement and Concrete Research* 15, 401–410.

RAVINA, D. (1997). Properties of fresh concrete incorporating a high volume of fly ash as partial fine sand replacement. *Materials and Structures/Mate´riaux et Constructions* 30, 473–479.

SHI-CONG, K., CHI-SUN, P. (2009) Properties of concrete prepared with crushed fine stone, furnace bottom ash and fine recycled aggregate as fine aggregate. *Construction and Building Materials* (23):2877–86.

TOPCU, I.B., BILIR, T. (2010) Effect of bottom ash as fine aggregate on shrinkage cracking of mortars. *ACI Materials Journal* 107(1):48–56.