MAURITIUS RESEARCH COUNCIL

FEASIBILITY OF THE ENCAPSULATED USE OF COAL BOTTOM ASH IN CONCRETE

Final Report

June 2013

MAURITIUS RESEARCH COUNCIL

Address:

Level 6, Ebène Heights,
34, Cybercity,
Ebène 72201,
Mauritius.

Telephone: (230) 465 1235
Fax: (230) 465 1239
Email: mrc@intnet.mu
Website: www.mrc.org.mu

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UNIVERSITY OF MAURITIUS

Faculty of Engineering

Department of Civil Engineering

FEASIBILITY OF THE ENCAPSULATED USE OF COAL BOTTOM ASH IN CONCRETE

FINAL REPORT

***Principal Investigator* – Professor T. Ramjeawon**

***Co-Investigator*- Mr A.S.Cadersa**

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Preamble

This research project has been funded by the Mauritius Research Council under the African Adaptation Programme (AAP) which is a regional initiative funded by the Government of Japan under its Cool Earth Partnership for Africa. The main aim of the AAP is to integrate and mainstream climate change adaptation into the institutional framework and in the core development policies, strategies and plans.

The research is in line with the policy of the Government of Mauritius to implement a sound management of coal ash on the island.

This research investigates the feasibility of the use of coal bottom ash as natural aggregates replacement in concrete. This application will reduce the exploitation of natural resources resulting in significant energy savings and reduction in green house gas emissions.

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Abstract

This project aims to investigate the feasibility of the use of coal bottom ash as replacement for all in aggregates in concrete in Mauritius, as a means to reduce the exploitation of natural resources and to contribute to a sound management of coal ash on the island.

In this research, the all in aggregates in both grade 40 and grade 15 concrete mixes were replaced by coal bottom ash in varying proportions by weight. The effect of bottom ash on the 7 and 28 days compressive strengths were then determined. In addition, leaching characteristics of heavy metals from the bottom-ash concrete at 90 days were determined as per BS EN12457-1:2002 and results compared with limits specified in BS6920:2000-Materials in Contact with Drinking Water and in Mauritian Drinking Water Standards.

Five grade 40 concrete mixes were designed comprising 15%, 26% and 54% respectively replacement by weight of all in aggregates by coal bottom ash. The 7 and 28 days compressive strength of cubes as well as the leaching characteristics of heavy metals from the bottom-ash concrete were determined. Results show that the compressive strength of concrete decreases drastically as bottom ash content increases and thus use of bottom ash in structural concrete is not technically and economically feasible.

Subsequently, two grade 15 concrete mixes were designed comprising 31% and 100% respectively replacement by weight of all in aggregates by coal bottom ash. 7 and 28 cube test results showed that compressive strengths of both mixes are comparable to those of control mix. In addition, leachability tests showed concentrations of heavy metals at 31% replacement were within limits.

However, limits for barium and lead at 100% replacement were slightly higher than the threshold limits.

This research concludes that the use bottom ash as all in replacement/aggregate replacement in structural concrete is not technically feasible and is uneconomical.

However, bottom ash in low strength concrete applications e.g. blinding, mass concrete and concrete infills is technically feasible and economical. In this respect, the replacement of all in aggregates by bottom ash up to 31% can be implemented safely.

Since there is a potential risk of the low strength concrete getting into contact with drinking water because of percolation, the replacement of all in aggregates by bottom ash up to 100% must be done with caution. This impact will have to be assessed in situ because of varying levels of dilution likely to occur in nature.

1.INTRODUCTION

Coal is the single largest fuel source for the generation of electricity worldwide and consists of 38% yearly electricity generation. In Mauritius, thermal power generation accounts for about 96 % of the total energy produced. Of the different fuels used for electricity production (heavy fuel oil, coal and kerosene), coal remained the most important input and its share rose from 22 % in 2000 to 46 % in 2008. With prospective setting up of coal power plants, the quantity of coal and coal ash production will definitely be greater.

Concrete is a material that symbolizes strength and longevity. It has been a material of choice and has emerged as the dominant construction material for infrastructural needs for the past twentieth century. Moreover, concrete is easily prepared and manufactured from readily available constituents and is widely used in all types of structural system. The challenge for the civil engineering community in the near future is to realize projects in harmony with the concept of sustainable development and this involves the use of high performance materials and products manufactured at reasonable cost while ensuring lowest possible environmental impact. The continuous reduction of natural resources and the environmental hazards posed by the disposal of coal ash will reach an alarming proportion such that the use of coal ash in concrete manufacture will therefore be more of a necessity than a desire.

The aim of this research is to investigate the encapsulated use of coal bottom ash in both structural and low strength concrete and assess the environmental impacts of these applications.

The objectives were as follows:

- Assess the effect of bottom ash on concrete strength
- Determine whether the use of bottom ash in structural concrete is technically feasible and assess any cost implications
- Determine a grade 15 concrete mix containing bottom ash without compromising on concrete strength
- Assess the environmental impacts of the concrete with respect to leachability of heavy metals

2. LITERATURE REVIEW

2.1 Coal Ash

Coal ash is the generic term referring to several very distinct materials produced when coal is combusted to generate electrical power. (ACCAEF, 2008) These materials produced are generally terms as “coal combustion products” (CCP). They include fly ash, bottom ash, boiler slag, flue gas desulfurization gypsum, and other power plant by-products. The term "product" was used by the U.S. Environmental Protection Agency to further encourage recycling these and other industrial byproducts. It is more beneficial to use these CCPs rather than discarding them, thereby preserving natural resources, and decreasing greenhouse gas emissions. (ACAA, 2008)

2.2 Coal Combustion Products

Coal Combustion Products (CCPs) are produced in coal-fired power stations that burn either hard or brown coal. Due to the mineral components of coal and the combustion technique fly ash, bottom ash, boiler slag and fluidized bed combustion ash as combustion products as well as the products from dry or wet flue gas desulphurization, especially semi dry absorption product and flue gas desulphurization gypsum are produced. (ECOBA, 2011)

2.2.1 Fly ash

Fly Ash is obtained by electrostatic or mechanical precipitation of dust-like particles from the flue gases of furnaces fired with coal or lignite at 1100 to 1400°C. Fly ash is a fine powder, which is mainly composed of spherical glassy particles. (ECOBA, 2011)

2.2.2 Bottom Ash

Bottom Ash is a granular material removed from the bottom of dry boilers, which is much coarser than fly ash though also formed during the combustion of coal. (ECOBA, 2011)

2.3 Coal ash Characteristics

Certain physical and chemical properties undoubtedly play key roles in ash-water interactions. Coal fly ash is the partially combusted solid waste particulates of small enough diameter to be entrained in flue gas. One study determined 63% of the examined fly ash particles were in the range of 2-50pm in diameter [El-Mogazi et al., 1988]. Forms of potentially toxic metals are selectively deposited on the outer surface of coal ash particles [Hopke, 1983]. Such surface components are not bound to the internal silicate matrix and therefore are readily leachable [Hopke, 1983]. Three major matrices compose fly ash, silicate glass, mullite quartz, and magnetic spinel [El-Mogazi et al., 1988] Investigations have found the magnetic matrix to be particularly important in the release of toxic elements [El-Mogazi et al., 1988].

2.4 How toxic is Coal Ash?

Typically, coal ash contains arsenic, lead, mercury, cadmium, chromium and selenium, as well as aluminum, antimony, barium, beryllium, boron, chlorine, cobalt, manganese, molybdenum, nickel, thallium, vanadium, and zinc. All can be toxic. Especially where there is prolonged exposure, these toxic metals can cause several types of cancer, heart damage, lung disease, respiratory distress, kidney disease, and reproductive problems, gastrointestinal illness, birth defects, impaired bone growth in children, nervous system impacts, cognitive deficits, developmental delays and behavioral problems. In short, coal ash toxics have the potential to injure all of the major organ systems, damage physical health and development, and even contribute to mortality (Gottlieb *et al.* 2010).

2.5 How toxic is coal ash as a leachate?

The leaching of heavy metals and other elements during regulatory tests may cause coal ash to be classified as hazardous waste, complicating land disposal. The hazardous nature of coal ash remains unclear because current toxicity tests fail to characterize effectively the elemental distribution and chemical solubility of trace metals in the landfill environment. Leaching characteristics of ash samples can be investigated with various laboratory extraction procedures in association with multi-elemental techniques (e.g. Neutron Activation Analysis and Inductively Coupled Plasma Atomic Emission Spectroscopy) (Gottlieb *et al.* 2010).

A report released by the EPA (Environmental Protection Agency) in 2009 documented that many of those toxicants leach at concentrations high enough to seriously endanger human health. The findings reflected the EPA's adoption of new and improved analytical procedures that, according to the EPA, are better able to determine how much toxic material would leach out of coal ash and scrubber sludge.49 The EPA's conclusions greatly altered our understanding of the toxicity of coal ash leachate. The report analyzed 73 samples of coal ash waste of different types and analyzed the physical properties, the content of elements, and the leaching characteristics. What the report found was that for some coal ashes and under some circumstances, the levels of toxic constituents leaching out of coal ash can be hundreds to thousands of times greater than federal drinking water standards (Gottlieb *et al.* 2010)..

Not only are these levels high enough to harm human health, they are also many times higher than the leaching levels that the EPA previously reported: for arsenic, more than 76 times higher than the highest levels reported and for antimony, more than 916 times the earlier levels. In short, the new and more sensitive test shows far higher levels of leaching of known toxic substances. The report notes that the leach test results represent a theoretical range of the potential concentrations of toxics that might occur in leachates rather than an estimate of the amount of a toxic that would actually reach any given aquifer or drinking water well. It cautions that “comparisons with regulatory health values, particularly drinking water values, must be done with caution.”

In Mauritius, the Technical Advisory Committee on Coal Ash Management compared coal ash leachate with BS 6920:2000 –Materials in Contact with Water and the Mauritian drinking standards. The leachability test results compared to the aforesaid standards are shown in Table 2.1. The results showed coal ash leachates were found to contain various heavy metals namely, aluminium, arsenic, barium, chromium, copper, iron, nickel, cadmium and zinc but no lead and mercury.

Table 2.1: Heavy Metal Content of Coal Ash Leachate Compared to BS6920:2000 - Materials in Contact with Drinking Water, (British Standard) and Mauritian Drinking Water Standards (Units: µg/litre)

	CTDS		CTBV		CTSAV		**BS 6920: 2000 Materials in Contact with Drinking Water**		**Mauritian Drinking Water Standards**
	Fly Ash (CTDS01)	**Bottom Ash (CTDS02)**	**Fly Ash (CTBV01)**	**Bottom Ash (CTBV 02)**	**Fly Ash (CTSAV02)**	**Bottom Ash (CTSAV01)**	Maximum allowable concentrations - µg/litre	Reporting limits - µg/litre	µg/L
Al	119	860	97	1315	6531	1164	200	20	200
As	724	ND	703	ND	ND	ND	50	1	10
Ba	152.6	7598	88	5450	242.8	6359	1000	100	No Std
Cr	19	16	34	ND	55.8	8.3	50	5	50
Cu	ND	ND	ND	ND	ND	ND	No Std	No Std	1000
Fe	ND	6	ND	ND	24	ND	200	20	No Std
Ni	571	15	569	11	9	11	50	2	20
Cd	2	ND	ND	ND	ND	ND	5	0.5	3
Pb	ND	ND	ND	ND	ND	ND	5	1	10
Zn	70	32	56	88	ND	ND	No Std	No Std	3000
Hg	ND	ND	ND	ND	ND	ND	1	0.1	1

2.6 Leaching Behaviour of Bottom ash in concrete

Bottom ashes (BA) obtained from a municipal solid waste incineration plant, have shown different pH and lead concentrations in leachate for different lines. In order to explain this behaviour, combustion tests were performed concerning the lines and the effect of the type of wastes. The BA obtained from the same waste has shown the same raw chemical composition, but different leachate characteristics for the different lines. The bottom ash from different wastes burned on the same line instead showed very similar leachate behaviour. The results suggest that the quality of leach ate depends on the plant and process conditions (in particular the ash quenching phase) and not on the composition of the waste.

A study conducted by Jimmy and Cheong. (n.d) on the use of municipal solid waste (MSW) incineration bottom ash as aggregates for the production of non-structural lightweight concrete in Singapore; showed that . The compressive strengths of concrete in three out of the four test series were able to achieve the ASTM standard requirement on compressive strength of 4.14 MPa for lightweight concrete. Leaching tests showed a higher arsenic and cadmium concentration than the US-EPA drinking water standards but were within the discharge limit to water courses. Four design mix compositions comprising 25%-50% OPC, 65%-40% bottom ash and 10% perlite were formulated and cast in 100mm cubes. Tests were carried out on the compressive strength of cubes as well as the leaching characteristics of heavy metals from the bottom-ash concrete.

2.7 Applications of Bottom Ash

According to ACAA 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. (RMRC, 2008) The beneficial use of bottom ash is shown in Figure 2.1.

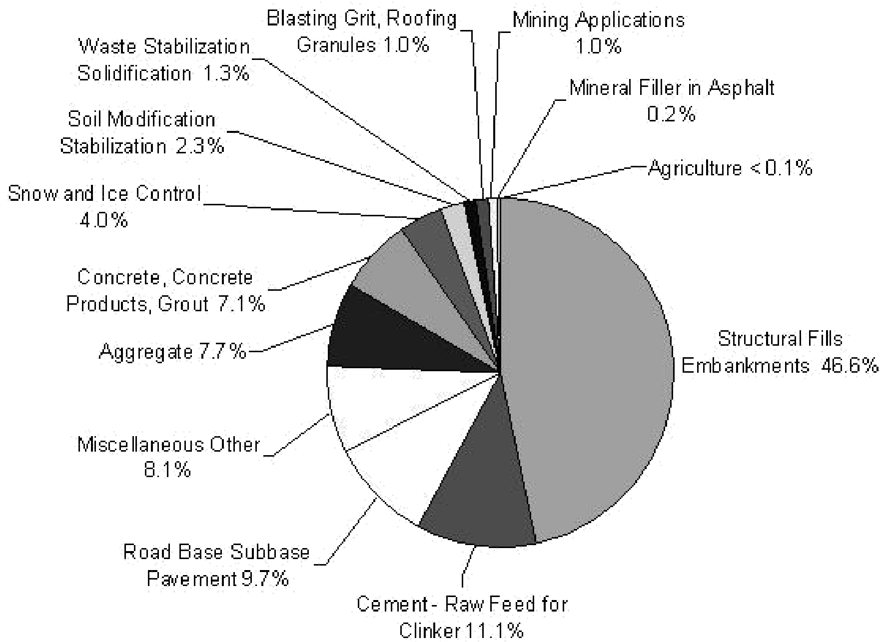

Figure 2.1: Bottom ash application as a percentage of totals reused (ACAA, 2006)

2.7.1 Use of Bottom Ash in Concrete Mixtures

Bottom ash has a porous surface structure that makes this material lighter than conventional aggregate and useful in lightweight concrete applications. The porous surface structure of bottom ash particles however makes this material less durable than conventional aggregates. However it is better suited for use in base course, as opposed to wearing surface mixtures.

2.7.2 Use of Fly Ash and Bottom Ash for Structural Fills or in Controlled Low Strength Material

Properties of coal fly ash make it highly suitable for use as structural fills or in "controlled low strength materials" (CLSM), provided that guidelines and regulations for their use are followed.

Structural fill is an engineered fill that is typically constructed in layers of uniform thickness and compacted to a desired unit weight (density) in a manner to control the compressibility, strength, and hydraulic conductivity of the fill.

Controlled low strength materials are easy to place, flowable mixes consisting of fly ash, bottom ash, cement, water and on occasion, sand. They provide engineers with a highly versatile, easy to use, low cost material for projects requiring backfill, temporary slabs, slope stabilization and erosion protection plus many more similar applications.

Structural fills or controlled low strength materials are a standard part of:

• Road construction, e.g. embankments for highways and roads.

• Foundations immediately below buildings and other structures.

• Vehicle parking areas.

• Slope stabilization and erosion control.

2.8 Bottom ash

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. The combustion technologies and furnace type determines the characteristics of the material generated. They are formed from agglomerated ash particles that are too large to be carried in the flue gases and fall through open grates to an ash hopper at the bottom of the furnace. Coal is reduced to powdered form before it is fed into the boiler. The carbon and other combustible matter in the fine coal are burned, with the non-combustible ash left behind. Due to the high temperature of the boiler, (around 1500-1700 degrees Celsius, for bituminous coal, 1300-1600 for lower rank coal.) the ash is softened and melted in the hot zones. The melted ash is carried away out of the higher-temperature zones where it is cooled into mostly solid spherical particles, which are swept out of the boiler as fly ash. Around 10-20% of melted ash is accumulated on the boiler walls and against steam tubes in the boiler and forms solidified masses sometimes called 'clinker'. The clinker eventually builds up and is blasted by jets of air or simply falls to the bottom of the boiler where it is removed, hence the term 'bottom ash' (Kentucky Ash, 2010).

Bottom ash can be incorporated into cement materials as a binder to replace cement or as an aggregate, as a partial natural sand replacement, according to the grain-size distribution of the material for utilization in mortar or in structural concrete (Andrade, 2004, Andrade et al., 2003, Ghafoori and Bucholc, 1996 and Ghafoori and Bucholc, 1997).

The bottom ash will influence many properties: (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 (Pandey and Sharma, 2000); 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 and Cheriaf et al., 1999).

2.8.1 Physical Properties

Bottom ash is mainly comprised of fused coarser ash particles. These particles are quite porous and look like volcanic lava. The porosity and density of bottom ash is controlled by the nature of the coals (Kentucky Ash, 2010). Bottom ash has a high porous surface, large particle size, angular shape, and glassy texture. The ash particles range in size from a fine gravel to a fine sand. Bottom ash is predominantly sand-sized, usually with 50 to 90 percent passing a 4.75 mm sieve and 0 to 10 percent passing a 0.075 mm sieve. The coarse bottom ash size typically ranging from 19 mm to 38.1-mm. Bottom ash is usually a well-graded material; however, possible variations in particle size distribution may occur in ash from the same power plant (RMRC, 2008).

2.8.2 Chemical Properties

The chemical composition of bottom ash is controlled by the source of the coal and not by the type of furnace. The three predominant oxides are silicon dioxide (SiO_2), ferric oxide (Fe_2O_3), and aluminum oxide (Al_2O_3), with smaller quantities of calcium oxide (CaO), potassium oxide (K_2O), sodium oxide (Na_2O), magnesium oxide (MgO), titanium oxide (TiO_2), phosphorous pentoxide (P_2O_5), and sulfur trioxide (SO_3). Bottom ash that originally comes from lignite or sub-bituminous coals has a higher percentage of calcium than that of derived from anthracite or bituminous coals. There can also be some percentage of carbon particulate resulting from incomplete combustion. Due to salt content and low pH, bottom ash can be potentially be corrosive. When using bottom ash in an embankment, backfill, sub base, or even in a base course, the ash can be exposed to metal structures and cause corrosion (RMRC, 2008).

2.9 Effects of Bottom Ash on Concrete Properties

2.9.1 Compressive Strength

Sani *et al.* (2010, p.73) studied the gain in strength of concrete where fine aggregate (natural sand) was partially replaced with washed bottom ash (WBA). The bottom ash used was first submerged in free water for 3 days to prevent carbon usage in concrete; hence, the bottom ash was called washed bottom ash (WBA). Five concrete mixes were investigated by replacing sand by equal weight of washed bottom ash in percentages of 10%, 20%, 30%, 40%, and 50% at a constant water to cement ratio of 0.55. Compressive strength of the concrete mixtures made with and without WBA was determined at 3, 7, 28, and 60 days of water curing. The use of WBA showed a lower strength concrete compared to the control sample strength. They noticed an increment of compressive strength of 77% to 89% at early age of concrete strength when compared to the control specimen. At 10% replacement, the compressive strength was the lowest even at later age; this development of strength was not applicable for concrete application. Sani *et al.* (2010) concluded that the use of WBA has revealed lower strength concrete compared to the control sample strength as shown in Figure 2.2 and attributed the lower strength gained due to the washing method which caused the bottom ash to lose its cementitious properties. The gain in strength was increasing after 7 days of curing. The results showed that 10% sand replacement yield a lower compressive strength at early ages, and 30% WBA replacement was found to be the optimum amount to get a favorable strength and good development pattern over increasing ages.

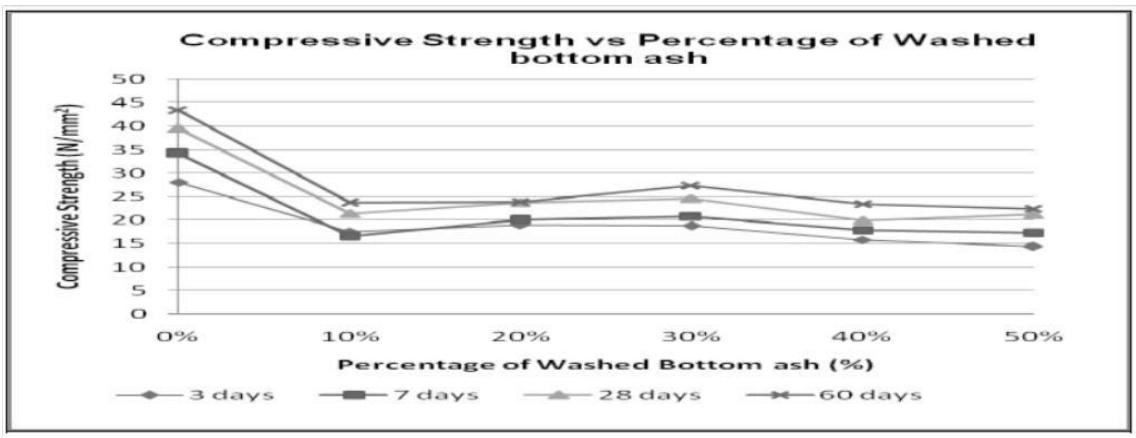

Figure 2.2: Effect of percentage replacement of washed bottom ash on compressive strength

***Source**: Sani et al. (2010, p.74)*

A research conducted by Kim and Lee (2010, p.1119) on the evaluation of bottom ash as fine and coarse aggregates in high strength concrete with compressive strength of 60-80 MPa revealed that the compressive strength were not strongly affected by the replacement of bottom ash. The experiments conducted were to replace fine and coarse bottom ash with normal sand and gravel in varying percentages of 25%, 50%, 75%, and 100%. Type 1 Portland cement, blast furnace slag, and silica fume were used in different proportions as binder. A polycarboxylic acid based superplasticizer was also added. Dosages of water, silica fume, and superplasticizer were fixed at 30.8%, 20%, and 2.5% by cement weight respectively for all the mixes. After curing in water, the 7 and 28 days compressive strengths were around 60 MPa and 70 MPa respectively as shown in Figure 2.3. However, Kim and Lee (2010, p.1119) claimed that this gain in compressive strength was linked to the higher cement content used. They suggested further research with respect to aggregate proportions and water absorption condition of the aggregate in order to clarify the effect of bottom ash on compressive strength.

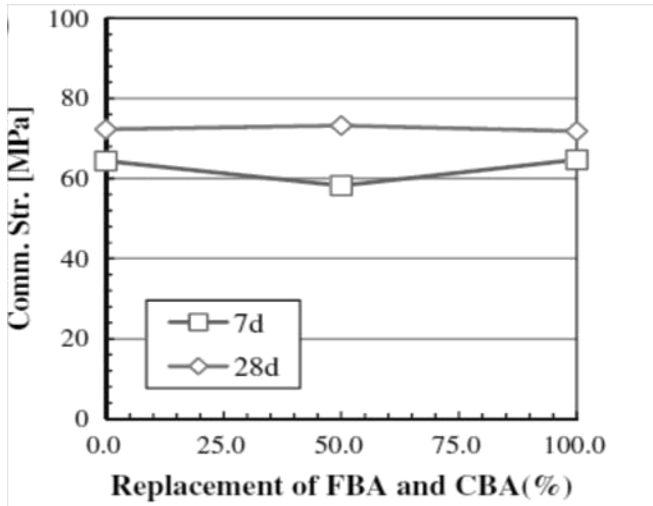

Figure 2.3: Effects of bottom ash on compressive strength

***Source**: Kim and Lee (2010, p.1120)*

Hardjito and Fung (2010, p.47) carried out research on geopolymer mortar incorporating bottom ash as partial and full replacement of sand. It was found that compressive strength decreased with an increase of bottom ash content. They related this low compressive strength to the water released in the mixture by bottom ash and, in term of absorption and adsorption, into and onto the bottom ash due to the high porosity and irregular surface. The concluded that 10% replacement of bottom ash as fine aggregate was suitable for the fly ash based geopolymer mortar without significant decreased in compressive strength.

Aggarwal *et al.* (2007, p.55) studied the compressive strength behavior when bottom ash was replaced from 0% to 50% as fine aggregate in concrete at fixed water to cement ratio. The compressive strength was determined at 7, 28, 56, and 90 days. Compressive strength gained with respect to 90 days varied from 56- 65% at 7 days, 75-85% at 28 days, and 86-90% at 56 days. They noticed slow gained in strength initially but acquired a faster rate beyond 28 days due to pozzolanic reaction of bottom ash. The reaction between calcium hydroxide liberated during hydration of cement did not bring any considerable densification of the concrete matrix at early ages. They concluded that the bottom ash concrete required to gain strength is more compared to the control; the strength difference between the control and bottom ash concrete became less distinct after 28 days; and continued gaining in strength.

Kasemchaisiri and Tangtermsirikul (2007, p.92) investigated the properties of self-compacting concrete by incorporating bottom ash as partial replacement of fine aggregate at 0%, 10%, 20%, and 30% by weight while fixing the water to cement ratio. It was found at replacement level above 10%, the compressive strength decreased. The reason for the declination in compressive strength was due to the increase in porosity on the hardened concrete caused by the bottom ash. However, the pore refinement effect due to pozzolanic reation canceled the effect of porosity at 56 days with a replacement level of 10%.

2.9.2 Flexural strength

Aggarwal et al. (2007) observed a reduction in the flexural strength is with an increase addition of bottom ash; however, at 40% replacement the flexural strength at 90 days gave suitable result and noticed a continuous increase in flexural strength with incremental ages. They believed it was due to the spherical nature of the bottom ash particles that induced poor interlocking of aggregates. The investigation carried out by Kim and Lee (2010, p.1121) showed that the flexural strength linearly decreased as the replacement ratio of fine bottom ash and coarse bottom ash was increased while the compressive was unchanged. The flexural strength was decreased to 19.5% when bottom ash was used as fine aggregate replacement compared to the control specimen. In addition, the findings from the study by Kim and Lee (2010, p.1121) also indicated that the cracks caused by the flexural load spread through the bottom ash particles while the normal aggregates were hard to pass through, which therefore had not affected the crack propagation with the use of normal aggregates.

2.9.4 Modulus of Elasticity

Andrade *et al.* (2006, p.1196) carried out a volumetric replacement of fine aggregates by bottom ash in percentages of 0%, 25%, 50%, 75%, and 100%. The elastic modulus carried out at 3, 28, and 90 days revealed a lowest elastic modulus for the highest bottom ash replacement. They pointed out a greater dispersion for the early ages (3 days) and a rise in elastic modulus of concrete with respect to increase in age (90 days), which was due to the pozzolanic potential of bottom ash in the long-term effect. However, the elastic modulus values were not only close to each other but also very close to that of the reference mixture. Kim and Lee (2010, p.1120) found that the modulus of elasticity decreased in accordance with an increase of replacement of fine and coarse bottom ash. The modulus of elasticity compared to the control specimen was 84.9% and 77.5% with fine bottom ash and coarse bottom ash respectively. With these findings, the use of bottom ash strongly affected the elastic modulus of concrete.

2.9.5 Drying shrinkage

Substitution of bottom ash as fine aggregate in concrete either decreased or increased drying shrinkage. The study carried out by Kasemchaisiri and Tangtermsirikul (2007, p.94) where bottom ash was used as fine replacement for self-compacting concrete showed a higher drying shrinkage for mixture with high bottom ash content. They observed stabilization in the drying shrinkage after 91 days of drying. They associated this increase in shrinkage due to the porosity of concrete that significantly increased with the bottom ash content. Whereas Bai et al. (2005) studied the effect of furnace bottom ash replacement as fine aggregate at 0%, 30%, 50%, 70%, and 100% by mass, were studied at fixed water-cement ratios, and fixed slump ranges. The results testified that the drying shrinkage decreased with the increase of the bottom ash content. However, the drying shrinkage increased with the increase of the bottom ash content beyond 30% replacement level. They agreed that fine aggregates could be replaced at 30% without affecting the drying shrinkage properties of concrete.

2.9.6 Hardened density

Kim and Lee (2010, p.1118) found that the density of hardened concrete linearly decreased with the replacement of fine bottom ash and coarse bottom ash. The density of concrete decreased by 4.6% and 9.6% when fine aggregate was replaced with 100% fine bottom ash and coarse aggregate were replaced with 100% coarse bottom ash respectively. The density of hardened concrete in this research was less than 2000 kg/m^3 when both fine bottom ash and coarse bottom ash was replaced at 100%. The associated this drop in density with the fact that the volume proportion of coarse aggregate was greater than the fine aggregate, which therefore led the coarse bottom ash to absorb more cement paste on the surface that forced the air bubbles out from the pores of the aggregates.

2.9.7 Workability

Aggarwal *et al.* (2007, p.55) showed that the workability of concrete decreased with an increase of bottom ash replacement of fine aggregates. It was associated with the fineness of bottom ash, which increased the specific surface and the large amount of water needed for mixing of the ingredients to get closer packing. However, the research carried out by Kim and Lee (2010, p.1117) showed that the workability was reduced by a small amount when coarse bottom ash was used and the fine bottom ash had no effect. This no effect on workability was due to the low porosity of fine bottom ash and smaller amount of water absorbed and cements paste. Moreover, the fine bottom ash absorbed only a very small amount of water and cement paste during mixing.

2.9.8 Bleeding

A study carried out on the use of quarry dust and bottom ash as controlled low strength materials. Bottom ash was substituted as fine aggregates in this research. They found out that bleeding was directly proportional to bottom ash content while inversely proportional to the cement content (Hardjito and Why, n.d.). Andrade *et al.* (2008, p.611) derived the same conclusion; they observed an increase in bleeding with increasing bottom ash replacement. Furthermore, the presence of bottom ash increased the quantity of water loss by bleeding, the bleeding time and the water release rate, and the higher the bottom ash content of the concrete the greater this effect.

3.0 Materials & Methodology

3.1 Raw Material Selection

3.1.1 Cement

Cement type CEM I 42.5 was obtained from Lafarge Cement (Mauritius) Ltd. The cement is in accordance with BS EN 197-1.

The chemical and physical characteristics of the cement were obtained from the Supplier.

3.1.2 Aggregates

The aggregates utilised were of basaltic origin and were of different fractions 0/2mm, 0/4mm, 6/10mm and 14/20mm.

The aggregates were obtained from United Basalt Production Ltd.

3.1.3 Water

Water is used for lubricating the ingredients and provides the workability of the mix. The water used for mixing the ingredients were used from Geoffroy/Bambous borehole.The same water is consistently used for manufacturing concrete by Pre-Mixed Concrete Ltd.

3.1.4 Bottom Ash

Bottom Ash was obtained from Omnicane Ltd, and the grading curve and absorption of bottom as was determined. The Bottom Ash obtained was 0/10mm.

3.2 Concrete Mix Design

The Boolomey method was used to determine the most suitable all in aggregate grading curve for use in grade 40 and grade 15 concrete mixes.

Méthodes	*Bolomey*
Formules	$Y = A + (100 - A)\sqrt{\frac{d}{D}}$ *(1)*
Paramètres	D= 20mm et A= 8.

3.2.1 Target Mean Strength

A safety factor of 10 N/mm^2 was utilised as not much information was obtained using bottom ash aggregates in concrete. This would cater for variations in the mechanical behaviour of the bottom ash aggregates.

3.2.3 Workability

A target slump of 140mm was targeted in order to obtain a mix which is flowable and which can be easily compacted.

3.2.4 Target Grading Curve

Using the Boolomey method, the reference combined grading curve for all in aggregates was achieved. Please refer to curve 4 in figure 3.0.

For each concrete mix, the quantity of bottom ash was varied such that the target grading curve for the all in aggregates was maintained.

3.3 Concrete Batching

Concrete Mixing was carried out at Pre-Mixed Concrete Ltd laboratory, using a 30 L pan Mixer

3.3.1 Fresh Properties

3.3.3.1 Slump Test

The Slump test was carried out in accordance with BS EN 12350-2:2009 and it is a means of assessing the consistency of fresh concrete. It is used, indirectly, as a means of checking that the correct amount of water has been added to the mix.

3.3.3.2 Fresh Density

The fresh density of the concrete as measured in accordance with BS EN 12350-6:2009.

3.3.3.3 Air Content

The air content in the concrete was measured in accordance with BS EN 12350-7:2009

3.3.2 Hardened Properties

Cubes were sampled from the concrete in accordance with BS EN 12390-2 and water cured. Three cubes were tested at 7 days and three cubes at 28 days.

3.3.3 Leaching

Leachability tests were carried out as per BS EN 12457-1:2002 at the Mauritius Standards Bureau. Since there are no environmental standards or regulatory limits against which ash leachate values can be directly compared to, leachability test results were compared with BS 6920:2000-Materials in Contact with Drinking Water. In order to cater for the worst case scenario where the bottom ash concrete gets into contact with drinking water as a result of percolation, the leachability test results were also compared to the Mauritian Drinking Water Standards.

4.0 Results and Discussion

4.1 Grading Curves

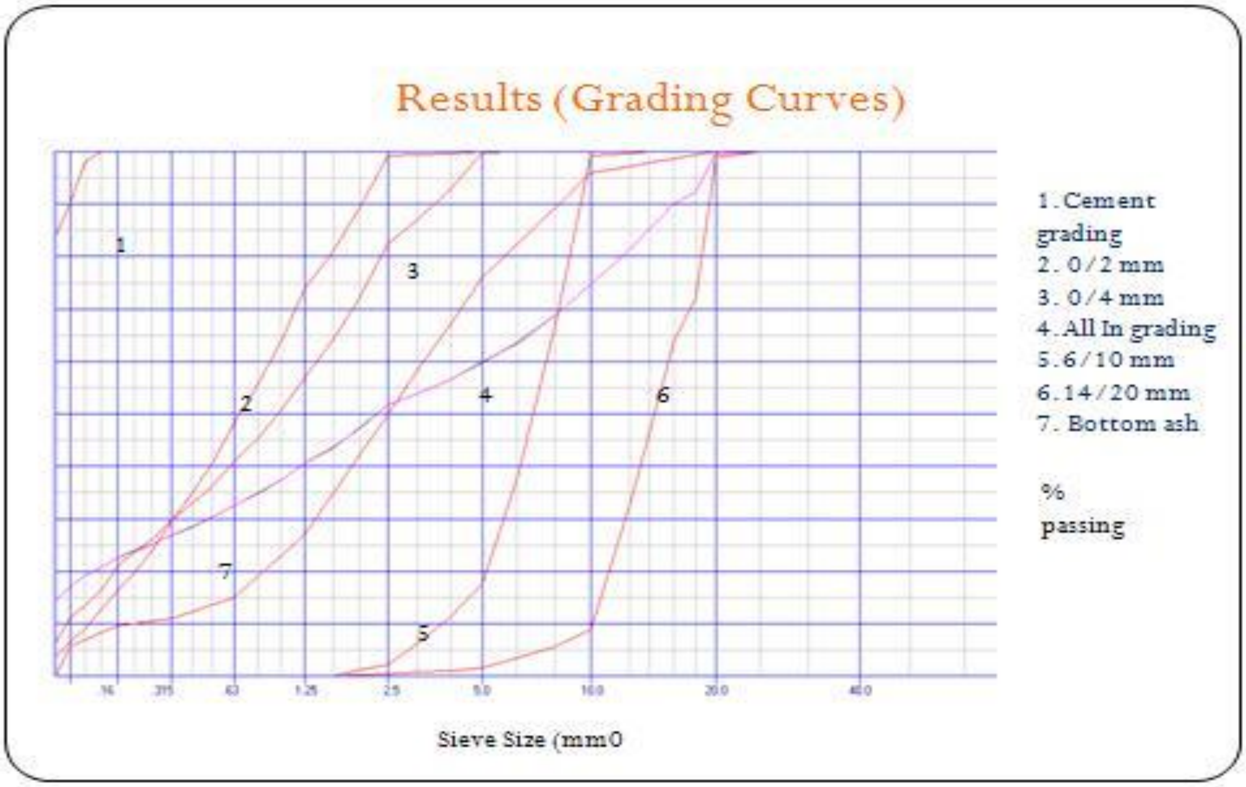

Figure 4.1: % passing vs. sieve sizes (mm) for all materials

Sieve analysis for bottom ash (curve 7) showed that particle size range from 0 to 10 mm.

4.2 Compressive strength results

Table 4.1: Results for compressive strength for all replacement with bottom ash in increasing percentages

	Control Mix	15% replacement	26% replacement	54% replacement	31% replacement	100% replacement
Cement CEM I 42.5 (kg)	350	350	350	350	250	250
Coarse Basaltic Aggregates 14/20 (kg)	620	620	620	620	620	620
Coarse Basaltic Aggregates 6/10 (kg)	360	300	175	150	185	
Bottom Ash 0/10 (kg)		160	240	370	300	1270
Basaltic Sand 0/4 Dry (kg)	650	285	175		320	
Basaltic Sand 0/2 Washed (kg)	300	500	560	535	465	
Total Water Added (kg)	250	270	280	307	180	261
w/c ratio	0.55	0.61	0.63	0.8	0.52	1.6
Fresh Properties						
Slump (mm)	140	140	140	140	140	140
Fresh Density (kg/m3)	2450	2350	2325	2200	2275	1778
Air content (%)	3.5	3.5	3.6	4	3.5	4.5
Hardned Properties						
Strength						
7days (N/mm2)	27	24	22	18	13	12
28 days (N/mm2)	40	33	30	26	20	18

The results obtained for compressive strength for grade 40 concrete confirms data obtained from literature review i.e. there is a significant reduction in strength as compared to control mix.

However, for the grade 15 mix, with 31% replacement of all in aggregate by bottom ash, a compressive strength of 20 N/mm^2 was obtained. This represents a margin of safety of 5 N/mm^2, which is the requirement for that particular mix. Using a grade 15 mix with 100% replacement by bottom ash yields a compressive strength of 18 N/mm^2 that is satisfactory but with a lesser margin of safety (3 N/mm^2).

4.3 Leachability test results

Table 4.2: Concentration level of heavy metals v/s increase in concentration of bottom ash

	% Bottom ash Replacement							
Element	Control	15%	26%	54%	31% (GD 15)	100% (GD 15)	BS 6920: 2000	Drinking Water Standards
As	ND	9	ND	ND	ND	ND	50	10
Ba	899	1347	1026	1374	437	1131	1000	No Std
Cd	ND	ND	ND	ND	ND	ND	5	3
Co	ND	ND	ND	ND	ND	ND	No Std	No Std
Cr	ND	ND	ND	ND	11	9	50	50
Cu	ND	ND	5	6	ND	ND	No Std	1000
Mn	ND	3	ND	3	ND	ND	No Std	No Std
Ni	ND	6	5	7	ND	ND	50	50
Pb	ND	ND	ND	ND	9	12	5	10
Se	ND	52	75	93	ND	35	No Std	No Std
V	15	12	8	12	14	22	No Std	No Std
Zn	45	14	109	145	67	132	No Std	3000
Hg	ND	ND	0.250	ND	0.600	0.220	1	1
Units: µg/l								

Since the use of bottom ash in structural concrete was ruled out, leachability tests for the structural mixes containing bottom ash have not been carried out.

On the other side, concentration of heavy metals in leachate from the grade 15 mix containing 31% replacement of all in aggregates by bottom ash were within limits prescribed in BS5920:2000 and in Mauritian Drinking Water Standards.

However, for the mix with 100% replacement, the barium and lead concentrations were slightly above the threshold limits. Though low strength concrete does not find its application in the construction of water retaining structures or water channels, there is potential risk of the concrete getting into contact with drinking water because of percolation. However, this impact will have to be assessed in situ because of varying levels of dilution likely to occur in nature.

5.0 Conclusions and Recommendations

The aims and objectives of this research were to investigate the encapsulated use of coal bottom ash in both structural and low strength concrete and assess the environmental impacts of these applications.

It can be concluded that the use bottom ash as aggregate replacement in structural concrete is not technically feasible and uneconomical. However bottom ash can be used as an economical filler in low strength concrete applications e.g. blinding, mass concrete, concrete infills.

31% replacement by weight of all in aggregates by bottom ash up can be implemented without affecting the strength of the concrete and without any environmental impacts.

Up to 100 % replacement of all in aggregates is both technically and economically feasible. However, for this mix barium and lead concentrations were slightly above limits prescribed by the BS6920:2000-Materials in Contact with Drinking Water and by the Mauritian Drinking Water Standards. Though low strength concrete does not find its application in the construction of water retaining structures or water channels, there is potential risk of the concrete getting into contact with drinking water because of percolation. However, this impact will have to be assessed in situ because of varying levels of dilution likely to occur in nature.

Due to time constraints repeated concrete testing and leachability tests for the aforesaid mixes have not been carried out. It is therefore recommended to repeat these tests and assess consistency of results.

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