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STRENGTH AND PERMEABILITY CHARACTERISTICS OF ROAD BASE MATERIALS BLENDED WITH FLY ASH AND BOTTOM ASH

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ABSTRACT: The Philippines has an extensive road network which handles most of its passenger and freight movements. Large volumes of aggregate embankment materials of good quality are required to primarily support these transport infrastructures, and this poses threat to the environment. Coal combustion by-products (CCPs) are seen to be its potential alternative mainly due to its vast production and disposal problems in the country. Representative samples of class C fly ash and bottom ash were gathered together with conventional road base materials. Fly ashes were substituted to act as fines; whereas, bottom ash substitutions were varied at different mixture ratios of 0%, 20%, 40%, 60%, 80%, and 100% of fine aggregates. Index properties (i.e. specific gravity, Atterberg limits, and maximum and minimum index densities), compaction characteristics, unsoaked and soaked California Bearing Ratios (CBR), and hydraulic conductivities were obtained for all the blends in order to produce empirical relationships with varying bottom ash content. Results show that the optimum strength can be produced at a blend of 100% bottom ash. However, permeability tests show a considerable decline in hydraulic conductivity with the addition of coal ashes to the typical aggregates. Thus, proper drainage must be carefully applied to these blended embankment materials so as to avoid substantial ingress of water.

Keywords: Fly Ash, Bottom Ash, Road Embankment, CBR, Permeability

1. INTRODUCTION

Transport infrastructure plays an important role in integrating the island economies of an archipelago such as the Philippines. Mostly comprising the highway embankment materials are the so-called aggregates. Due to the increasing public attention being paid to the environment, the coal combustion by-products (CCPs) are often looked upon as an attractive alternative to these aggregates mainly due to its large production and disposal problems. In fact, the coal-fired power plants which produce considerable amount of CCPs contribute the largest share of 27.06% of the total installed capacity of 15,571 MW last 2009 [1].

The main objective of this paper is to determine the optimum blending proportion of fly ash and bottom ash to the conventional road base materials used as highway embankments. Aside from illustrating the morphological characteristics of the materials in their pure forms, emphasis is given to the determination of their geotechnical properties when blended at different mixture ratios.

2. METHODOLOGY

2.1 Ash Properties

Using ASTM D854, the specific gravity of each soil blend was determined. The specific gravity of the soil mixtures was reduced by the addition of fly ash [2] since the usual of the specific gravity of fly ash is much lower compared with the soil.

The Particle Size Analysis was performed in accordance with ASTM D422 [3]. It determines the quantitative distribution of particle sizes of fly ash, bottom ash, and conventional materials used in the study. Sieve analyses were done for particle sizes larger than 75 μm (or those retained at No. 200 sieve); while hydrometer analyses were conducted for particle sizes smaller than 75 μm (or those passing No. 200 sieve).

Conventional materials, fly ash, and bottom ash samples were individually subjected to microscopic examinations in order to characterize their particle angularity, assemblage, and surface texture. These were performed using Scanning Electron Microscopy (SEM). With the purpose of characterizing the chemicals present on the introduced materials and their corresponding proportions, Energy-Dispersive X-ray Spectroscopy (EDS) was performed to both coal ashes. All three materials were subjected to X-ray Diffraction (XRD) Analysis so to investigate their structures.

To provide initial results, the following Index tests were conducted on all the pure materials conforming to the ASTM procedures.

a. Specific Gravity of Soils (ASTM D854)
b. Atterberg Limits (ASTM D4318 and D427)
c. Maximum and Minimum Index Densities (ASTM D4253 and D4254)

These tests were also performed on the blended materials while keeping its grain size distribution constant. It should be noted, however, that the grain size distribution curve (GSDC) used for all the specimens were arithmetically computed to comply with the requirements stipulated by Department of Public Works and Highways (DPWH) for sub-base and base courses. With this, fly ash was used to substitute the entire fines content constituting 10% of the total mass. On the other hand, the fine aggregates which comprise 32.5% of the total mass were replaced by bottom ash at different mixture ratios of 0%, 20%, 40%, 60%, 80%, and 100%.

2.1 Mechanical Properties

Following ASTM D698, Standard Proctor Test determined the OMC at which dry unit weight is greatest and compaction is best. The OMC that were obtained from these tests were used for sample preparation on strength and permeability tests for each blend.

Water was added to the sample to prepare the specimens such that the moisture contents are closed to 100% of OMC obtained in the Standard Proctor Test. After compaction, the compacted specimen in the mould was trimmed level with the top surface and then inverted to have the previously bottom surface tested under the Uniframe. CBR tests (ASTM D1883) were conducted under soaked and unsoaked conditions. The penetration test was performed immediately after the compaction for unsoaked condition.

Falling Head Permeability Tests (ASTM D5084) were conducted so as to illustrate the drainage behavior of all the blends under Relative Compaction, RC=100%. However, since the desired RC=100% is somehow unattainable in the laboratory due to tamping constraints, tests were instead conducted under varying relative compactions (i.e. 80%, 85%, and 90%) to produce a reliable empirical model.

3. RESULTS AND DISCUSSIONS

3.1 Gradation

It can be seen on Figure 1 that 57.5% of the total mass is composed of coarse aggregates, whereas 32.5% are fine aggregates and 10% are fines.

Fly ash is predominantly composed of silt- to clay-sized particles or those finer than 0.075 mm (No. 200 sieve). On the other hand, bottom ash has a better grain size distribution than the former with mostly sand-sized particle composition.

3.2 Soil Classification

Shown on Table 1 are the results of soil classification according to Unified Soil Classification System (USCS) [4, 5]. These were then verified using the AASHTO Soil Classification System following the Group Index Method.

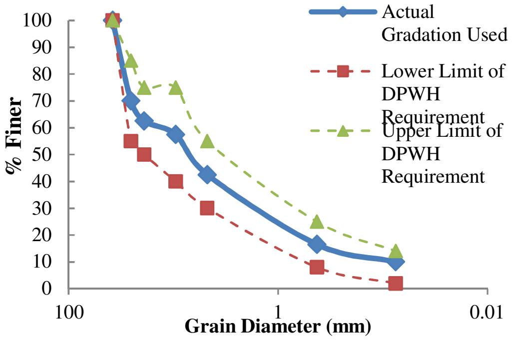

Fig. 1. Actual Grain Size Distribution Curve Used for All Tests

Table 1. USCS and AASHTO Soil Classifications of Pure Materials

Material	USCS (ASTM D2487)	AASHTO (Group Index Method)
Conventional Materials	Well-Graded Gravel with Silt and Sand (GW-GM)	Gravel and Sand
Fly Ash	Silt (ML)	Silty Soils
Bottom Ash	Poorly Graded Sand with Gravel (SP)	Fine Sand

3.3 Microscopic Examination

Apparently, its structure is composed of coarse and fine particle sizes with a few silt-sized ones shown on Figure 2. This supports the result of its soil classification which was “well-graded gravel with silt and sand”. However, at higher magnification, flakes at random direction were detected to comprise its grains; while few inter-assemblage pore spaces were also noted.

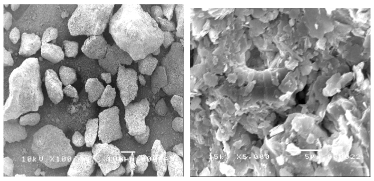
(a) (b)

Fig. 2. SEM Photomicrographs of Conventional Road Base Materials at (a) 100X and (b) 5000X Magnifications

Fly ashes are composed generally of spherical silt-sized particles with smooth surface as shown on Fig. 3. It can be seen that they flocculate with one another thereby producing larger and denser clustered particles. This tends to result in high volume of voids. Hence, at higher magnification, large inter-granular voids can be observed. This validates the high air void content, associated with its compaction behavior.

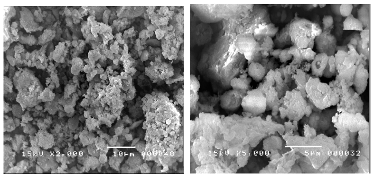
(a) (b)

Fig. 3. SEM Photomicrographs of Fly Ash at (a) 2000X and (b) 5000X Magnifications

As presented in Fig. 4, comparing its shape and surface characteristics, bottom ashes are seen comparable to the conventional materials in terms of particle sizes. However, the large grains can be observed to have clothed contacts since some of the silt-sized particles attach themselves to the much coarser grains. Few inter-assemblage pore spaces can also be observed with the 5000X magnification.

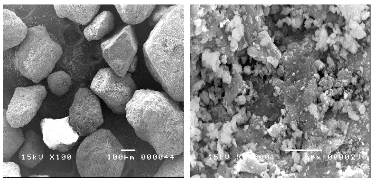
(a) (b)

Fig. 4. SEM Photomicrographs of Bottom Ash at (a) 100X and (b) 5000X Magnifications

3.4 Chemical Analysis

The chemical properties of the coal ashes greatly influence the environmental impacts that may arise out of their use/disposal as well as their engineering properties. The adverse impacts include contamination of surface and subsurface water with toxic heavy metals present in the coal ashes, loss of soil fertility around the plant sites, and the like. In practice, EDS is most often used for qualitative elemental analysis, simply to determine which elements are present on the materials and their relative abundance.

The bulk composition of fly ash is similar to many geologic materials. Fly ash is primarily composed of silicon, aluminum, iron, calcium, potassium, and rubidium, associated with oxygen as oxides, silicates, and aluminates. The combined silicon, aluminum, and iron content (reported as oxides) are frequently used to provide an indication of the pozzolanic or cementitious nature of fly ash.

Table 2. EDS Results of Fly Ash

Elements	Weight (%)
Al	14.58
Si	30.37
K	4.77
Ca	6.58
Fe	2.71
Rb	34.29
Mo	1.06
I	1.1
Ba	1.44
Np	3.1

Table 3. EDS Results of Bottom Ash

Elements	Weight (%)
O	44.04
Mg	1.49
Si	6.83
Ca	16.4
Fe	2.66
Rb	7.54
Sb	10.37
I	2.28
Ba	0.88
Er	7.51

A combined value of 70% of these components indicates a pozzolanic fly ash, while a value of between 40% and 70% indicates a cementitious fly ash. Based on the results of EDS, fly ash samples are to be considered cementitious because the total content of oxides is 47.66%.

Although similar in size and behavior to natural sand, the chemical composition of bottom ash provides unique pozzolanic properties that, as with cementitious materials, can result in a favorable time-dependent increase in strength. This is mainly due to its high calcium content which tends to react with water from which pozzolanic reaction occurs.

3.5 Geotechnical Properties of Pure Materials

Relevant geotechnical tests conforming to ASTM were individually conducted on all three materials in order to come up with the results, as shown on Table 4.

The obtained specific gravity of the aggregate samples is about 2.81, which is within the typical range of 2.40 to 3.60 depending on the nature of the mineral constituents. It can be seen that coal ashes have much lower specific gravities than the conventional aggregate materials. Bottom ashes have higher specific gravity than fly ash owing to the presence of heavier particles. It appears that ashes having high iron oxide content may have high specific gravity [6].

Atterberg Limits Test using the Percussion Cup Method was used to obtain the liquid limit (LL) of 15.60 and plasticity index (PI) of 1.96 for conventional road base materials. Both are within the restrictions of sub-base and base courses as per DPWH requirements.

With the results from the three materials, it is evident that coal ashes are indeed lighter than the conventional materials and is supported by the specific gravities obtained prior. The void ratio of a soil is largely associated with particle size distribution, particle size, shape, and texture. Lower maximum and minimum void ratios were observed for conventional materials; thus, indicating that it has better distribution of particle sizes.

Table 4. Geotechnical Properties of Pure Materials

Property	Conventional Materials	Fly Ash	Bottom Ash
Specific Gravity, G_s	2.813	2.335	2.643
Liquid Limit, LL	15.60	-	-
Plasticity Index, PI	1.96	-	-
Minimum Index Density, γ_{dmin} (kN/m^3)	16.960	5.614	11.785
Maximum Index Density, γ_{dmax} (kN/m^3)	22.289	8.330	16.869
Optimum Moisture Content, OMC (%)	4.938	46.164	14.058
Maximum Dry Density, MDD (kN/m^3)	23.621	10.184	17.298
Unsoaked CBR	43.05%	48.83%	30.27%
Soaked CBR	33.60%	-	-
Hydraulic Conductivity, k (cm/sec) at RC=100%	4.58E-4	4.35E-5	1.04E-5

Results demonstrate that fly ash has less variation of dry density compared to that for a well-graded soil. This is why fly ash is allowed to be compacted over a larger range of water content [7]. Furthermore, because of the generally low specific gravities of coal ash compared to soils, ash fills tend to result in lower dry densities. This decrease in the MDD is due to the extensive agglomeration of ash particles that prohibits the specimens to be compacted properly. Soils can be stabilized effectively by cation exchange using fly ash [8]. There are laboratory experiments using local samples [9, 10, 11, 12] of bottom ashes that can be used for validation. A noticeable decrease in CBR strength was manifested when the specimens were tested after soaking it in water for four (4) days [13].

Falling Head Permeability Tests were conducted at different relative compactions of RC=80%, 85%, and 90% in order to illustrate the effect of varying void ratios. Smaller particles come with smaller voids between them; and hence concluded that the resistance to flow of water increases with decreasing size of particles. As a result, the permeability decreases. Also, particles with a rough surface texture provide more frictional resistance to flow than smooth-textured particles.

3.6 Geotechnical Properties of Blended Materials

Relevant geotechnical tests conforming to ASTM were individually conducted on all three materials in order to come up with the results, as shown on Table 4.

3.6.1 Specific Gravity of Blended Materials

Since specific gravity (G_s) is one of the most important physical properties required in characterizing the usability of coal ashes for geotechnical and other applications, it was obtained for all the blending proportions as shown on Fig. 5.

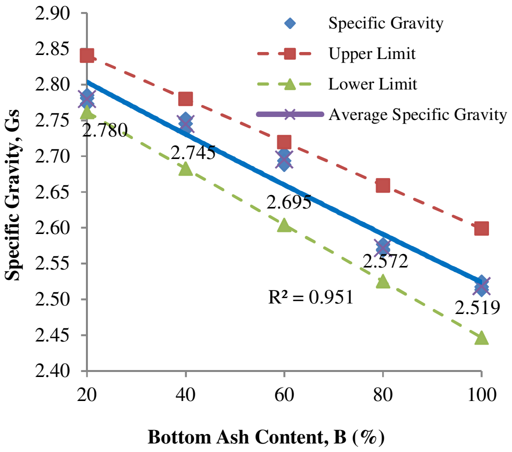

Fig. 5. Specific Gravity vs. Bottom Ash Content

3.6.2 Maximum and Minimum Index Densities of Blended Materials

To see and understand its behavior with varying bottom ash content, Equations 1 and 2 was generated. As observed, there is a significant decrease in both γ_{dmin} and γ_{dmax} when fly ash is present in mixture with aggregates, this is due to the significantly lighter weight of fly ashes which are hollow particles that were used to substitute the fines content of natural soil to complement the study of Kim [13].

Further addition of bottom ash tends to increase the values of both γ_{dmin} and γ_{dmax}. The addition of bottom ash leads to increasingly more well-graded size distributions, which allows the fly and bottom ash particles to pack more closely with the coarse aggregates, resulting in the increase in γ_{dmax}.

$$\gamma_{dmin} = 16.6277exp^{0.0004B} \quad (1)$$
$$\gamma_{dmax} = 20.4409exp^{0.0001B} \quad (2)$$

where: γ_{dmin} = minimum index density;
γ_{dmax} = maximum index density; and
B = bottom ash content (%)

3.6.3 Compaction Behavior of Blended Materials

In summary, Fig. 6 shows the behavior of the OMC with increasing bottom ash content. As observed, it shows a sudden increase in OMC when fly ash was introduced to the mixture to act as its fines content passing No. 200 sieve. This is mainly due to the capability of fly ash to contain large amount of water because of its high air void content nature. Further increase in bottom ash content slightly increases the OMC owing to the same reason. Moreover, an abrupt decrease in MDD was also noted with the use of fly ash because of its much lighter weight and the agglomeration of its particles prohibiting the specimens to be properly compacted.

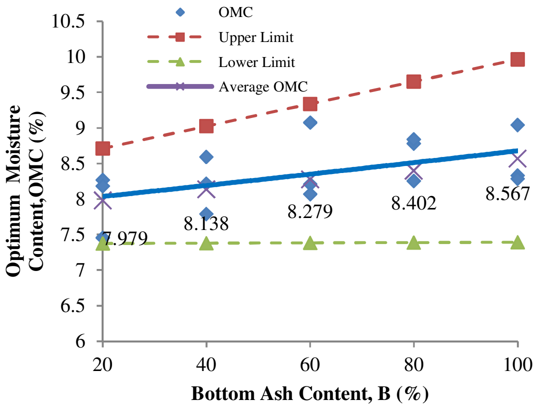

Fig. 6. Optimum Moisture Content (OMC) vs. Bottom Ash Content

The empirical equations correlating OMC and MDD with the bottom ash content are respectively illustrated in Equations 3 and 4.

$$OMC = 7.8816exp^{0.0010B} \quad (3)$$
$$MDD = 22.7896exp^{-0.0005B} \quad (4)$$

where: OMC = optimum moisture content (%);
MDD = maximum dry density (kN/m^3); and
B = bottom ash content (%)

3.6.4 Strength Behavior of Blended Materials

Presented on Figs. 7 and 8 are the corrected CBR values obtained for unsoaked and soaked conditions, respectively. These were plotted to clearly illustrate its behaviors with increasing bottom ash content while fly ash percentage was fixed at 10% of total mass.

It can be observed that there is a significant increase in CBR strength when fly ash was used to substitute the entire fines content constituting 10% of the total mass. The strength of fly ash generally improves with time due to cementitious reactions. Reactive silica and free lime contents are necessary for this reaction to take place. Given all these data, empirical relationships expressed in Equations 5 and 6 were established with which unsoaked and soaked CBR values can be respectively calculated at any given bottom ash content.

As affirmed, a continuous increase in CBR with increasing bottom ash content lead to a conclusion that the blend F10-B32.5-C57.5, in which 100% of fine aggregates are substituted by bottom ash, is the optimum blend which provided the highest CBR values. This blend provided a notable unsoaked CBR of 88.90% and a remarkable soaked CBR of 212.87%, indicating its strength to be more than twice that of crushed rock.

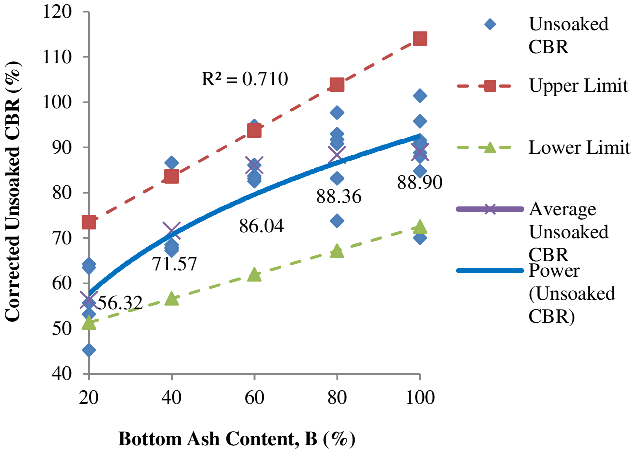

Fig. 7. Unsoaked CBR Values vs. Bottom Ash Content

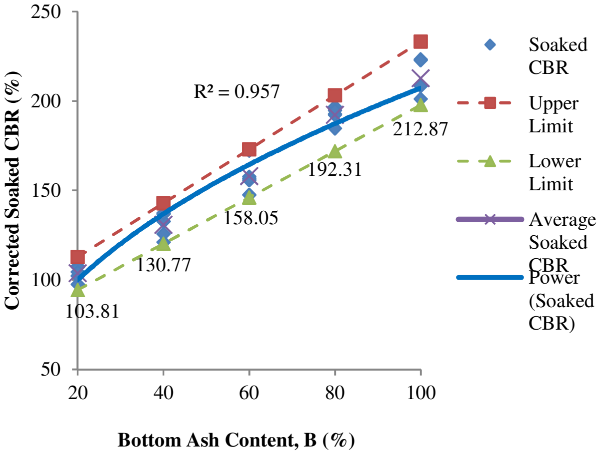

Fig. 8. Soaked CBR Values vs. Bottom Ash Content

$$CBR_{unsoaked} = 23.8905B^{0.2940} \quad (5)$$
$$CBR_{soaked} = 25.7953B^{0.4525} \quad (6)$$

where: $CBR_{unsoaked}$ = unsoaked CBR value (%);

CBR_{soaked} = soaked CBR value (%); and
B = bottom ash content (%)

3.6.5 Permeability Behavior of Blended Materials

Falling Head Permeability Tests in this study were conducted only under varying relative compactions of RC=80%, 85%, and 90% because samples with RC=95% and higher were found to be unattainable since specimens were only to be tamped using hands. Shown on Fig. 9 are the raw data obtained for all the blends.

$$\boldsymbol{k} = (\mathbf{2.99x10^{-7}})\boldsymbol{exp}^{(\mathbf{15.0522}\boldsymbol{e} + \mathbf{0.00796}\boldsymbol{B})} \qquad (7)$$

where: k = hydraulic conductivity (cm/sec);
e = void ratio of the material; and
B = bottom ash content (%)

Due to the large specific surface of fly ash, it causes more resistance to flow of water through the voids. With this, the addition of fly ash in the mixture resulted to a sudden decrease in permeability compared to the controlled mix which has a hydraulic conductivity of $4.58x10^{-4}$ at RC=100%.

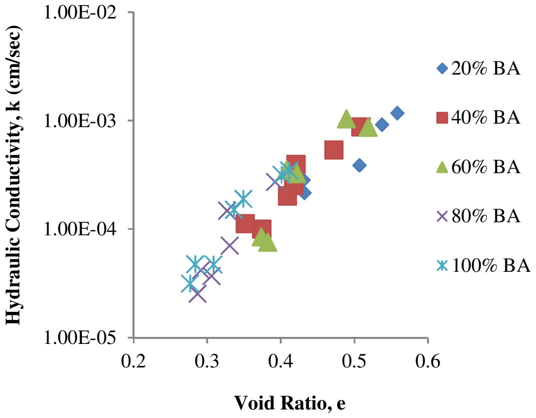

Fig. 9. Hydraulic Conductivity vs. Void Ratio

Subsequently, the results were compared to the drainage characterization as presented by Hazelton and Murphy [15] wherein it was found that all of the blended materials were categorized to have "very slow infiltration" at RC=100%. There are also local studies that will complement the results of blended materials [16],[17].

4. CONCLUSIONS AND RECOMMENDATIONS

After performing all the necessary geotechnical tests, it can be concluded that both class C fly ash and bottom ash produced from burning local coals can be safely utilized as road embankment materials together with the natural aggregates typically used. Also, the self-cementing and pozzolanic hardening properties of class C fly ash and bottom ash impart additional strength to the road embankments. Since percolation of water through the soil is highly anticipated especially during rainy season, cementitious reaction can be expected to take place thereby strengthening the blended materials. The addition of bottom ash from 0% to approximately 50% of fine aggregates gave increasing hydraulic conductivity because they act just like the natural sands wherein water can flow freely. Ultimately, the utilization of coal ashes in highway embankment not only diminishes construction cost, but also helps in disposal problem of these previously regarded as waste by-products.

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