Jurnal
Teknologi

Full Paper

Properties of Coal Bottom Ash from Power Plants in Malaysia and its Suitability as Geotechnical Engineering Material

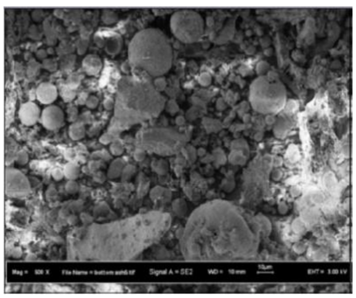
Aminaton Marto[a]*, Choy Soon Tan[b]

[a]Soft Soil Engineering Research Group, Faculty of Civil Engineering, Universiti Teknologi Malaysia, 81310 UTM Johor Bahru, Johor, Malaysia
[b]Faculty of Engineering, Technology and Built Environment, UCSI University, 56000 Cheras, Kuala Lumpur, Malaysia

Article history
Received
18 January 2016
Received in revised form
8 March 2016
Accepted
18 March 2016

*Corresponding author
aminaton@utm.my

Graphical abstract



Abstract

Coal is one of the world's most important sources of energy, fuelling almost 40% of electricity worldwide. Some power plants in Malaysia use coal as a raw material in generating the electricity since the year 1988. During the burning process of coal for the electricity generation, coal waste is produced which includes coal ash in the fraction of about 75-85 % Fly Ash (FA) and 15-25 % Bottom Ash (BA). The FA has been widely used in the cement industry but the BA is still not largely utilised in Malaysia. This might be due to the fears on the environmental hazard that might be occurred as a result of possible leaching of metal from the BA to the ground water. Research on the possible usage of BA in Geotechnical Engineering work has been taken place in Universiti Teknologi Malaysia since 2008, in collaboration with the Tanjung Bin, Sultan Salahuddin Abdul Aziz Shah (or Kapar) and Sultan Azlan Shah (or Manjung) power plants in Johor, Selangor and Perak, respectively. This paper presents the physical, morphological, mineralogical, chemical and mechanical properties of BA and explores the possibility of using BA as alternative materials in Geotechnical Engineering works. Analysis of the results from the laboratory and physical model tests show a huge potential of utilising this BA.

Keywords: Coal ash; soil improvement; laboratory test; physical model test

Abstrak

Arang batu adalah salah satu sumber yang paling penting di dunia, yang menyumbangkan hampir 40 % tenaga elektrik di seluruh dunia. Beberapa loji tenaga di Malaysia menggunakan arang batu sebagai bahan mentah dalam menjana elektrik sejak tahun 1988. Semasa proses pembakaran arang batu untuk penjanaan elektrik, sisa arang batu terhasil termasuk abu arang batu dalam pecahan kira-kira 75-85 % abu terbang (FA) dan kira-kira 15-25 % abu dasar (BA). FA telah digunakan secara meluas dalam industri simen tetapi BA masih belum digunapakai secara meluas di Malaysia. Ini mungkin disebabkan oleh kerisauan terhadap bahaya alam sekitar yang mungkin berlaku akibat larut lesap logam dari BA ke dalam air bawah tanah. Penyelidikan mengenai kemungkinan penggunaan BA dalam kerja-kerja Kejuruteraan Geoteknik telah dilakukan di Universiti Teknologi Malaysia sejak tahun 2008 dengan kerjasama pihak loji janakuasa Tanjung Bin, Sultan Salahuddin Abdul Aziz Shah (atau Kapar) dan Sultan Azlan Shah (atau Manjung) masing-masing di Johor, Selangor and Perak. Kertas kerja ini membentangkan sifat-sifat fizikal, morfologi, mineralogi, kimia dan mekanikal BA serta menerokai kemungkinan penggunaan BA sebagai bahan alternatif di dalam kerja-kerja Kejuruteraan Geoteknik. Analisis terhadap keputusan dari ujikaji makmal dan model fizikal menunjukkan BA mempunyai potensi besar untuk digunakan.

Kata kunci: Abu arang batu; penambahbaikan tanah; ujikaji makmal; ujian model fizikal

1.0 INTRODUCTION

Sustainable development is defined as development that meets the needs of the present, without compromising the ability of future generations to meet their own needs. The three main aspects in sustainable development are economy, environment and social community. Geotechnical sustainability is one of the crucial stages within the context of Civil Engineering project because it is one of the very earliest stages in construction process [1, 2]. One of the key factors in sustainable development is the three R's rules, which indicated as Reduce, Reuse and Recycle. The reuses of engineering waste materials such as coal combustion by-products in civil engineering works has become the trend recently [3].

Coal is one of the world's most important sources of energy, fuelling almost 40% of electricity worldwide. In Malaysia, seven of its power plants use coal as a raw material in generating the electricity since the year 1988. Table 1 summarises the capacity of coal powered power plants in Malaysia.

The coal is crushed and blown into the combustion compartment by a spurt of air. Throughout the combustion process, for the electricity generation, about 10 % of the coal will turn into coal combustion products (CCPs) including fly ash (FA), bottom ash (BA), boiler slag and flue gas desulfurization (FGD) gypsum. The production of CCPS is increasing tremendously over the years as gas-fired plants in Malaysia have been replaced by coal combustion power plant [4]. Among these CCPS, about 75-85 % of them are FA that channelled into the pipe gases and later extracted from the gas by electronic precipitators. On the other hand, about 15-25 % BA will accumulate from the combustion compartment as coarser material.

Table 1 Capacity of coal powered plants in Malaysia [5]

Power Plant	Commissioning year	Capacity (MW)
Jimah, Negeri Sembilan	2009	1400
Manjung, Perak	2002	2295
Kapar, Selangor	1988	2420
Tanjung Bin, Johor	2006	2100
Mukah, Sarawak	2009	270
PPLS, Sarawak	2006	110
Sejingkat, Sarawak	1997	100

Generally, FA is a fine grained material that consists of grain size ranging in between 10 to 100 micrometre. The coal become molten and forms small spherical shape during the high temperature combustion process. On the other hand, BA has coarser angular particles. With cementitious properties [6], thus the FA has been widely used in the cement industry but the BA is still not utilised in Malaysia [7]. In Tanjung Bin Power Plant itself, more than 65,000 tonnes/year of BA is produced [5]. The BA produced is conveyed to the ash pond for storage purposes. However, without utilising the BA, the pond will be filled rapidly. To provide a new ash pond will incur a lot costs. In addition to that, there is another environmental concern regarding the possibility of leachate that might occur if excessive amount of BA lump together in the pond. Thus, various investigations were conducted to explore the applicability of BA in various disciplines in civil engineering work. Some researcher [8] look into the possibility on utilising BA in producing lightweight concrete while some researcher [9] investigate on the thermal insulation properties of concrete by adding in the BA. On the other hand, if there is a potential usage of BA in geotechnical works, particularly for backfill materials and soil improvement works; it is not only beneficial by providing an ideal solution to solve the geotechnical problems but also reduces the volume of waste to be post process after the coal combustion.

This paper provides an overview of the usability of BA as a material in geotechnical engineering works such as in soil improvement works. Research on the possible usage of BA in geotechnical works had been taken place in Universiti Teknologi Malaysia since 2008 through the collaboration with Tanjung Bin, Sultan Salahuddin Abdul Aziz Shah, also known as Kapar, and Sultan Azlan Shah, also known as Manjung, power plants in Johor, Selangor and Perak, respectively. Initially, the research was focussing on the characterisation of FA, BA and FA-BA mixtures. Hence, this paper first summarises the physical, morphological, mineralogical, chemical and mechanical properties of BA obtained from different coal combustion power plants in Malaysia. By doing so, the possibility of using BA as embankment fill materials and in soil improvement work could be identified based on both the index and engineering characteristics of BA. Secondly, this paper presents some evaluation results from the laboratory and physical model tests.

2.0 CHARACTERISTICS OF BOTTOM ASH

Generally, BA could be sub classified into two main categories which are either dry bottom ash or wet bottom ash, depending on the kind of boiler used in the power plants. Dry bottom ash is produced as a solid while wet bottom ash is stored in molten state. Wet bottom ash is also known as boiler slag. If the ash is not stable enough to be carried by the flue gas, it will solidify and agglomerates into coarse particle. These ashes are the dry bottom ash. These BA is then removed by conveyor belt in sluice way into disposal pond or storage area. Due to the combustion process, BA is accumulating as coarser material as compared to FA. BA has a rough surface texture and is quite angular and irregular in shape. Its colour ranges from grey to black and also black and glassy in appearance for some particles, especially in smaller sizes. Recent research [10] shows that the use of biomass bottom ash in cement mortar will giving significantly influence on both physical and mechanical properties of cement mortar. Since the physical properties is very coarse like fine aggregate, there is a potential to use BA as the replacement material of fine aggregate in concrete mix. Result of Onprom *et al.* [11] indicated that the density of cellular concrete decreased while the water absorption was increased when additional amount of BA was included in the concrete mix. Thus, as introductory, this section summarises physical, morphological, mineralogical, chemical and mechanical properties of BA obtained from different coal combustion power plants in Malaysia.

2.1 Physical Properties

Some physical properties of BA are discussed in the following subsections including the specific gravity, particle size distribution and permeability. Table 2 shows the summary of physical properties of the BA, obtained from Tanjung Bin, Kapar and Manjung power plants.

Table 2 Physical properties of bottom ash in some power plants in Malaysia [5,12,13,14,15]

Properties	Power Plant		
	Tanjung Bin	Kapar	Manjung
Specific gravity	1.99-2.44	2.00-2.01	2.39
Particle size (mm)	0.06 – 20	0.06 – 20	0.06 – 20
Coefficient of uniformity, C_U	16.56	27.0	13.33
Coefficient of curvature, C_C	1.01	8.74	1.42
Permeability at maximum compaction (m/s)	0.172-6.88 x 10^{-3}	5.25 x 10^{-5}	8.44 x 10^{-5}

The specific gravity of a material is often depending on two elements, which are chemical composition and particle structure. However, the specific gravity of coal ashes is also largely depending on the method use in combustion process. Generally the specific gravity of BA is larger than the FA. From previous studies by other researchers around the world, the specific gravity of bottom ash lies within 2.0 to 2.6 [5]. On the other hand, the popcorn like structure of BA lowered down the specific gravity of BA to as low as 1.6 [5]. As could be seen in Table 2, the specific gravity of Tanjung Bin BA ranged between 1.99 and 2.44, which is in great agreement with the values obtain by others. For Kapar and Manjung, the specific gravity are also within the same range obtained by other researchers [5]. However, these values are found to be lower than normal values for soils. Das [16] stated that the presence of iron content in coal ash will lower down the value of specific gravity.

FA is finer material as compared to BA thus it could fly out from the combustion compartment. BA itself is a well graded material if classified in accordance to the British Soil Classification System. Figure 1 shows the particle size distribution of Tanjung Bin BA. The particle size is ranging from 0.06 mm to 20 mm. However, more than 90 % of BA has the size of less than 6 mm. The BA is therefore is a coarse grained material and would have the properties of sandy materials.

The falling head permeability test was conducted to determine the permeability coefficient of BA. Due to the high porosity of BA material, the permeability value was quite high. As can be seen in Table 2, the reasonably higher permeability coefficient of BA compared to laterite soil [5, 17] allows BA to be used as backfill material in the construction of road embankment, besides as subgrade materials. This is because the characteristic of high porosity in BA could provide good drainage system. Similarly, the findings of Siddique [18] indicated that the self-compacting concrete mix, that has bottom ash as replacement of sand also, show high permeability at the age of 90 days.

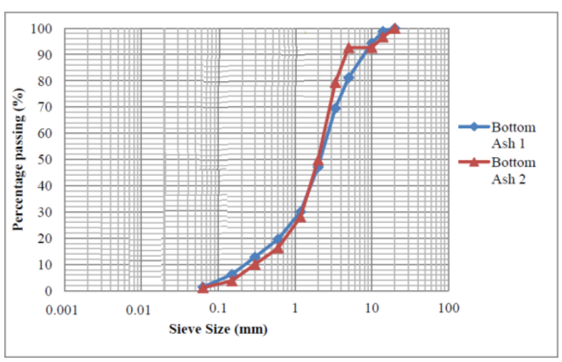


Figure 1 Particle size distribution of Tanjung Bin fly ash, bottom ash, and fly and bottom ashes mixtures [17]

2.2 Morphological Properties

Awang, *et al.* [19] used the scanning electron microscopy (SEM) of model ZEISS SUPRA 35-VP to obtain the morphological properties of BA. The result of the electron micrograph of Tanjung Bin BA is shown in Figure 2. Due to the limitation of the test, only BA with particle size finer than 0.075 mm was utlised to observe the morphological properties at a magnification of 500. It can be seen from the figure that most of the BA particles are shattered in shape. With this angularity shape and rough surface texture, it makes BA very suitable to be used as the material to construct the highway bases and sub-bases.

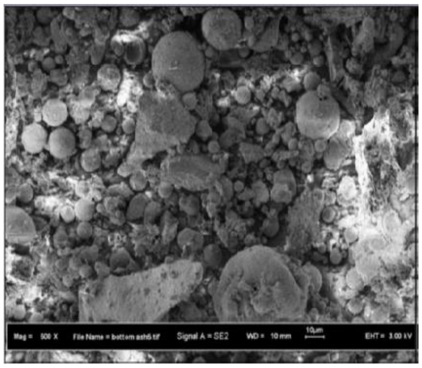
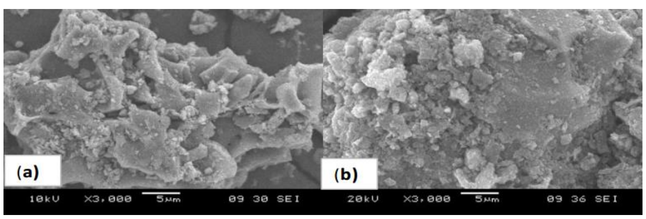


Figure 2 Photomicrograph of Tanjung Bin bottom ash [19]

Figure 3 shows the surface morphology of BA obtained from Manjung at 7 and 28 days as reported by Ayob *et al*. [20]. Generally, it shows that the angularity of Manjung BA is irregular and the surface is rough and uneven. Figure 3(b) shows the BA at 28 days after compaction. It can be seen that the particle surface is shiny, clean and free of dust.

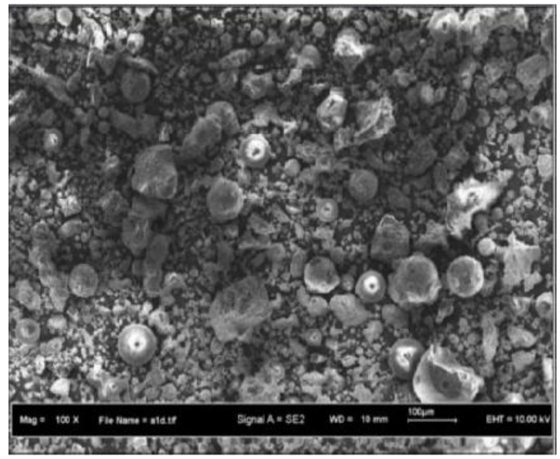


(a) 7 days (b) 28 days

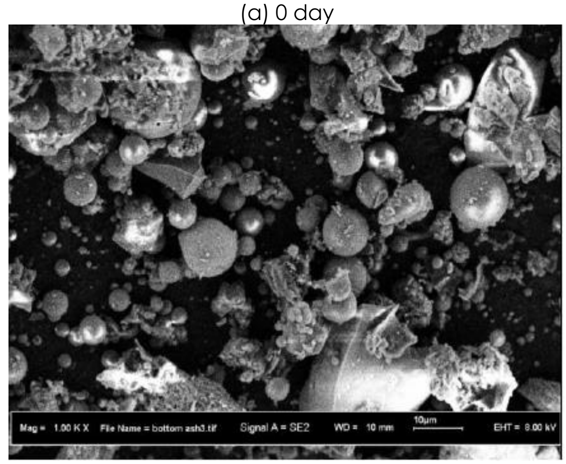
Figure 3 Photomicrograph of Manjung bottom ash [20]

The microstructure of Tanjung Bin BA, compacted at optimum moisture content (OMC) and cured at three different curing periods (0, 7 and 28 days) was observed by using SEM [19]. The results are shown in Figure 4. As already explained before, BA particles appears to be angular in shape and there are some FA materials surrounding the BA in which they are observed to be loosely held to the surface of larger BA particles.

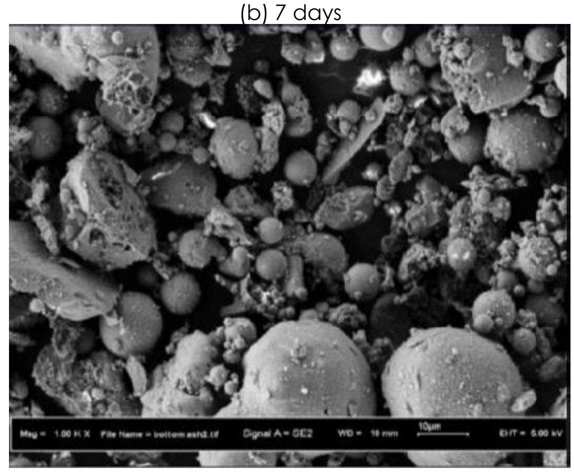
The compacted BA without curing is shown in Figure 4 (a). After the compaction work was done, there is a slight amount of water presented in the BA. It can also be seen that the BA particles became finer due to crushing effects. The microstructure of BA has largely changed for the curing periods of 7 and 28 days. The particle of BA grew bigger and become rounded as the curing period increased from 0 to 7 days and then to 28 days, as shown in Figure 4 (b) and 4 (c). In fact, the FA was also presence in a very small amount in BA, in which it attached to the particle of BA itself. With the presence of cementitious FA material and water, there are more agglomerates bonded particles existed after the 7 days curing period. This process is known as pozzolanic reaction. As the curing periods increased, the pozzolanic reaction occurred more significantly.



(a) 0 day



(b) 7 days



(c) 28 days

Figure 4 SEM of compacted Tanjung Bin bottom ash [19]

2.3 Mineralogy

The X-ray Diffraction (XRD) of model Siemens Diffractometer D5000 was used by [19] to obtain the mineralogy of BA. Result of XRD analysis shows that the mineral exists in Tanjung Bin BA includes mullite, silicon oxide and silicon phosphate. The same batch of BA material was compacted and cured for 28 days, then tested again for the mineral content with XRD. The mineral present includes quartz in crystalline form and also in combination with alumina as mullite. In addition, the iron also present partly as oxide magnetite and hematite. One important thing to be noted is that some of the existing crystalline compound such as silicon phosphate, calcium alumina oxide and calcium oxide were disappeared. The longer the curing period, the more amounts of these crystalline compounds being disappeared. This might be due to the chemical reaction between the water and the mineral of limiting FA, attached with BA.

For comparison purpose, Abdul Talib [20] conducted the XRD analysis for the BA samples obtained from three different coal power plants in Malaysia. The result shows that the mineralogical properties of BA obtained from Tanjung Bin, Kapar and Manjung is almost similar. The majority of the mineral compounds are mullite, quartz, silicon oxide, silicon phosphate and calcite.

Awang *et al.* [21] carried out XRD analysis onto the coal ash mixtures at 6 different proportions as summarized in Table 3. From the results shown, it can be noted that the crystalline compound of Calcium Phosphide (CaP) does not appear in FA. In addition, Cristobalite appears in the coal ash mixtures if the percentages of BA is higher than 30 %.

Table 3 XRD analysis result of Tanjung Bin FA-BA mixtures [21]

Crystalline Compounds					
0%FA	30%FA	50%FA	70%FA	90%FA	100%F A
Mullite ($3AI_2O_3$.2 SiO_2), Quartz (SiO_2), Calcium Phosph-de (CaP), Calcite ($CaCO_3$, Cristobali te and Hematite	Mullite ($3AI_2O_3$ .2SiO_2), Quartz (SiO_2), Calciu m Phosphi -de (CaP), Calcite ($CaCO_3$ Cristob alite and Hemati- te	Mullite ($3AI_2O_3$ .2SiO_2), Quartz (SiO_2), Calciu m Phosphi -de (CaP), Calcite ($CaCO_3$ Cristob alite and Hematit -te	Mullite ($3AI_2O_3$. 2SiO_2), Quartz (SiO_2), Calciu m Phosphi de (CaP), Calcite ($CaCO_3$) and Hemati -te.	Mullite ($3AI_2O_3$ .2SiO_2), Quartz (SiO_2), Calciu m Phosphi -de (CaP), Calcite ($CaCO_3$) and Hemati- te	Mullite ($3AI_2O_3$ 2SiO_2), Quartz (SiO_2), Calcite ($CaCO_3$) and Hemati -te.

2.4 Chemical Properties

The X-ray Fluorescene (XRF) of model Bruker AXS S4 Pioneer was used to obtain the chemical properties of BA [19]. The results of XRF indicated that the major chemical content of Tanjung Bin BA is silica (42.7 %), alumina (23.0 %), iron oxide (17 %) and calcium oxide (9.8 %). Limiting chemical content of magnesium, kalium, barium, potassium, sodium and titanium oxides are also presence in BA.

Similarly, the chemical property of Kapar FA was examined by other researcher [22] using XRF setup (model Ringaku RIX 3000). The result shows that Kapar FA contains 59 % of silica, 21 % of alumina, 4 % of iron oxide and other chemicals.

2.5 Mechanical Properties

For the mechanical properties, the Tanjung Bin BA had been tested with compaction test, shear strength test and compressibility test [19]. The results from the standard proctor compaction test identified the OMC and the maximum dry density (MDD) of BA as 24 % and 1.14 Mg/m^3, respectively [19]. On the other hand, the values of OMC and MDD for BA from Manjung were 20.5 % and 1.13 Mg/m^3, respectively [15]. Generally, the OMC and MDD of BA varied according to the source of the material. There is no typical values could be in global agreement at this moment for these parameters.

One of the important engineering characteristics of soil is the shear strength. Shear strength is the maximum shear resistance that a soil can offer under predefined condition of effective pressure and drainage. Table 4 summarises the shear strength parameters of BA obtained through different tests; direct shear and both drained and undrained triaxial tests.

Table 4 Shear strength parameters of bottom ash [15, 23, 24]

Location	Test Name	Internal frictional angle (°)	Cohesion (kN/m²)
Tanjung Bin	Direct shear	31	0
	Drained triaxial	46	0
	Undrained triaxial	44	0
Manjung	Direct shear	40	0

The results indicated that the strength of BA solely depend on the friction between the particles, similar like non-cohesive soils. More importantly the results showed that BA could be compacted to obtain the friction angle similar to a very dense sand condition. The BA is therefore suitable to be used as backfill materials in embankment construction. The shear strength of Manjung BA that was obtained from direct shear test is higher than Tanjung Bin BA. This is because the source of the coal use is different for both coal combustion power plants. The factors that influence the shear strength are particle size distribution, particle surface characteristics, mineralogy and density [22].

As for the compressibility behaviour of BA, it is largely depending on the initial degree of saturation, initial density, and self-hardening characteristics. From the results of consolidation test, the BA shows slightly more compressible as compared to the typical behaviour of sand. Since the porosity is quite high as in BA, the angularity and rough surface of BA making it possible to be compressed. However, the popcorn like structure is very weak and causing it to be prone to deformation when extra stress is exerted onto it. Hence BA will cause high deformation initially but once settled, it will have no further long term settlement as what generally occurred in cohesive soils, due to consolidation process.

3.0 PROPERTIES OF COAL ASH MIXTURES

Research had been carried out on the properties of coal ash mixtures by [24]. Bottom ash of less than 2 mm particle sized was mixed with FA. Table 5 summarises the specific gravity of FA and BA mixtures at various composition percentages by weight. It can be observed that the value of specific gravity decreased with the increased amount of FA in the mixtures.

Table 5 Specific gravity of Tanjung Bin fly and bottom ashes mixtures [24]

Bottom Ash (%)	Fly Ash (%)	Specific Gravity
100	0	2.36
70	30	2.34
50	50	2.33
30	70	2.23
10	90	2.20
0	100	2.19

Figure 5 shows the particle size distribution of the Tanjung Bin FA and BA mixtures at four different percentages by weight as reported by [5]. At the same time, the grading curve of pure Tanjung Bin FA and BA were also shown. The particle size of FA and BA are largely ranges from 0.002 mm to 0.6 mm and from 0.06 mm to 2 mm, respectively. It can be seen that the overall grading curve shifted from right to left when the presence of FA by weight increased.

Figure 6 shows the photomicrographs of Tanjung Bin FA and BA mixtures at 1000 magnification. BA particles are angular as shown in Figure 6 (a) while FA particles are finer and rounder, as shown in Figure 6 (f). The micrographs result demonstrates that the mixtures of FA and BA can eliminate the porosity within the particle structures. This could decrease the compressibility of the coal ashes itself.

From the permeability test results with no curing period, the presence of FA in BA, decreased the permeability as the fine grained FA filled within the void spaces of coarse grained BA. Without the pores, the permeability will be smaller. However, the permeability coefficient increased after the content of FA exceeded 50 % by weight. Based on the work of Marto and Tan [25], it could be said that the arrangement of the coal ashes mixture was transformed from sand dominant to fine dominant when the threshold fines content (f_{th}) was exceeded. For this particular Tanjung Bin coal ash, the f_{th} might be identified to occur at about 50 % of FA by weight. This however, needs to be further investigated.

The unconfined compressive strength (UCS) tests on FA-BA mixtures at various curing periods showed that the UCS increased with the increased in FA content up to 50% then decreased thereafter. The 50%FA–50%BA mixture had the highest UCS of 127 kPa, 291 kPa and 447 kPa at 0, 14 and 28 days curing periods, respectively [24]. The results were in line with permeability tests of the mixtures. Hence, this mixture of 50 % FA and 50 % BA could be the optimum mixture for coal ashes from Tanjung Bin power plant based on compressive strength.

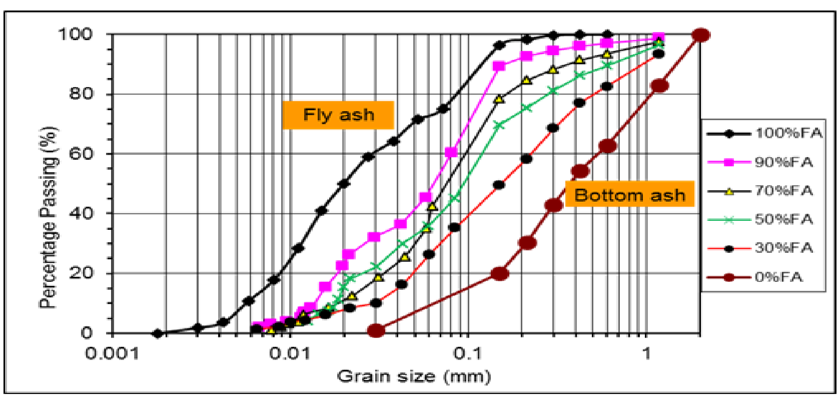


Figure 5 Particle size distribution of Tanjung Bin fly ash, bottom ash and fly and bottom ashes mixtures [5]

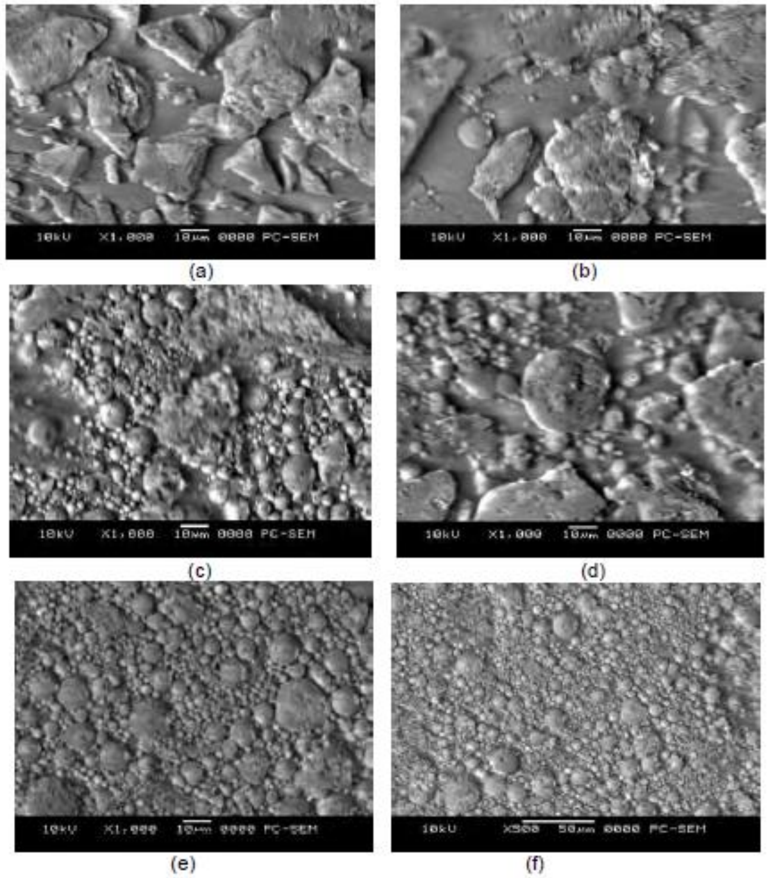


Figure 6 SEM microphotograph of Tanjung Bin coal ashes mixtures [19] (a) 100 % BA, (b) 70% BA:30 % FA, (c) 50% BA:50 % FA, (d) 30% BA:70 % FA, (e) 10% BA:90 % FA and (f) 100 % FA

4.0 APPLICATION OF BOTTOM ASH IN SOIL IMPROVEMENT WORKS

BA particle is physically coarse, porous and granular. The engineering characteristics of BA is almost similar to sand with the shear strength is contributed by the friction between the particles. In addition, the permeability characteristics is also good because of the porosity existed within the BA particles. Although the material is crushable if in large sizes, there is still a huge potential whereby the BA could be used as the material for embankment fills or standalone as the material to improve the soft soil. Kumar *et al.* [26] investigated the geotechnical properties of fly ash and bottom ash mixtures in different proportions. The following sub-sections present some initial results of the evaluation on the utilisation of BA in soil improvement works.

4.1 Bottom Ash Mixed with Soft Clay

A research had been carried out by adding three percentages of Kapar BA (25 %, 50 % and 60 % by weight) into soft kaolin to observe the changes of the engineering characteristics of kaolin [12]. It has been observed from the findings that the specific gravity of soft kaolin decreased when the amount of BA added increased. This is because the Kapar BA has lower value of specific gravity compared to kaolin. The specific gravity of Kapar BA and kaolin is 2.01 and 2.66, respectively. On the other hand, the permeability coefficient increased as the Kapar BA was added to soft kaolin soil. The permeability coefficient of kaolin with 25 %, 50 % and 60 % of BA by weight were 4.42 x 10^{-5}, 5.84 x 10^{-5} and 5.97 x 10^{-5} m/s, respectively.

As for the consolidation behaviour, the increasing amount of Kapar BA expedites the consolidation process. This is because the permeability coefficient of BA is high, thus providing extra drainage and it catalyst the dissipation process of pore water. The measured coefficient of consolidation for 25 %, 50 % and 60 % of BA in kaolin were 0.95, 2.01 and 2.86 m^2/year, respectively [12].

The shear strength parameters of kaolin added with Kapar BA at different percentages by weight was also tested with direct shear test and unconsolidated undrained triaxial test. It showed that the higher the amount of kaolin was replaced by Kapar BA, the lower the cohesion the soil has. On the other hand, the higher the amount of kaolin was replaced by Kapar BA, the higher the friction angle the soil has. This is true because the BA has very similar engineering characteristics with sand. As discussed earlier, the Tanjung Bin BA itself has no value of cohesion when tested with direct shear and triaxial test. Thus, with the addition of BA in kaolin; the BA plays the role in contributing the shear strength through the friction between the particles. This is attributed by the physical characteristics of BA in which it has rough surface texture and angular in particle shape.

By considering the above mentioned influence of BA when mixed with kaolin, it can be stated that BA appears to be a suitable material to be used in soil improvement work on soft soils. In addition, the utilisation of such waste materials is definitely an ideal solution to achieve the sustainable development in civil engineering.

4.2 Bottom Ash as Stone Column

Stone column is one of the ground improvement method in which a portion of soft soil is replaced with granular material such as crushed rocks or sand. As the BA is quite similar to the properties of sand both physically and in engineering aspect, there is a potential where BA could be used as the material to form as a stone column.

Figure 7 shows the installation of Tanjung Bin BA stone column in soft kaolin soil. The BA stone column was installed in the soft kaolin both individually (singular) and in a group of three columns. The cylindrical sized soil samples of 50 mm diameter and 100 mm height, installed with the BA stone column were tested under the consolidated undrained (CU) triaxial tests to determine the shear strength parameters. The study investigated the effect of different area and height replacement ratios of BA stone column in soft kaolin. The BA stone column was installed with two different diameter sizes which were 10 mm and 16 mm. The stone column was also divided into another three set which was installed to a height of either 60 %, 80 % or to the full height of the cylindrical sized soil specimen.

(a) Singular b) Group

Figure 7 Soft kaolin installed with BA stone column [17]

Figure 8 shows the shear strength parameter obtained from the CU triaxial tests reported by [17]. Results indicated that the apparent cohesion of soft kaolin installed with partially penetrating BA stone column, especially at a penetrating height of 0.8, was higher than the fully penetrated column. This 0.8 had been identified as the critical height penetration ratio for BA column. The internal friction angles were almost similar for all the specimens. In addition, the soft kaolin installed with group BA columns has higher value of cohesion compared to the soft kaolin installed with singular BA column. This indicated that the higher the area replacement ratio, the higher the value of apparent cohesion was observed.

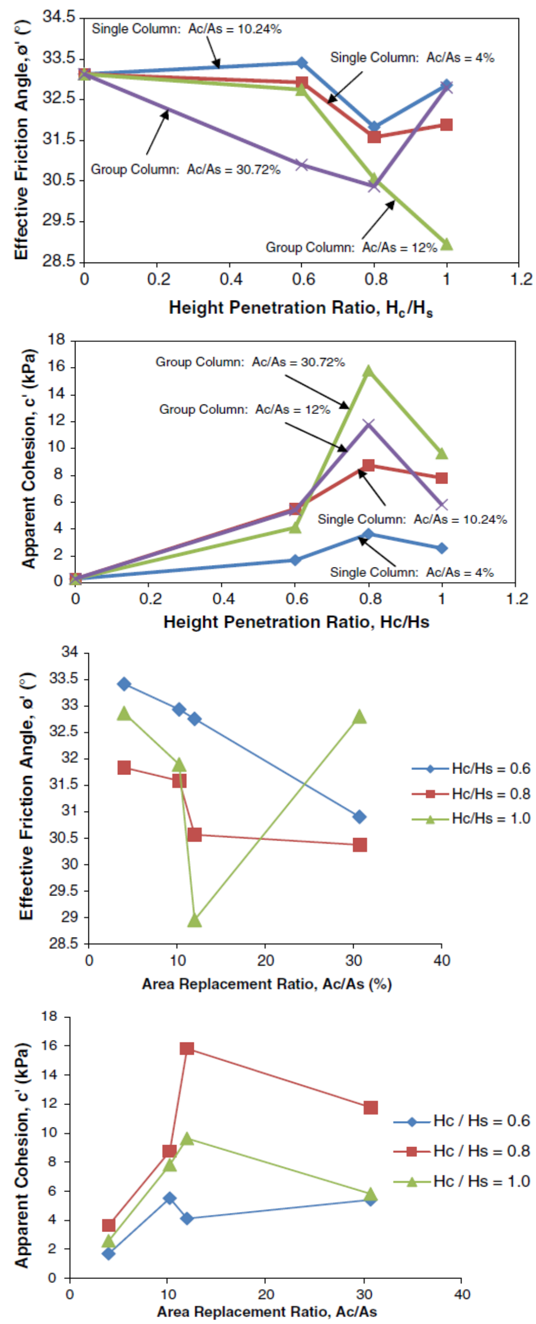


Figure 8 Shear parameter of kaolin with BA column [17]

4.3 Mixture of Fly Ash and Bottom Ash as Soil Replacement

The physical model tests had been carried out to investigate the settlement performance of soft kaolin with and without the replacement with Tanjung Bin FA and BA mixtures [27]. The results are summarised in Tables 6 and 7. Table 6 shows the settlement of kaolin and the FA and BA mixtures as full replacement ($H_m/H=1$, H_m is thickness of mixture, H is initial thickness of soil) of the kaolin while Table 7 shows the settlement of kaolin with various replacement ratios of 50 % FA and 50 % BA mixtures. From Table 7, it shows that the replacement of soft clay by FA and BA mixtures reduced the settlement significantly. Besides that, the settlements of the mixtures were constant when it reached 14 days of loading. By comparing different percentages of the mixtures, the 50 % BA and 50 % of FA has the smallest settlement compared to other ratio of coal ash mixtures.

Table 6 Settlement performance of soft kaolin mixed with FA and BA mixtures with full replacement [24]

Materials	Settlement (mm) at curing periods (days)			
	3	7	14	28
Kaolin	13	16	18	19
50 % BA & 50 % FA	1.9	2.7	2.9	2.9
30 % BA & 70 % FA	2.6	3.5	3.7	3.7
10 % BA & 90 % FA	5.6	7.7	8.5	8.6

Table 7 Settlement performance of soft kaolin mixed with partial replacement of 50 % BA and 50 % FA [15]

Replacement ratio, H_m/H	Settlement (mm) at various curing periods (days)			
	3	7	14	28
1.0	1.9	2.7	2.9	2.9
0.375	8.6	10.1	12.0	13.9
0.125	12.9	14.9	16.6	18.2

Table 7 shows the settlement performance for the coal ashes mixtures at three different replacement ratios. It can be observed that the settlement is the lowest at full replacement ratio. Thus, from the results shown in Table 6 and 7, it can be stated that the settlement performance is the best for full replacement of soft clay using coal mixtures of 50 % FA and 50 % BA by weight.

Similarly, the finding of Kim *et al*. [28] had proven that the coal ash mixture is an ideal material to be use in constructing highway embankment as compared to those conventional material. The results shows that coal ash mixtures exhibit well defined moisture density relationship, more compressible due to higher crushability of bottom ash and higher shear strength as compared to conventional material used for constructing the highway embankment.

5.4 Mixture of Bottom Ash and Rubber

Kim and Kang [29] studied the mechanical characteristics of BA and rubber crump mixtures as recycling material. The mixtures were prepared at five different percentages of rubber content and three different percentages of bottom ash content. Results show that the addition of BA increased the unit weight and the unconfined compressive strength at a given rubber content. However, the addition of rubber content at same percentages of BA resulting an opposing observation.

Similarly, Kwon and Kim [30] added the waste fishing net in the mixtures of BA and rubber crump. In general, the rubber crump had decreased the internal friction angle of the soil mixtures due to the existing compression behaviour of rubber crump. However, the internal friction angle is increasing if the mixtures were added with the reinforced fishing net. The interlocking effect causing by the fishing net increased with the number of interlocking layer.

5.0 CONCLUSION

This paper reviews the engineering characteristics of bottom ash and the applicability of the material in geotechnical engineering works. From the laboratory and physical model tests results, the bottom ash shows a huge potential to be utilised as alternative materials in geotechnical works. It can be used as standalone or mixed with the fly ash or the natural soils as fill materials in embankment construction or for soil improvement works. By doing so, it is not only beneficial by providing an ideal solution to solve the geotechnical problems but also reduces the volume of waste to be post process after the coal combustion.

Acknowledgement

The authors would like to extend their appreciation to the Ministry of Higher Education (MOHE), Malaysia for funding most of the research. Acknowledgements are also due to the Faculty of Civil Engineering (FKA), Universiti Teknologi Malaysia (UTM) for providing the necessary facilities. Not to forget to all the former and current members of Soft Soil Eng. Research Group, FKA, UTM, who had contributed in the research.

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