The potential of coal combustion products as soft soil improvement materials

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ABSTRACT
In recent years more constructions such as buildings and embankments have been built on soft soils, especially in south-east Asia countries. Such soils exhibit large volume changes, low shear strength and relatively high moisture contents. This phenomenon increased the need for soil improvement techniques such as stone columns, surface vibratory compaction, and the likes, with an additional price tag on the overall cost of the project. These have raised the need for new innovative, efficient, environmentally friendly soil improvement techniques and, if possible, reduce cost.
Coal combustion products are produced in large amounts from coal burning electrical power plants. To some extent, such products have been successfully utilized in concrete either as an additives or a substitute for the aggregates. However, such materials are not being utilized, in soil improvement, as compared to concrete.
A pilot study was initiated at University Technology PETRONAS, Malaysia, to investigate the potential of some coal combustion products, such as Pulverized fly Ash (PFA) and Bottom Ash (BA), as soil stabilization materials for soft soils. In this paper, the findings for the impact of such materials on the California Bearing Ratio (CBR) of soft soils are presented.
A significant increase of the soaked CBR values of the treated soils were noticed. Further, fly ash seems to be more effective in improving the CBR as compared to bottom ash.

RÉSUMÉ
Au cours des dernières années plus de constructions comme les bâtiments et les digues ont été construites avec des terres molles, surtout dans le sud-est de l'Asie. De ces terres exposent un grand volume de changements, un décalage dans leur résistance et relativement de hautes teneurs en humidité. Ce phénomène a augmenté le besoin d'améliorer les techniques de la terre avec une étiquette supplémentaire sur le prix général du projet. Pour y parvenir, il faut qu'il y ait de nouveaux techniques innovants, efficaces, et un environnement amical pour améliorer la terre, et, si possible, qu'on réduise le prix considérablement. Les produits de combustion à charbon sont fabriqués en grandes quantités dans les usines de génération électrique fabricant du charbon brûlant. Ces produits, dans une certaine mesure, sont utilisés avec succès dans le béton comme des additifs ou un produit de substitution pour les agrégats. Pourtant, un tel matériel n'est pas utilisé, dans le renforcement de la terre, en comparaison du béton.
Une étude pilote a été transmise à l'Université Technologique de PETRONAS, Malaisie, pour enquêter sur le potentiel de quelques produits de combustion à charbon, les Cendres volantes Pulvérisées (CVP) et les Cendres Lourdes (CL), comme matériaux de stabilisation de la terre pour les terres molles. Dans ce papier, les conclusions relatives à l'impact de ces matériaux sont indiquées dans le Rapport de Support de Californie (RSC) des terres molles.

1 INTRODUCTION

Soft, swampy and organic soils are, generally, abundant in tropical countries such as Malaysia. Such soils normally possess high moisture content, lower shear strength and exhibit high compressibility. Utilizing such soils as construction materials and/or bearing foundation layers without some means of improving such adverse properties is almost impossible. Several techniques are currently available, and have been successfully being implemented to treat such soils. Still, research is definitely needed to enhance such techniques and/or introduce other more economical and efficient techniques.

Every year large amounts of coal is burned in electrical power generating plants in Malaysia. The process will, annually, produce large amounts of coal combustion products (CCPs) such as pulverized fuel ash (PFA) and bottom ash (BA). The amount of PFA and BA generated by those electrical power plants is increasing year by year. By the year 2008, Malaysia will use about 11.2 million tons of coal per annum. This will produce more than 2 million tons of PFA and BA annually which need to be disposed and/or buried in landfill areas, Ministry of Finance (2000). As such, a tremendous increase in coal combustion products is anticipated unless an alternative energy sources are introduced. Hence, means of utilizing such material for beneficial effective usage has to be introduced to minimize the cost of landfill and introduce an environmentally friendly utilization of such waste materials. In fact such materials have been utilized as in concrete either as replacement to some of the aggregates or as admixtures to make use of their pozzolanic reactions, because of the calcium cation exchange.

Lime, being a highly pozzolanic material, is an excellent choice for the improvement of soil properties. It can modify, almost, all fine-grained soils while the dramatic improvement occurs in clayey soils of moderate to high plasticity. The soil improvement occurs because the calcium cations supplied by lime replace the cations normally present on the surface of the clay mineral. This cation exchange results in reduction in plasticity, swell and moisture-holding capacity, improve stability and, generally, increase in shear strength of the clayey soils, Rogers (2000). In addition, lime has the advantage that higher temperature has a positive impact on the stabilization process, or the pozzolanic reaction compared, for an example, to the adverse impact of temperature in cement stabilization. However, one drawback for lime stabilization, at least in Malaysia, is its high cost. Though this might be compensated by the lower percentages of lime required for the soil improvements as compare to other additives, still, other more viable means of soil improvements are needed to be investigated.

A comprehensive research program is currently underway in University Technology Petronas to study the feasibility of PFA, BA and lime as stabilizing additives to improve some engineering properties of soft soils. Awad and Harahap (2007) presented the initial findings of the impact of lime on soft soils from Malaysia. In this article, the potential of coal combustion products, namely pulverized fly ash (PFA) and bottom ash (BA), on the California Bearing Ratio (CBR) is discussed. Section 2 present soft soils in Malaysia, while the soil improvement technique is presented in Sec. 3. Testing and results are provided in Sec.4 and the conclusions and recommendations are provided in Sec.5.

2 SOFT SOILS IN MALAYSIA

Soft and swampy soils consisting of peat and organic cover about 2.7 million hectares in Peninsular Malaysia, 1.66 million hectares in Sarawak and 66,000 hectares in Sabah. This comprises about 8% of the total land area of the whole country, Huat et al, 1998; Hobbs, 1986; Nieuwolt, 1982. Within the stretch of Ipoh-Rawang double track project, for an example, the soil improvements required to enhance the soft soil properties encountered in the area formed a substantial percentage of both the budget and the construction time frame of the project. For that project, several techniques such as stone columns, cement columns, surface vibratory compaction, to name few, aside from the regular removal and replacement of the unsuitable soils, had to be adopted for the site to obtain some favourable soil properties.

Soft soils have low shear strength and are susceptible to large volume changes and may be composed of sands, silts, clays, organic soils or combination of these materials. Such soils show a significant variation in engineering properties such as void ratio, permeability and strength, possibly due to the sedimentary process. Furthermore, they may exhibit high compressibility and, in their in-situ untreated condition, provide unsuitable construction material and/or poor founding material.

Generally, soft soils need to be investigated because of the problems they may create during and/or after construction. They can cause cracking to the structures, excessive total and differential settlements, pavement ruptures as well as increasing the maintenance cost of the structure at hand. Such problems may be alleviated if the soft soils are treated or removed.

It is to be noted, however, that 'soft soils' is a general terminology that is used in the industry, in south east Asia, to distinguish a certain type of soil and, generally, there is nothing to relate with the consistency limits of that soil. They are identified as 'soft' if the soil exhibits black and/or grey colour, has fine grains, may have unpleasant sewage-sludge like odour. This characterization, the author feel, is vague and need more definitive limits for the soils to be classified as 'soft'. On the other hand, the term 'organic', as applied to soils designates those containing an appreciable amount of decayed animal and/or vegetable matter. All organic soils, be it peat, organic clays, organic silts or even organic sands are, generally viewed with suspicion as foundation and/or construction materials. Certain type of organic matter may not be detrimental but others may be objectionable for their low shear strength, high compressibility and may contain toxic gases that are released during excavation, Lambe (1968). The geotechnical engineers, generally, resort to other research findings such as soil science to augment the understanding and/or classification of organic soils or peat. In this article, the term 'soft' coincides with the normal terminology in soil mechanics, i.e. when the unconfined compressive strength of the clay material is less than 50kPa.

3 SOIL IMPROVEMENT APPROACH

In times of urbanization, growth of population and associated developments, construction activities are more and more focused on soft soils which are considered unsuitable in the past decades. These soil deposits have a low bearing pressure, or shear strength, and exhibit large settlements when subjected to loadings. It is therefore inevitable to treat such soil deposits prior to construction activities in order to prevent unfavoured total and/or differential settlements and subsequent potential damage to the proposed structure.

Soil improvement has been widely used in almost every type of soils. The most common application is in the strengthening of highways, airfield pavements, railways and the likes. There are also different techniques and approaches that may be suitable to some type of soils but not as effective to other types. Each and every soil improvement technique shall lead to an increase of shear strength, a reduction of soil compressibility and, generally, improved permeability. The choice of a specific soil improvement technique depends on the geological formation of the soil, soil characteristics, cost, availability of backfill material and experience in the specific methodology. One may refer to Schaefer (1997) for more details or the classic article by Lambe (1962) in which a comprehensive material on the subject is provided. For this research, the additive approach is adopted where pulverized fly ash (PFA) and bottom ash (BA) are utilized to investigate and/or quantify their potential in improving soft soils in Malaysia.

Generally, pozzolanic materials such as lime are effective additives to stabilize plastic soils and have been proven to reduce the soil moisture, improve workability, reduce the Liquid Limit and Plasticity Index, limit volumetric changes and increase the shear strength of such soils, Collota et al (2003), Greaves (1996) and Bell (1993). The addition of lime to fine grained soils initiates the following three reactions:

a. Drying out of moisture by absorption and evaporation that will result in an immediate moisture content reduction.
b. Rapid physio-chemical reaction between lime and the clay minerals resulting in changes in soil plasticity and workability, and
c. Long-term soil-lime pozzolanic reactions resulting in the increase of strength and durability.

Ash, on the other hand, is a by-product of coal thermal power generating plants. Two types of ashes are produced from this process, namely bottom ash (BA) and pulverized fuel ash, also called fly ash, (PFA). Both ashes are sometimes referred to as coal combustion products (CCP). When coal is burned, it leaves behind ashes some of which fall to the bottom of the boilers, and hence the name bottom ash, and some are carried upward by the hot gases, and thus the name of fly ash. Bottom ash is almost sand-like material with particles, generally, passing 12.7mm sieve, grey to black in colour. However, PFA is a finely divided residue of particles ranging from 0.1-1.0μm and resembles talcum powder. Both BA and PFA are pozzolanic in nature consisting of silica, alumina and calcium-based materials. While PFA is one of commonly used additive in soil stabilization, BA is hardly utilized as such. Still, BA has been used as filler, backfill material, base course and even embankment materials.

Previous research in soil stabilization concentrates mainly on the use of fly ash, lime, cement micro silica or combination of such. In fact, not much research is carried out on what impact bottom ash may have on soft soils. Nevertheless, some studies were carried out to determine the potential of BA fine aggregates substitute in both road construction and concrete such as Jaturapitakkul et al (2003), Churchill and Amirkhanian (1999) and Ghafoori and Bucholc (1996), to name few. BA has been used as fine aggregate substitute in hot mix asphalt wearing courses and more frequently in base courses, probably because of the BA durability nature. Apart from that, BA has been used in concrete mixes to improve workability and replace the fine aggregates as well as reduce the dead load of the structure due to the lower unit weight as compared to the regular fine aggregates.

Sahu (2001) reported that the CBR of soils increased with fly ash content with substantial increase in the CBR of sandy soils as compared to fine-grained soils. Those soil samples were cured for seven days prior to conducting the soaked CBR test. Kuan-Yeow et al (2003) indicated that PFA is a potential source of jet-grouting admixture for soil improvement. Tuncer (2006) indicated that adding 10 and 18% fly ash to fine grained soils compacted at typical in situ moisture contents (in Wisconsin, USA) resulted in an increase in CBR by a factor of 4 and 8 respectively. For the research at hand, the investigation is concentrated on both BA and PFA to quantify their impact on the soft soils of Malaysia.

4 TESTING AND RESULTS

The planned testing program for this research includes both unconfined compressive strength and the California Bearing Ratio (CBR) for the soil-ash mixtures. In this article, however, only the impact of two types of ash BA and PFA on CBR is presented. The chemical composition, using X-Ray Fluorescence (XRF) test, of the soil, BA and PFA is provided in Table1. This type of ash is referred to as Class F Fly Ash, ASTM C618.

Table 1. Chemical composition of the test materials.

Oxide	Soil	Bottom Ash (BA)	Pulverized Fuel Ash (PFA)
Na_2O	0.21%	0.20%	0.22%
MgO	0.59%	0.98%	1.03%
Al_2O_3	36.7%	20.1%	21.9%
SiO_2	55.1%	57.1%	56.8%
P_2O_3	0.13%	0.26%	0.34%
K_2O	3.15%	1.4%	1.92%
SO3	0.17%	2.22%	0.77%
CaO	0.40%	6.39%	6.78%
Fe_2O_3	2.62%	8.87%	7.31%
TiO_2	0.70%	1.82%	2.18%

Table 2 presents values of some of the basic properties of the selected soil. As shown there, the initial moisture content of the sample was higher than its liquid limit. This clearly indicates that the natural sample was, more or less, in the liquid state. The soil can be classified as ‘inorganic clay of medium plasticity as per the Unified Soil Classification System.

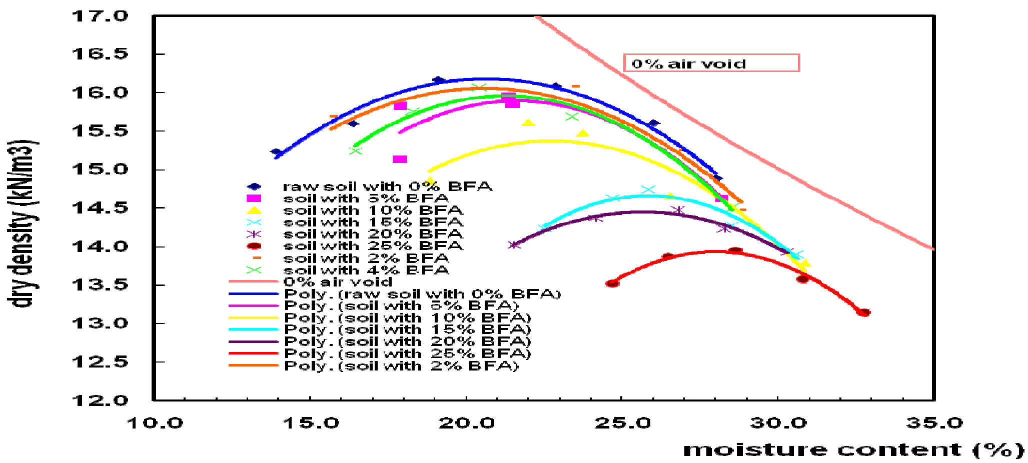
Table 2. Basic properties of the utilized soil.

Property	Value
Natural Moisture Content, ω_n	58%
Liquid Limit, L.L.	45%
Plasticity Index, P.I,	17%
Optimum Moisture Content, ω_{opt}	21%
Maximum Dry Density, γ_{dry}	16.3 kN/m^3
Organic Content	4.5 – 10%
Soil Classification, USCS	Inorganic Clay of Medium Plasticity

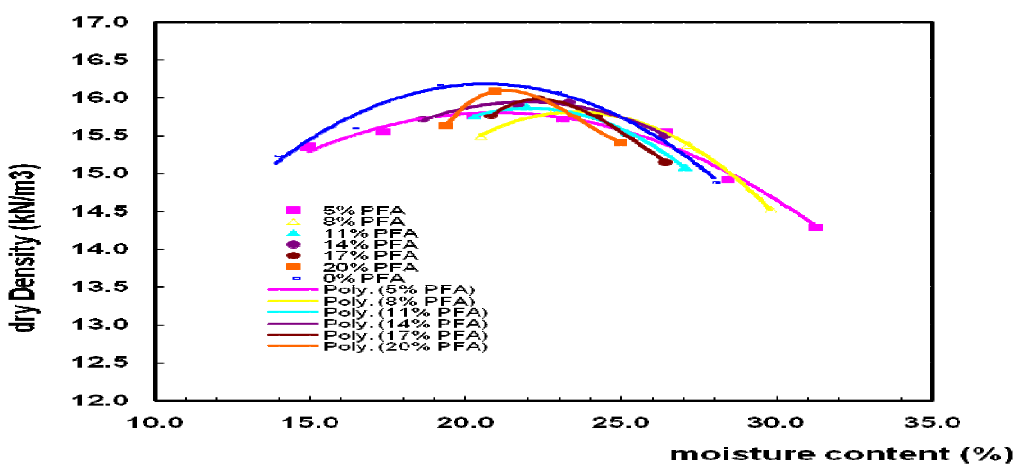
Figs. 1 (a) and (b) present the compaction test results conducted on the soil with different percentages by weight of BA and PFA respectively. Fig.1 (a) indicates that the maximum dry density of the BA-soil mixture decreased and the optimum moisture content decreases as the percentage of added BA is increased in the mixture. Generally, this is the anticipated trend in soil stabilization when the additives are of lower specific gravity than that for the natural untreated soils. On the other hand, Fig. 1(b) indicates the followings:

i. The maximum dry density of the soil-PFA mixture is less than that of the row soil,
ii. For the soil-PFA mixture, the maximum dry density of the mixture increased with the increase in PFA percentage.
iii. There is hardly any impact of PFA on the optimum moisture content on the soil-PFA mixture.

This trend is also reported by Sahu (2001), though it might be contradicting with the soil stabilization norm.



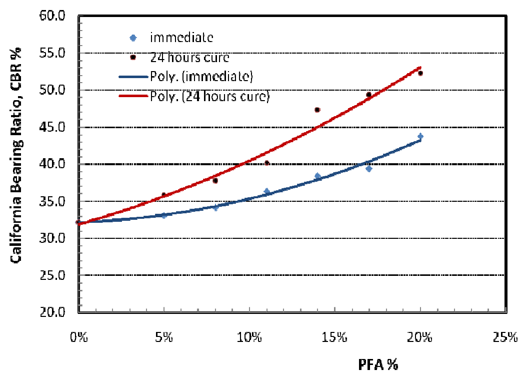
(a) Soil + BA



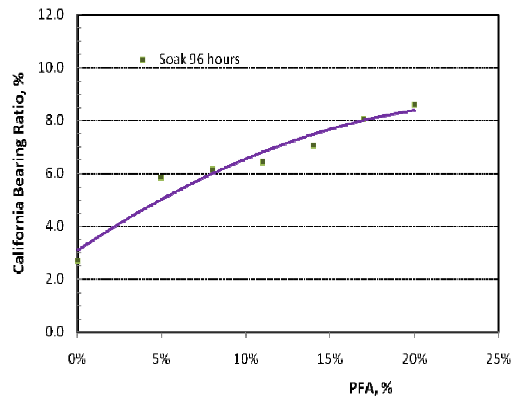
(b) Soil + PFA

Figure 1. Results of the compaction test for the stabilized soil.

Figs. 2 (a) and (b) present the California Bearing Ratio (CBR) test results of the soil stabilized with different percentages of fly ash (PFA). As indicated in Fig. 1(a), the unsoaked CBR value increased as the percentage of the PFA is increased. The increase is about 34% with the addition of 20% by weight of PFA. The increase in CBR becomes more apparent when the treated samples are allowed to cure where the increase in CBR value of the treated soil is 60% more than that of the untreated one for curing of only one day. This suggests that the pozzolanic reaction, which requires some time to develop, is taking place. The increase in the CBR values of the treated soil becomes more apparent when the soaked CBR values are compared with each other. As shown in Fig. 2 (b), the CBR of the soil samples treated with only 10% PFA and tested after 96 hrs soaking is more than double that of the untreated soaked soil. The increase becomes more than three folds when the percentage of PFA is 20% by weight. This substantial increase will have a big impact on the design of pavements by reducing the thickness of the base courses. Needless to say that the impact on the cost might, also, be substantial.



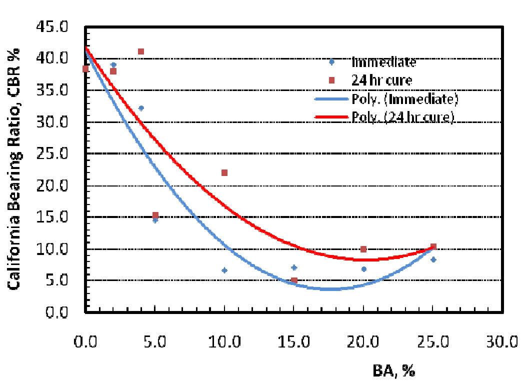
(a) Unsoaked CBR



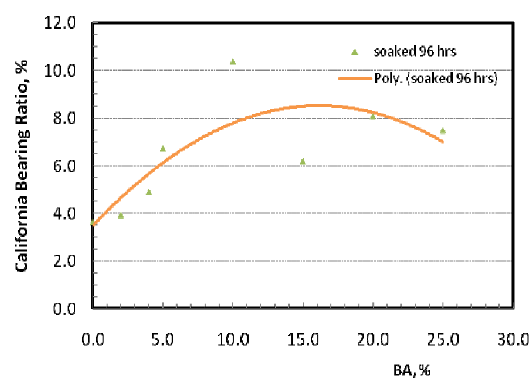
(b) Soaked CBR

Figure 2. Impact of pulverized fuel ash (PFA) on the CBR of the treated soil

The results of the CBR tests for the bottom ash treated soils are shown in Figs. 3 (a) and (b). The unsoaked CBR test results; Fig. 3 (a) indicated that the CBR values decreased as the percentage of bottom ash is increased and the minimum value is at about 18% BA by weight beyond which the CBR value increased slightly. Samples cured for 24 hrs exhibited the same trend though a slight gain in the CBR values is realized when compared with their counterparts of the same BA content but tested immediately. This increase in CBR may be attributed to the pozzolanic reaction, which requires time to develop. On the other hand, the soaked CBR values increased as the percentage of added BA is increased up to about 16% beyond which the CBR started to decrease. The optimum BA content, then, is around 16% for which the CBR value is more than double its counterpart for the untreated soil. This notable increase in CBR may be attributed to the sufficient time and/or water provide for the pozzolanic reaction to materialize, especially that the percentage of calcium oxide available for in BA is low as compared, for example, to lime. Taking into consideration that the only the soaked CBR values are considered in the design of base courses, this appreciable increase in CBR can be of great impact on both the thickness of the base course layers and the cost of such.



(a) Unsoaked CBR



(b) Soaked CBR

Figure 3. Impact of bottom ash (BA) on the CBR of the treated soil

It is to be noted that these test results confirm those reported by Tuncer et al (2006). Still, additional testing is highly recommended to confirm the findings and to extend the curing time for all samples. It is, also, worthwhile to investigate the impact of both BA and PFA on the swell properties of the treated soils.

5 CONCLUSIONS AND RECOMMENDTIONS

A comprehensive testing program to investigate the potential of lime, bottom ash and pulverised fly for the improvement of soft soils is being conducted at the University Technology PETRONAS (UTP), Malaysia. The said program concentrates on the unconfined compressive strength and the California Bearing Ration (CBR). For this article, the results of the impact of fly ash (PFA) and bottom ash (BA) on the California Bearing Ratio (CBR) are discussed. Such results shed some light on the behaviour of treated soil and provided the following conclusions:

- The addition of BA or PFA to the soft soils reduced the maximum dry density of the treated soil. Also, this reduction in the dry density is more noticeable in BA treated soil as compared to the PFA treated one.
- The optimum moisture content of the BA treated soil increases with the increase in the percentages of added bottom ash. On the other hand, the optimum moisture content of the PFA treated soil is hardly affected by the percentage of added fly ash.
- A significant increase in the soaked CBR values is achieved, as compared to untreated soil, when the soft soil is treated with either bottom ash or fly ash.
- Fly ash seems to be more effective than bottom ash in improving the California Bearing Ration of the utilized soft soil. This may be attributed to the pozzolanic reaction being more effective in the finer fly ash.
- Samples cured for just one day exhibited higher CBR as compared to those tested immediately after compaction, i.e. without curing time. This trend is noticed for PFA as well as BA treated samples.

It is highly recommended to enhance the test program and to investigate, and quantify, the impact of the curing period on the CBR of the treated samples. In addition, the swell properties are needed to be quantified, too.

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