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# Applicability of coal bottom ash for the rehabilitation of clay mines: Potential as a backfill material

## Applicabilité des mâchefers de charbon pour la réhabilitation des mines d'argile: potentiel comme matériau de remblai

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ABSTRACT: The higher cost associated with the restoration of clay mines and shortage of suitable filling materials have created many abandoned clay mines in Sri Lanka, which leads to many environmental and health issues. Coal bottom ash (CBA) generated during the coal combustion process as a by-product is a potential fill material. Currently, most of the CBA is open dumped into nearby lands creating environmental pollution and utilizing CBA as a fill material for clay mine restoration will be a suitable solution for these problems. Therefore, main objective of this study is to investigate the applicability of CBA as a partial or full replacement of the existing fill materials for clay mine rehabilitation. CBA produced from Lakvijaya coal power plant, Sri Lanka was used and the basic properties, shear strength parameters, compressibility characteristics and heavy metal leachability of CBA were investigated. According to results, CBA behaves as a poorly graded and non-cohesive material with a friction angle of 35°. Further, CBA can be considered as a free draining material with low compressibility. The highly porous structure of CBA caused a lower dry density (975 kg/m$^3$). However, it can be improved using 10 – 25% of soil to CBA. Further, the leachability potential of trace metals in CBA does not exceed the allowable limits. Thus, CBA would be a suitable fill material for clay mines restoration or similar uses.

RÉSUMÉ : Le coût plus élevé associé à la restauration des mines d'argile et la pénurie de matériaux de remplissage appropriés ont créé de nombreuses mines d'argile abandonnées au Sri Lanka, ce qui entraîne de nombreux problèmes environnementaux et sanitaires. Les mâchefers de charbon (CBA) générés pendant le processus de combustion du charbon en tant que sous-produit sont un matériau de remplissage potentiel. Actuellement, la majeure partie du CBA est déversée à ciel ouvert dans les terres voisines, créant une pollution environnementale et l'utilisation du CBA comme matériau de remplissage pour la restauration des mines d'argile sera une solution appropriée à ces problèmes. Par conséquent, l'objectif principal de cette étude est d'étudier l'applicabilité de CBA en tant que remplacement partiel ou complet des matériaux de remplissage existants pour la réhabilitation des mines d'argile. Le CBA produit à partir de la centrale au charbon de Lakvijaya, au Sri Lanka, a été utilisé et les propriétés de base, les paramètres de résistance au cisaillement, les caractéristiques de compressibilité et la lixiviabilité des métaux lourds du CBA ont été étudiés. Selon les résultats, le CBA se comporte comme un matériau mal gradué et non cohésif avec un angle de frottement de 35°. De plus, le CBA peut être considéré comme un matériau à drainage libre avec une faible compressibilité. La structure très poreuse du CBA a entraîné la densité sèche plus faible (975 kg/m$^3$). Cependant, cela peut être amélioré en utilisant 10 - 25 % de sol en CBA. De plus, le potentiel de lixiviabilité des métaux traces dans le CBA ne dépasse pas les limites admissibles. Ainsi, le CBA serait un matériau de remplissage approprié pour la restauration des mines d'argile ou des utilisations similaires.

KEYWORDS: clay mines, coal bottom ash, compaction characteristics, fill material, geotechnical applications

## 1 INTRODUCTION

### 1.1 *General Background*

In the world, about 64 million metric tons of clay was mined in the year of 2019 to facilitate the increasing population and the industrial needs (US geological survey 2020). To supply this need, hundred thousand of clay pits are mined all over the world and the mining has become mechanized. This mechanized clay mining generated larger pits with average depth of 8-24 feet (Ranasinghe 1996). As a result of continuous mining, many topological changes like unstable slopes and soil erosion tend to occur (Matsumoto et al. 2016). In addition, the soil degrades and brings a lot of health hazards for the people in the area due to collection of water in those pits in rainy seasons (Ranasinghe 1996).

Many countries have formed rules and regulations for rehabilitation of those pits after mining. Mineral resources act of 1989 in Australia, mineral act of 1967 in Thailand, mining law no 11 of 1967 in Indonesia, mining enactment of 1929 in Malaysia, ordinance on mineral resources of 1989 in Vietnam, mines and mineral act 1957 of India and mines and mineral act no 33 of 1992 in Sri Lanka are some of those regulations in several countries which bound the holder of the mining license to rehabilitate the mined pits. However, these pits are abandoned by miners without any rehabilitation due to higher cost and non-availability of suitable fill materials. Nevertheless, the demand is increasing day by day and limitations could not be imposed as the supply must be increased relative to the demand. Hence, it is needed to identify a practical and feasible solution for the rehabilitation of these abandoned clay mines.

### 1.2 *Coal Bottom Ash (CBA)*

CBA is an industrial waste by-product of coal combustion process that fall to the bottom side of the furnace and its management is a growing concern globally due to its huge volumes. The common method used for disposal of the CBA is open dumping into lands which creates environmental issues such as air, water and soil pollution. According to the study of World of Coal Ash (WOCA) the estimated generation of CBA from coal thermal power plants has been moved to an approximate amount of 730 million metric tons per annum (Singh et al. 2019). In Sri Lanka at Lakvijaya power plant, 250,000 metric tons of coal ash (50,000 metric tons of CBA and 200,000 metric tons of fly ash) are produced annually (Gimhan et al. 2018). It is estimated that 20 metric tons of CBA per day are directly dumped to the yard, without being used for any purpose (Erandi & Sakunthala 2013).

Hence, power plant must bear extra costs for disposing this CBA since it is part of the national regulations in managing and disposing the wastes products. And it may have some effects to the end users as there is a tendency for these power plant companies to transfer the extra costs to them. Therefore, the engineers had to think of good reuse options to mitigate the stacking of CBA in high volumes as a result of this.

### 1.3 *Characteristics of CBA*

CBA is an incombustible by product of coal which predominantly contains coarse grained particles. Jayaranjan et al. (2014) found that particle diameter of CBA is between 0.1 – 10 mm and ranges from sand to fine gravel. Yuksel & Genc (2007) stated that with some deviations in the size of particle distribution, CBA is a well-graded material. The physical nature of CBA varies from sample to sample because of the variations in types of coal used by the coal thermal power plants (Kim & Lee 2015). Generally, CBA is angular and irregular in shape. The surface texture of CBA is rough and gritty (Kim et al. 2005). Moreover, the structure of CBA is microporous with fine fragments (Matsumoto et al. 2016).

CBA expresses comparatively high permeability with well-graded particle distribution, which enables the usage of it in direct interaction with impermeable materials (Maliki et al. 2017). In addition, CBA exhibits high shear strength and low compressibility (Lynn et al. 2017). These engineering properties make CBA as an ideal and economical material in civil engineering applications.

### 1.4 *CBA for geotechnical applications*

CBA is utilized for many different purposes in various ways in different countries on par with the necessities and also used for geotechnical related applications. Further, CBA has been tested in different forms as mixtures of CBA and fly ash, CBA and soil, CBA alone and etc.

The usage of CBA for mechanical stabilization of subgrade soil has been discussed by few researchers (Cadersa et al. 2014, Sivakumar 2014). Kim et al. (2005) has described the suitability of fly ash-CBA mixture in embankment construction and have stated that CBA can be used in massive projects like in highway embankment construction. Further, CBA can be used as a geotechnical drainage material due to the porous nature and high permeability (Kim & Lee 2015). The test done using CBA and fly ash generated by a power plant in Indiana, United States has proved the ability of CBA to be used as a sand mat as well (Kim et al. 2005). Prevention of soil erosion by using CBA is also investigated by Matsumoto et al. (2016) after exposing soil samples with different proportions of fly ash and CBA to artificial rainfall tests. They observed the soil loss percentages are relatively lower when the soil was mixed with more than 30 % of CBA (Matsumoto et al. 2016). CBA has been tested as a source material for geopolymers because CBA itself is a material produced at temperatures around 800°C with detention time of a few hours. Hence, it can be used as a geopolymer material without activation, thus saving energy (Slavik et al. 2008).

### 1.5 *Environmental aspects*

The leaching of hazardous heavy metals from coal combustion ashes is a common problem arises in the field application process. This causes for negative public perception in the usage of coal ashes due to the health risks. Some trace elements observed in CBA are Arsenic (As), Cadmium (Cd), Chromium (Cr), Copper (Cu), Mercury (Hg), Nickel (Ni), Lead (Pb), Selenium (Se), and Zinc (Zn). The concentration of these elements depends on the composition of coal which is used in the coal power plant (Wang & Sweigard 1996).

Hence, in the applications where CBA is contacted with ground water table, there is a possibility of water pollution with trace metal contamination. Therefore, it is essential to conduct a chemical study of sufficient details to assess whether it contained any chemical traces that are harmful to the environment and all living beings. Conversely, recent literature showed that the heavy metal concentrations and radioactivity of CBA is within acceptable ranges using CBA samples from power plants in India (Bhangare et al. 2011) and Lakvijaya power plant, Sri Lanka (Chrishanthi 2019). However, testing the possibility of trace metal leachability of CBA is recommended before the field application.

### 1.6 *Present study*

This research study focuses on identifying the suitability of CBA-soil mixture as a fill material in rehabilitation of clay mines. Currently, only 30% of CBA is reused (Kim & Lee 2015). Hence, utilizing CBA in large scale as a clay mine restoration material will help to considerably reduce these gigantic amounts of stockpiled CBA. One main significance of this research study is the use of locally available waste product for the mine rehabilitation which reduces the cost of transportation as locations of coal power plant and clay mines are located nearby in Sri Lanka. Further, abundant CBA piles stocked in the coal power plants provide ample amount of materials to fill the clay mines easily. Hence, the cost associated with searching for suitable back fill materials and transportation costs are saved. This is an added advantage of this research. The applicability of CBA as a backfill material will not only help for clay mines but also the rehabilitation of the other types of mines, quarries and as a general backfill material during geotechnical applications as well.

According to past studies, the nature of CBA is benefitting the crops by giving nutrients and also discuss the suitability of bulk usage of CBA as an agricultural soil amendment material (Kowapradit et al. 2017). Therefore, different proportions of CBA and soil mixtures can be also tested as an insight for the potential of native plant growth on the rehabilitated mines for environmental and aesthetic feasibility.

## 2 EXPERIMENTAL PROGRAMME

### 2.1 *Sample preparation*

CBA for this study was obtained from Lakvijaya coal power plant, Sri Lanka and gravelly lateritic soil was used to prepare CBA – soil mixtures. The mix proportions used for the study are shown in Table 1.

Table 1. Proportion of CBA and soil used

| Notation | *100BA* | *90BA* | *75BA* | *60BA* | *50BA* | *Soil* |
|---|---|---|---|---|---|---|
| CBA (%) | 100 | 90 | 75 | 60 | 50 | 0 |
| Soil (%) | 0 | 10 | 25 | 40 | 50 | 100 |

### 2.2 *Basic properties*

First, the basic properties of samples were assessed by standard laboratory tests. Particle size distribution was determined by using dry sieving for 100BA and wet sieving along with the hydrometer test for the rest according to ASTM D7928 – 17. Specific gravity was obtained in accordance with ASTM D854. The cone penetration test was used to determine liquid limit of the samples (ASTM D4318-17). Plasticity test was conducted for samples except 100BA as it is considered as non-plastic material by referring to the literature (Gimhan et al. 2018). Three replications were done for all the tests due to the higher heterogeneity of CBA which may cause for deviations of the final results. Modified Proctor compaction tests were conducted according to ASTM D1557-02 to obtain compaction properties of CBA. Constant head permeability method was used in accordance with ASTM D4234-19 for all samples except the soil sample as it contains more than 50% of fines. Hence, falling head permeability test was conducted to soil sample. The soil sample was compacted and was kept in water to become saturated by avoiding any particle loss.

## 2.3 *Compressibility and shear strength parameters*

The compressibility characteristics of CBA were established by conducting one-dimensional consolidation tests on Oedometer (according to ASTM D2435) on the samples after saturation of the compacted samples under modified Proctor effort at optimum moisture content. The samples were subjected to loading, unloading and reloading sequences. Shear strength was assessed by conducting direct shear test in accordance with ASTM D3080-04 on samples extruded from the compaction mould at optimum moisture content under consolidated drained condition for 50 kPa, 100 kPa and 200 kPa normal stresses.

## 2.4 *Trace metals*

The leaching concentrations of trace metals in samples were determined by column leaching test. The columns used were designed under following specifications. The column was made of perspex and 60 mm in diameter, 300 mm in height and a 150 mm compacted CBA layer was used (to ensure field conditions). A sand bed was placed to ensure no clogging or loss of the sample at the bottom of the column. Bottom of the column was lined with geotextile to prevent the soil fractions flowing through the column. Then, it was hung vertically from a rack. The test was carried out for a period of 96 hours as used by Takao et al. (2009) and the leachate dropping from the bottom of the column collected in a collection unit. A schematic diagram of the experimental setup of column leaching test is shown in Figure 1. Collected leachate samples during the testing were analyzed for metal concentration using inductively coupled plasma – mass spectrometry (ICP – MS) technique due to its lower detection limits and multi element technique (Wilschefski & Baxter 2019).

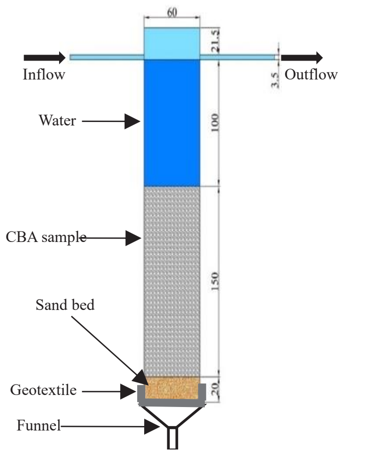


Figure 1. Column leaching set-up (dimensions are in mm)

# 3 RESULTS AND DISCUSSION

## 3.1 *Suitability of CBA as a fill material*

An acceptable fill material should be able to be compacted to a good density and possess adequate strength and stiffness once compacted. The free draining nature would also be an added advantage. Following sections present the results of the samples tested on this regard.

### 3.1.1 *Basic properties*

The particle size distribution curves of CBA and soil samples are presented in Figure 2 and summary of the tested parameters are listed in Table 2. According to Figure 2, 100BA sample shows a uniformly graded nature while other samples are deviated with the introduction of soil to the mixture. The classification of samples tested according to Unified Soil Classification System (USCS) are given in Table 2.

Specific gravity values of CBA – soil mixtures ranged from 1.88 to 2.5 where the specific gravity has increased with the reduction of CBA content in the mixture. Further, 100BA has a very low specific gravity of 1.88 which is smaller than a normal inorganic soil showcasing the chemical composition and presence of hollow particles with vascular textures in CBA.

Regarding the permeability of the tested samples, all the samples lie under well drained soils (ranging from $10^{-2}$ to $10^{-6}$ m/s, Terzaghi et al. 1996). However, with the increment of soil fraction in the CBA-soil mixture, permeability has dropped gradually. Hence, having a higher fraction of CBA in the mixture is more suitable for a proper free draining as a back fill material.

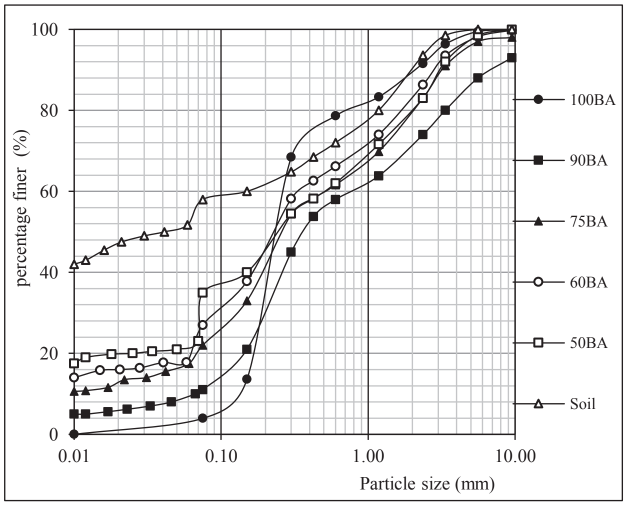


Figure 2. Particle size distribution curves CBA and soil samples

Table 2. Properties of CBA and soil samples

| Properties | *100BA* | *90BA* | *75BA* | *60BA* | *50BA* | *Soil* |
|---|---|---|---|---|---|---|
| Classification symbol | SP | SC-SM | SC | SC | SC | MH |
| Specific gravity | 1.88 | 1.89 | 1.99 | 2.18 | 2.23 | 2.50 |
| Liquid limit (%) | 20 | 27 | 33 | 40 | 43 | 58 |
| Plastic limit (%) | - | 10.5 | 20.4 | 25.4 | 27.5 | 33.5 |
| Maximum dry density ($kgm^{-3}$) | 975 | 1082 | 1215 | 1350 | 1462 | 1715 |
| Optimum moisture content (%) | 37 | 34 | 31 | 28 | 25 | 18 |
| Coefficient of permeability (x $10^{-5}$ m/s) | 9.90 | 4.04 | 3.04 | 0.31 | 0.25 | 0.03 |
| Compression ratio | 0.071 | 0.068 | 0.065 | 0.060 | 0.053 | 0.038 |
| Recompression ratio | 0.042 | 0.038 | 0.047 | 0.048 | 0.050 | 0.034 |
| Cohesion (kPa) | 0 | 3.3 | 5.6 | 12.7 | 19.0 | 20.0 |
| Friction angle (°) | 35 | 32 | 29 | 27 | 26 | 18 |

### 3.1.2 *Compaction characteristics*

Figure 3 shows the results of modified Proctor compaction test. CBA used for the present study has lower maximum dry density (MDD) (975 kg/m$^3$) and a comparatively higher optimum moisture content (OMC) (37%) like a soil with higher plasticity. However, CBA samples mixed with water were non-plastic and workable at all used moisture contents, during the compaction tests. Even with the absorption of significant amount of water into the porous structure, MDD is still quite lower than a conventional fill material (refer Figure 4). Therefore, depending on the field requirement, CBA of the present study may be used as a mixture of soil and CBA for higher MDD.

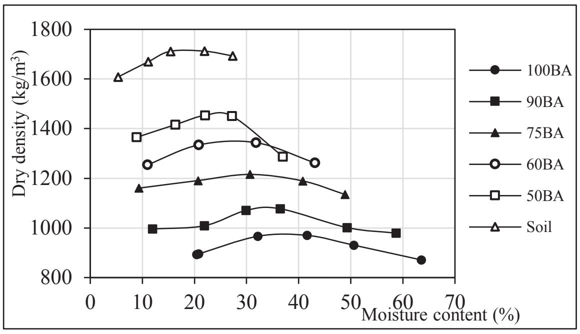



Figure 3. Relationship between dry density and moisture content

When comparing the MDD results with the literature, even the MDD of CBA from same power plant has disparities (refer Table 3). For example, Chrishanthi (2019) has obtained 1060 kg/m$^3$ as MDD while the present study provided only 975 kg/m$^3$ of MDD after modified Proctor test for CBA from the same source. These variations in the MDD of CBA are due to the higher heterogeneity of the source material (coal) even though they are from the same region and same power plant. For example, the origin of the CBA used for Chrishanthi (2019)'s study and the present study are from South Africa and yet has around 9% variation in MDD values. Therefore, the basic properties of CBA should be tested prior to the application in field.

However, for the present study, the MDD of the mixture was improved with the addition of soil to the CBA as shown in Figure 3. Therefore, CBA used in the present study shall be used as a mixture of soil and CBA upon the required compaction levels during the field application. Table 3 shows a comparison of proctor compaction results for the CBA samples from different literature.

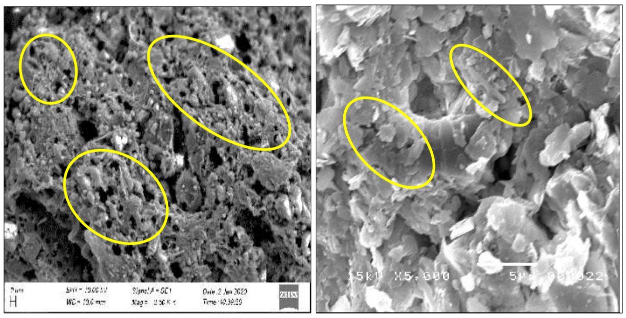
Table 3. Comparison MDD of CBA from literature

| Reference | *CBA was collected from* | *MDD (kg/m$^3$)* | *OMC (%)* | *Gs* |
|---|---|---|---|---|
| Marto et al. (2014) | Tanjung power plant, Malaysia | 1338 | 22.5 | 2.35 |
| Dungca (2017) | Philippines | 1730 | 14.0 | 2.64 |
| Reddy et al. (2018) | Kakatiya thermal power plant, India | 1010 | 40.4 | 1.77 |
| Chrishanthi (2019) | Norochcholai power plant, Sri Lanka | 1060* | 37.5 | 1.80 |
| Nu et al. (2019) | An Khanh power plant, Vietnam | 1630 | 9.0 | 2.48 |
| Pant et al. (2019) | Jhajjar power plant, India | 1402 | 24.0 | 2.35 |
| Ullah et al. (2020) | Tanjung power plant, Malaysia | 1120 | 24.0 | 2.28 |

*MP – Modified Proctor Test; SP – Standard Proctor test

According to Table 3, CBA samples that have a lower MDD, have quite high OMC as for a highly plastic material. As suggested by Jinwoo (2013) this may be due to the microstructure where the CBA structure could be absorbing significant amount of water to the pores. The porous structure was confirmed subsequently through Scanning Electron Microscope (SEM) monographs obtained for the present study and SEM images from past study as shown in Figure 4. These pores are getting filled easily by the water added for the compaction, thus requiring more water for the process of compaction. This porous structure has caused for the lower density of the compacted material and confirms the lower specific gravity (Gs) values observed for the present study and previous studies (refer to Table 3).

Conversely, the CBA samples having higher MDD, has a lower OMC and also higher specific gravity. This was also due to the pore structure where it showcased finer micro pores than the present study (refer to Figure 4).



(a) Present study 2500X (b) Power plant in Philippines 5000X (Dunga et al. 2017)

Figure 4. Morphological structure of CBA (The circled areas show the porous structures)

### 3.1.3 *Compressibility characteristics*

Figures 5 (a-c) show the variation of coefficient of volume compressibility ($m_v$), rate of consolidation ($C_v$) and void ratio ($e$) variation of the samples tested. According to Figure 5, $m_v$ values have increased with the increasing soil content (Figure 5(a)) whereas $C_v$ and void ratio values have been decreased with increasing soil content (Figures 5(b)&(c)).

Table 4 shows a comparison of the compressibility characteristics of Asian CBA from different literature. According to Table 4, the $k$ of all the samples is in the range of 1E-06 to 1.72E-04 which is comparable to those of medium to fine sand with a small amount of silt or clay mixtures. In addition, these $k$ values are lower when the fine content of CBA is higher. Further, $C_v$ is high, and this confirms that the CBA can be considered as a free draining material as indicated by the permeability and behaves similar to a sandy soil. However, the Indian CBA is compressible than the Sri Lankan and Malaysian CBA. This might be due to the higher fine content and popcorn-like structure of CBA which tend to break at lower stress levels and create higher deformations (Kim et al. 2005).

Table 4. Comparison of compressibility characteristics of Asian CBA from literature

| Reference | *k (m/s)* | $C_v$ *(m$^2$/year)* | $C_c$ | $m_v$ *(m$^2$/kN)* | *Fine (%)* |
|---|---|---|---|---|---|
| Sri Lankan CBA (Present study) | 9.9E-05 | 6.11 – 36.14 | 0.168 | 2.1E-05 – 3.5E-04 | 4 |
| Indian CBA (Pandian 2004) | 9.9E-07 – 7E-06 | 2.42E-03 – 0.11 | 0.057 – 0.484 | 2.94E-03 – 6.76E-02 | 6 – 14 |
| Malaysian CBA (Marto et al. 2010) | 1.72E-04 | Not mentioned | 1.54 | Not mentioned | 3.4 |

The void ratio vs applied stress plots (Figure 5(c)) show a similar behaviour as for normal soils for CBA only samples and the CBA-soil mixtures. A pre-consolidation effect introduced by the compaction process is also clearly evident in the Figure 5(c). Further, compression ratio values have been decreased with increasing soil content (refer to Table 2). Therefore, higher the CBA content, the soil mixture will have a lower compressibility. Consequently, if samples are used as a fill material to rehabilitate clay mines by compacting in layers, further settlement due to application of loads will be quite low. In addition, the higher $C_v$ with higher CBA content indicates that any settlements would dissipate rapidly.

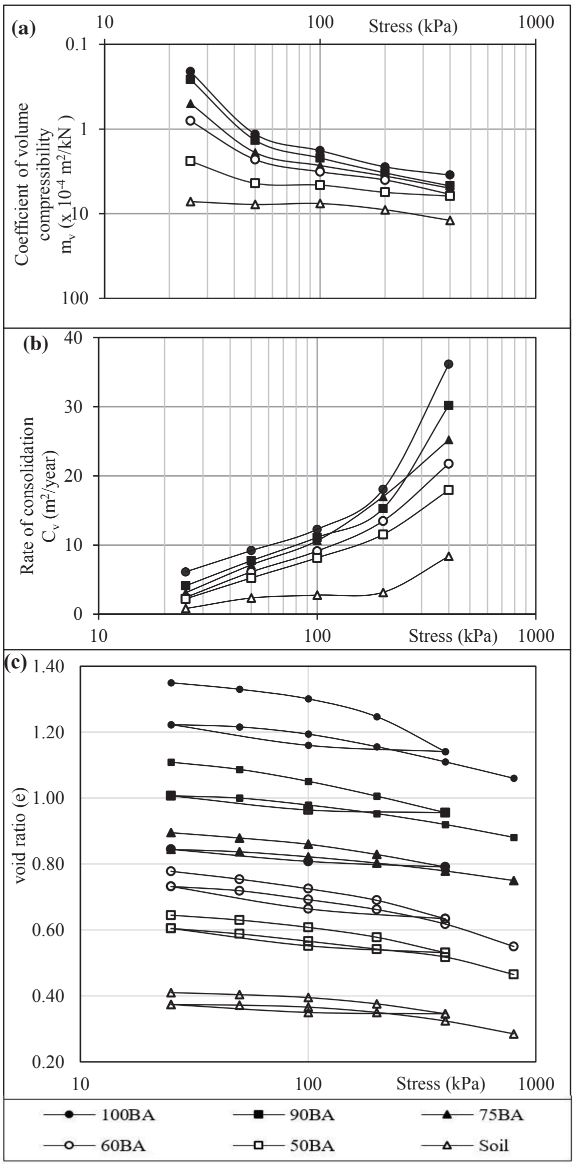



Figure 5. Comparison of (a) – coefficient of volume compressibility, (b) - rate of consolidation, (c) – void ratio with the applied stress

### 3.1.4 *Shear strength*

According to Table 2, CBA sample shows non cohesive nature. Similar non cohesive behavior was observed for Indian CBA with 30° to 37° friction angle (Pandian 2004) and Malaysian CBA with 31° friction angle (Marto et al. 2010). With the increment of soil fraction in the CBA-soil mixtures, the cohesive nature has been increased up to 20kPa. Even though the samples with high CBA content show less cohesion values, the friction angle is increased with the CBA content. For the application as a fill material, friction angle and cohesion need to be at a desirable level specially at slopes to maintain the stability. According to the standard of mines, maximum slope angle for the mine rehabilitation is 35° (Matsumoto et al. 2016). As it is a mild slope, a lesser cohesive material with higher friction angle is suitable for this particular application. Hence, CBA shall be mixed with soil according to the requirements for the field applications.

## 3.2 *Trace metals leachability*

The concentration of As, Cd, Cr, Cu, Hg, Ni, Pb, Se and Zn obtained from column leaching tests along with allowable limits as per drinking water for United States Environmental Protection Agency (USEPA) guidelines are summarized in Table 5.

Table 5. Trace metal concentration of CBA after column leaching test

| *Trace metals* | *Concentration in CBA sample (ppm)* | *Allowable Limits (ppm)** |
|---|---|---|
| As | - | 0.01 |
| Cd | - | 0.005 |
| Cr | 0.017 | 0.1 |
| Cu | 0.023 | 1.3 |
| Hg | - | 0.002 |
| Ni | 0.012 | 0.02 |
| Pb | 0.008 | 0.015 |
| Se | - | 0.05 |
| Zn | 0.034 | 5 |

*According to United States Environmental Protection Agency (USEPA) guidelines

When compared with the allowable limits, concentrations of trace metals were within the allowable limits and hence, is suitable for application as fill material. However, long-term effect on ground water with the trace metals leachability of CBA should be studied prior to application in the field.

## 4 IMPLICATIONS FOR FIELD APPLICATION

The results obtained from the conducted tests showed that CBA has the potential to use as a fill material. In this context, initially the suitability of CBA as a fill material was assessed establishing the engineering characteristics. It was found to be a granular material of high permeability and hence free draining. With the lower specific gravity, lower bulk and dry densities of CBA, it can be considered as a lightweight fill material which is suitable to fill soft grounds like abandoned clay mines. With higher CBA content, the soil mixture will have a lower compressibility. Consequently, if CBA or CBA-soil mixtures are used as a filling material by compacting in layers, the further settlement due to application of loads will be quite low. This will be helpful when considering the rehabilitation of the abandoned clay mines with recreational parks etc.

When CBA content is higher, angle of internal friction is also higher so that the shear failure through the embankment can be prevented. Since, higher CBA content cause lower cohesion, the embankment will have to be done at a very mild slope.

The content of the leached-out trace metals such as As, Cd, Cr, Cu, Hg, Ni, Pb, Se and Zn are not detected or well below the acceptable limit according to USEPA standards and therefore, no threat to health, water bodies or environment for utilizing as a backfill material in clay mines.

The outcome of this proposed research will therefore help the clay miners to fulfil the regulations of rehabilitating the clay mines at a lower cost after mining. In addition, these areas can be converted into recreational areas after restoring with vegetation. This process is not only eco-friendly but also provide economic opportunities for the local inhabitants. A series of tests should be conducted prior to the application of CBA as these characteristics can vary due to the higher heterogeneity of the origin of the source material (coal) even though they are from the same region.

## 5 CONCLUSIONS

The physical, chemical and geotechnical properties of CBA showed that the CBA has potential to use as a backfill material for clay mine rehabilitation and some properties of CBA can be altered in favor to the application when it is used as a mixture of CBA and soil depending on the CBA properties. The optimum results of the present study are summarized in Table 6.

Table 6. Summary of optimum results of CBA for mine restoration

| *Properties tested* | *Sample with optimum results* | *Value* |
|---|---|---|
| Compaction characteristics | 75% of CBA or below depending on the field requirements | MDD ≥ 1215kg/m$^3$ OMC ≤ 31% |
| Coefficient of permeability | 75% of CBA or above | $k \geq 3.04\text{x}10^{-5}$ m/s |
| Compression ratio | 90% of CBA or below | $Cc/(1+e_0) \leq 0.070$ |
| Recompression ratio | 75% of CBA or above | $Cr/(1+e_0) \leq 0.045$ |
| Cohesion | 75% of CBA or below | c ≥ 5.0 kPa |
| Friction angle | 75% of CBA or above | Φ ≥ 30° |

By considering all the obtained results and economic benefits, it can be concluded that 75% of CBA and 25% of soil mixture is the most suitable combination for restoration of abandoned clay mines, according to the present study. However, it is highly dependent on the type of CBA and requirements in the field application. Further, application of CBA is not harmful for the living beings and environment as trace metal leachability of CBA does not exceed allowable limits.

## 6 RECOMMENDATIONS FOR FUTURE STUDIES

- Application of CBA should be investigated through field test for long durations to observe potential threats to environment in long run.
- Potential of CBA to cause any pozzolanic reaction during the application as a partial replacement of soil should be investigated.
- The stability of the slope should be analyzed using numerical software in order to obtain a maximum slope without any failures.
- CBA and soil mixtures shall be tested for availability of nutrients for the purpose of possible vegetation on the rehabilitated mines.

## 7 ACKNOWLEDGEMENT

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