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Settlement of soft soil treated with group of floating bottom ash columns

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ABSTRACT

The global annual production of bottom ash as a waste of coal-burning has been rapid increases in the last decades. Therefore huge amounts of bottom ash have been disposed of in ash ponds areas which pose a significant environmental problem. Bottom ash has quite similar engineering characteristics to natural sand, thus it can be used as a replacement for sand in various civil engineering aspects; since it has been considered as a non-hazardous material. By utilizing bottom ash as a substitute material to sand, the ash storage areas problem can be solved; moreover, the cost of the project will be reduced. This paper presents an experimental study performed on soft soil treated with a group of floating bottom ash columns through physical model tests. The laboratory tests were conducted on the unreinforced soft ground and reinforced by floating bottom ash columns. For treated cases, bottom ash columns of 25 mm diameter and 150 mm length were installed in the soft ground with an area replacement ratio of 13%. The experimental test results revealed that the inclusion of floating bottom ash columns in the soft soil ground enhances the carrying capacity and accelerates the settlement compared to untreated ground.

Keywords: Foundation; Granular column; Ground improvement; Clay soil; Coal ash

1. Introduction

Coal is the most abundant and broadly dispersed fossil fuel throughout the world and it plays an essential role in the global energy generating sector. According to BP's statistical review of world energy, coal provided more than 27% of global primary energy requirements and about 38% of the globe's electricity generation in 2017 [1]. As reported, China is the world's largest power producer with approximately 25% share of the worldwide electricity generation, while America is the second world's largest electricity producer with about 17% share of the whole use in the world, furthermore for other developing countries such as India, Japan, and Canada, coal is considered the main power-generating fuel [2]. The dramatic growth in population and economic development increases the demand for coal-fired power generation and is expected to be continued particularly in developing countries due to the fact it's an economically viable source of electricity production.

The generation of electricity using coal burning produces a huge amount of coal ash annually which is considered as waste material [3]. According to the American Coal Ash Association (ACAA), more than 100 million tons of coal ash are produced from U.S coal-fired power plants every year. This coal waste mainly consists of fly ash, bottom ash and boiler slag [4], however, the major by-products are fly ash and bottom ash [4]. Globally, fly ash is utilized in large volumes in civil engineering applications such as cement production and cement replacement in concrete works. In Europe (EU 15) about 6 million tons of bottom ash were produced in 2003; only about 2.7 million tons were used

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in the construction industry [5]. The unused fly ash along with bottom ash is discharged off in open landfills in the wet or dry form [6]. At present, the disposal of coal ash in ponds has become a major problem worldwide due to the increased requirements of dumping landfills in addition to its possible has detrimental environmental impacts. Based on U.S. Environmental Protection Agency (EPA), there are over 2,000 coal ash ponds in space and landfills in the U.S. The massive quantity of coal ash becomes a considerable issue to the power plant companies due to the increasing requirements for ash storage areas [7]. These coal ash ponds are typically placed near the power plants and since the disposal expenses increasing; it will lead to environmental pollution further to numerous health risks. Coal ash is considered a non-hazardous waste material in the United States, Australia, Canada, Europe, Israel Japan, Russia, and South Africa and it's broadly used in construction work [8]. In the same line, coal ash is not classified as a hazardous material based on its chemical composition as well as human health risk basis. The hazardous in using bottom ash, it can be migrated and contaminated the groundwater or surface water since the unlined coal ash dumps sit close to a river, stream or lake [9]. The amount of leaching that takes place at coal ash storage facilities varies from one site to another, depend on the kind of coal ash that is stored, its concentration and acidity, and the nature of the dumping site [10].

The leaching properties of coal ash are primarily controlled by several factors such as its chemical composition, mineralogy, and morphology. Many researchers have been attempted to investigate the chemical composition of coal ash (bottom ash and fly ash) using X-ray diffraction and X-ray fluorescence analysis such as; [11–19]. Based on their results the major chemical compounds are silica (SiO_2), alumina (Al_2O_3), iron oxide (Fe_2O_3) and calcium oxide (CaO); however small quantities of magnesium oxide (MgO), potassium oxide (K_2O), sodium oxide (Na_2O), sulfur trioxide (SO_3), phosphorus pentoxide (P_2O_5) and titanium dioxide (TiO_2) are also reported. Furthermore, both coal bottom ash and coal fly ash are classified as Class F ash according to ASTM C618A because of the total composition of silica (SiO_2), alumina (Al_2O_3) and iron oxide (Fe_2O_3) more than 70%. It has been observed that the predominant compound in coal ash is SiO_2, which reaches up to 68% for bottom ash [20].

In order to evaluate the toxicity hazards of coal ash as construction materials, a common method is the determination of the amount of leachability of their chemical compounds. Conducted leaching tests according to Toxicity Characteristics Leaching Procedure (TCLP) on concrete containing fly ash and bottom ash as a replacement of cement and sand [21]. The results showed that the heavy metal concentrations in coal ash concrete are well below the recommended amount in the USEPA SW 846 [22,23]; there is no leachate of hazard elements in the coal bottom ash and it is acceptable to be used in construction aspects. Moreover, the concentration of metallic elements in fly ash is much higher than that in bottom ash, therefore bottom ash possesses a lower risk of dangerous leaching metals compared to fly ash [24]. The suitability of bottom ash as substitutes for granular materials in highway construction considering the environmental impacts. Leaching tests were conducted according to the Extraction Procedure toxicity test (EP) and Indiana leaching method on bottom ash samples and the results were compared with the standards of drinking water [6]. The results revealed that the concentrations of constituents are much lower than the maximum contaminant limits in EP toxicity. Furthermore, the concentrations of most compounds in the contaminated water are lower than the drinking water standard. Thus, bottom ashes can be characterized as non-hazardous based on the EP toxicity test.

The physical and mechanical properties of coal bottom ash have been investigated by several researchers in the literature such as [25–31], based on their results bottom ash is considered a well-graded material with grain size ranging from fine sand to fine gravel. As well as bottom ash exhibits free drainage characteristics similar to sand and gravel, therefore it can be suitable as construction material, particularly for geotechnical application. There have been several studies on the use of granular material such as crush rocks, natural gravel and sand in granular columns to improve the properties of soft clay [32–36]. In order to prevent the uncontrollable usage of natural materials, there is an urgent need for substitute materials such as waste or by-products materials. Since the properties of bottom ash are quite similar to those of natural sand [37]. Thus, there is a good potential of utilizing this bottom ash as a substitute material to sand in granular columns and by introducing bottom ash columns, the cost of construction projects will be significantly reduced as well as the need for a disposal area for bottom ash will be solved [3,4].

Many researchers dealing with the performance of granular columns in soft clays, but few of them attempted to study the use of bottom ash as substitute materials to sand in granular columns [38–42]; performed laboratory model tests to investigate the improvement of the shear strength for soft kaolin clay reinforced with a single and group of bottom ash columns. The results showed that the shear strength of soft ground enhanced significantly after incorporating bottom ash columns and the improvement depend on area replacement ratio, height penetration ratio, and column diameter. These results are using sand column; they found that the degree of improvement of soft clay was influenced by the area of replacement ratio and the height of the column over column diameter ratio [43,44]. The bearing capacity of floating and end-bearing encased bottom ash columns installed in the soft ground [45,46] through conducting a series of small-scale physical modeling tests. The results revealed that the bearing capacity increase with increasing the area replacement ratio, moreover a significant improvement was achieved when the geotextile encasement was used. The effect of column penetration ratio and the number of columns was observed by the height penetration ratio showed more significant influences on the bearing capacity of soft kaolin clay compared to the number of bottom ash columns [47].

2. Material and methods

2.1. Testing material

Two types of material were used in this study which is clay and bottom ash. The brown kaolin clay powder (L2B20) was obtained from kaolin (Malaysia) Sdn. Bhd., whereas bottom ash obtained from Tanjung Bin Power Plant, Johor, Malaysia was used to construct the granular column. Fig. 1 shows a sample of kaolin powder and bottom ash fragments.

2.2. Testing model chamber

A rigid testing box has a dimension of 400 mm width, 150 mm length and 430 mm height were used for experimental modeling. Three sides of the box are made from aluminum and the front side has a removable 20 mm thick Perspex panel to allow real-time visualization of soil movement during the testing. All sides are fixed tightly which prevented lateral movement during the consolidation and loading of the ground model [48–52].

2.3. Preparation of soft ground

In order to prepare the soft ground, kaolin clay powder was oven-dried for 24 h at 110°C. The kaolin slurry was prepared by mixing 16 kg of dry kaolin powder and 16.64 kg of distilled water (which is twice times its liquid limit) [50–52]. Initially, mixing was carried out by hand for about 10 min using spatulas to dissolve lumps, then a hand machine drill was used for 50 min to attain a homogenous specimen. Before pouring the slurry into the testing chamber, a porous desk was located at the bottom of the chamber, then the kaolin slurry was poured into the testing chamber until reached the designed initial height and another porous desk was placed at top of the slurry. The slurry was left for 24 h to consolidate under its own weight, after several consolidation pressures were applied incrementally on the kaolin slurry using a pneumatic cylinder to final stress of 50 kPa and then the pressure was reduced to 5 kPa to attain an over consolidation ratio of 10 [51], each pressure was maintained for 24 h. The final ground height of 200 mm was achieved at the end of the consolidation stage.

2.4. Model tests process

After the consolidation of soft ground was completed, the bottom ash columns were installed. In order to construct the columns thin-wall brass tubes with a diameter of 25 mm were pushed slowly into the clay ground at the predetermined locations in the template corresponding to an area replacement ratio of 13% until reach a height of 150 mm as shown in Fig. 2. The boring of soil was conducted using a steel auger whereas a plastic rod with a 24 mm diameter was

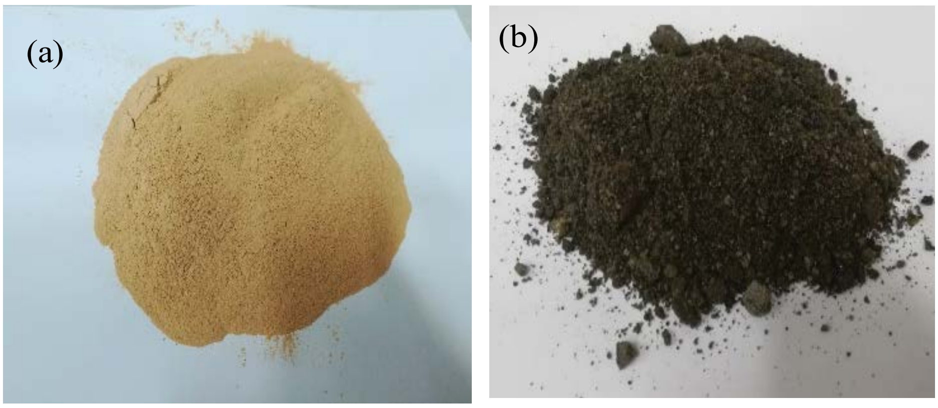

Fig. 1. Sample of testing material (a) kaolin powder and (b) bottom ash.

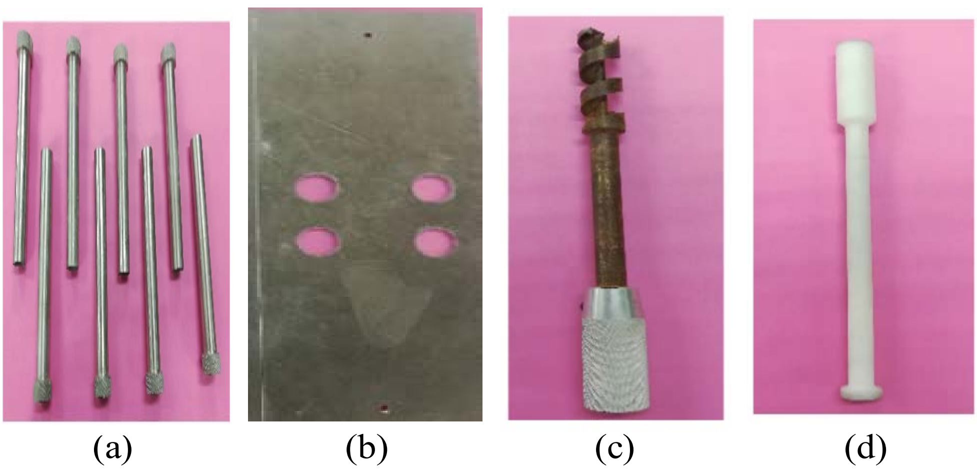

Fig. 2. Column's installation equipment (a) thin-wall brass tubes, (b) steel template, (c) auger, and (d) plastic rod.

used to compact the bottom ash material. The equipment used to install columns is presented in Fig. 2.

The loading test was conducted after 9 d of consolidation to measure the ultimate load and displacement of the soil. However, the undrained shear strength of soft ground; was measured using a hand vane shear test immediately after the loading test was completed.

2.5. Load tests

A rigid steel plate has a size of 149 mm length, 100 mm width, and 20 mm depth was located at the top of the ground model and adjusted at the center. A group of four columns with an area replacement ratio of 13% were tested for a column height of 150 mm. The testing program is comprised of two types of load tests. The first load test was carried out to obtain the ultimate load capacity of unreinforced and reinforced with bottom ash columns using a constant displacement controlled system, the strain rate of 1.2 mm/min was used which represents the undrained behavior of rigid footing. The testing setup for a constant rate of displacement is shown in Fig. 3.

In order to measure the stress concentration under the design load, three miniature pressure transducers were installed on the top of the column, at the bottom of the column and at surrounding soil furthermore, two-pore water pressure transducers were used to measure the excess of pore water pressure. The testing was conducted using a dead load system and the test setup is presented in Fig. 4.

3. Results and discussion

3.1. Characteristics of kaolin and bottom ash

The physical properties of kaolin and bottom ash were conducted according to British Standard (BS) and the American Society of Testing Material (ASTM). The test results were summarized in Table 1. The liquid limit and the plastic limit for kaolin were found as 52% and 34% respectively. According to the Unified Soil Classification System (USCS), kaolin is classified as Clayey SILT of high plasticity (MH), while the bottom ash shows non-plastic behavior. The grain size distribution of bottom ash is presented in Fig. 5. The results show the particle size ranging from 0.063 to 20 mm. Based on the USCS, the bottom ash is classified as well-graded sand (SW). According to the Unified Soil Classification System (USCS); bottom ash can be also categorized as good

Fig. 3. Constant rate of displacement system.

Fig. 4. Dead load system.

Table 1
Properties of kaolin and bottom ash

Identification properties	Results
Kaolin	
Liquid limit (%)	52
Plastic limit (%)	34
Plasticity index (%)	18
UCS	MH
Specific gravity	2.67
Coefficient of permeability (m/s)	1.959×10^{-8}
Optimum moisture content (%)	21.60
Maximum dry density (g/cm^3)	1.530
Bottom ash	
Particle size	0.063–20 mm
AASHTO	A-1-a
UCS	SW
Specific gravity	2.23
Coefficient of permeability (m/s)	2.41×10^{-3}
Maximum index density (mg/m^3)	1.120
Minimum index density (mg/m^3)	0.896

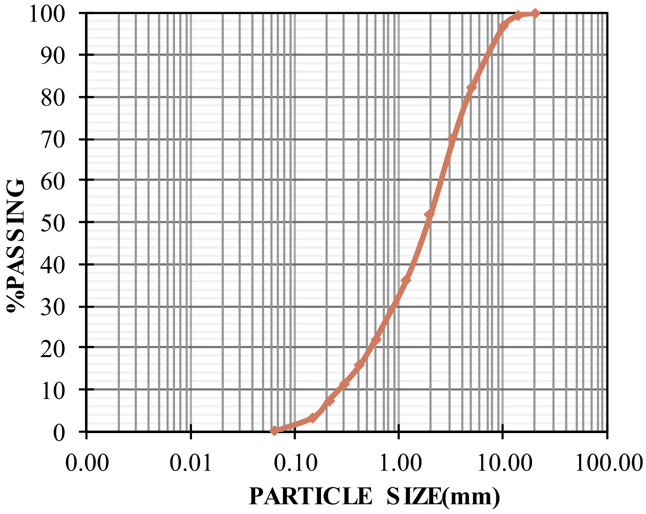

Fig. 5. Grain size distribution for bottom ash.

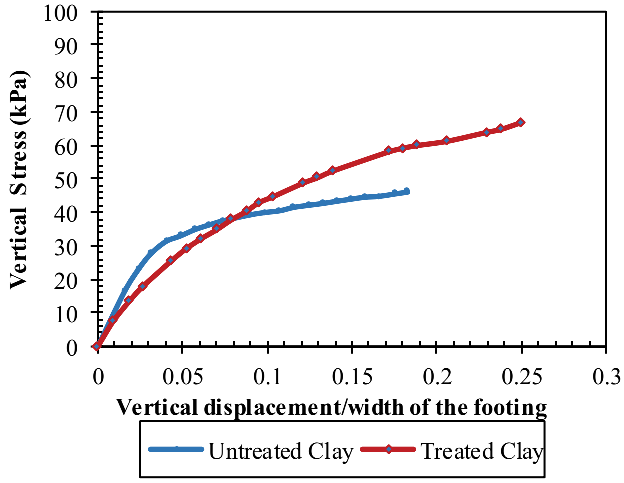

Fig. 6. Vertical stress vs. vertical displacement/width of the footing for untreated and treated conditions.

draining material such as gravel and sand with a coefficient of permeability of 2.41×10^{-3} m/s whereas; for kaolin clay, the coefficient of permeability was 1.959×10^{-8} m/s which is considered as poor drainage material [53].

3.2. Bearing capacity

The common stone column diameter used in the site typically varies from 600 to 1,700 mm while the column length usually ranging from 10 to 20 m. As considering the column length ratio for physical model test and field condition 1:50, the column diameter and length of 25 mm and 150 mm were used in this physical test to study the improvement in bearing capacity of soft clay reinforced by floating bottom ash columns using 13% area replacement ratio. For the untreated condition, the load test was conducted immediately after the consolidation stage was completed. For the treated test; four bottom ash columns were installed in the soft ground which represents a 13% area replacement ratio [54]. The relationship between vertical stress and vertical displacement/footing width is illustrated in Fig. 6.

From the graphs, the ultimate bearing capacity of untreated clay was found as 47.32 kPa however, the ultimate bearing capacity of the improved ground was found as 66.84 kPa. Based on these results the ultimate bearing capacity of the treated bed increased by 41% over the untreated condition. The shear strength was measured at the end of the tests and it's found as 8 kPa for both treated and untreated conditions using hand vane shear tests.

3.3. Settlement

According to a recent study, there're two important parameters that should be verified regarding the design of foundation resting on reinforced ground by granular columns, namely, adequate bearing capacity and acceptable settlement [55]. In order to evaluate the settlement performance of floating bottom ash columns under the design load (2/3 of the ultimate bearing capacity) where two load tests were conducted. Each load was applied for 24 h continuously. Fig. 7 shows the relationship between vertical settlement and time for untreated and treated ground under the design load. For the untreated ground, the settlement detected after 24 h loading was 2.35 mm whereas the magnitude of the settlement of the treated case was found as 5.17 mm. It can be noticed that the settlement of the soft ground accelerated after using bottom ash columns in compression to the untreated ground [56] for floating stone columns. Therefore, bottom ash columns can be considered as vertical drains such as stone columns.

The stress distribution on the top and bottom of the columns are presented in Figs. 8 and 9, whereas the pressure at the surrounding soil is shown in Fig. 10. From these figures, it can be recognized that immediately after applying the design load the pressure at the surrounding soil and the top, bottom of the columns increased rapidly. From Figs. 8 and 10, it can be seen that the pressure at surrounding soil is greater than the pressure developed at the top of the column, this can be due to the fact that the stiffness

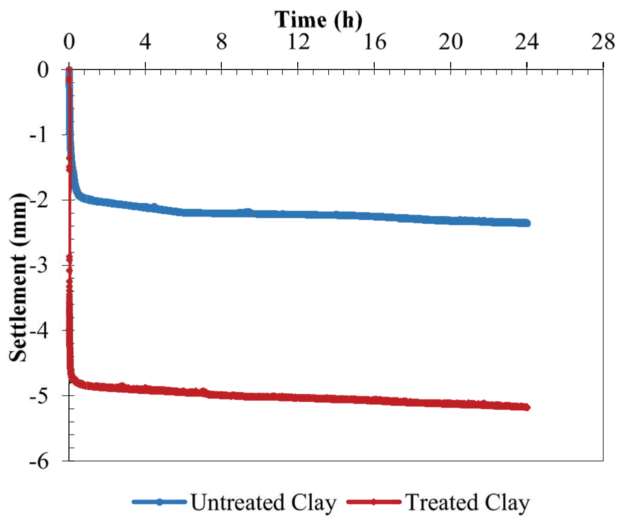

Fig. 7. Settlement vs. time.

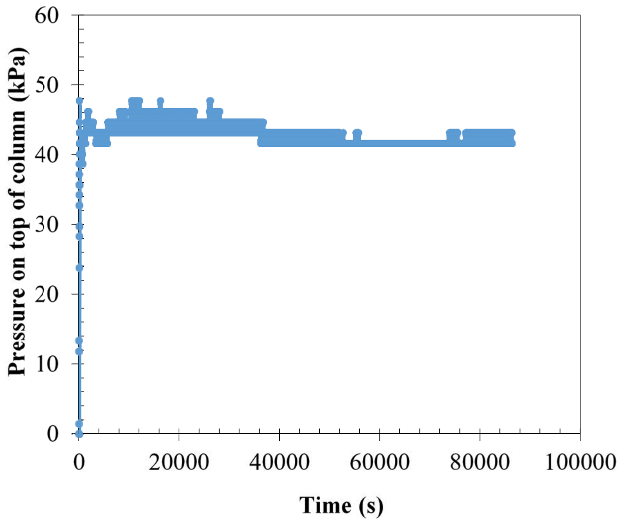

Fig. 8. Pressure on the top of the column vs. time.

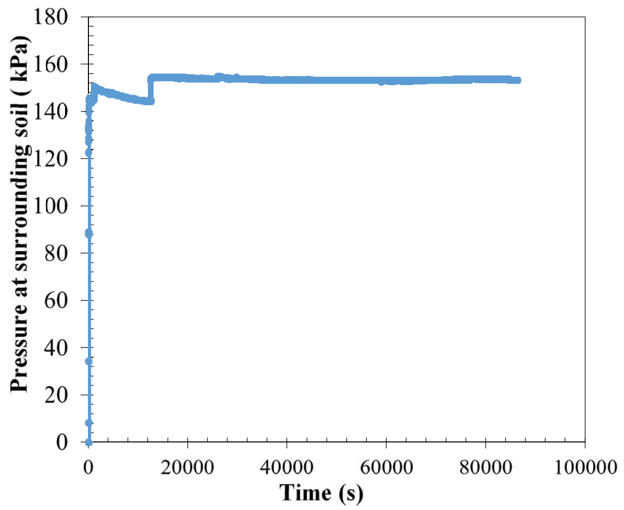

Fig. 9. Pressure at the bottom of the column vs. time.

of the column material is higher than that of the surrounding soil. Moreover, the stress at the bottom of the column is less than that detected at the top of the column [57–60].

4. Conclusions

The results indicated that bottom ash is distributed from fine sand to fine gravel with lower specific gravity compared to the natural sand and gravel. The ultimate bearing capacity of the soft ground increased after being reinforced with floating bottom ash columns. An enhancement of 41% was achieved when using a 13% area replacement ratio over the untreated case. The settlement of soft ground was accelerated significantly after using bottom ash columns, therefore bottom ash can be recommended as a substitute material to sand or gravel in ground improvement work. Since bottom ash is classified as non-toxic material, the utilization of bottom ash in construction applications can help

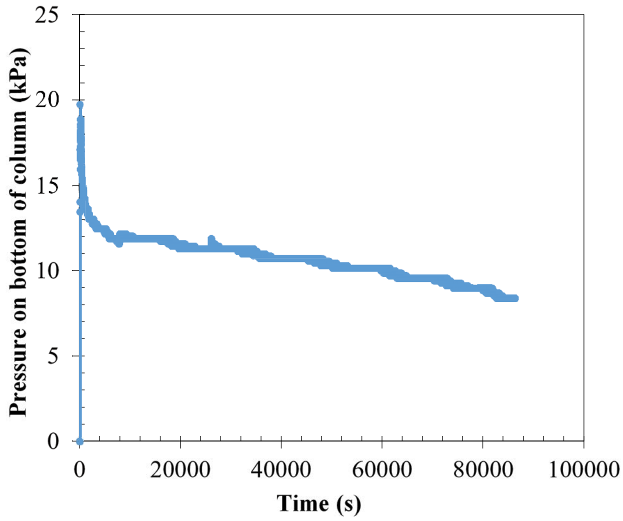

Fig. 10. Pressure at surrounding soil vs. time.

to reduce the environmental impact of the disposal of the bottom ash as well as the project's costs.

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