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AN EXPERIMENTAL INVESTIGATION OF COAL BOTTOM ASH AS SAND REPLACEMENT

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ABSTRACT: The ash from burned coal that falls to the bottom of a furnace is called coal bottom ash (CBA). This ash contributes to about 20% of total coal ash, and it has been disposed of on open land and in landfills for decades, resulting in environmental pollution issues. This research investigates the potential use of coal bottom ash from the Manjung Power Plant as a substitute for sand aggregates in concrete. Therefore, an experimental investigation that includes particle size distribution, fineness modulus, specific gravity, water absorption, x-ray fluorescence (XRF), and scanning electron microscope (SEM) was carried out to determine the characteristics of coal bottom ash. The results revealed that coal bottom ash has a particle size distribution and fineness modulus comparable to that of sand particles. Both materials have rounded to angular particles with interlocking characteristics. However, coal bottom ash seems to have rough surfaces with porous particles and it is lighter than sand particles. These characteristics cause coal bottom ash to have a lower specific gravity and a high water absorption rate. Besides, coal bottom ash used in this investigation has been classified as Class C. It has pozzolanic materials and high calcium content, thus helping to improve C-S-H gels with high cementitious properties, resulting in higher strength performance. In conclusion, coal bottom ash from Manjung Power Plant has its advantages and looks like sand particles. Therefore, it has the potential to be used as a material substitute for concrete.

Keywords: Manjung Power Plant, Coal bottom ash, Sand replacement, Concrete

1. INTRODUCTION

Environmental issues related to disposal problems are considered as the most significant aspect of the research to investigate the potential use of coal bottom ash (CBA). Bottom ash is one of the biggest sources of industrial waste that is produced by coal-fired power plants. It has been classified as hazardous waste because toxic remains of coal burned in coal-fired power plants are full of chemicals that cause cancer, developmental disorders a,n,d reproductive problems [1]. However, the increasing denergy demand has led to higher coal consumption, resulting in high waste rates of bottom ash. In general, bottom ash represents around 20% of total coal ash. Fly ash is mostly utiliutilizede bottom ash is not being used in any form.

The disposal of bottom ash without being utilized tends to increase every year and poses environmental risks to living beings [2]. Bottom ash is generally disposed of in open land or landfills, or ash ponds located in coal-fired power plants. Thus, so much bottom ash is stored that this leads to a series of environmental pollution problems for decades. Nowadays, it has become a serious concern due to the limitation of dumping sites and the continued rate of production. The enormous volume of bottom ash at dumping sites may pose a risk to human health and the environment. Dangerous elements in bottom ash may pollute ground or surface water, thereby endangering living beings. It is also a concern that the harmony of natural ecosystems and human beings would be damaged if these issues are not resolved.

Construction materials such as natural sand are the main focusofn this investigation. Due to a rise in demand for concrete construction, natural resources such as river sand are being depleted. On the other hand, the integration of industrial waste in concrete provides additional advantages in terms of environmental and economic benefits [3]. Researchers from all around the world are starting to look into bottom ash as partial sand replacement for sustainable development. This helps to conserve natural sand that is being depleted day by day [4], as well as preserve natural resources.

Most research studies in the past have investigated the characteristics of bottom ash. The results varied according to the data collected and this is the main problem that needs to be tackled before bottom ash can be applied in the construction industry. On the other hand, it has been found that investigations of bottom ash from the Manjung Power Plant are still limited. The characteristics of bottom ash produced have not been studied by other researchers. Therefore, this current research aims to investigate the potential use of bottom ash produced by Manjung Pthe ower Plant as a substitute for sand in concrete. This includes the examination of particle size distribution, specific gravity, fineness modulus, water absorption, chemical composition and ,microstructure.

2. RESEARCH SIGNIFICANCE

The goal of this research is to explore alternate solutions to the environmental issues due to massive amounts of coal bottom ash (CBA) industrial waste. Despite that, construction materials such as natural sand are concerned due to their depleting resources. It is projected that extensive and productive usage of CBA might perhaps reduce the burden of sand natural resources while also balancing the environment. The advancement of concrete innovation that uses CBA in the production of concrete can help to build a more sustainable future. Therefore, the findings of this research will help readers to understand more about the properties of CBA. The outcome of the research could also be helpful for basic research and the development of practical concrete innovations.

3. EXPERIMENTAL PROGRAMME

The coal bottom ash (CBA) utilized in this investigation was obtained from Manjung Power Plant in Perak, Malaysia, as shown in Fig.1. The CBA was dried in the oven for 24 hours at a temperature of 110 ºC to reduce moisture content that could affect experimental testing. Next, CBA was screened using a 5.0 mm opening sieve to remove large particles as depicted in Fig.2. CBA has been designed as fine aggregate (sand) replacement in concrete. Therefore, the characteristics of CBA particles were studied.

Fig.1 CBA produced by Manjung Power Plant in Perak

Fig.2 Screened CBA eliminates larger particles

The samples were prepared before performing material testing (standard of sand according BS 882: 1992). Sieve analysis, fineness modulus, specific gravity and water absorption of CBA were among the physical properties performed in these experiments. Other tests of chemical properties of CBA were performed using x-ray fluorescence (XRF) while microstructural testing was performed using scanning electron microscope (SEM). However, all of the data was compared to that of sand particles in the experiments. The potential use of CBA (produced by Manjung Power Plant) as a sand replacement is discussed in the section below.

4. RESULTS AND DISCUSSIONS

In this subsection, all material characteristics results are presented. The discussion includes comparisons to the standard and/or results of previous research.

4.1 Sieve Analysis

Raw CBA was collected from Manjung Power Plant. It was dried in an oven at 110 ºC before a sieve test was performed. This test is important to determine particle size distribution to compare aggregate sizes. Figure 3 illustrates the particle size distribution of raw CBA, sieved CBA and sand particles using sieve analysis according to the standard stated in BS 882: 1992 (specification for aggregates from natural sources for concrete).

Referring to Fig.3, the grading curve of raw CBA was not in full compliance with the grading limits suggested in BS 882: 1992. It deviated from the lower range limits in the sieve size of 10 mm to 2.36 mm. Nevertheless, the raw CBA met the grading limits for sieve sizes ranging from 1.18 mm to 150 µm. It was observed that the size of raw CBA particles from the Manjung Power Plant ranges from fine gravel to fine sand. Most of the particle sizes were between 10 mm and 75 µm. In this study, the particle size of CBA was compared to that of sand particles. Therefore, raw CBA that passed through a 5.0 mm opening sieve was considered and it has been classified as CBA aggregate. The particle of CBA aggregate is shown in Fig.4.

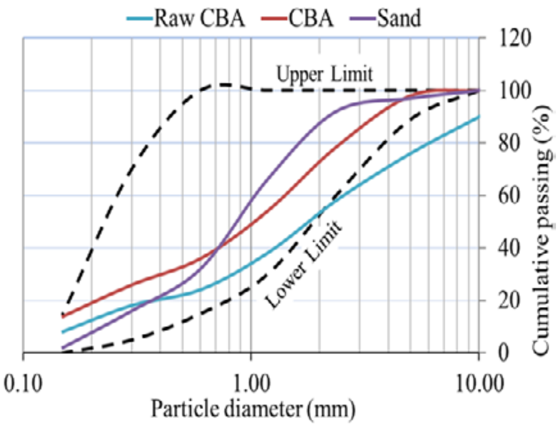

Fig.3 Particle size distribution of raw CBA, sieved CBA and river sand

Fig.4 The particle of CBA aggregate

However, the result shows that CBA aggregate and sand meet the requirements, and that both materials fell within the upper and lower grading limits. It was observed that CBA aggregate has a graded distribution of coarse to medium sand, which is comparable to the sand examined in this test according to BS 882: 1992. On the other hand, CBA aggregate had a median particle size (d_{50}) of 1.10 mm while that of sand was 0.88 mm. It revealed that CBA aggregate had a cumulative passing through 50% coarser than river sand. It can be concluded that the CBA aggregate from Manjung Power Plant has particle size similarities to that of sand, and hence, it might be suitable for use as a sand substitute in concrete manufacturing.

4.2 Fineness Modulus

The fineness modulus of aggregate is a numerical index that represents the mean particle size in aggregate. It also describes that the greater the fineness modulus, the coarser the aggregate. In the present study, the fineness modulus of CBA and sand was determined through sieve analysis tests where the sum of the total cumulative weight percentage was retained at each specified series of sieves divided by 100. The fineness modulus results obtained in this study were compared to that of previous studies and summarised in Table 1.

The fineness modulus of CBA is important because using it as a fine aggregate in concrete mixes can change the properties of concrete. In this study, the fineness modulus of river sand was found to be 2.94 while the fineness modulus of CBA was found to be 2.93. Observations indicated that the fineness modulus values of both CBA and river sand were quite similar. According to ASTM C33, the fineness modulus of fine aggregate should not be less than 2.3 and not more than 3.1. Fine aggregate with a fineness modulus of more than 3.1 is considered unsuitable for use as fine aggregate replacement. Nonetheless, the CBA and river sand that were tested in this experiment were classified as coarse sands.

Table 1 Fineness modulus of CBA and river sand

Authors	CBA	River Sand
[5]	1.70	–
[6]	2.32	2.60
[1]	2.79	3.00
[7]	1.50	–
[8]	2.09	3.07
Our research	2.93	2.94

Table 1 shows that previous studies have found that the fineness modulus of CBA is often less than the fineness modulus of river sand. It has a wide range of fineness modulus values for CBA, but most of its values lie within the normal range for fine aggregates and fall into the categories of fine and medium sand. According to Abdulmatin [8], the CBA obtained from Mae Moh Power Plant in Thailand has a fineness modulus value of 2.09. Besides, Pal [6] found that the fineness modulus of CBA obtained from the National Thermal Power Station in India has a value of 2.32. The other power plant in India called Ropar Thermal Power Station has a fineness modulus of 1.50 [7]. Further, Hasim [5] and Ramzi Hannan [1] looked into the fineness modulus values of CBA taken from the Tanjung Bin Power Plant and found that they were 1.70 and 2.79, respectively. It can be concluded that varying fineness modulus values were obtained even though the CBA was produced in similar power plants. However, the fineness modulus obtained from Manjung Power Plant was 2.93, which is slightly higher than the fineness modulus reported in past research.

According to Gooi [9], the fineness modulus of CBA can be modified to suit different applications through grinding. However, according to ASTM C33, materials that fail to fulfill the fineness modulus requirements might be approved if concrete made of similar fine particles from the source performs well. Furthermore, since the fineness modulus of the CBAutilizedd in this study is comparable to that of standard fine aggregate, the usage of CBA as a sand substitute in concrete mixtures is acceptable. In addition, the higher the fineness modulus of CBA, the coarser the CBA particles. It has the advantage of coarser sand with a fineness modulus of about 3.0, which helps it to produce concrete with the best workability and highest compressive strength with high cement content as reviewed in the literature. Besides, a lower fineness modulus produces more paste, making the concrete easier to finish. It should be noted that the fineness modulus does not determine the grading curve, and different grading systems could result ina similar fineness modulus. As a result, particle gradation and fineness modulus should be considered during concrete preparation.

4.3 Specific Gravity

Specific gravity is the ratio between the weight of a given volume of aggregates and the weight of an equal volume of water. Normally, the specific gravity of an aggregate is considered to be a measure of its strength and qualities. Aggregates having a low specific gravity are generally weaker than those with a high specific gravity. The specific gravity of CBA and river sand was measured with a pycnometer as shown in Fig.5. This test was performed by BS EN 1097-6: 2013.

Fig.5 The pycnometer used to measure specific gravity of aggregates

The results obtained from the tests showed that CBA has a specific gravity of 2.32, while river sand has a specific gravity of 2.63. As shown in Table 2, the specific gravity of CBA was found to be less than that of river sand. In general, CBA has a porous internal structure (voids present on the particle surface) thus making CBA lighter and more brittle than river sand. According to Singh [10], CBA has a porous texture with micro and macro pores, resulting in lower specific gravity values. The results of previous studies performed at different power plants have shown that the specific gravity of CBA ranges from 2.01-2.54. Even though the sources came from similar power plants, it was found that the specific gravity values differed. For example, Ramzi Hannan [1] and Ghadzali [11] studied the specific gravity of CBA from Tanjung Bin Power Plant in Pontian, Johor. It was found that the specific gravity values of CBA were 2.21 and 2.34, respectively. Also, Marto & Tan [12] and Ayob [13] looked at the specific gravity values from Manjung Power Plant in Perak and found different CBA values of 2.39 and 2.54, respectively.

Table 2 Specific gravity values of CBA and river sand

Authors	CBA	River Sand
[14]	2.01	–
[1]	2.21	2.81
[11]	2.34	2.86
[12]	2.39	–
[13]	2.54	–
Our research	2.32	2.63

Recent studies indicated that the specific gravity value of CBA from the Manjung Power Plant was approximately 2.32. It has a lower value compared to findings from a similar power plant. Several factors that affected the specific gravity values of CBA were the coal combustion method [15], as well as the condition and source of coal [10]. On the other hand, Ankur & Singh [16] stated that the specific gravity of CBA particles increases with the increase in the grinding period. Through the grinding process, the fineness of CBA increases and its porosity decreases, resulting in high specific gravity values. Most of the river sand used in construction has an SG value between 2.5 to 3.0. Current studies indicate that the specific gravity value of river sand is estimated to be around 2.63. Compared to the specific gravity of utilized in these investigations, it reduced by 11.38%. The specific gravity of river sand fulfilled the standard requirements. However, the specific gravity of CBA was found to be within the range outlined in previous studies, making it ideal for use in concrete applications since it is possible to be used as a lightweight material.

4.4 Water Absorption

The high water absorption of aggregate causes a high slump loss and makes concrete hard to work with, thereby affecting the strength of concrete. The water absorption test measures the amount of water that an aggregate can absorb into its pore structure. As seen in Table 3, the water absorption of CBA is higher than that of river sand.

Most studies reported that the percentage of water absorption for CBA varies. In comparison to fine aggregates, CBA has been found to have the highest water absorption values. The present study reveals that CBA has a water absorption value of 26.38%, whereas river sand has a value of 1.66%. It is interesting to note that the porous structure of CBA influences the rate of absorption. As shown in Fig.6, the SEM images indicate that the CBA particles have a large number of voids and therefore, a large amount of water gets absorbed by these voids. However, the water absorption of CBA obtained in this study falls in the range of previous studies that is 6.80% to 31.48%. Besides, previous studies have shown that the highest water absorption in river sand is 2.46%. According to BS 812-2: 1995, the water absorption of aggregate should not be more than 3%.

Table 3 Water absorption of CBA and river sand

Authors	CBA (%)	River Sand (%)
[3]	20.15	–
[7]	6.80	–
[6]	14.80	1.02
[17]	21.09	–
[18]	31.48	2.46
Our research	26.38	1.66

Since CBA absorbs more water, it might affect the slump values of CBA concrete. Previous studies using oven-dried CBA in concrete showed that the slump of concrete continues to decrease as the amount of CBA in concrete increases [15]. However, it also depends on the percentage replacement of CBA. Most research studies utilised around 10% of CBA to obtain a better slump value. In contrast, concrete containing 20% to 40% of CBA led to a substantial drop in slump values [19]. On the other hand, these problems can be resolved by adding superplasticizer in concrete mixtures as suggested by several studies. The outcomes of previous research suggest that it is acceptable to use CBA as a partial replacement for fine aggregate.

4.5 Chemical Composition

Table 4 shows the chemical composition of CBA and river sand determined through X-ray fluorescence (XRF). The main chemical compounds in CBA were SiO_2, Al_2O_3, Fe_2O_3 and CaO, which account for about 26.40%, 10.83%, 18.30% and 11.18%, respectively. On the other hand, river sand contains a high amount of SiO_2, contributing to about 54.30%.

Referring to Table 4, the chemical compounds of SiO_2 , Al_2O_3 and Fe_2O_3 present altogether in CBA were determined to be at 55.53%. Meanwhile, the values of SO_3 and LOI were 0.43% and 3.18%, respectively. According to ASTM C618-12a, CBA has been classified as Class C material since the sum of SiO_2 , Al_2O_3 and Fe_2O_3 ranges between 50% and 70% while SO_3 and LOI cannot exceed 5% and 6%, respectively. Having a high LOI value means that there is unburned carbon in the CBA, which makes the particles of CBA more porous [10]. However, most studies found that CBA is more common in Class F instead of Class C. Different classes exist because the chemical compounds in CBA differ depending on coal source, operating conditions, and processing conditions [9].

Table 4 Chemical composition of bottom ash and river sand

Oxides content (%)	Bottom Ash	River Sand
Silicon dioxide (SiO_2)	26.40	54.30
Aluminium oxide (Al_2O_3)	10.83	6.14
Iron oxide (Fe_2O_3)	18.30	0.21
Calcium oxide (CaO)	11.18	0.83
Potassium oxide (K_2O)	0.48	0.28
Titanium oxide (TiO_2)	0.81	0.32
Magnesium oxide (MgO)	2.84	–
Sodium oxide (Na_2O)	0.23	–
Sulphur trioxide (SO_3)	0.43	–
Loss of ignition (LOI)	3.18	–
SiO_2+Al_2O_3+Fe_2O_3	55.53	–

The standards of ASTM C618-12a explain that Class F material produced from burning anthracite (bituminous coal) contains pozzolanic materials and has a small amount of calcium. Meanwhile, Class C material produced from burning lignite (sub-bituminous) also contains pozzolanic materials and has a high calcium content. In the current study, the calcium content present in CBA has a value of 11.18%, which is slightly higher compared to the calcium content in Class F, which accounts for about 1.32% to 9.30% [3-6]. Besides, Table 1 also shows the results of river sand, which has a lower percentage of aluminium (6.14%), iron (0.21%), calcium (0.83%), potassium (0.28%), and titanium oxides (0.32%), with the exception of silicon dioxide which has a higher percentage of 54.3% compared to CBA which is 26.4%. However, the other elements of magnesium, sodium, and sulphur were not found in river sand.

One of the most significant chemicals in concrete is silicon oxide as it is required for the mixing process. Since CBA has pozzolanic properties with silicate-based materials, it will react with calcium hydroxide produced during cement hydration, resulting in the formation of calcium silicates hydrates (C-S-H) gels. The C-S-H gels react as the main binder in cement and concrete. Furthermore, the high calcium content of CBA helps in the improvement of C-S-H gels with high cementitious properties, resulting in better strength performance. Therefore, as CBA has pozzolanic and cementitious properties, its usage as a partial replacement for sand in concrete has a beneficial effect on concrete strength.

4.6 Microstructural Characteristics

The scanning electron microscope (SEM) was used to investigate the microstructure of CBA and river sand. CBA was observed through SEM images, as shown in Fig.6. It has been found that CBA has porous rounded and angular particles as well as a small number of spherical particles.

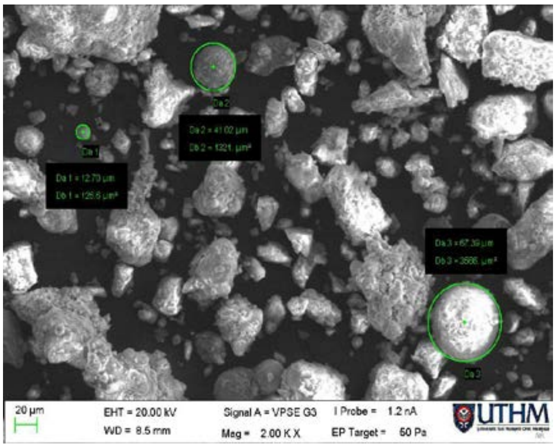

Fig.6 SEM image of CBA particles

Baite [3] observed the microstructure of CBA and found that CBA has an angular structure and a high number of micro pores on its surface. In addition, CBA is also found to have a rough surface texture. This observation was similar to a study by Abdulmatin [8] which looked at the surface texture of CBA and found that its texture is rough. Moreover, a large number of voids present on CBA particles can result in a greater amount of water uptake. Besides, the SEM images of sand particles were also observed, as shown in Fig.7. It can be seen that the sand particles were rounded or angular along with a smooth surface.

According to Singh & Siddique [21], the smooth surface of sand is resulted by weathering effects. Meanwhile, sand seems to have denser particles whereas CBA has particles that look like popcorn which is easier to degrade when compacted. The CBA has been observed to have interlocking characteristics, so it has the potential to be binded to each other like sand particles. There were different surface morphologies between CBA and sand, but the particle size of CBA seemed comparable to that of sand.

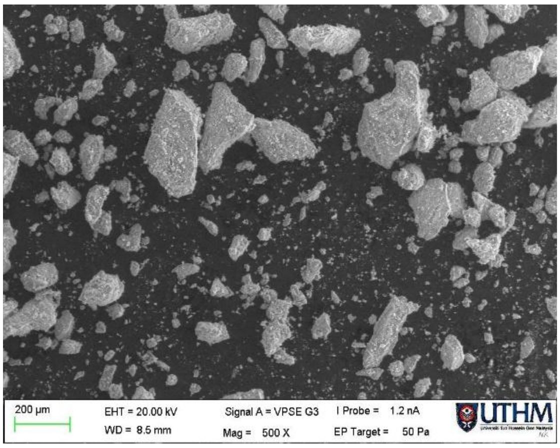

Fig.7 SEM image of sand particles

5. CONCLUSIONS

The present paper was investigated the properties of coal bottom ash from Manjung Power Plant. The use of CBA as a sand substitute in concrete has been accepted based on the following fundamental findings:

1. The particle size distribution of CBA was comparable to that of sand since CBA particles fall within the upper and lower grading limits of sand standards.
2. The CBA has a fineness modulus that is comparable to sand, with values of 2.93 and 2.94, respective. Both materials have been classified as coarse sands.
3. The SEM images shown that CBA has a porous structure and has particle characteristics similar to sand which is either round or angular. Therefore, both materials have interlocking characteristics.
4. Sand particles seem to have a smooth surface texture, but CBA has a rough surface texture. The rough texture of the CBA indicates a huge number of voids inside. This is proven through the water absorption test, in which CBA absorbs 26.38% more water than sand for about 1.66%.
5. Sand seems to have denser particles, but CBA looks to have lighter and more brittle particles. The porous structure and light particles of CBA results in it having a lower specific gravity than sand, respective for 2.32 and 2.63.

6. The CBA utilised in this investigation was classified as Class C according to its total composition of about 55.53%. It contains pozzolanic materials and has a high calcium content. Since bottom ash has a high calcium concentration, this helps in the enhancement of C-S-H gels with high cementitious characteristics, resulting in higher strength performance.

The results of this research demonstrate that CBA from Manjung Power Plant has the potential to be used as a sand substitute in concrete since its characteristics are identical to that of sand particles. However, further studies are required to explore the application of Manjung bottom ash as a construction material. It is suggested that future investigations be conducted on the mechanical properties of Manjung bottom ash.

6. ACKNOWLEDGMENTS

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7. REFERENCES

[1] Ramzi Hannan N. I. R., Shahidan S., Ali N., Bunnori N. M., Mohd Zuki S. S., and Wan Ibrahim M. H., Acoustic and Non-Acoustic Performance of Coal Bottom Ash Concrete as Sound Absorber for Wall Concrete. Case Study in Construction Materials, Vol. 13, 2020, p. e00399.

[2] Singh M. and Siddique R., Compressive Strength, Drying Shrinkage and Chemical Resistance of Concrete Incorporating Coal Bottom Ash as Partial or Total Replacement of Sand. Construction and Building Materials, Vol. 68, 2014, pp. 39–48.

[3] Baite E., Messan A., Hannawi K., Tsobnang F., and Prince W., Physical and Transfer Properties of Mortar Containing Coal Bottom Ash Aggregates from Tefereyre (Niger). Construction and Building Materials, Vol. 125, 2016, pp. 919–926.

[4] Rafieizonooz M., Mirza J., Salim M. R., Hussin M. W., and Khankhaje E., Investigation of Coal Bottom Ash and Fly Ash in Concrete as Replacement for Sand and Cement. Construction and Building Materials, Vol. 116, 2016, pp. 15–24.

[5] Hasim A. M., Shahid K. A., Ariffin N. F., Nasrudin N. N., and Zaimi M. N. S., Properties of High Volume Coal Bottom Ash in Concrete Production. Materials Today: Proceedings, Vol. 48, 2021, pp. 1861–1867.

[6] Pal S., Shariq M., Abbas H., Pandit A. K., and Masood A., Strength Characteristics and Microstructure of Hooked-End Steel Fiber Reinforced Concrete Containing Fly Ash, Bottom Ash and Their Combination. Construction and Building Materials, Vol. 247, 2020, p. 118530.

[7] Singh N., Mithulraj M., and Arya S., Utilization of Coal Bottom Ash in Recycled Concrete Aggregates Based Self-Compacting Concrete Blended with Metakaolin. Resources, Conservation and Recycling, Vol. 138, 2019, pp. 257–271.

[8] Abdulmatin A., Tangchirapat W., and Jaturapitakkul C., An Investigation of Bottom Ash as a Pozzolanic Material. Construction and Building Materials. Vol. 186, 2018, pp. 155–162.

[9] Gooi S., Mousa A. A., and Kong D., A Critical Review and Gap Analysis on the Use of Coal Bottom Ash as a Substitute Constituent in Concrete. Journal of Cleaner Production, Vol. 268, 2020, p. 121752.

[10] Jorat M. E., Marto A., Namazi E., and Amin M. F. M., Engineering Characteristics of Kaolin Mixed with Various Percentages of Bottom Ash. Electronic Journal of Geotechnical Engineering, Vol. 16, 2011, pp. 841–850.

[11] Ghadzali N. S., Ibrahim M. H. W., Zuki S. S. M., Sani M. S. H., and Al-Fasih M. Y. M., Material Characterization and Optimum Usage of Coal Bottom Ash (CBA) as Sand Replacement in Concrete. International Journal of Integrated Engineering, Vol. 12, No. 9, 2020, pp. 9–17.

[12] Marto A. and Tan C. S., Properties of Coal Bottom Ash from Power Plants in Malaysia and its Suitability as Geotechnical Engineering Material. Jurnal Teknologi, Vol. 5, 2016, pp. 1–10.

[13] Ayob A., Zahid M. Z. A. M., Zaki M. F. M., Hamid S. H. A., Yussuf M. A. H. M., and Yunus A. N. M., Physical, Morphological and Strength Properties of Jana Manjung Coal Ash Mixture for Geotechnical Applications. Advances in Environmental Biology, Vol. 8, No. 22, 2014, pp. 25–29.

[14] Singh N., Shehnazdeep, and Bhardwaj A., Reviewing the Role of Coal Bottom Ash as an Alternative of Cement. Construction and Building Materials, Vol. 233, 2020, p. 117276.

[15] Muthusamy K., Rasid M. H., Jokhio G. A., Budiea A. M. A., Hussin M. W., and Mirza J., Coal Bottom Ash as Sand Replacement in Concrete: A Review. Construction and Building Materials, Vol. 236, 2020, p. 117507.

[16] Ankur N. and Singh N., Performance of Cement Mortars and Concretes Containing

Coal Bottom Ash: A Comprehensive Review. Renewable and Sustainable Energy Reviews, Vol. 149, 2021, p. 111361.

[17] Kadam M. P. and Patil Y. D., The Effect of Sieved Coal Bottom Ash as a Sand Substitute on the Properties of Concrete with Percentage Variation in Cement. American Journal of Civil Engineering and Architecture, Vol. 2, No. 5, 2014, pp. 160–166.

[18] Singh M. and Siddique R., Properties of Concrete Containing High Volumes of Coal Bottom Ash as Fine Aggregate. Journal of Cleaner Production, Vol. 91, 2015, pp. 269–278.

[19] Muthusamy K., Jamaludin N. F. A., Kamaruzzaman M. N., Ahmad M. Z., Zamri N. A., and Budiea A. M. A., Compressive Strength of Palm Oil Clinker Lightweight Aggregate Concrete Containing Coal Bottom Ash as Sand Replacement. Materials Today: Proceedings, Vol. 46, 2020, pp. 1724–1728.

[20] Mangi S. A., Wan Ibrahim M. H., Jamaluddin N., Arshad M. F., and Putra Jaya R., Short-Term Effects of Sulphate and Chloride on the Concrete Containing Coal Bottom Ash as Supplementary Cementitious Material. Engineering Science and Technology, an International Journal, Vol. 22, No. 2, 2019, pp. 515–522.

[21] Singh M. and Siddique R., Effect of Coal Bottom Ash as Partial Replacement of Sand on Properties of Concrete. Resources, Conservation and Recycling, Vol. 72, 2013, pp. 20–32.