



## Physiochemical Properties of Poly-vinyl alcohol-modified Fly-Bottom Ash Mixture for Engineering Utilization

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### ABSTRACT

Despite the current advancements in, and increasing use of renewable types of energy, approximately 40% of the world's electricity is still produced by coal fired power stations. This trend is significantly higher in some continents, for example approximately 70% in India and up to 90% in South Africa. In this study the fly-bottom ash (FBA) mixture with different component percentages of BA (bottom ash)100, FA (fly ash) 25-BA75, FA50-BA50, FA75-BA25 and FA100 were modified with 2% of poly-vinyl alcohol (PVA), and tested in terms of particle size distribution, specific gravity, pH, surface morphology, mineralogical-compound content, and engineering properties. The physiochemical modified FBA were examined via scanning electron microscope (SEM), X-ray fluorescence, and Fourier transform infrared spectroscopy (FTIR) analysis. Polymeric-modified FBA for all compositions exhibited high pH values within the range of 10.11–10.70. SEM image exhibited agglomerated and strongly bonded PVA-modified FBA with FA50-BA50 composition because of the effect of polymer that reacted with the fine ashes. The unsubstantial shift in peak position of Si/Al-O stretches showed electrostatic interaction between PVA and FBA based on FTIR analysis. The PVA-modified FBA at composition of FA50-BA50 increased the gradient of stress–strain curves, which significantly improved the strength behavior of PVA-modified FBA sample. It is thus imperative that other sustainable methods of managing coal combustion-by products be expanded.

### Keywords:

Modified fly-bottom ash, PVA, polymer, bulk ash waste

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## 1. Introduction

Coal ash is a very abundant technogenic waste generated during coal combustion and is a huge environmental threat. Due to this, its recycling has been a concern of intensive research for a long period. Coal combustion by-products (CCPs) are the materials produced when coal is burned to generate electricity in a power plant. In developing nations, management of CCPs has created a challenge for utilities and regulators. Moreover, these countries have enhanced environmental perception and awareness by imposing stricter instructions and guidelines for new construction

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project of coal power plants. In 2024, approximately 83% of electric power in Malaysia will consume fossil fuels of 58% coal and 25% gas which signify increase of coal consumption from 43% in 2014 to 58% in 2024 [1]. Thus, the CCPs will increase due to the increased coal consumption.

CCPs are categorized as hazardous substances and usage of them is limited in many countries. Most types of ash, including fly ash (FA) and bottom ash (BA) are dumped in landfills because of the bulk quantity produced. This disposal method creates environmental, economic, and health problems [2, 3]. Many determinants, such as the particle size, initial concentration of trace elements, pH of extraction solution, leaching time, and solid/liquid ratio, effect the mobility of the trace elements in aqueous environment. The trace species readily leached from the dumped fly ash, thereby posing threats to the air, surface and groundwater, soil and crop produce. On the contrary, these CCPs have chemical and physical properties that make them suitable for beneficial use in engineering and construction applications. Recycling of these by-products in green concrete industry helps to reduce energy demand as well as carbon dioxide (CO<sub>2</sub>) emissions, for example, every ton of cement which is replaced by CCPs in the concrete manufacturing facility results in the decrease of CO<sub>2</sub> emission in the amount of 0.7–1.2 tons [2, 4, 5].

The global annual CCPs production was about 780 Mt in 2011. The major CCPs-producing country was China (395 Mt). Next, the countries or regions of the subscribers were the US (118 Mt), India (105 Mt), Europe (52.6 Mt), Africa (31.1 Mt), and the Middle East [2, 6]. Accordingly, from these figures and forecasts, the global CCPs production will remain increasing steadily over the next few decades, because of the continued energy demands from coal combustion. In 2012, 470 coal-fired electric utilities actively generated million tons of coal ash by-products, where only 44% are productively reused [2, 7]. From this figure, approximately 54 million tons was the fine particulate FA. Only 38% of this material is productively recycled, primarily as supplementary pozzolanic material in the concrete industry, making it the largest FA reuse sector. Productive application in bulk reduces the impact of waste disposal and causes a substantial reduction in the use of virgin material that leads to energy saving as well. The properties of CCPs related to chemical constituent, mineralogy, geochemistry, and trace features are of basic significance in establishing different applications of CCPs. Furthermore, these specific characteristics depend on the type of coal used, the percentage of incombustible substance in the coal, the nature of the mineral substance in the coal, sulphur constituent, the pulverization mechanism, furnace systems, the combustion processes, and the collector systems are among other factors [8].

The coal FA are principally fine powdery particles, spherical in shape, either solid or hollow, mostly amorphous in nature and consist of a small proportion of porous unburnt carbon. The majority of the FA particles are smaller than those in cement, with the size distribution ranging from 1 µm to several hundred µm, that is generally similar to that silt size [9]. Since it represents a CCPs with the highest proportion of total CCPs generation, application of FA can be an excellent replacement for Portland cement in concrete and the use of FA as a mineral additive in cement. The partial replacement of Portland cement with FA reduces the heat of hydration, improves the workability and durability of the concrete due to the particular engineering properties for example, pozzolanic character, specific gravity, permeability, internal angular friction, and consolidation characteristics. In China, approximately 41% and 19% of the total ashes generation were, respectively, used to cement and concrete manufacture in 2011 [10]. In addition to its incorporation in concrete construction, Prashanth et al., (2001, 11) suggested the potential of pozzolanic FA as a hydraulic barrier in landfill, as the FA possessed low shrinkage; thus, it did not crack. By contrast, BA is heavier and coarser CCPs and mainly consisted of agglomerated ash particles formed in pulverized-coal furnaces that fall via the airflow to the bottom of the boiler and mechanically removed [12]. This ash does not possess the same enhanced workability. However, the chemical constituents of both two

materials are very similar, with the main difference in their particle shape and size. The latter material is larger in size, irregular in shape, and contains porous surface structure and cavities [13].

With respect to the chemical constituents, the major constituents of FA are silica, alumina, ferrous, and other metal oxides, for example calcium, potassium, and sodium oxides, with different amounts of carbon [2, 9]. These contents of metal oxides in FA are typically the decreasing sequence of  $\text{SiO}_2 > \text{Al}_2\text{O}_3 > \text{Fe}_2\text{O}_3 > \text{CaO} > \text{MgO} > \text{K}_2\text{O} > \text{Na}_2\text{O} > \text{TiO}_2$ , which due to the difference in the source and combustion systems [14]. Additionally, given the aforementioned major difference, high-Ca Class C FA is usually generated from the burning of low-rank lignites or sub-bituminous coals. However, low-Ca Class F FA is typically generated from the burning of higher percentage bituminous coals or anthracites [2]. Class C is categorized by cementitious properties of self-hardening when reacted with water. Meanwhile, Class F has pozzolanic characteristics of hardening when reacted with  $\text{Ca}(\text{OH})_2$  and water [9].

FA is not yet completely utilized; thus, a large amount of BA is still dumped. Therefore, reusing both the FA and the BA for example roadway construction, embankment soil stabilization, subgrade base coarse material, as aggregate filler, as a bituminous pavement additive, and as a mineral filler for bituminous concrete has a significant benefit. The hydrated ash had stiffness equal to or greater than that of lime rock when used in both subgrade stabilization and base course application. Therefore, both the ashes of FA and BA can be effectively utilized in civil engineering projects [10].

FA alone cannot be utilized effectively in various fields of application. Owing to the pozzolanic properties with high capacity of the FA to react with lime to form a hydraulic agglomerate, the cements produced from FA are classified by high water retention potential. One of the most useful solutions to this problem is to modify FA with different admixtures. Many other materials, such as lime [15] and organic polymer [16], have been used as modifiers or additives. Several researchers have discussed aqueous polymer modification on polymer-soil interaction that defines the effectiveness of polymer solution in various applications [17]. Additionally, using surfactants as simulators will affect configurations, microstructure of matrix, and would improve the inert particles in the deposit. Thus, the stability of solution through the hydrophobicity of the surface charge of suspended particles will increase as well as electrostatic adsorption between the polar inorganic and non-polar organic. Meanwhile, utilizing FA as filler in different polymeric materials shows no binding between the polymer and individual FA, where the quality of the product is unsatisfactory [18]. Thus, a fly-bottom ash (FBA) mixture is proposed to be a new sustainable material in engineering application. The spherical shape of FA and uneven surface of BA facilitate dispersion and fluidity when modified with polymeric material. If the surface properties of fly and bottom ash can be modified in such a way a new market for the utilization of FBA mixture can be materialized. Thus, this current study investigates the physiochemical properties of FBA mixture modified by poly-vinyl alcohol (PVA) and studies its polymeric effect on the engineering utilization.

## **2. Methodology**

The coal FA and BA samples were obtained from the Jana Manjung, Perak coal power plant and then oven-dried for 48 hours before use. The mixture proportions in different percentages were denoted as BA100, FA25-BA75, FA50-BA50, FA75-BA25, and FA100 and were measured based on the weight of the total FBA. Sieve analysis and grain size distribution were conducted to achieve the gradation curve of the FBA mix according to ASTM D422-63 (2007, 19). The specific gravity of the FBA mixtures was measured using a small pycnometer method, as stated in ASTM D854-14 (2000, 20).

PVA of  $M_w \approx 200 \text{ K}$  were fully hydrolyzed purchased from MERCK and used as received. Each set of FBA mixture was modified with PVA at concentrations of 2.0 wt%. PVA was dissolved in distilled

water at 80°C to prepare solutions of about 2.0 wt%. Under a temperature of 50°C, the FBA aqueous suspension containing PVA solution was stirred for 6 h by a water bath shaker at 130 rpm. Then, pH values were determined after stirring the samples of unmodified and modified FBA of PVA for 15 min to allow the pH of the slurry to stabilize. Thereafter, the samples were filtered with filter funnel, washed thrice with distilled water, and poured into cylinder molds for 48 hours. Then, the samples were wrapped in cling film and left to cure for 14, and 28 days. The mineralogical and morphological characterizations of unmodified and PVA-modified FBA were studied through scanning electron microscope (JEOL JSM 6460 LA), X-ray fluorescence (MiniPAL 4), and FTIR (PerkimElmer Spectrum). For engineering properties, the strengths of the samples were determined through Proctor compaction [21] and unconfined compression tests [22].

### **3. Results**

#### *3.1 Particle-size distribution, specific gravity, and pH values*

The fine grain composition increases when mixtures contain more FA particles. Particle-size distribution of FBA mixtures covers the range between clay to gravel, with the size ranging from 0.001 mm to 5.0 mm (figure not shown). The fine size of spherical FA particles contributes to a better packing of the aggregate materials, which decreases porosity [23], and thus considerably enhances the workability of FBA mixture for engineering utilization. However, this silt-sized particle content of FA mixtures has certain advantages on the compressibility characteristics of soil. The compressibility of FBA increases with the increase of FA percentage composition. The mixture that contains BA100 can be categorized as coarse-grained soil particle, which is distributed within the range of 0.08–5.0 mm.

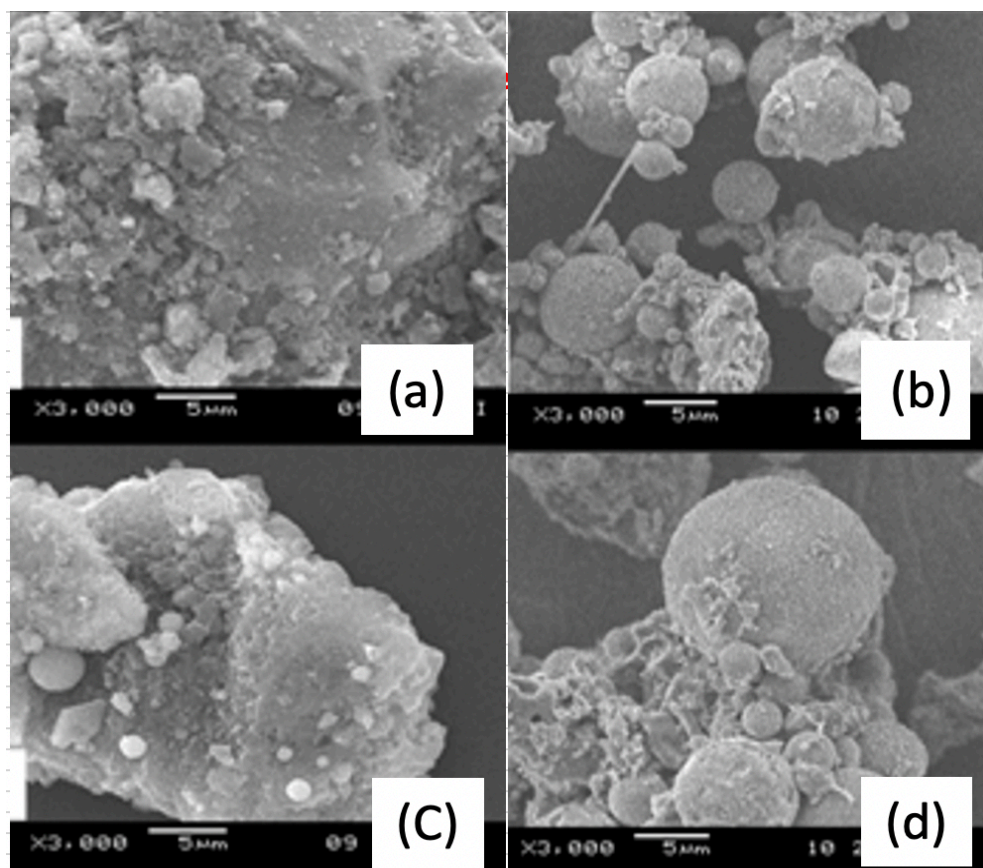
The specific gravity value reduces as the FA content in the mixture increases. The specific gravity values are 2.50, 2.42, 2.32, 2.21, and 2.10 for BA100, FA25-BA75, FA50-BA50, FA75-BA25, and FA100, respectively. Meanwhile, a study from Pal and Ghosh (2010, 24) mentioned that no specific trend of relationship between particle-size distribution and specific gravity of FA mixture has been observed. The difference in the range of specific gravity value can be attributed to the chemical composition and presence of hollow FA particles or either BA particles with porous or vesicular structure. Given that higher iron oxide contents result in higher specific gravity of BA, the amount of iron oxide contents of coal ash specimens depends on the source of coal used in the burning process.

Typically, during the pH value measurement, the solubility of these oxides determined the release of elements to the solution. Both unmodified and PVA-modified FBA solutions are alkaline. The pH values ranging from 9.20 to 9.80 and 10.11 to 10.70 for unmodified and PVA-modified FBA, respectively, which is caused by the FA that contains higher free lime and alkaline oxides. The pH value of the ash-water system depends mainly on the Ca/S molar ratio in ash, although other minor alkalis or alkaline earth cations may also contribute to the balance [25-26]. Thus, FBA utilization could enhance the physical, chemical, and environmental qualities of soils to which it is applied. This result is caused by the physicochemical properties of FBA, including silt- and clay-sized particles, low bulk density, higher water-holding capacity, favorable pH, and source of essential plant nutrients, thereby conferring it with potential soil-engineering utilization [27]. With regard to the engineering application, PVA-modified FBA is safe for use, and corrosion can be reduced even if the reinforcement bar is placed in the concrete during the construction work.

### 3.2 Morphological characterization of PVA-modified FBA mixture

SEM images show the morphologies of unmodified and PVA-modified FBA (Fig. 1) at 28 days of curing. SEM image shows that at BA100 composition of unmodified FBA, the particles are angular and irregular in shape, with rough and uneven surface texture for day 28 (Fig. 1a). The particle surface is shiny, clean, and free of dust, which tends to be relatively inert due to the larger size and fused that attribute to less pozzolanic mechanism. However, as for modified mixture of BA100, the angular and irregular shapes are replaced by rounded and spherical particle shapes (Fig. 1b).

At composition of FA50-BA50, a distinct morphological of unmodified FA particle agglomerated with thin wall, glassy spheres, and its surface appears to be smooth (Fig. 1c). The particle morphology and size of a mixture play an important role in the determination of its potential use in engineering utilization. Additionally, the PVA-modified FA50-BA50 composition is packed more closely and suggests higher pozzolanic reaction, which will enhance its cementing properties (Figs. 1d). Pozzolanic reaction is important to improve the plasticity and strength characteristics of soil. Furthermore, the particles for PVA-modified FBA significantly agglomerated and strongly bonded similar to a popcorn shape because of the effect of PVA that reacted between the coal ashes. Thus, this observation shows higher level of chemical interaction between the coal ash particles, which significantly enhances its engineering properties.



**Fig. 1.** SEM surface morphology of for 28 days curing period of (a) unmodified BA100; (b) PVA modified BA100; (c) unmodified FA50-BA50; and (d) PVA-modified FA50-BA50

### 3.3 Mineralogical contents of PVA-modified FBA

Almost all known natural inorganic compositions are detected in unmodified and PVA-modified FBA. The primary oxide content (POC =  $\text{SiO}_2 + \text{Fe}_2\text{O}_3 + \text{CaO} + \text{Al}_2\text{O}_3 + \text{MgO} + \text{SO}_3 + \text{K}_2\text{O} + \text{TiO}_2$ ) ranges from 98.30%-98.81% for unmodified FBA (Table 1).

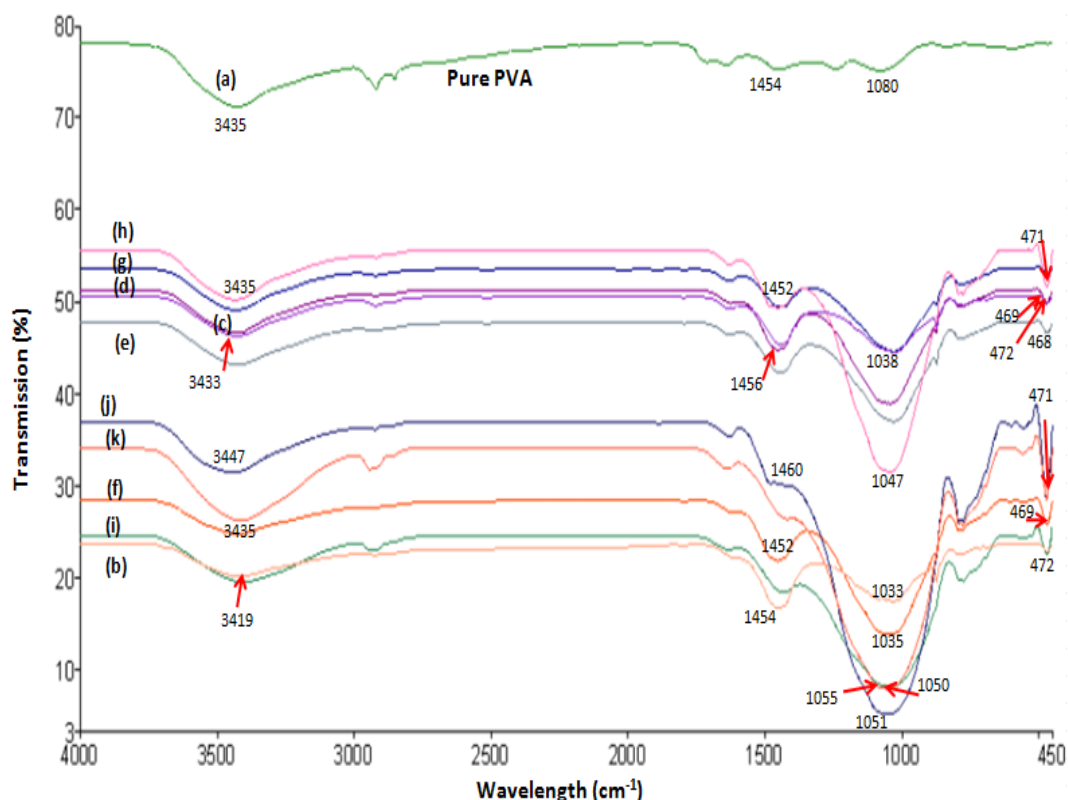
**Table 1**  
 Primary oxide contents analyzed by XRF

POC	Coal ash composition									
	Unmodified					PVA-modified				
	BFA100	FA25-BA75	FA50-BA50	FA75-BA25	FA100	BFA100	FA25-BA75	FA50-BA50	FA75-BA25	FA100
$\text{SiO}_2$	33.30	39.40	40.91	45.00	47.20	32.10	38.40	39.30	43.60	47.30
$\text{Fe}_2\text{O}_3$	26.48	23.06	21.60	18.09	16.11	28.16	24.54	24.28	20.19	16.60
CaO	19.90	16.30	15.10	12.10	9.70	20.30	17.10	15.90	11.90	9.41
$\text{Al}_2\text{O}_3$	10.20	14.70	16.01	18.70	20.50	10.00	14.10	14.80	18.70	20.80
MgO	3.70	-	-	-	-	3.00	-	-	-	-
$\text{SO}_3$	2.66	2.02	1.97	1.55	1.21	1.900	1.20	0.88	0.48	0.44
$\text{K}_2\text{O}$	1.11	1.63	1.75	1.91	2.28	1.2	1.56	1.68	2.04	2.30
$\text{TiO}_2$	1.13	1.28	1.49	1.46	1.64	1.08	1.32	1.34	1.57	1.69

The recorded values of POC for PVA-modified FBA at concentration of 2.0% range from 97.74%-98.54%, where the percentages of POC did not change significantly. The amounts of other oxide components, for example MnO, SrO, HgO, and RuO<sub>2</sub> which are identified in unmodified and PVA-modified FBA, range from 1.15%–1.73%, and 1.43%-2.20%, respectively (data not shown). No apparent change in mineral phases is observed as a consequence of the modified FBA sample. Both POC and minerals of FBA samples clearly show no change in the mineralogical contents because of the modification process with polymer.

### 3.4 FTIR Analysis

The FTIR spectra for various compositions of unmodified and PVA-modified FBA at 28 day curing period is shown in Fig. 2. The stretching vibrations of Si–O–Al bonds mainly occur within the range of 1200–400  $\text{cm}^{-1}$  [18, 21]. All the major bands are centered at 1033, 1038, 1035, 1047, and 1051  $\text{cm}^{-1}$ ; and 472, 472, 469, 471, and 471  $\text{cm}^{-1}$  for the vibrations of Si–O/Al–O and Si–O bonds [29] respectively, for unmodified FBA at BA100, FA25-BA75, FA50-BA50, FA75-BA25, and FA100 composition (Figs. 2b, 2d, 2f, 2h, and 2j). Meanwhile, the bands within the range of 1452–1460  $\text{cm}^{-1}$  could be due to the stretching vibrations of O–C–O, which signify the presence of carbonates and possible traces of calcite, whereas the bands within the range of 3419–3447  $\text{cm}^{-1}$  are ascribed to bending (H–O–H) vibrations of bound water molecules for all unmodified FBA samples (Figs. 2b, 2d, 2f, 2h, and 2j, 28).



**Fig. 2.** Comparison of FTIR spectra for various composition of (a) 2% pure PVA, unmodified FBA (b) BA100, (d) FA25-BA75, (f) FA50-BA50, (h) FA75-BA25, (j) FA100; and PVA-modified FBA (c) BA100, (e) FA25-BA75, (g) FA50-BA50, (i) FA75-BA25, and (k) FA100 at 28 day curing period

Additionally, the changes that occur in the PVA-modified FBA, the first observation is for the higher shifting bands of FA75-BA25 and FA100 compositions from 1047 and 1051  $\text{cm}^{-1}$  (Figs. 2h and 2j) to wave numbers of 1050 and 1055  $\text{cm}^{-1}$ , respectively (Figs. 3i and 3k). The other peaks changed to slightly lower wave numbers of 1031, 1031, and 1032  $\text{cm}^{-1}$ , respectively, for BA100, FA25-FA75, and FA50-BA50 composition of PVA-modified samples (Figs. 2c, 2e, and 2f).

Same to wave numbers assigned to Si-O group, the frequencies are unchanged for PVA-modified FBA of FA100 at 471  $\text{cm}^{-1}$  (Figs. 2j and 2k). Meanwhile, the wave numbers of PVA-modified FBA FA50-BA50 slightly changed to higher frequency from 469  $\text{cm}^{-1}$  (Fig. 2f) to 472  $\text{cm}^{-1}$  (Fig. 2g); meanwhile, for BA100 and FA25-BA75, the wave numbers changed to lower bands of 469 (Fig. 2c) and 468  $\text{cm}^{-1}$  (Fig. 2e), respectively, from 472  $\text{cm}^{-1}$  for both patterns (Figs. 2b and 2d). All these shifts are significantly small, and the interaction between PVA and FBA could be due to electrostatic interaction.

The shifting to higher frequencies could result from the physical bonding between the Al-O/Si-O/other oxides in FBA with highly active polar group in PVA, such as  $-\text{COOCH}_3$  group. Meanwhile, the actions of physical bonding between hydroxyl ( $-\text{OH}$  group) in PVA and Al-O/Si-O/other oxides on FBA surfaces molecules changed the band of related bonds to lower frequencies with reduction in the sharpness of peaks. This phenomenon presents under atmospheric condition, when metal and metal oxides surfaces are well-known to be absorbed/adsorbed with  $-\text{OH}$  group or ions, thus forming physical bonding with other substrates. The magnitude of the shift depends on the amount of silica in the FBA. These changes could indicate the occurrence of a new product, an amorphous alum inosilicate ( $\text{Al}_2\text{SiO}_8$ ) phase [30].

The  $-\text{OH}$  group has been observed in fully hydroxylated silica powder, quartz, mullite, and glassy alumina-silicates in the PVA-modified FBA, approximately within the band of 469–472  $\text{cm}^{-1}$  (Figs. 2c,



2e, 2g, 2i, and 2k). The –OH group occur on the surface of the modified FBA could be due to the improved interfacial interactions with PVA chain by physical and/or chemical bonding. The distinct absorption peak at about 3403–3435  $\text{cm}^{-1}$  for the PVA-modified FBA (Figs. 2b, 2d, 2f, 2h, and 2j) is for the –OH group due to the stretch of the hydrogen bond with OH groups. The stronger stretches at these frequencies show a higher degree of water molecule retention in the mass of PVA-modified FBA.

### 3.5 Engineering Properties of PVA-Modified FBA

#### 3.5.1 Maximum dry density (MDD) and Optimum Moisture Content (OMC)

The MDD and OMC values among the different compositions of unmodified and PVA-modified FBA are shown in Table 2. The highest MDD value of unmodified FBA was 1.2  $\text{g}/\text{cm}^3$  for FA50-BA50 composition. Meanwhile, for PVA-modified FBA of BA100, FA25-BA75, and FA50-BA50 composition, the MDD value are significantly increased from 1.09  $\text{g}/\text{cm}^3$  to 1.24  $\text{g}/\text{cm}^3$  (Table 2). Thus, the PVA-modified samples had increased the MDD in most of the FA composition when compared with the unmodified samples. For PVA-modified FBA of FA100 composition, the MDD value decreases from 1.18  $\text{g}/\text{cm}^3$  to 1.11  $\text{g}/\text{cm}^3$ .

**Table 2**

MDD, and OMC values for unmodified and PVA-modified FBA

Composition of FBA	MDD ( $\text{g}/\text{cm}^3$ )	OMC (%)
Unmodified		
BA100	1.07	17.20
FA25-BA75	1.13	16.60
FA50-BA50	1.25	18.40
FA75-BA25	1.13	17.60
FA100	1.11	14.20
PVA-modified FBA		
BA100	1.09	16.80
FA25-BA75	1.14	16.50
FA50-BA50	1.24	17.50
FA75-BA25	1.14	18.20
FA100	1.18	16.80

The OMC values of PVA-modified FBA from the Proctor test samples increased from 17.06%, 17.30%, and 18.91%, respectively for BA100, FA25-BA75, and FA50-BA50 composition (Table 2). The content of the BA increases which provides a well-graded size distribution, which significantly increases in MDD. A different trend of MDD values for PVA-modified FBA at FA75-BA25 and FA100 composition which could due to FA and BA particles that separated into two groups during a certain level of mixing. In this case, certain void between the FBA contained more water, but another part of the mixtures has smaller void filled less water, which result in lower MDD of 1.14  $\text{g}/\text{cm}^3$  and 1.18  $\text{g}/\text{cm}^3$  for FA75-BA25 and FA100 composition, respectively. Finer ash particles within the range of 0.001–5 mm give less amount of water for lubricating effect, which reduces OMC when mixed with PVA. However, for unmodified FA100 composition, some weak, large cenosphere FA particles are crushed into finer particles during compaction, resulting in decreased air content because the fines occupy the voids between FA particles, thereby contributing to the increase in MDD value (1.11  $\text{g}/\text{cm}^3$ ) and decrease in OMC value (14.20%, Table 2).



Typically, specific gravity proportionally relates to the dry density value of FA, regardless of the moisture contents and compaction energy [18]. The FA50-BA50 composition at a specific gravity value of 2.36 contributes the highest MDD value of 1.24 g/cm<sup>3</sup> for PVA-modified BFA. This phenomenon could be due to the equal composition of FA50-BA50, which allows the closely packed arrangement of the particles; thus, dry density level increased. The particle structure could affect the MDD and OMC values of FBA. Additionally, the hollow FA particles with porous or vesicular textures have lesser MDD values than that of solid particles. The FA particles with irregular shape, holes, and crevices resulted in the entrapped air in the sample mixture during compaction, which then could contribute to the decrease in the MDD value and increase in the OMC values in this present study.

Higher OMC values could be attributed to the tendency of FBA particles to achieve the cation exchange reaction for more modifiers' solution. Likewise, with the application of compaction effort, the voids are filled by higher amounts of PVA solution. Thus, in the application of soil stabilization with FA, the values of MDD and OMC largely depend on the fraction of FA in the mixture as well as the source of ash.

### 3.5.2 Strength behaviour of PVA-modified FBA

Results of unconfined compression strength (UCS) and undrained shear strength (USS) are illustrated in Fig. 3, following Eq. 1:

$$S_u = q_u/2 \tag{1}$$

where  $q_u$  is the UCS, and  $S_u$  is the USS.

The UCS and USS values of both unmodified and PVA-modified FBA for BA100, FA25-BA75, and FA75-BA25 composition increased starting from day 14 and 28 of the curing period. The highest UCS strength values recorded for PVA-modified FA50-BA50 composition significantly increases from 43.37 kPa on day 14 of curing to 43.07 kPa when curing is completed. This phenomenon is explained by the fact that PVA content resulted in enhanced bond mechanism of the FA-BA emulsion interface. The adsorption mechanism of PVA emulsion will possibly attach to fine FA composition than to the BA particles. The PVA is categorized as cationic polymer which the PVA molecules can easily form an electrostatic bond with the FA particles [18]. The retention on FA appears mostly through sorption of polymer molecules on both internal and external pore surfaces or microscopic interlayer spaces, which causes higher cohesion of particles in FA and increase in UCS value. The adsorption causes the PVA to change in conformation; thus, it tends to exist as random coils in solution, and uncoils and spreads out at the solid interface.

For, the PVA-modified FA100 composition the UCS and USS significantly decreased from 39.85 kPa to 33.30 kPa and 19.93 kPa to 16.65 kPa, respectively (Fig. 3). This condition could be due to the interlocking between the FA particles created from the chemical reactions. FA particles gain higher UCS from the cementitious reaction or via hydrolysis process of the particles on day 14 of the curing period (Fig. 3). The lowest strength observed for PVA-modified BA100 composition is 15.34 kPa, which is due to its low cohesive characteristics. This results means that with PVA addition, the modified FBA shows a better strength at the same strain level. Modification by PVA also leads to an increase in the stiffness trends for the FBA. The USS of that particular composition is determined at 21.54 kPa. In this case, PVA binds the coal ash particles; thus, the shear strength of the polymeric-modified FBA is increased, and its engineering properties are enhanced for further utilization.

Observing the stress–strain plots on days 14 and 28 of the curing period, the gradient of stress–strain curves significantly increases with an increased FA composition from 0% to 50% of the PVA-modified FBA samples (Figs. 4a and 4b).

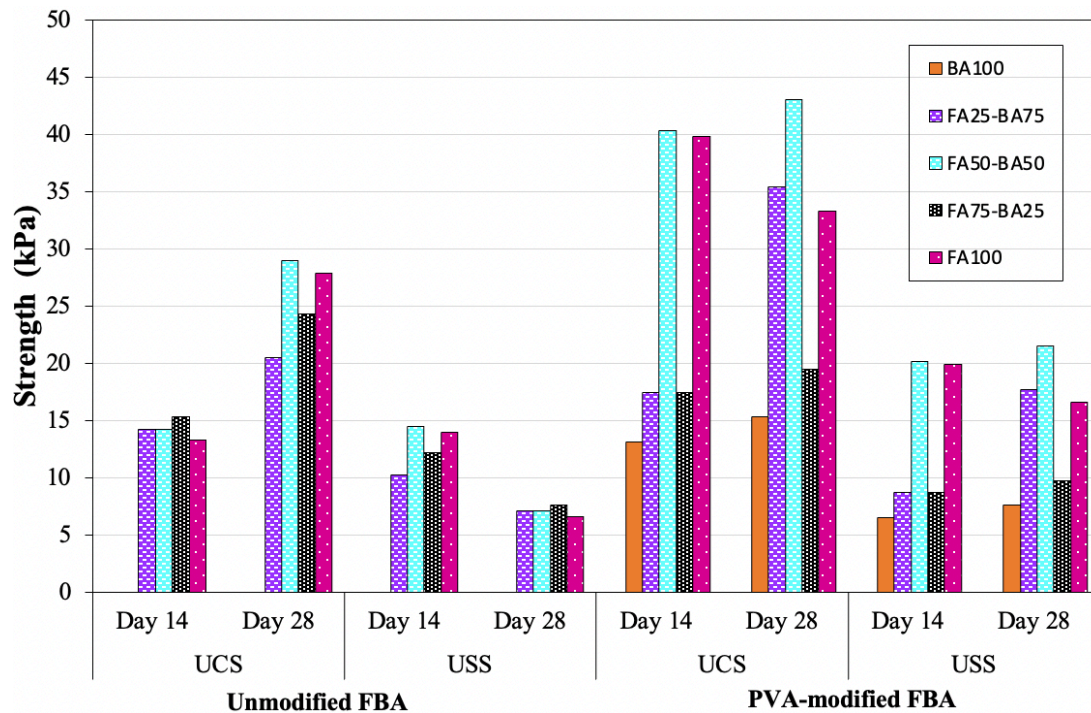


Fig. 3. Unconfined compressive strength and undrained shear strength values

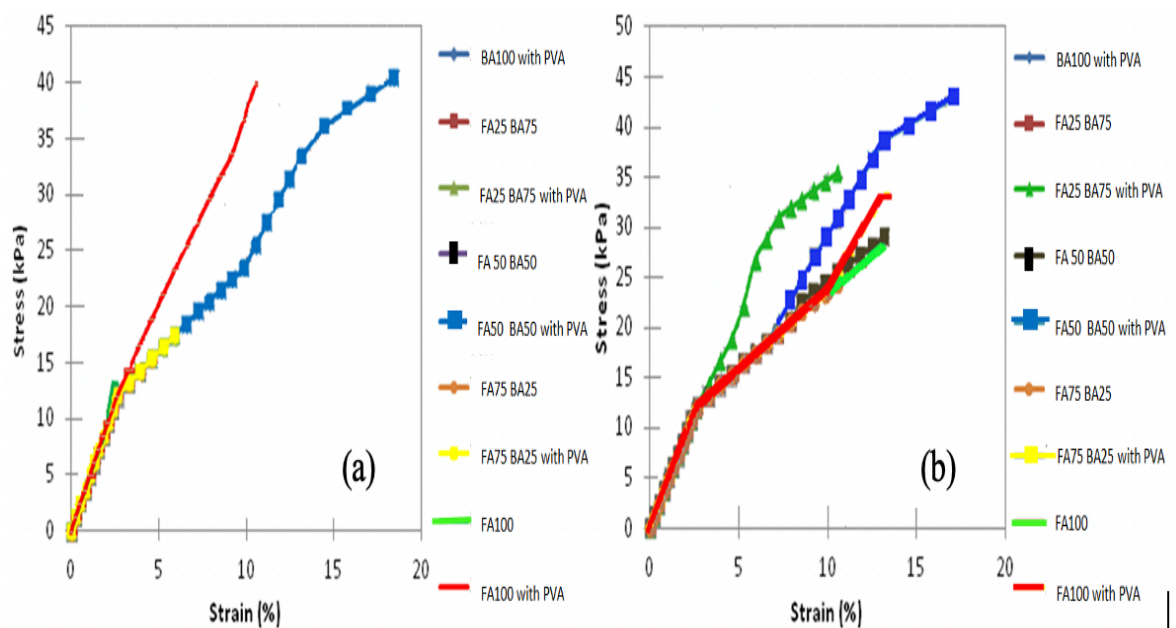


Fig. 3. a) Stress and strain behaviour for unmodified and PVA-modified FBA after (a) 14 day and (b) 28 day curing period

#### 4. Conclusion

The chemical composition of the PVA-modified FBA give significant changes of its physiochemical properties. SEM image shows that the PVA-modified FBA at FA50-BA50 composition agglomerated and strongly attached due the effect of PVA that reacted between the coal ashes, which significantly enhances the pozzolanic chemical reaction, and thus the engineering properties. The possibility of interaction between FBA and PVA could be deduced from the FTIR analysis, because of the small shift in peak positions of the Si/Al–O stretch, which may be indicative of the electrostatic interactions rather than the bonding interactions between FBA and PVA. As the FA composition increases from 0% to 50% in the PVA-modified FBA samples, the gradient of stress–strain curve significantly increases, consequently enhancing the strength and giving possibility for further sustainable engineering utilizations.

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