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A NOVEL APPROACH TO FLY ASH IN ROADBED CONSTRUCTION

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ABSTRACT: Sand is commonly used in the construction of roads, however, sand resources are becoming depleted in many areas. The loose grain structure and low elastic modulus of most sand means it often cannot meet the technical requirements of road base construction. As a result, alternative materials such as soil reinforced with inorganic binders, natural aggregates, and macadam are often employed for constructing road embankments. The use of these alternative materials contributes to the increase in construction costs and potentially, in environmental pollution. Therefore, it is important to identify new types of materials that can be used for road construction. This study investigates the mechanical properties of fly ash–sand mixtures through various laboratory tests to identify the optimal composition for road construction applications. The test results show that the sand-fly ash mixture, which features an optimal ratio of 70% sand to 30% fly ash with a dry volume of 1.821 g/cm^3, not only satisfies the requirements for road base materials but also increases the use of fly ash. By employing geopolymer technology and incorporating an alkaline solution to strengthen the sand-fly ash mixture with 70% to 30% sand-fly ash mixture, the fly ash is activated to produce a gelatinous material through a series of reactions. The gelatinous material exhibits high-strength and tightly linked molecular structures. In addition to being a suitable material for road construction, the sand-fly ash mixture can also be used as a foundation layer for pavement structures.

Keywords: Roadbed, Fly ash, Sand, Laboratory test, Aggregate.

1. INTRODUCTION

Fly ash, a waste product that is discharged from the combustion of fuel in thermal power plants comprises approximately 80% of the unburned inorganic material volume generated during coal burning [1]. Fly ash is collected using a static dust filter as it is emited from the combustion. The production of fly ash is associated with the continuous expansion of coal-fired thermal power plants.

Recent research on fly ash reveals that fly ash typically consists of fine, lightweight spherical particles. The material can be pyrolyzed into different substances through the hydraulic process. The characteristics of fly ash are as follows: 1) Particle size typically ranges from 1μm to 15 μm, 2) The dry mass density is approximately 0.95 g/cm3 to 1.44 g/cm^3, and 3) The particle volume mass is about 2.4 g/cm^3 [1]. Fly ash often contains some unburned coal particles, which can hinder the activation of fly ash during the reuse process, including the fly ash is lighter than sand (e.g., the particle mass density of sand is about 26.5 kN/m^3) [1]. In addition, fly ash particles are small and so compact tightly in the presence of coarser grained particles of soil. Thus, fly ash can be used for construction on soft ground to reduce the load applied to the ground effectively.

Chemical analyses of fly ash are commonly reported as oxide compounds, including SiO2, Al_2O_3, CaO, MgO, Fe_2O_3, FeO, SO_3, Na_2O, K_2O, and others. The key components SiO2, Al_2O_3, CaO, and MgO determine the fundamental properties of fly ash. Na_2O, K_2O, SO_3 and residual coal are considered detrimental to the activation reaction of fly ash.

Fly ash can be classified into two main categories: Class C and Class F. Class C fly ash is better than Class F due to its low level of impurity. Class C fly ash contains a CaO content of greater than 5%. The CaO content typically stays in the range of 15 - 35% and has a low unburned impurity content smaller than 2%. Class F fly ash has a CaO content of smaller than 5% and an impurity content of greater than 2% [2].

Numerous studies have been conducted on fly ash and the by-products resulting from the combustion of coal in the thermal power industry [3-7]. Researchers have been attempting to explore the advantages of these by-products as well as solve the environmental problems caused by them by-products. Some studies have adopted the Geopolymer technology which incorporates alkaline activators to enhance the strength of fly ash material. The enhanced material can then be used as a replacement for traditional binders such as cement, lime, and many others [8-10]. Fernandez-Jimenez and Palomo studied the characteristics of fly ash and its potential reactions, such as alkalinized cement [11-13]. These studies provided an insight into the concept of fly ash materials, revealing the following characteristics of fly ash: 1) Percentage of completely unburned particles is less than 5%, 2) Approximately 80-90% of particles have a size of less than 45 µm, 3) Fe_2O_3 content (iron (III) oxide) is less than 10%, 4) CaO (calcium oxide) content is almost negligible, and 5) About 40-50% of SiO_2 (silicate) in fly ash reacts with the alkaline activators.

The study in [14] investigated the effect of the activating solution on the durability of fly ash material. A new mechanism was introduced to signal the increase in alkaline content, which then produced a material with a denser structure and a higher strength. Water is not directly involve in the activation reaction of fly ash. It only helps to improve the workability of the material as a lubricant. Water, however, may reduce the strength of the material when its rate is too high. One study [1] investigated the application of ash and slag in filling to determine the physical and mechanical properties of ash and slag. The research also evaluated the durability of the ash-cement mixture with varying cement content levels. For the physical and mechanical features, the authors conducted compression, tensile strength, and shear strength tests to measure the development of strength over time for the samples whose ratios of ash/cement are: 100%/0%, 95%/5%, 90%/10%, 85%/15%, and 80%/20%. The results show that the physical and mechanical properties of the materials combined with ash and slag are superior compared to the properties of those combined with inorganic binders. Ash and slag contain geotechnical characteristics which allow them to be used as filling materials.

Davidovits conducted a study on the ratios of molecules constituting fly ash cement material to introduce products that exhibited sufficient durability and strength [15-19]. Nath and Sarker studied the use of fly ash as a binder in concrete [20]. Zhang and Tao examined the environment-friendly materials that could reduce the greenhouse effect due to CO_2 emissions from Portland cement production [21]. Kien et al. evaluated the chemical properties, the elemental composition, and the application of fly ash material [22]. They concluded that geopolymer concrete could provide many advantages, such as high strength, excellent corrosion resistance, and low CO_2 emission. In addition, the authors discussed the limitations of geopolymer concrete. The use of alkaline activators in the production process could pollute soil and water, contributing to greenhouse effects. Geopolymer technology appears to be the best method for manufacturing non-fired and precast components.

The use of fly ash waste discharged from thermal power plants to make fly ash-soil piles for soft ground reinforcement not only takes advantage of local materials but also reduces environmental pollution. Nguyen et al. presented research findings on the fly ash content and pile diameter in the context of soft ground reinforcement. These results serve as a foundation for the design, construction, and operation management units to develop solutions that optimize material performance and enhance the stability of roadbeds during exploitation [23].

This article investigates the properties of sand-fly ash mixture and employs the use of an alkaline solution with geopolymer technology to determine a new mixture that can be used for the roadbed construction as well as for the bottom layer of the foundation that is located at least 30 cm below the pavement structures.

2. RESEARCH SIGNIFICANCE

The application of sand-fly ash material can reduce the consumption of conventional materials such as sand, natural Aggregate, and macadam. These resources are being exploited extensively, posing a threat to their long-term availability. Furthermore, the use of this material can mitigate the environmental impacts associated with the exploitation of the aforementioned conventional resources. It was found that the employment of sand-fly ash material in road foundation preparation can lead to a reduction of approximately 30% in the amount of filling sand required [24]. In addition, non-alkali sand-fly ash material can be used as a back-filling material for the area below the load-bearing part of the roadbed. This helps reduce the volume of exploited sand, discourage illegal sand extraction, and lower the risk of depleting sand resources in rivers and lakes. This type of back-filling material also mitigates the negative impacts on the river ecosystem and the agitation of sediments, which can lead to an increase in turbidity and a decrease in light penetration.

3. MATERIALS AND METHOD

3.1. Determination of Physical and Mechanical Properties of Fly Ash, Filling Sand

3.1.1. Fly Ash

Fly ash is generated during the process of firing finely crushed coal in thermal power plants. During the combustion process, minerals in coal are melted, suspended, and blown out of the combustion chamber along with the flue gas. When they are cooled down, fly ash is generated as spherical particles. The fly ash used in this study comes from Vinh Tan thermal power plant in Vietnam. The chemical composition of this fly ash is determined by using X-ray fluorescence (XRF) and the results are summarized in Table 1.

From the test results, the total Content of the components is: (SiO_2 + Al_2O_3 + Fe_2O_3) > 70%, CaO < 30%, and Na_2O < 1,5%. The results satisfy the standard requirements for fly ash based on ASTM C618-94a [25].

Table 1. Analysis result of chemical composition and Content (%) of fly ash.

Components	Content (%)	Components	Content (%)
SiO_2	56.27	TiO_2	1.01
Al_2O_3	27.52	CaO	0.96
Fe_2O_3	6.48	SO_3	0.41
K_2O	5.36	Na_2O	0.21
MgO	1.22	MKN	20.81

The physical criteria of fly ash are summarized in Table 2.

Table 2. Physical criteria of fly ash

Physical criteria	Applicable standards	Result
Specific weight (kN/m^3)	[28]	24
Percent passing 0.05mm sieve (%)	[26] [29]	93.5
Strength index after 28 days (%)	[26] [29]	92.7
Strength index after 7 days (%)	[26] [29]	79.2
Loss after burning (g)	[26] [27]	1.1

The 0.05 mm sieve passing ratio is greater than 66%, which indicates that the fly ash is very fine.

3.1.2. Filling sand

Filling sand is used for preparing the foundation or the cushion for soft ground in a saturated state (e.g., clay ground, pasty clay ground, sandy ground, muddy ground, and coal mud ground). Filling sand ensures that the road base can reach the designed elevation (Fig. 1).

Fig. 1. Filling sand

The physical and mechanical properties of filling sand are shown in Table 3. The relationship between dry unit weight and optimal moisture content of the filling sand is shown in Fig. 2.

Table 3. Physical and mechanical properties of filling sand

No	Test criteria	Unit	Result	Test Method
1	+ Particle analysis - Size modulus - Particle content> 5mm - Particle content< 0.14mm	 % %	 1.2 0 7.15	TCVN 7572-2: 2006
2	+Porous mass density	(kg/m^3)	1350	TCVN 7572-6: 2006
3	+ Content of dust, mud and clay	%	5,1	TCVN 7572-8: 2006
4	+ Standard compression Max dry mass density Optimal moisture	 g/cm^3 %	 1.67 15.3	22TCN 333-06 (I-A) [30]
5	+ CBR (California bearing ratio) At density K95 At density K98	 % %	 25.6 31.6	22TCN 332-06 [31]

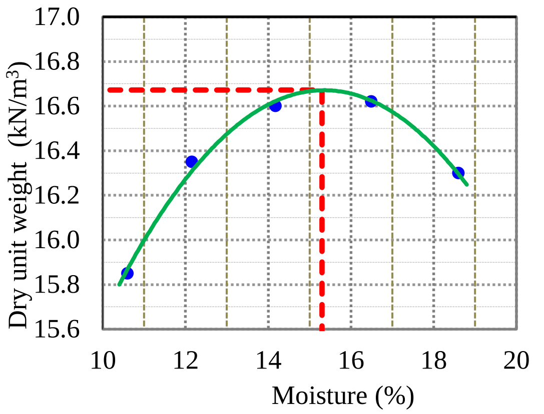

Fig. 2. The relationship between dry unit weight and optimal moisture

3.2. Testing of Filling Sand-Fly Ash Mixture

In this test, filling sand and fly ash are combined in various proportions. The ratio of filling sand/fly ash is selected as 90/10; 80/20; 70/30; 60/40; 50/50 by weight percentage. After the mixing process, the mixture is poured into a mold to determine the standard density, the optimal moisture level, and the California Bearing Ratio (CBR). The codes of samples are shown in Table 4.

Table 4. Codes of the test sample

Code	Weight percentage of filling sand	Weight percentage of fly ash
CP90/10	90%	10%
CP80/20	80%	20%
CP70/30	70%	30%
CP60/40	60%	40%
CP50/50	50%	50%

4. RESULTS AND DISCUSSION

4.1. Standard Compression Test

This test was performed in accordance with the standard 22TCN 333: 2006 (method II-A) [30]. The instruments are innovative proctor mortar with the dimension of D x H = 101.6 mm x 116.43 mm, a pestle of 4.54 kg, and a high drop of 457 mm. The sample is compacted into five layers, with each layer carrying 25 times the weight of the pestle.

After the compaction process is completed, dry weight densities corresponding to various moistures are calculated. The maximum dry weight is determined from the chart that shows the relationship between moisture and dry unit weight. The results are shown in Fig. 3.

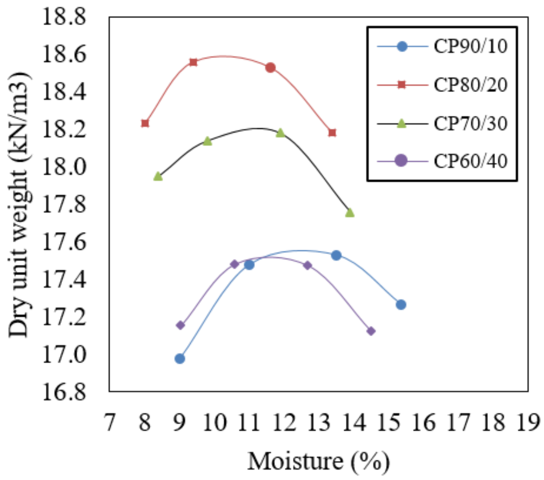

Fig. 3. Standard compression of different C.P. mixture

When the fly ash content in the mixture is increased from 10% to 20%, the dry unit weight increases from 17.58 kN/m^3 to 18.61 kN/m^3. However, if the Content of fly ash in the mixture continues to increase, the standard density will start to decrease gradually. When the fly ash content in the mixture is 50%, the dry unit weight is found to be at the minimum value of 17.4 kN/m^3 among the samples.

When the fly ash content in the mixture is between 20% and 30%, the dry unit weight is greater than 18 kN/m^3. This value is acceptable for the application of filling sand-fly ash mixture to the bottom foundation layer of the pavement structure.

4.2. The determination of CBR

The test sample for determining the CBR index in the laboratory is prepared using various filling sand/ fly ash ratios, including CP80/20, CP70/30, CP60/40, and CP50/50. This test is conducted according to the standard 22TCN 332: 2006 [31]. The sample is formed in a CBR mold with the dimension of D x H = 152.4 mm x 177.8 mm. Each sand–fly ash ratio is applied to three samples: 1) Sample 1 is applied with 65 times pestle per layer, 2) Sample 2 is applied with 30 times of pestle per layer, and 3) Sample 3 is applied with 10 times pestle per layer. The samples are then immersed in water to be cured for 96 hours.

Table 5. CBR indexes corresponding to each density of various mixtures

Filling sand/fly ratio	Density	K = 0.95	K = 0.98	K = 1.00
100% Filling sand	γ (kN/m^3)	15.84	16.34	16.67
	CBR (%)	25.6	31.6	35.8
80/20	γ (kN/m^3)	17.68	18.24	18.61
	CBR (%)	22.6	29.5	30.9
70/30	γ (kN/m^3)	17.30	17.85	18.21
	CBR (%)	10.9	19.4	23.5
60/40	γ (kN/m^3)	16.66	17.19	17.54
	CBR (%)	6.6	13.8	16.0
50/50	γ (kN/m^3)	16.55	17.07	17.42
	CBR (%)	5.4	8.6	9.9

When conducting the CBR test, the compression tip penetrates the sample with the specified speed of 1.27 mm/min. Compression forces are recorded at the time when the compression tip penetrates the sample at 0.64 mm;1.27 mm; 1.91 mm, 2.54 mm; 3.75 mm; 5.08 mm and 7.62 mm. Appropriate calculations are used to determine the CBR index of the tested samples. CBR test results are summarized in Table 5 and illustrated in Fig. 4.

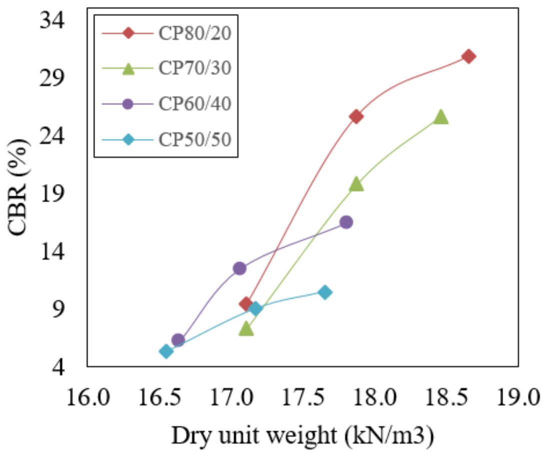

Fig. 4. CBR and dry unit weight corresponding to each mixture

The CBR indexes of the samples, which correspond to the different filling sand-fly ash mixtures, are smaller than those of the filling sand. This can be explained by when being immersed in water for 96 hours, fly ash with high expansion properties will reduce the density of the mixture and increase the porosity of the mixture. Consequently, the increase in the fly ash content will lead to a decrease in the CBR of the mixture. The mixing of filling sand- with fly ash increases the density of the mixture to a greater degree compared to the filling sand. The appropriate fly ash content, which can be used to increase density, is approximately 20-30% of the total volume of the mixture. However, the CBR of the filling sand-fly ash mixture is lower than that of the filling sand. Therefore, the use of filling sand-fly ash mixture for road pavement layers is not guaranteed.

4.3. Determination of Confined Compressive Strength and Elastic Modulus

To improve the efficiency of using filling sand-fly ash mixture in roadbed construction, this study combines the mixture of filling sand-fly ash with an alkaline activator solution (ASS) with AAS-over-solid ratios of 4%, 6% and 8% of the weight of the mixture. The mixture of filling sand-fly ash is selected with 70% filling sand and 30% fly ash. The alkaline activator (AAS) used in this study is the combination of NaOH solution and liquid glass solution (Na_2SiO_3) at the ratio of 1/2.5 by weight.

The test samples with elastic modulus and confined compressive strength are prepared in the molds, which have the size D x H = 101.6 mm x 116.43 mm. The sample is a mixture of 70% filling sand and 30% fly ash mixed with water and an alkali activator at appropriate proportions. The material mixture is compacted using a method similar to the standard compression test. After casting, the molds are removed, and the samples are cured in moisture conditions for 7 days and 28 days. The total number of calculated cast samples corresponding to the two curing periods and the three types of AAS ratios is 28. Elastic modulus and confined compressive strength are determined by performing laboratory tests according to [32]. The test results are summarized in Tables 6-8. The chart of the relationship between the AAS ratio and confined compressive strength Rn, the 7-day and 28-day elastic modulus is shown in Figs. 5-8.

Table 6. Test results for the sample with an AAS ratio of 4%

AAS ratio	Wet Weight Density (kN/m^3)		Elastic Modulus E (MPa)		R_n (MPa)	
4%	R7	R28	R7	R28	R7	R28
1	20.76	20.91	157	194	0.66	0.90
2	20.84	20.56	160	189	0.74	0.93
3	20.77	20.78	164	182	0.71	0.92
Average	20.79	20.75	160	189	0.70	0.92

Table 7. Test results for the sample with an AAS ratio of 6%

AAS ratio	Wet Weight Density (kN/m^3)		Elastic Modulus E (MPa)		R_n (MPa)	
6%	R7	R28	R7	R28	R7	R28
1	20.75	20.79	365	427	1.81	2.39
2	20.85	20.88	371	415	1.78	2.09
3	21.01	21.04	367	409	1.63	2.22
Average	20.87	20.90	368	417	1.80	2.31

Table 8. Test results for the sample with an AAS ratio of 8%

AAS ratio	Wet Weight Density (kN/m^3)		Elastic Modulus E (MPa)		R_n (MPa)	
8%	R7	R28	R7	R28	R7	R28
1	21.08	21.08	395	432	2.30	2.73
2	21.10	21.18	407	445	2.50	3.36
3	21.14	21.15	416	455	2.62	3.70
Average	21.11	21.14	401	444	2.47	3.27

The increase in confined compressive strength of the test sample is directly proportional to the alkaline activator content. The confined compressive strength of the sample increases significantly when the active substance content in the mixture is increased from 4% to 6%. Specifically, at 7 days of age, the compressive strength increases from 0.7 MPa to 1.80 MPa corresponding to an increase of 154.6%. Similarly, at 28 days of age, the compressive strength rises from 0.92 MPa to 2.31 MPa, corresponding to a 151.3% increase in the active substance content.

However, when the Content of the alkaline activator is increased from 6% to 8%, the compressive strength of the test sample rises slowly. Specifically, at 7 days of age, the compressive strength rises from 1.80 MPa to 2.47 MPa, corresponding to a 37.7% increase in the Content of the active substance. Similarly, at 28 days of age, the compressive strength rises from 2.31 MPa to 3.27 MPa, corresponding to a 41.7% increase in the active substance content.

Based on the technical requirements of the soil consolidated with inorganic, chemical and synthetic binders for roadbed or pavement [32], it was found that the test sample with AAS content below 4% does not satisfy the technical requirements of consolidation material on compressive strength according to TCVN 10379: 2014 [33]. The results show that the confined compressive strength of the test sample with AAS content above 6% reaches level II and that of the test sample with AAS content above 8% reaches the level I [33].

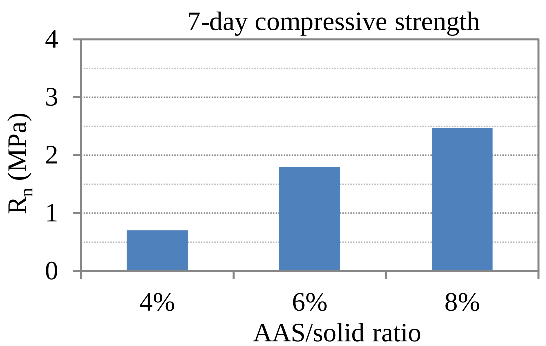

Fig. 5. Relationship between AAS ratio and 7-day confined compressive strength R_n

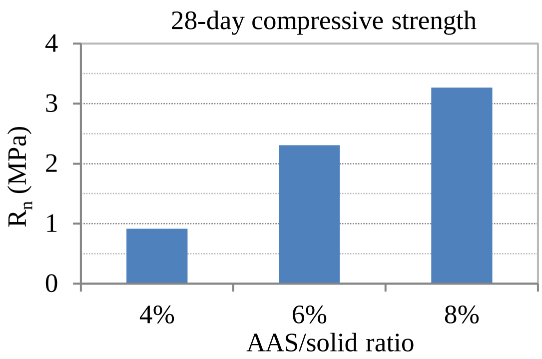

Fig. 6. Relationship between AAS ratio and 28-day confined compressive strength R_n

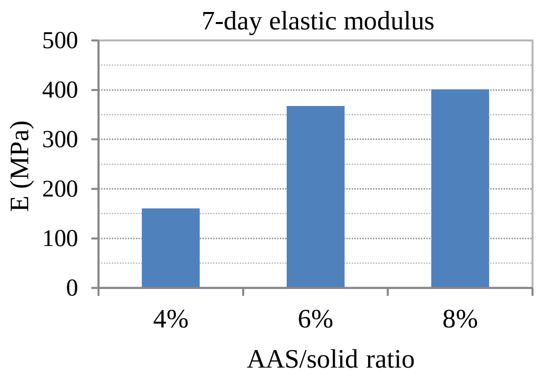

Fig. 7. Relationship between AAS ratio and 7-day elastic modulus E

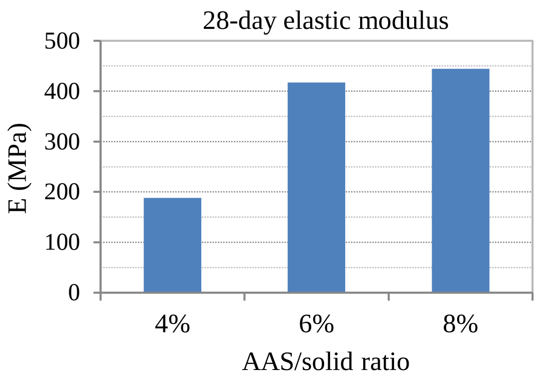

Fig. 8. Relationship between AAS ratio and 28-day elastic modulus E

The elastic modulus of the test sample increases proportionally with the alkaline activator content. The elastic modulus of the sample rises dramatically when the Content of the activator in the mixture is increased from 4% to 6%. Specifically, at 7 days of age, the elastic modulus rises from 160 MPa to 368 MPa, corresponding to 129.1%. Increase in the active substance content Similarly, at 28 days of age, the elastic modulus rises from 189 MPa to 417 MPa, corresponding to a 121.2% increase in the active substance content. However, when the Content of the alkaline activator is increased from 6% to 8%, the elastic modulus of the test sample does not rise significantly. Specifically, at 7 days of age, the elastic module rises from 368 MPa to 401 MPa, corresponding to a 9.1% increase in the active substance content. Similarly, at 28 days of age, the elastic modulus rises from 417 MPa to 444 MPa, corresponding to a 6.5%, increase in the active substance content.

5. CONCLUSIONS

If the sand/fly ash ratio in the mixture is 70%/30%, the dry mass density is greater than 1.8 g/cm³. This value is acceptable for the preparation of the foundation bottom layer (which covers the first 30 cm of the roadbed's length).

When the non-alkaline fly ash-sand material is used, the material has a lower CBR than that of the filling sand due to the small fly ash particles, which, in theory, can penetrate into the voids between the sand particles, making the material become tighter. However, when soaked in water, fly ash will expand, leading to a reduction in density and an increase in porosity. As a result, the non-alkaline fly ash-sand material is not suitable for the bottom layer of the foundation and the active areas of road pavement.

When Geopolymer technology is employed along with the alkali solution for the sand–fly ash mixture (ratio of sand/fly ash is 70/30), the fly ash will be activated by the alkali solution through a series of reactions to form a gelatinous and high-strength material whose molecules are tightly linked together. The ratio of alkali in the mixture is 4% with an elastic modulus of 189 MPa after 28 days, which is suitable for building the bottom layer of the foundation or the entire active area of pavement. When the alkali content in the mixture is 6% or more, the elastic modulus is greater than 400MPa, and the confined compressive strength is greater than 2MPa after 28 days. This mixture can therefore be used for road foundations. However, a comprehensive understanding of other material properties, such as splitting tensile strength and flexural tensile strength, is essential for drawing accurate conclusions about the potential application of this material in the foundation layer of pavement structures.

When the 4% alkali-reinforced fly ash-sand material is applied to the foundation, the strength of the roadbed increases from 76.4 MPa to 85.2 MPa corresponding to an increase of 11.5%. This results in a reduction of approximately 34% in the thickness of the pavement structure and the reduction of approximately 17.5% in the consolidation settlement of the ground.

Research has shown that the use of alkali-reinforced fly ash materials can provide great environmental benefits. One significant benefit is the potential to make use of fly ash in thermal power plants, which can help reduce the amount of air pollution caused by lightweight ash particles becoming airborne. These ash particles can negatively impact the lives of people near disposal sites. Furthermore, the use of fly ash will require less land for waste disposal. This consequently frees up space for economic development and afforestation effort and mitigates pollution risks for the community surrounding disposal sites. Efficient treatment of waste fly ash minimizes water pollution and limits its hardening due to Ca+, Al+, Fe+ ions, etc.,

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