



Journal of Materials and Engineering Structures

Research Paper

Fly ash-cement based concrete for road construction: engineering properties and pavement design

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ARTICLE INFO

Article history:

Received : 14 November 2024

Revised : 26 December 2024

Accepted : 28 December 2024

Keywords:

Fly ash

Strength

Abrasion resistance

Rigid pavement structure

ABSTRACT

This research investigates various fly ash (FA) levels of 0%, 15%, 25%, and 35% for cement replacement in concrete, specifically for rural roads in southern Vietnam. The slump values of the fresh concrete mixture were kept under 40 mm to maintain workability based on the requirement of rigid pavement. Concrete's mechanical properties, including its elastic modulus, flexural strength, and compressive strength, and the abrasion resistance were examined at three different stages of curing of 7, 28, and 56 days. Results indicated FA may not contribute to strength development as effectively as cement at early stages. However, the strength of concrete achieved the highest value at a 15% FA replacement level at the long-term curing age. The findings indicated that FA could enhance the long-term strength of concrete regarding its flexural and compressive strengths. According to the results of the abrasion resistance test, abrasion loss rises between 3.2 kg/m² and 4.21 kg/m² as FA increases. Finally, the calculation results revealed that 15% and 25% of FA replacement for cement can be used in rigid pavement with good performance.

1 Introduction

In Vietnam, the development of highways and rural roads has led to a significant increase in the demand for concrete over the past few decades. Based on the predictions of Mehta et al. [1], the concrete demand will be 18 billion tons by 2050. The production of cement can include four procedures. First, limestone and clay are crushed and ground to increase the surface area of the raw materials, facilitating better chemical reactions during the subsequent steps. Then, the crushed and ground raw materials are mixed in the correct proportions. This step ensures that the final product has the desired chemical composition, which is crucial for cement quality. The composite materials are subsequently subjected to high-

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temperature heating in a rotary kiln, approximately 1450 °C. Calcination is the process that produces the desired chemical composition in the form of clinker nodules through chemical reactions. Once the clinker exits the kiln, it is cooled to around 80°C. Gypsum is subsequently incorporated, and the clinker is milled into fine cement powder, prepared for storage, packaging, and transportation. The final product is known as Portland cement. For Portland cement blended, certain chemical modifications are added to adjust the properties of cement. A considerable amount of carbon dioxide is released during the cement production process. Strict laws and restrictions on CO₂ emissions are being implemented in developed nations. It is essential that substantial amounts of cement in the concrete industry be replaced with supplemental cementing components from the viewpoint of global sustainable development.

Fly ash (FA) is indeed a significant by-product produced from the combustion of pulverized coal in thermoelectric power stations, requiring designated waste material disposal sites and backfill zones for its management. Primarily composed of silica, alumina, and other mineral compounds, it is considered a priority tool for sustainable materials. In the concrete industry, FA is an additional cementitious substance. FA can be applied in civil engineering materials to reduce carbon dioxide emissions. FA has increasingly become more popular as a cement substitute throughout the past few years [2]. Several environmental benefits can be achieved with the use of FA in concrete production, including: (a) enhancing the durability of concrete, which extends the lifespan of roads and structures; (b) lowering energy consumption and reducing greenhouse gas emissions by substituting FA for cement; (c) minimizing the volume of coal combustion byproducts that need to be sent to landfills; and (d) conserving natural resources and raw materials [3]. Fly ash significantly contributes to cement concrete by filling the voids between larger particles during the initial curing phase [4]; (b) at long ages of curing, FA has a significant reaction with Ca(OH)₂ in cement; as a result, C-S-H (calcium silicate hydrate) gel finally forms [5].

In road engineering, the basic principle of rural road construction is to use local materials to reduce transportation costs, take advantage of resources and labor, and reduce construction costs. To cut down on landfill usage, save resources, and lessen environmental damage, industrial waste products including fly ash, ash, slag, and mining waste can be used. Among these waste materials, FA from thermal power factories is widely employed. Specific studies proved the advantages of FA in improving the engineering properties of concrete. For instance, Edwin et al. [6] investigated FA in a range of 5–25%; Bahedh and Jaafar [7] used 0–40% FA in high-strength concrete. Saidand Zeidan [8] combined 30% FA and nano-silica to enhance the reactivity in concrete; Concrete's durability and compressive strength were examined by Shaikh and Supit [9] using 40–60%. Tran and Phan [10] indicated the potential of 30% FA for cement replacement to produce high-strength concrete in rigid pavement. Incorporating fly ash (FA) into concrete can significantly enhance its properties, particularly regarding workability, permeability, and durability [11]. As mentioned by Kawashima et al. [12], FA replacement should be limited below 40% to prevent decreased compressive strength in early-age concrete. The durability properties indicate that an increase in FA resulted in reduced shrinkage of concrete when compared to standard concrete, as documented in prior publications [13, 14]. In addition, water absorption and chloride ion penetration were found to be high in FA concrete [15, 16]. Even though lots of research has been done on the application of fly ash in concrete, its application in road surfaces in Vietnam remains limited. Despite various studies concerning the utilization of fly ash in building materials, its application in road surfaces in Vietnam is still limited.

By replacing cement with FA, this study examined the mechanical characteristics of concrete. The FA content was used as 15%, 25%, and 35% for cement replacement. The slump test was controlled by superplasticizer, which could be applied in road construction. Mechanical properties that were examined included flexural strength, compressive strength, abrasion resistance, and elastic modulus. At various stages of curing (i.e., 7, 28, and 56 days), the samples were analyzed. The obtained data were collected and discussed. Finally, reported data were employed to solve the rigid pavement design on rural roads. Results indicated that using fly ash as an alternative material for rural roads, particularly when conventional construction materials are scarce, has been supported by experimental results and calculations.

2 Materials used and experiment

The materials employed in this investigation included cement, fly ash, fine aggregate, coarse aggregate, superplasticizers, and water.

2.1 Portland cement blended grade 40 (PCB) and FA

The PCB grade 40 was used in this study. As indicated in the previous part, PCB is a cement that adds certain chemicals to the compositions. The cement requires 115 minutes for early setting and 200 minutes for final setting in this study, with a specific gravity of 3.1. According to the first test, cement's compressive strength was 45.2 MPa after 28 days.

FA of the Vinh Tan thermal power plant was classified as F Type. This is explained by the simultaneous presence of iron oxide (FeO_3), silicon dioxide (SiO_2), and aluminum oxide (Al_2O_3), which totals 88.4%, exceeding the 70% threshold [17]. FA has a specific gravity of 2.5. The SO_3 content is 0.4%, and the loss ignition is 4%. Table 1 presents the fundamental properties of FA. The utilized FA demonstrates a reduced susceptibility to corrosive environments.

Table 1 – Fundamental characteristics of FA utilized in this research

No	Properties	Unit	Values
1	$\text{SiO}_2 + \text{Al}_2\text{O}_3 + \text{Fe}_2\text{O}_3$	%	88.4
2	SO_3	%	0.4
3	CaO	%	0.04
4	Loss in ignition	%	4.0
5	Cl-	%	0.001
6	MgO	%	0.97

2.2 Coarse and fine aggregates

This study used raw materials, incorporating both coarse and fine aggregates. For coarse aggregate, made of commercial basalt crushed stone, it was sourced from Binh Duong. Specific gravity was 2.78 g/cm^3 , and the nominal maximum diameter was 19 mm. The coarse's particle size distribution is plotted Fig. 1a, which meets the ASTM standard requirements for the percentage passing [18]. Commercial sand from the Dong Nai River was used as a fine aggregate. The fine aggregate's specific gravity is 2.66, while its fineness modulus is 2.3. Lastly, as illustrated in Fig. 1b, the size distribution of the sand grains conforms to the ASTM requirement.

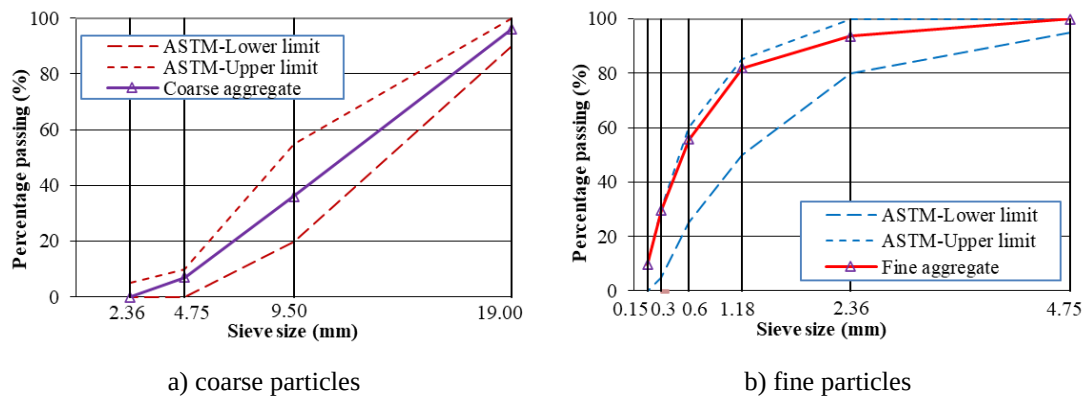


Fig. 1 – Distribution of raw materials' grain sizes.

2.3 Superplasticizer

Superplasticizer is designed for concrete mixtures, requiring superplasticizers to control the water/binder (W/B) ratio, which is far more important when applying FA to concrete. FA particles can diminish the slump of concrete, hence influencing its workability. Adding a superplasticizer at the same W/B ratio can greatly improve the workability of fresh concrete. The principle of a superplasticizer works by dispersing cement particles in the mix, reducing the attraction between them. This study employed the superplasticizer SikaPlast®-319 H to cast concrete incorporating FA. SikaPlast®-319 H is a premium water-reducing additive formulated with a blend of third-generation PCE polymer specifically

designed for concrete production. SikaPlast®-319 H complies with ASTM C494 type G. In Fig. 2, all raw materials are displayed.



Fig. 2 – Raw materials (cement, FA, superplasticizer, water, fine and coarse aggregates).

2.4 Mixed proportions

In this study, the target compressive strength was set at 30 MPa after 28 days of curing. FA is used in various proportions in the mix compositions, including 0%, 15%, 25%, and 35% by total binder content. All concrete mixtures maintained a 0.46 water-to-binder ratio. The superplasticizer was gradually added to control the slump value of the mixtures, keeping it below 40 mm. It is observed that the quantity of superplasticizer used in Table 2 was determined through triaxial mixes. Table 2 presents the calculated raw components of the six mixes.

Table 2 – Material composition for 1m³ of concrete

Mixture	C	FA	CS	S	W	Superplasticizer
CP-0%FA (control)	373	0	1239	650	175	3.73
CP1-15%FA	317	56	1239	650	175	4.66
CP2-25%FA	280	93	1239	650	175	5.59
CP3-35%FA	243	130	1239	650	175	6.34

Note: C = cement (kg); FA = fly ash (kg); CS = crushed stone (kg); S=sand (kg); W = water (l); S= superplasticizer (l)

2.5 Sample preparation

2.5.1 Mixing

The homogeneous dispersion of fly ash in a mixture is influenced by its high surface area and the distinctive behavior of micrometer-sized particles. To achieve a uniform mix and high stability, certain steps were suggested: a detailed mixing sequence developed from both literature [19] and trial-and-error methods. The proposed steps controlled the amount of water and reduced dust formation and initial agglomeration of fly ash, including: a) mixing cement, coarse aggregate, and fine aggregate during 2 min; b) using 20% required water to mix the mixture during 1 min; c) adding FA and 50% required water and mixing the mixture during 2 min, which allows the particles to be more uniformly integrated without clumping; d) continuously adding 20% required water and superplasticizer and mixing the mixture during 2 min. It is noticed that the last 10% required water was gradually added in the last step.

2.5.2 Mold and cure the samples

Various dimensions were used in this study. A cubic specimen with dimensions of 15 cm x 15 cm x 15 cm was employed for the evaluation of compressive strength. Flexural strength testing was conducted on prisms measuring 15 cm in width, 15 cm in height, and 60 cm in length. A cylinder having a diameter of 15 cm and a height of 30 cm was utilized for the determination of elastic modulus. The fresh mixtures were cast into mold. The vibrating machine operates at a frequency of 2800 to 3000 rpm and an amplitude of 0.3 to 0.5 mm, continuing until all large air bubbles are eliminated and

the cement paste achieves uniform flotation. Finally, A trowel was used to remove excess mixture and smooth the surface of the sample. Each sample was permitted to remain in the molds for 24 hours at ambient temperature prior to extraction. Thereafter, all samples were cured by being immersed in water and taken out one day before testing. This study tested compressive and flexural strengths at 7, 28, and 56 days. Following 28 days of curing, the elastic modulus and abrasion resistance were measured. The program of testing is shown in Fig. 3.

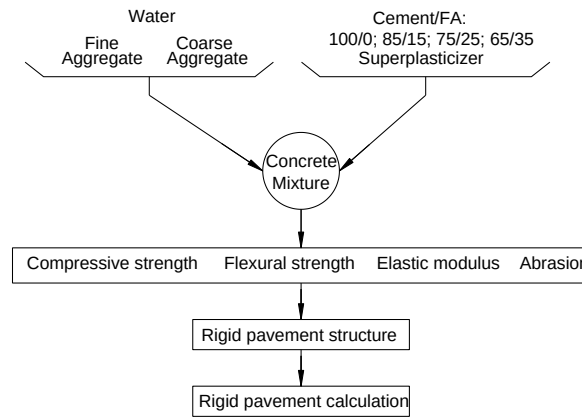


Fig. 3 – Testing program in this study.

2.5.3 Tests

ASTM C39 [19] was employed to ascertain the compressive strength of concrete. In this test, a regulated loading of 0.3 MPa/s was used. The following formula (Eq. (1)) was used to get the compressive strength

$$f'_c = \frac{P}{A} \quad (1)$$

where P is maximum loading (N); A is the cross-section area of the sample (mm²).

The flexural test was conducted by a three-point bending test according to ASTM C78 [20]. The tested sample was subjected to a continuous, shock-free application of 1.0 MPa/min. Using the following formula (Eq. (2)), the flexural strength (also known as the modulus of rupture) was calculated

$$R = \frac{PL}{bd^2} \quad (2)$$

where R denotes the flexural strength (MPa); P represents the maximum load exerted on the sample (N); L denotes the span between the two supports of the beam (mm); b indicates the width of the sample (mm); d signifies the height of the sample (mm).

Following ASTM C469 guidelines, the elastic modulus test was conducted [21]. The applied load and accompanying deformation are recorded during the test. The elastic modulus was computed and reported based on the test's relationship between the stress and strain curve. The data reported in this study is based on triplicate samples.

When designing rigid pavement, one of the most crucial elements is the abrasion resistance, according to Vietnamese standard [22]. The abrasion resistance was evaluated by the mass loss divided by a square meter after certain rotations. In the context of Vietnamese standards, specific thresholds for abrasion resistance may be established to ensure that materials used in rigid pavements can withstand local traffic conditions and climatic factors. Regular testing and adherence to these standards are vital for successfully implementing durable pavement solutions. To do this test, 20 grams of dry sand were used. During the test, samples were applied a load of 0.6 kg/cm², which simulates the loading of a vehicle on the surface. 5 full cycles with a total of 150 m were used. It is noted that each 30m of grinding path replaced the new grinding sand, as shown in Fig. 4.



Fig. 4 – Abrasion resistance test.

3 Results and discussion

3.1 The compressive strength

Fig. 5 plots the compressive strength of concrete with various FA substitutions of 0%, 15%, 25%, and 35%. According to the data in this figure, both with and without FA in the mixture, the concrete improves compressive strength over a period of curing. The compressive strength of FA-concrete at 7 days varies from 75.25% to 89.11% of that of the control concrete. From this, at the beginning of the curing process, the FA-containing concrete has a weaker strength than the control concrete. However, the difference is insignificant, suggesting that FA concrete achieves a substantial portion of its strength within 7 days.

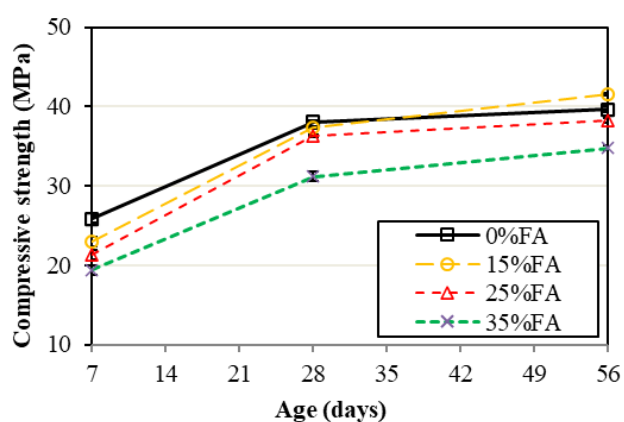


Fig. 5 – Compressive strength of various samples.

More than 30 MPa of compressive strength is achieved following a 28-day cure period. The pozzolanic reaction in the FA concrete mixtures become more evident, effectively compensating the diminished cement content relative to the control sample. The generation of hydrates from calcium silicate is the principal factor enhancing concrete strength. Additionally, it is noted that the compressive strength measurements indicate that FA concrete with FA replacement ratios ranging from 15% to 35% achieves between 81.91% and 98.01% of the strength of the control concrete. The obtained data show lower percentages of fly ash substitution (around 15%), which results in compressive strengths close to the control mix. In comparison, higher substitution levels (up to 35%) show a slight reduction in strength at the 28-day mark.

At 56 days, the pozzolanic reactions were active in strength to compensate for the reduced amount of cement. Therefore, compared to the control concrete, the fly ash-concrete mixture had a 15% higher compressive strength. Particularly, the FA concrete exhibited a compressive strength of 104.62 %.

3.2 The flexural strength of concrete

Flexural strength refers to the capacity of concrete to withstand bending forces introduced by loads. In practical design, concrete structures mainly experience bending conditions. This section discusses the findings of flexural strength testing, emphasizing the impact of several parameters, including curing time, mix composition, and the presence of additives, on the flexural performance of concrete. The flexural strength of FA concrete after 7 days varies between 86.01% and 97.40% of the strength of the control concrete, as shown in Fig. 6. The incorporation of fly ash marginally diminishes the flexural strength at an early curing age in comparison to the control concrete. However, the reduction is not substantial with 15% FA replacement for cement. The findings indicated that the flexural strength of fly ash concrete remains robust even after a partial replacement of cement with the use of fly ash. After 28 days, the flexural strength of FA concrete ranges from 89.67% to 98.76% of that of the control sample. When concrete containing 15% fly ash is cured for 56 days, its flexural strength is 101.92% higher than that of the control sample. This suggests that the addition of 15% fly ash makes up for the lower cement content and gradually increases the concrete's overall strength. The pozzolanic reaction between the constituents of fly ash and calcium hydroxide in cement has resulted in a rise in flexural strength, hence promoting continuous strength growth and contributing to elevated flexural strength. Additionally, using well-graded fine aggregate improves packing density and reduces voids, further contributing to the overall strength enhancement.

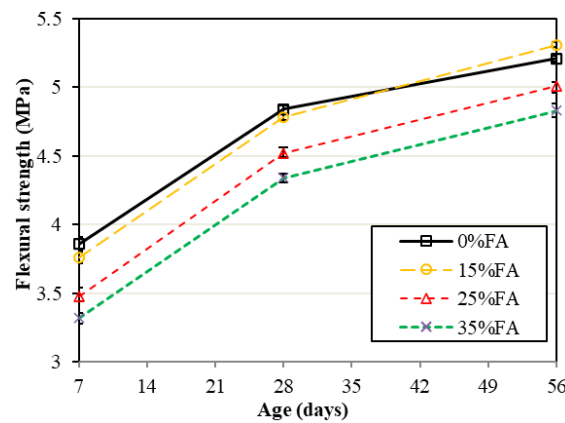


Fig. 6 – Developing concrete's flexural strength with age.

3.3 The Elastic modulus

Fig. 7 plots the 28-day elastic modulus of various FA contents in concrete. As is well known, the elastic modulus is one of the main elements that determines how strong pavement is. Results show that when using fly ash increases from 15% to 35%, the elastic modulus value varies between 27.5 GPa and 30.1 GPa. In addition, the elastic modulus for 15% FA and 25% FA exhibits a slight decrease. Additionally, the obtained values align with the design regulations for rural pavement, as specified in Vietnamese standards [23], and can be applied to data in designing concrete pavement.

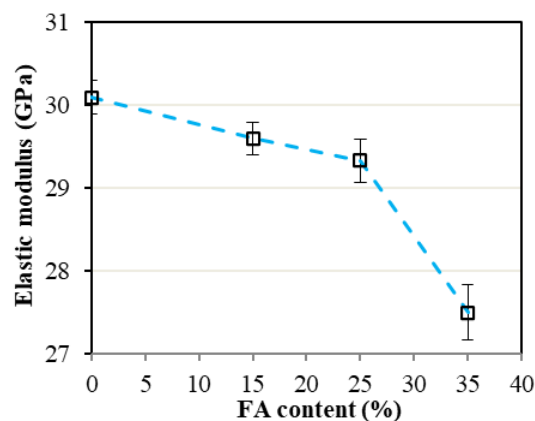


Fig. 7 – Elastic modulus.

Specifically, at 15% replacement, the E value of FA concrete is almost the same as the E value of the control concrete, indicating that a 15% fly ash substitution maintains similar stiffness and elasticity as the control mix. As the FA content rises to 25% and 35%, the E value exhibits a decline relative to the control concrete. The drop in elastic modulus is consistent with the fly ash concrete's measured strength values. Higher FA content typically reduces early-age strength and stiffness, as the cementitious matrix is partially replaced by the pozzolanic material, which reacts more slowly than cement.

3.4 Abrasion resistance

Fig. 8 presents the abrasion resistance of various FA contents for cement replacement. Additionally, the abrasion loss increases from 3.2 kg/m² to 4.21 kg/m² when the FA concentration rises from 0% to 35%, which reflects a decline in surface durability. The phenomenon can be explained by the way that the FA content increases, it serves as a partial substitute for cement, the mixture has less clinkers. In the cement hydration process, fly ash, a pozzolanic substance, reacts with calcium hydroxide, leading to the creation of additional calcium silicate hydrate (C-S-H) gel. This gel improves the material's long-term strength and durability. Nevertheless, when the FA content is elevated (e.g., approximately 35%), the synthesis of C-S-H may be inadequate to offset the diminished total cement quantity, leading to a less dense and weaker microstructure during the initial curing phases. This can make the material more susceptible to wear and abrasion, as indicated by the increased abrasion loss, as observed in Fig.8. Vietnamese guidelines state that rigid pavement surfaces classified as Level IV abrasion resistant can be used using concrete that has an FA concentration within the range employed in this investigation [23]. Despite the increased abrasion loss with higher FA, the concrete still meets the minimum requirements for durability in this type of application. The use of FA concrete in pavements is beneficial for reducing costs and improving sustainability, but designers must consider the potential reduction in abrasion resistance with higher FA contents.

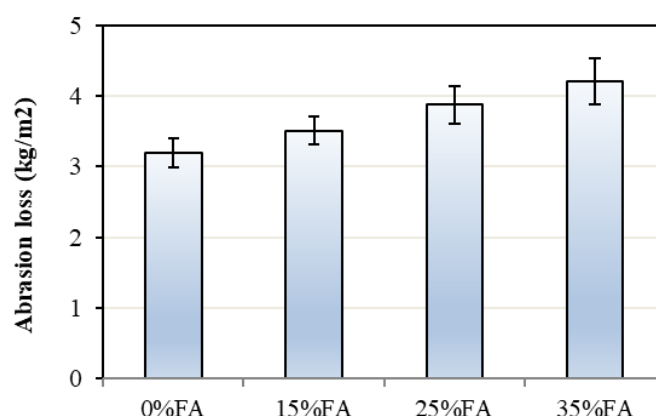


Fig. 8 – Abrasion resistance.

4 Application in rigid pavement

Based on the current Vietnamese standard [23], the requirement values for flexural strength, compressive strength, and elastic modulus are 4.5 MPa, 36 MPa, and 29 GPa, respectively, for lower grade 4. The results showed that CP-15%FA and CP2-25%FA concrete can pass the minimum values. Therefore, the further objective of this study is to utilize the obtained data for calculating the rigid pavement. The slab and pavement structure were shown in Fig. 9. Two typical 4.5 m and 4.7m slab lengths were selected and calculated. The base layer over the subgrade consists of approximately 180 mm of crushed stone aggregate material. The input parameters used included a Poisson's ratio of 0.20 and an elastic modulus (E1) of 300 MPa. The subgrade consists of clayey soil with a 40 MPa elastic modulus.

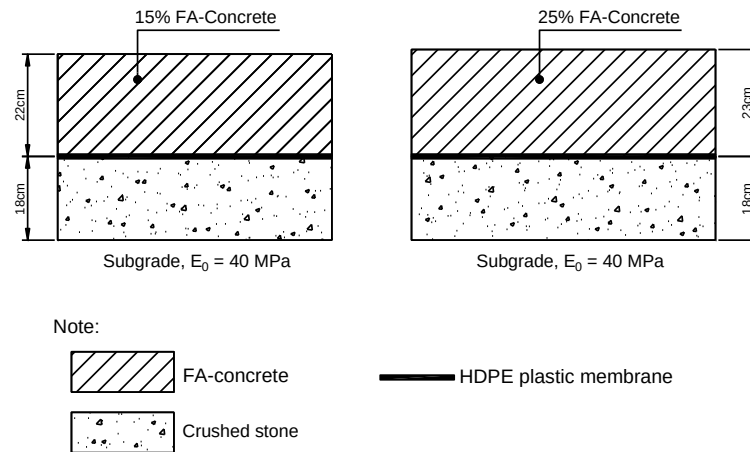


Fig. 9 – Concrete pavement structure.

Table 3 – Rigid pavement calculation sheet.

No	Characteristics	Length L(m)			
		CP1-15%FA		CP2-25%FA	
		4.5	4.7	4.5	4.7
1	Thickness, h_c (mm)	220	220	230	230
2	Tensile stress due to standard axial load (P_s) [σ_{ps}], (MPa)	2.047	2.047	1.925	1.925
3	Tensile stress due to maximum axle load (P_{max}) [σ_{pm}], (MPa)	2.997	2.997	2.818	2.818
4	Flexural tensile stress causes fatigue due to P_s [σ_{pr}], (MPa)	3.670	3.670	3.451	3.451
5	Flexural tensile stress causes fatigue due to P_{max} [σ_{pmax}], (MPa)	2.997	2.997	2.818	2.818
6	Maximum tensile stress by the temperature gradient [σ_{tmax}] (MPa)	1.435	1.539	1.311	1.422
7	Thermal stress (fatigue) [σ_{tr}] (MPa)	0.541	0.620	0.477	0.561
8	$\gamma_r \cdot (\sigma_{pr} + \sigma_{tr})$ (MPa)	4.379	4.272	4.085	4.173
9	$\gamma_r \cdot (\sigma_{pmax} + \sigma_{tmax})$ (MPa)	4.609	4.462	4.295	4.410
10	Allowable tensile strength, [f_r] (MPa)	4.78	4.78	4.52	4.52
11	Satisfaction if [σ_m], [$\sigma_{p,tmax}$] $\leq$ [f_r]	Pass	Pass	Pass	Pass

Note: [R] is flexural strength of FA-cement concrete

As suggested by Vietnamese standard [13], the standard axle load is chosen as 100 kN, while the maximum axle load is selected as 150 kN. In this study, the region is Southern Vietnam, where the greatest temperature gradient, $T_g = 860^\circ\text{C/m}$, is used. The reported findings suggested that two types of slabs meet the requirements in the design of the rigid pavement. The calculation conditions indicate that the simultaneous occurrence of the maximum axle load and the stipulated maximum thermal gradient in the FA blended concrete surface layer does not result in cracking, as shown in Eqs. (3-4). Based on the calculated procedure guided by standards, the calculation sheet based on Vietnamese standards is presented in Table 3.

$$\sigma_m = \gamma_r \cdot (\sigma_{pr} + \sigma_{tr}) \leq R \quad (3)$$

$$\sigma_{p,t_{max}} = \gamma_r \cdot (\sigma_{pmax} + \sigma_{tmax}) \leq R \quad (4)$$

whereas σ_m : Fatigue stress (MPa), σ_{pr} : The stress due to standard axial loads applied to the concrete (MPa), σ_{tr} : Stress that arises due to variations in temperature across the concrete section, which can cause differential expansion and contraction, leading to internal stresses (MPa), $\sigma_{p,t_{max}}$: Maximum flexural stress (MPa), σ_{pmax} : The maximum stress that the concrete undergoes due to the heaviest vehicle (MPa), σ_{tmax} : The maximum stress resulting from the greatest difference in temperature across the concrete section, which could exacerbate the effects of thermal expansion or contraction (MPa), R : the concrete's design flexural strength, as determined by experiment (MPa), and γ_r : linear reliability system.

5 Conclusion

This study used various FA content of 0, 15, 25, and 35% for cement replacement. Compressive strength, flexural strength, elastic modulus, and abrasion resistance are among the mechanical tests that have been performed on the samples. The test was cured in standard condition on different days of testing. Based on the experiment in the laboratory of the FA-cement concrete, certain conclusions can be drawn as follows:

At 28 days of curing, concrete with 0 to 35% FA substitution for cement achieved compressive strengths greater than 30 MPa. Increasing the FA content reduces early-age strength and stiffness because the more slowly reacting pozzolanic material partially replaces the cementitious matrix. When compared to the control concrete, flexural and compressive strengths are highest at 56 days when 15% FA is substituted. This phenomenon, which increases the strength of FA concrete, is probably caused by the reaction of the chemicals in FA with the calcium hydroxide in cement, which forms calcium silicate hydrate. Additionally, a well-graded fine aggregate used improves packing density and reduces voids, further contributing to the overall strength enhancement.

As FA content increased, the elastic modulus decreased. However, concrete with 15% FA substitution had an elastic modulus nearly equivalent to the control concrete. The elastic modulus value is greater than 29 GPa. The reduction in elastic modulus with higher FA content suggests that increased pozzolanic materials reduce the stiffness of the concrete. However, a 15% replacement remains a balance that maintains similar stiffness to the control mix.

With the rise in FA content, the abrasion resistance of the concrete diminished. The abrasion loss varied between 3.2 kg/m² and 4.21 kg/m². The less dense microstructure brought on by a higher pozzolan content may be the cause of the decrease in abrasion resistance with increasing FA content, making the surface more susceptible to wear and tear. While the abrasion resistance decreases with higher FA, concrete with FA substitution still meets the requirements for rigid pavement surfaces as per Vietnamese standards (Level IV).

Based on the calculations, concrete with 15% and 25% FA substitution could be used for designing rigid pavement with slab lengths of 4.5–4.7 meters and thicknesses of 220 mm and 230 mm, respectively. However, it is suggested that the practical in situ should be tested to verify the calculation results.

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