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Efficiency factor-based mix design of Class F fly ash concrete for rigid pavements: Calibration and experimental validation using Vietnamese materials

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Abstract: This study systematically investigates the calibration of the efficiency factor (k) and the development of a mix design procedure for fly ash cement concrete using Class F fly ash from the Pha Lai thermal power plant, for use in road pavements in Vietnam. In light of the urgent need to reduce infrastructure's carbon footprint and valorise industrial waste, replacing a portion of cement with fly ash provides environmental benefits and significant technical enhancements. Using a modified Bolomey strength model, the research team established a quantitative relationship between the fly ash replacement ratio (f), the water-to-binder ratio (ω), and the strength ratio (R_s) in order to derive the experimental k values. The findings reveal that the k-factor varies with fly ash content: for a replacement range of 15% to 35%, k-values fluctuate between 0.70 and 0.40. An 8-step k-based mix design procedure was proposed and validated through comprehensive testing of workability, mechanical properties, and durability. The experimental results showed that all of the fly ash mixtures achieved the target flexural strength requirement for the intended rigid pavement application. However, mixtures containing 15–25% fly ash provided the most balanced combination of workability, later-age strength, abrasion resistance and impermeability. The use of fly ash was also found to reduce the peak hydration temperature and delay the time to peak, which is beneficial in terms of the early-age thermal response of pavement concrete. Overall, this study provides a basis for the proportioning of Class F fly ash concrete for rigid pavements using Vietnamese materials that is supported by experimentation.

Keywords: Class F fly ash; efficiency factor; mix design; rigid pavements; flexural strength; abrasion resistance.

1. Introduction

Portland cement concrete remains the primary material for rigid pavements due to its ability to provide the necessary combination of load-carrying capacity, stiffness and surface durability under repeated vehicle loading. However, for pavement applications, performance cannot be judged by compressive strength alone.

Flexural strength is more directly related to slab bending resistance, while abrasion and moisture resistance are essential for preserving long-term surface integrity and functionality. Accordingly, the proportioning of rigid pavement concrete should consider structural demand, durability, and field constructability simultaneously [1], [2].

At the same time, the paving industry is under increasing pressure to reduce its consumption of cement and embodied carbon. The International Energy Agency continues to identify the cement and concrete industries as priority sectors for accelerated decarbonisation, repeatedly highlighting the expanded use of supplementary cementitious materials as a near-term action for reducing emissions intensity [3]. In this context, fly ash is an attractive option as it can replace Portland cement while making use of a significant industrial by-product. ASTM C618 classifies coal fly ash for concrete applications, and recent reviews continue to identify fly ash as one of the most practical ways to achieve lower-carbon cementitious systems [4], [5]. In the case of Vietnam, the environmental rationale is further strengthened by the need to utilise thermoelectric by-products, as well as by recent domestic assessments showing that replacing cement with fly ash can lead to measurable reductions in concrete-related carbon emissions [6].

A substantial body of research has demonstrated that incorporating fly ash can enhance workability, reduce heat evolution and refine the pore structure of cementitious systems. However, its impact on strength development depends heavily on the level of replacement, curing conditions and age [5], [7], [8]. In many conventional concretes, early-age strength decreases because the pozzolanic contribution of fly ash develops more slowly than Portland cement hydration. However, later-age strength and selected durability indicators often improve when the replacement ratio is properly controlled [7], [8]. Similar tendencies have also been reported in pavement-oriented studies. Investigations in Vietnam and internationally have shown that Class F fly ash can be used in concrete pavements or road concretes with acceptable fresh properties and competitive long-term mechanical and durability performance, provided that the proportions of the mixture are selected appropriately [9], [10], [11], [12].

Despite these advantages, the practical proportioning of fly ash concrete is not straightforward. A key challenge is that fly ash cannot simply be substituted for cement on a mass-for-mass basis, as its cementing efficiency varies depending on the characteristics of the fly ash, the replacement ratio, the mixture proportions, the curing age and the performance property being considered [11-14]. Studies on the k-value or efficiency-factor concept have shown that a single constant factor is rarely adequate across broad replacement ranges [11-13]. More recently, local Vietnamese research has confirmed that the efficiency factor of Class F fly ash varies with age and replacement ratio, emphasising the importance of calibration rather than directly adopting generic literature values [15]. Nevertheless, most studies focusing on pavements still concentrate on comparing performance or empirically optimising mixtures rather than establishing a locally calibrated, efficiency-factor-based design method that can be used directly for pavements made from concrete under Vietnamese material conditions [8-10].

However, what remains insufficiently established is a reproducible, pavement-oriented design workflow that links locally calibrated *k*-values to mixture proportioning under Vietnamese material conditions. Against this backdrop, the present study examines the use of Class F fly ash from the Pha Lai thermal power plant in the production of cement for rigid pavement construction in Vietnam. The specific objectives are: (i) calibrating the fly ash efficiency factor k as a function of the fly ash-to-binder and water-to-binder ratios using a modified Bolomey strength model; (ii) establishing a k-based mix design procedure for rigid pavement concrete; and (iii) experimentally validating the designed mixtures by testing their fresh properties, early-age thermal response, mechanical performance and durability-related indicators. The scope of the present study is intentionally limited to rigid concrete pavements, as the design targets, performance criteria and validation tests were all defined in reference to specific structural and durability requirements for pavements.

The present study is novel not only because it calibrates the efficiency factor for Vietnamese Class F fly ash, but also because it integrates this calibration with a pavement-oriented proportioning procedure and a multi-criterion experimental validation framework. This approach moves the study beyond source-specific parameter fitting, proposing a reproducible design workflow for rigid pavement concrete under the investigated local material conditions.

2. Materials and Methods

2.1. Materials

Ordinary Portland cement (PC40) from Nghi Son was used as the primary binder in this study. According to the manufacturer's quality certificate and supporting material characterisation in the thesis, the cement satisfied the requirements for pavement concrete and had a 28-day mortar strength of 54.3 MPa. Portland cement was selected as the principal binder for rigid pavement concrete due to recommendations from both international practice and Vietnamese specifications [13], [14]. The supplementary cementitious material was commercial fly ash, supplied by PHALAMI and produced at the Pha Lai thermal power plant in northern Vietnam. This fly ash satisfied the requirements of ASTM C618 [4] for Class F fly ash. Key characteristics included a 45 µm sieve residue of 10.6%, a loss on ignition of 0.73%, a moisture content of 0.10%, and a combined $SiO_2 + Al_2O_3 + Fe_2O_3$ content of 94.25%. The activity indices at 7 and 28 days were 82.3% and 84.73%, respectively. This material was selected as it is one of the most representative and commercially available fly ashes for practical applications in northern Vietnam.

The fine aggregate was Lo River sand from Phu Tho Province. It had a specific gravity of 2.654, a loose bulk density of 1.618 g/cm³, a void ratio of 39.0%, a water absorption rate of 0.68% and a fineness modulus of 2.9. The measured clay, silt and dust content was 1.12%, which was within the acceptable limit for pavement concrete. The grading also satisfied the relevant Vietnamese and ASTM requirements for concrete aggregates.

The coarse aggregate was crushed limestone from Phu Ly, with a nominal maximum size of D_{max} = 12.5 mm. This aggregate had a specific gravity of 2.717, a rodded unit weight of 1,650 kg/m³, a water absorption rate of 0.76%, an LA abrasion loss rate of 22.36%, and a parent rock compressive strength of 140 MPa. This aggregate source was selected because it satisfied the mechanical and grading requirements for rigid pavement concrete.

Potable water was used for all mixtures. A water-reducing, plasticising admixture (Sikament R4) was added to the concrete mixtures to improve workability whilst controlling the amount of water required. This admixture provided a water reduction of approximately 10–20%; an average reduction of 11.5% was adopted in the final mixture design.

2.2. Experimental programme

First, the fly ash efficiency factor was calibrated at the mortar scale, based on the idea that the effects of the fly ash-to-binder and water-to-binder ratios on strength development in mortar and concrete are similar enough to support an initial calibration stage [15], [16]. Nine fly ash replacement ratios and three water-to-binder ratios were considered. This yielded a total of 27 mortar mixtures. The calibration stage was defined to span a broad experimental domain of nine fly ash-to-binder ratios (f = 0, 10, 15, 20, 25, 30, 40, 50 and 70%) and three water-to-binder ratios (ω = 0.35, 0.40 and 0.50). This wide range was chosen to show how the efficiency factor varies from low to high replacement levels, rather than restricting the calibration to mixtures that are practical for pavements. The resulting calibrated concrete envelope was summarised as k = 0.70÷0.40 for f = 15÷35% and k = 0.40÷0.27 for f = 35÷70%.

Mortar specimens were prepared using standard sand and a binder-to-sand mass ratio of 1:3. Each batch contained 450 g of binder and 1,350 g of standard sand. The specimens were cast and cured in accordance with TCVN 6016:2011 [17], after which they were tested for 28-day compressive strength in accordance with TCVN 3121-11:2003 [18]. One set of six specimens was tested for each mixture, resulting in 162 specimens in total. The complete calibration matrix and specimen allocation are summarised in Table 1.

Following the initial calibration of the efficiency factor, the proposed design approach was applied to concrete for rigid pavements. The target application was jointed plain concrete pavement for roads of Grade III and below. The minimum design flexural and compressive strengths were taken as 4.5 MPa and 41.3 MPa, respectively [19], [20]. Two stages were then considered:

Table 1. Experimental plan and test methods

No.	Item		Water/binder ratio (ω)		
			0.35	0.4	0.5
I	Standard:		TCVN 3121-11:2003 [18]		
	Specimen age (day):		28	28	28
II	Number of specimens per set				
1	Fly ash/binder ratio (f)	0	6	6	6
2		0.1	6	6	6
3		0.15	6	6	6
4		0.2	6	6	6
5		0.25	6	6	6
6		0.3	6	6	6
7		0.4	6	6	6
8		0.5	6	6	6
9		0.7	6	6	6
Total			162 specimens / 27 sets		

In the first stage, the focus of the concrete verification was on five levels of fly ash replacement (15%, 20%, 25%, 30% and 33%), which were selected from a broader calibration envelope. This range was chosen because recommendations for use in pavements indicate that practical replacement ratios for Class F fly ash and the targeted strength level generally fall within the low-to-moderate range. Meanwhile, EN 206 [21] permits values of up to around 33% in cases where local calibration is unavailable. The purpose of this stage was therefore to identify the part of the broad k-calibration envelope that remained compatible with the design requirements of rigid pavement concrete. Additionally, mixtures proportioned using the experimentally calibrated k-values were compared with those proportioned using the conservative fixed k-value of 0.4 from EN 206 [21]. Strength verification showed that the 33% replacement level did not satisfy the required design compressive strength. Consequently, the practical pavement interval was restricted to 15–30% fly ash. Within this range, design k-values for pavement concrete were selected from the experimentally calibrated values and the conservative EN 206 benchmark [21]. The resulting practical bands were 0.55÷0.52, 0.52÷0.48, and 0.48÷0.44, and these were used in subsequent mixture designs.

- In the second stage, four final fly ash concrete mixtures (denoted FC15, FC20, FC25 and FC30) and a control concrete mixture without fly ash (PC) were prepared for validation testing. These final mixtures were proportioned using the k-value ranges recommended by the experimental study, and were then used in workability, thermal, mechanical and durability tests.

2.3. Calibration of the efficiency factor k

The calibration procedure was based on a modified Bolomey-type strength formulation for both plain cement and fly ash concretes. For control concrete without fly ash, the compressive strength was expressed as follows:

$$R_{PC} = AR_x\left(\frac{X_{PC}}{N} - 0.5\right) \quad (1)$$

or fly ash concrete, the corresponding expression was written as:

$$R_{FC} = AR_x\left(\frac{X_{FC} + kF}{N} - 0.5\right) \quad (2)$$

where R_x is the cement strength, and R_{FC} are the compressive strengths of the control and fly ash concretes, respectively, X_{PC} is the cement content in the control concrete, X_{FC} and F are the cement and fly ash contents in the fly ash concrete, N is the water content, and A is the aggregate quality coefficient [15].

For the paired control and fly ash mixes used in the calibration stage, the aggregate system and cement type remained unchanged and the total binder mass was kept constant. Consequently, when forming the strength ratio $R_s = R_{FC}/R_{PC}$, the common terms A and R_x cancel and X_{PC} can be written as X_{FC} + F. The substitutions f = F/(X_{FC} + F) and ω = N/(X_{FC} + F) then lead directly to Eq. (3):

$$R_s = 1 + (k-1)\frac{f}{1-0.5\omega} \quad (3)$$

which leads to the efficiency factor:

$$k = \frac{(R_s - 1)(1-0.5\omega)}{f} + 1 \quad (4)$$

The mortar test data were then used to establish regression expressions for R_s. For the low fly ash range (f = 0.1÷0.15), the relationship was governed by both f and ω^{-1}:

$$R_s = 0.67f - 0.063\omega^{-1} + 1.018 \quad (5)$$

For the broader range f = 0.15-0.70, the influence of ω became much less pronounced, and the strength ratio could be expressed primarily as a function of f:

$$R_s = 1.093f + 1.149 \quad (6)$$

For clarity, the statistical significance of each regression is discussed in terms of the model-level F(P) value and the parameter-level P-values of the corresponding predictors. The statistical quality of the regression models was evaluated using the underlying regression analysis. For the low fly ash range (10–15%), the two-variable regression corresponding to Eq. (5) showed R^2=0.899 and F(P)=0.0316<0.05, indicating that the fitted model was statistically significant. In this range, both *f* and ω^{-1} were significant predictors of R_s, with P-values of 0.0338 and 0.0359, respectively. For the broader fly ash range (>15–70%), ω^{-1} became non-significant in the two-variable form (P = 0.246), while f remained significant (P = 2.5×10^{-9}). After removing ω^{-1}, the one-variable regression corresponding to Eq. (6) gave R^2 = 0.884, with F(P) = 1.4×10^{-9} < 0.05, while the coefficient associated with f remained statistically significant (P = 5.84×10^{-17}). These results confirm that the proposed expressions provide a statistically sound representation of the strength-ratio response over the investigated calibration ranges.

As the initial calibration was conducted using mortar, the k-values for concrete were conservatively set at 0.9 times the corresponding mortar values. This coefficient should not be interpreted as a universal transformation rule between mortar and concrete. Instead, it has been adopted as a conservative engineering transfer assumption consistent with previous studies indicating that the effects of the fly ash-to-binder and water-to-binder ratios on cementing efficiency in mortar and concrete are broadly similar.

However, the effective k-value in concrete may be slightly lower due to the more complex material system [15], [16]. The validity of this assumption in the present study was subsequently validated through the analysis of the designed pavement concretes. The resulting calibration showed that k reached its maximum at approximately 15% fly ash replacement, after which it decreased as the fly ash content increased. For practical use, the calibrated concrete k-values were summarised into two ranges: k = 0.70÷0.40 for f = 0.15÷0.35 and k = 0.40÷0.27 for f = 0.35÷0.70. For pavement concrete specifically, the recommended values were later narrowed to: k = 0.55÷0.52 for 15÷20% fly ash; k = 0.52÷0.48 for 20÷25%; and k = 0.48÷0.44 for 25÷30% (Table 2).

Table 2. Recommended ranges of the fly ash efficiency factor (k) for pavement concrete

Fly ash-to-binder ratio, f	15 ÷ 20%	20 ÷ 25%	25 ÷ 30%
Range of fly ash efficiency factor, k	0.55 ÷ 0.52	0.52 ÷ 0.48	0.48 ÷0.44

2.4. k-based mix design procedure

The concrete mixture design procedure was developed by adapting ACI 211.4R [22] for use in the context of Vietnamese pavement concrete. However, unlike approaches that adopt a single fixed k-value or treat fly ash as a direct mass-for-mass replacement of cement, the present procedure adjusts the contents of cement and fly ash through calibrated k-ranges. These are derived from the experimentally established relationship between R_s, f and ω. This approach is further anchored in the specific strength, workability and durability requirements of rigid pavement concrete, making it application-oriented rather than generic. The procedure consists of eight steps.

- First, the target mean compressive strength was derived from the required design strength. For the selected pavement application, the design compressive strength was 41.3 MPa, which corresponds to a minimum flexural design strength of 4.5 MPa. In the absence of prior statistical production data, the required mean strength was calculated as follows:

$$R_{yc} = 1.1f_c^{'} + 4.8 \quad (7)$$

which gave R_{yc}=50.2MPa. The target slump was selected as 2.5 cm, together with a water-reducing admixture.

- Secondly, a nominal maximum aggregate size of 12.5 mm was selected to balance strength, workability and pavement surface quality.

- Thirdly, the coarse aggregate content was determined based on the fine aggregate fineness modulus and the selected aggregate size, in accordance with ACI 211.4R. With Vod = 0.67 and a rodded unit weight of 1650 kg/m³, the coarse aggregate mass was:

$$D = V_{od}\rho_{od} = 1106 \text{ kg/m}^3 \quad (8)$$

- Fourthly, the initial water demand and air content were selected from ACI 211.4R, and were then adjusted to account for the actual void ratio of the sand.

$$N = N_{bd} + (V_r - 35) \times 4.72 \quad (9)$$

Using N_{bd}=175L and V_r=39.0%, the initial water demand was calculated as 194 L.

- Fifth, the water-cement ratio for the control concrete was selected as 0.44 based on the required mean strength and aggregate size.

- Sixth, the initial cement content of the control concrete was determined from the water demand and selected water-cement ratio, giving X_0=440 kg/m³. As this value exceeded the target for the practical cement content adopted for the optimised pavement mixtures (400 kg/m³), fly ash replacement was introduced at the next design stage.

- Seventhly, for a given fly ash replacement ratio (f) and efficiency factor (k), the contents of cement and fly ash in fly ash concrete can be obtained using the following relationships:

$$X_{FC} = \frac{1-f}{1+(k-1)f} X_0 \quad (10)$$

$$F = \frac{f}{1+(k-1)f} X_0$$

- Finally, the fine aggregate content was corrected by the absolute-volume method to account for the introduction of fly ash:

$$C_{FC} = \left(1000 - \frac{X_{FC}}{\rho_X} - \frac{F}{\rho_F} - N - \frac{N}{\rho_D} - V_{kk}\right)\rho_C \quad (11)$$

Trial batches showed that, while fly ash improved workability, water reduction was still necessary to achieve the desired balance between workability and strength. Therefore, approximately 1 L of Sikament R4 was used per 100 kg of cement, reducing the water content by 11.5% in the final mixtures. During the validation stage, the final water content was kept constant across all mixtures to enable the impact of incorporating fly ash and the k-based proportioning procedure to be evaluated on an equal footing.

Based on this procedure, the final mixtures adopted for validation were: FC15 (400 kg of cement and 73 kg of fly ash); FC20 (390 kg of cement and 96 kg of fly ash); FC25 (380 kg of cement and 125 kg of fly ash); FC30 (370 kg of cement and 160 kg of fly ash); and a control PC mixture (440 kg of cement and no fly ash). The control mixture was retained as an experimental reference for comparison purposes only and should not be interpreted as the optimised recommended pavement mixture. All mixtures contained 1,106 kg/m³ of coarse aggregate and 172 kg/m³ of water. The respective fine aggregate contents were 700 kg/m³, 685 kg/m³, 665 kg/m³, 640 kg/m³ and 740 kg/m³, and the respective admixture dosages were 4.0 L/m³, 3.9 L/m³, 3.8 L/m³, 3.7 L/m³ and 4.4 L/m³.

2.5. Test methods for validation

2.5.1. Fresh properties and setting time

The slump of the fresh concrete was measured in accordance with TCVN 3106:1993 [23] and ASTM C143 [24]. A standard slump cone with heights of 300 mm and diameters of 200 mm (bottom) and 100 mm (top) was used. In addition to the initial slump, slump retention was measured after 45 and 60 minutes to evaluate the effect of fly ash on workability stability.

The setting time of the binder system was determined according to TCVN 6017:2015 [25] using the Vicat method [26]. For each binder composition, three specimens were tested for initial setting time and three for final setting time, and the average values were reported.

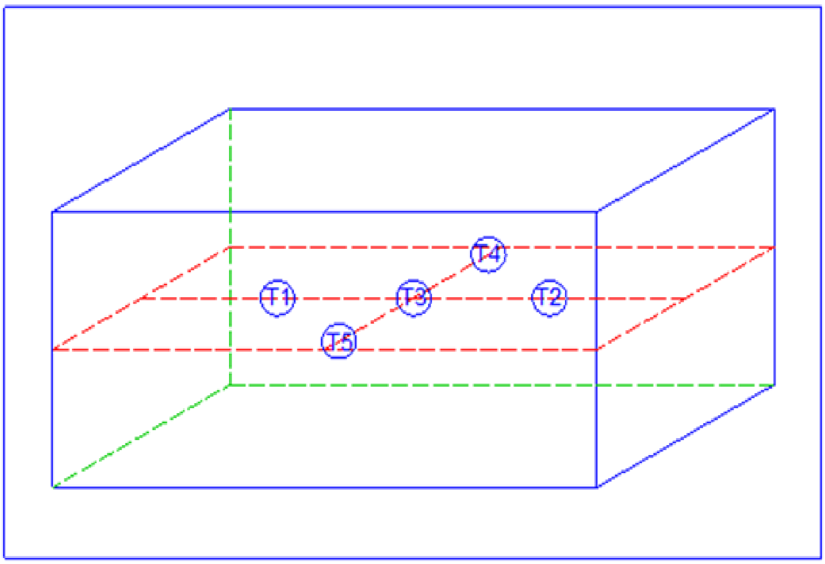


Fig. 1. Layout of temperature sensor positions in the concrete specimen

2.5.2. Early-age thermal response

The temperature development due to cement hydration was monitored in concrete blocks cast from PC and FC30 mixtures. Each specimen measured 250 mm × 250 mm × 400 mm. The sensor arrangement is illustrated in Fig. 1.

Temperature sensors were installed in the centre and near the wall of each block, as well as at intermediate positions, together with measurements of bath and ambient temperatures. The specimens were placed in an insulated enclosure to limit heat exchange with the surroundings. The highest internal temperature, adiabatic temperature rise and time to reach peak temperature were then evaluated. The thermal test should be interpreted as a comparison of relative temperature development in an insulated laboratory, rather than as a fully adiabatic or isothermal calorimetry procedure. The specimen size of 250 mm × 250 mm × 400 mm was chosen to allow for the sensor layout and to distinguish between core and near-wall temperature development within a controlled laboratory block. Accordingly, the thermal results are used for comparative interpretation between mixtures rather than as a direct representation of field behaviour of mass concrete.

2.5.3. Mechanical properties

Compressive strength was determined on cylindrical specimens with a diameter of 150 mm and a height of 300 mm, in accordance with ASTM C39 [27]. Tests were conducted at 7, 14, 28 and 56 days, with six specimens per mixture at each age. The characteristic compressive strength was calculated from the test results.

Flexural strength was measured at 28 days on beam specimens measuring 150 mm × 150 mm × 600 mm, in accordance with ASTM C78 [28]. The beams were tested under three-point loading and one set of six beams was tested for each mixture. A one-way analysis of variance (ANOVA) was used to compare the 28-day flexural strength results among the fly ash concretes, with a significance level of 0.05.

The static elastic modulus was determined at 28 days using 150 mm × 300 mm cylindrical specimens in accordance with ASTM C469 [29]. Each mixture was tested on six specimens and the loading rate was maintained at 0.241 ± 0.034 MPa/s until a stress equivalent to 40% of the 28-day compressive strength was achieved.

2.5.4. Durability-related properties

Abrasion resistance was determined according to TCVN 3114:2022 [30], with reference to ASTM C944 [31]. The abrasion loss of each specimen was calculated from the mass difference before and after the test as:

$$M_m = \frac{m_0 - m_4}{F} \tag{12}$$

where m_0 and m_4 are the specimen masses before and after four abrasion cycles, respectively, and F is the abraded surface area. One set of six specimens was tested for each mixture, and the characteristic abrasion loss was reported.

Water permeability was evaluated in accordance with TCVN 3116:2022 [32] on cylindrical specimens 150 mm in diameter and 150 mm in height. Water pressure was increased stepwise, with each pressure level maintained for 16 h, until visible water penetration occurred. The permeability grade of the concrete was defined as the maximum water pressure at which four out of six specimens remained unpenetrated.

3. Results and Discussion

3.1. Calibrated efficiency factor k

The calibration results show that the fly ash efficiency factor k is not constant across the investigated replacement range (Fig. 2). Therefore, it should not be treated as a fixed, universal coefficient. Instead, its value varies systematically with the fly ash-to-binder ratio, and to a lesser extent with the water-to-binder ratio. Generally, k increases as the fly ash replacement ratio rises from 10% to 15%, reaching a maximum at around 15%. However, it then decreases progressively as the replacement level increases further. This behaviour reflects the balance between the pozzolanic contribution of the fly ash and the reduction in cement content that occurs simultaneously. At low replacement levels, there is sufficient fly ash to react with the calcium hydroxide released by cement hydration, generating additional cementitious products and improving the effective contribution of the binder system. Beyond approximately 15%, however, the reduction in cement becomes increasingly dominant and the additional reaction products formed by the fly ash are insufficient to fully compensate for the loss of strength. For pavement applications, the design range of k was intentionally narrower than the full calibrated envelope. The broader ranges, k = 0.70÷0.40 for f = 15÷35% and k = 0.40÷0.27 for f = 35÷70%, describe the overall response of the efficiency factor across the entire investigated replacement domain. In contrast, the practical pavement ranges of 0.55÷0.52, 0.52÷0.48 and 0.48÷0.44 were only retained after concrete-stage screening of the candidate mixtures. This screening revealed that the 33% replacement level no longer met the required design compressive strength, resulting in the pavement-applicable interval being restricted to 15÷30% fly ash. Within this interval, the selected k-bands preserve the trend revealed by the calibration results while remaining compatible with the strength requirements of the designed pavement concretes. Therefore, the recommended pavement values should be understood as practical design values derived from the calibrated envelope rather than as a restatement of the full experimental range.

However, the calibrated k ranges reported here remain specific to the investigated Pha Lai Class F fly ash and the associated local material system. Transferring them to other fly ash sources should therefore be preceded by material characterisation and local recalibration, particularly where fineness, loss on ignition or chemical composition differ substantially.

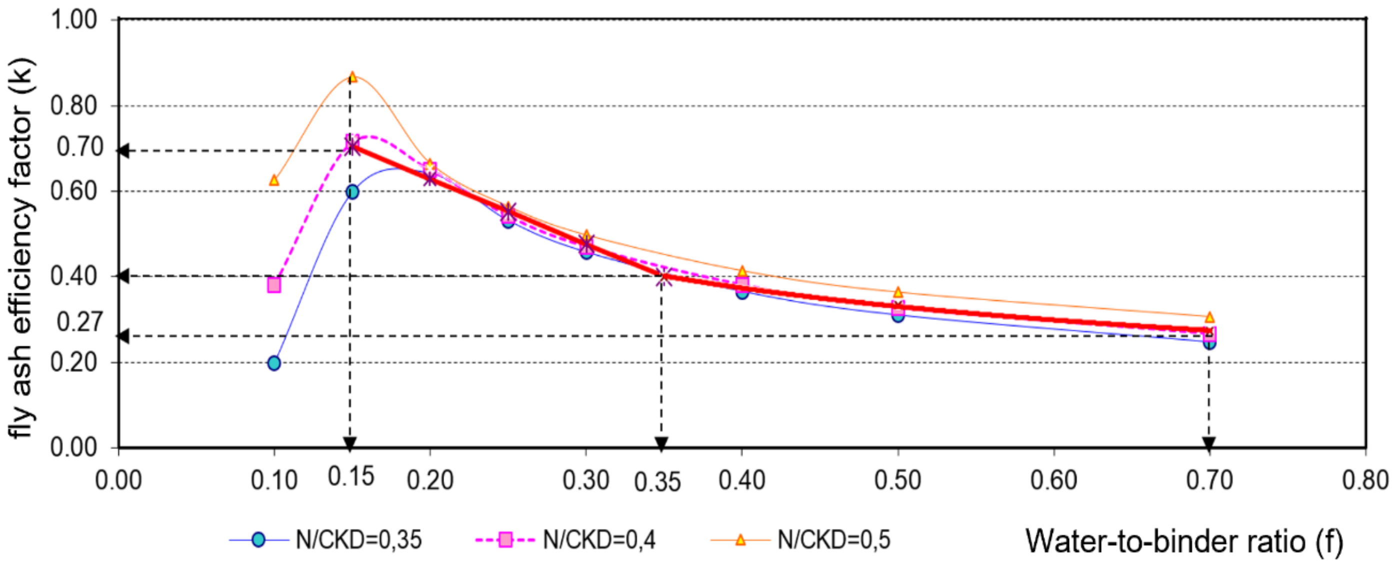


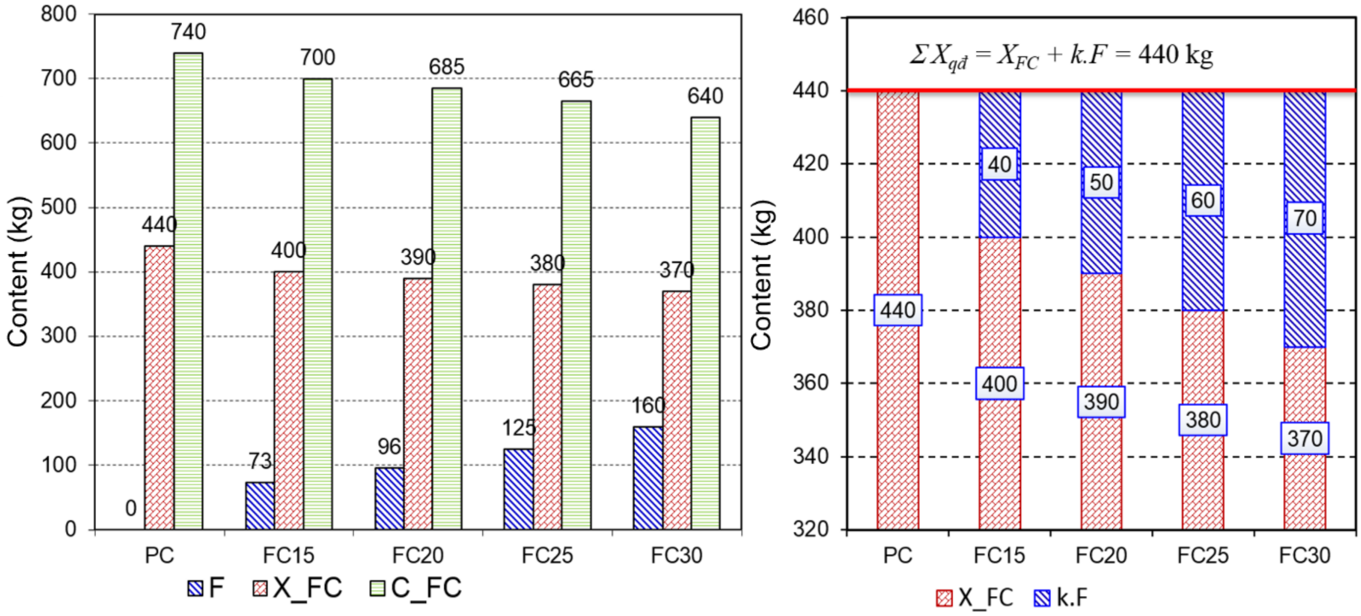
Fig. 2. Variation of the fly ash efficiency factor (k) with the fly ash-to-binder ratio

3.2. Mixture design outcomes using calibrated k

The calibrated efficiency factor was incorporated into the mix design procedure to produce four fly ash concrete mixtures (FC15, FC20, FC25 and FC30) and one control concrete mixture (PC). As the fly ash replacement ratio increased from 15% to 30%, the cement content decreased from 400 to 370 kg/m³, while the fly ash content increased from 73 to 160 kg/m³. Over the same range, the total binder content increased from 473 to 530 kg/m³, while the equivalent water-to-cement ratio, based on the converted cement mass, remained constant at 0.39. A key outcome of the proposed design concept is that, despite the substantial change in the physical composition of the binder, the total equivalent cementitious contribution was maintained at 440 kg/m³, thereby preserving the design basis of the mixture system.

From a practical viewpoint, the resulting proportions remained realistic for pavement construction. The coarse aggregate content remained at 1106 kg/m³, the water content was held at 172 kg/m³, and the fine aggregate content was adjusted slightly to account for the volume of fly ash. Consequently, the designed mixtures remained within the desired range of composition for pavement concrete, achieving the targeted balance of strength and workability. This is an important outcome because it demonstrates that the calibrated k-concept can be translated into an operational proportioning tool, rather than remaining a purely laboratory parameter. The mix design stage thus serves as a bridge between the fundamental calibration results and the experimental validation presented in the subsequent subsections. The corresponding changes in constituent contents are compared in Fig. 3.

3.3. Fresh properties



a) Fly ash content (F); Cement (X_FC) and Sand (C_FC)

b) Equivalent cement content (k.F); Total equivalent cement content

Fig. 3. Comparison of constituent contents in the designed pavement concrete mixtures

3.3.1. Slump

The slump results indicate that fly ash clearly had a positive influence on the workability of the fresh concrete. At the initial measurement, the slump increased from 42.4 mm for the control concrete to 47.0 mm, 53.5 mm, 59.0 mm and 64.5 mm for FC15, FC20, FC25 and FC30, respectively. The corresponding ratios of the fly ash concretes to the control concrete ranged from 1.1 to 1.5. This trend was maintained at 45 and 60 minutes, demonstrating that fly ash improves both the initial consistency and the retention of workability over time. As the final water content was kept constant during the validation process, the increased slump of the fly ash mixtures should primarily be seen as evidence of improved workability based on a standard design, rather than as the result of optimising the water content separately for each mixture. Notably, the slump loss after 60 minutes decreased from 26.0 mm for the control concrete to 22.7, 19.6, 16.5 and 14.4 mm for FC15 to FC30, respectively. A statistical analysis of the slump results showed that the content of fly ash had a significant effect on the slump at all three observation times. The adjusted R^2 values were 0.875, 0.919 and 0.894, and the corresponding p-values were 0.013, 0.006 and 0.010 for the initial slump, the slump after 45 minutes and the slump after 60 minutes, respectively. The time-dependent slump responses are presented in Fig. 4.

This behaviour is consistent with the physical characteristics of Class F fly ash. The spherical particle shape, smoother surface texture, and lower carbon content reduce internal friction and improve particle packing, which in turn enhances flowability and helps maintain slump during the transport and placing period [7], [8]. For rigid pavement concrete, this is not a minor benefit. Improved slump stability contributes directly to more uniform spreading, better compaction, and more reliable surface finishing in field construction. Accordingly, the workability results support the suitability of the k-based design approach not only from a strength standpoint but also from a constructability standpoint.

3.3.2. Setting time

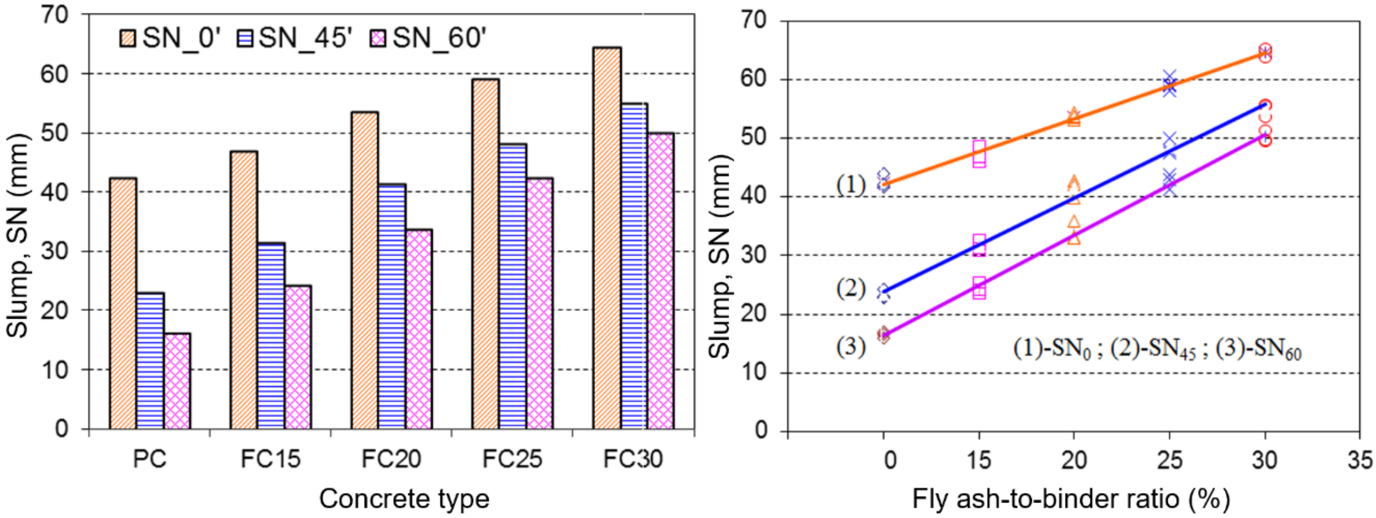


Fig. 4. Initial slump and slump retention of the control and fly ash concretes

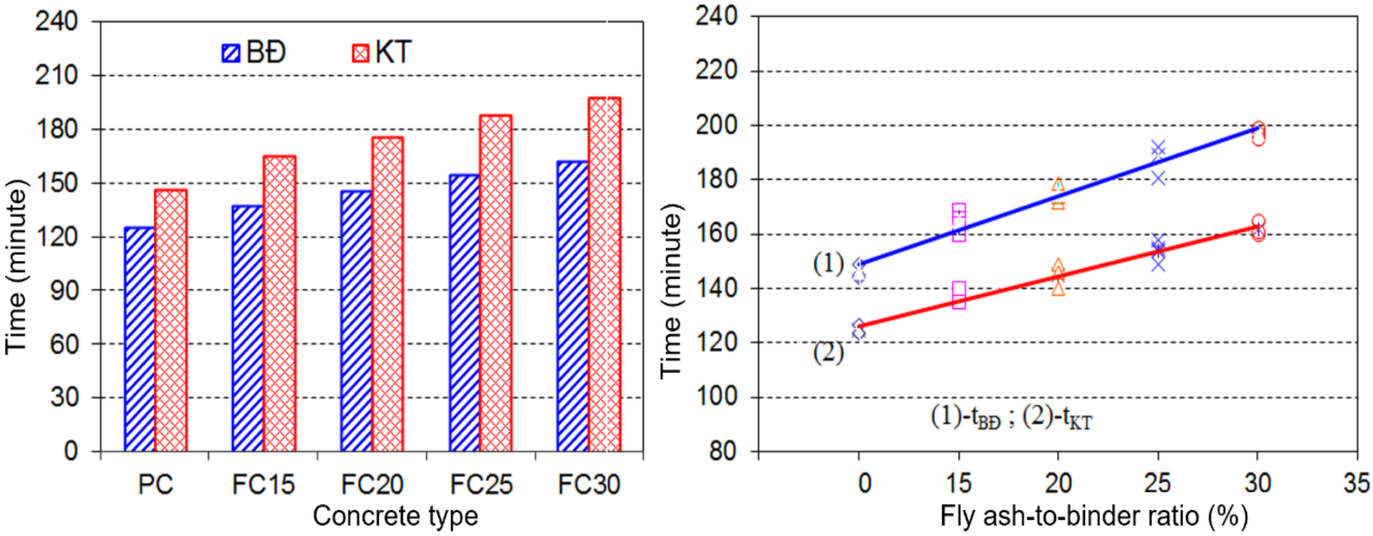


Fig. 5. Initial and final setting times of binder systems containing fly ash

The incorporation of fly ash also delayed the setting process. Compared with the cement-only binder, the initial setting time increased by 12–37 minutes and the final setting time by 19–51 minutes as the fly ash ratio increased from 15% to 30%. Further ANOVA-based statistical analysis indicated that fly ash content significantly affected both the initial and final setting times. The adjusted R^2 values were 0.875 and 0.919, with corresponding P-values of 0.013 and 0.006, respectively. The interval between the initial and final settings also increased, rising from 21 minutes for the control system to 28–35 minutes for the fly ash systems. This delayed setting can be attributed to the slower reaction kinetics of fly ash compared to Portland cement hydration, particularly at the beginning when the pozzolanic reaction is still limited [8], [33]. The measured initial and final setting times are compared in Fig. 5.

From a practical perspective, the longer setting period indicates an extended timeframe for the transportation, placement, compaction and finishing of pavement concrete. The implications of fly ash for hydration, heat evolution, and the thermal response at an early age are discussed separately in Section 3.4.

3.4. Early-age thermal behavior

Further thermal measurements confirmed the effect of fly ash on the early-age behaviour of concrete. For the PC control concrete, the maximum core temperature was 64.8°C after approximately 40 hours of mixing. For FC30, it was 53.4°C after approximately 48 hours. Therefore, using 30% fly ash reduced the peak temperature by 11.4°C (a 17.6% reduction) and delayed reaching the peak temperature by 8 hours. Correspondingly, the adiabatic temperature rise decreased from 41.9°C for PC to 31.1°C for FC30. The corresponding temperature histories are shown in Fig. 6.

These results suggest that fly ash can significantly reduce the heat released by the binder system. This is consistent with the reduced clinker content and slower pozzolanic reaction of fly ash compared to Portland cement. While this paper does not involve full thermal stress modelling of pavement slabs, the reduction in peak temperature and delayed temperature rise are favourable for early-age crack resistance. Therefore, the thermal results should be interpreted as a material-level advantage of the fly ash mixtures, particularly when the pavement is exposed to conditions where thermal gradients and restrained deformation may become critical.

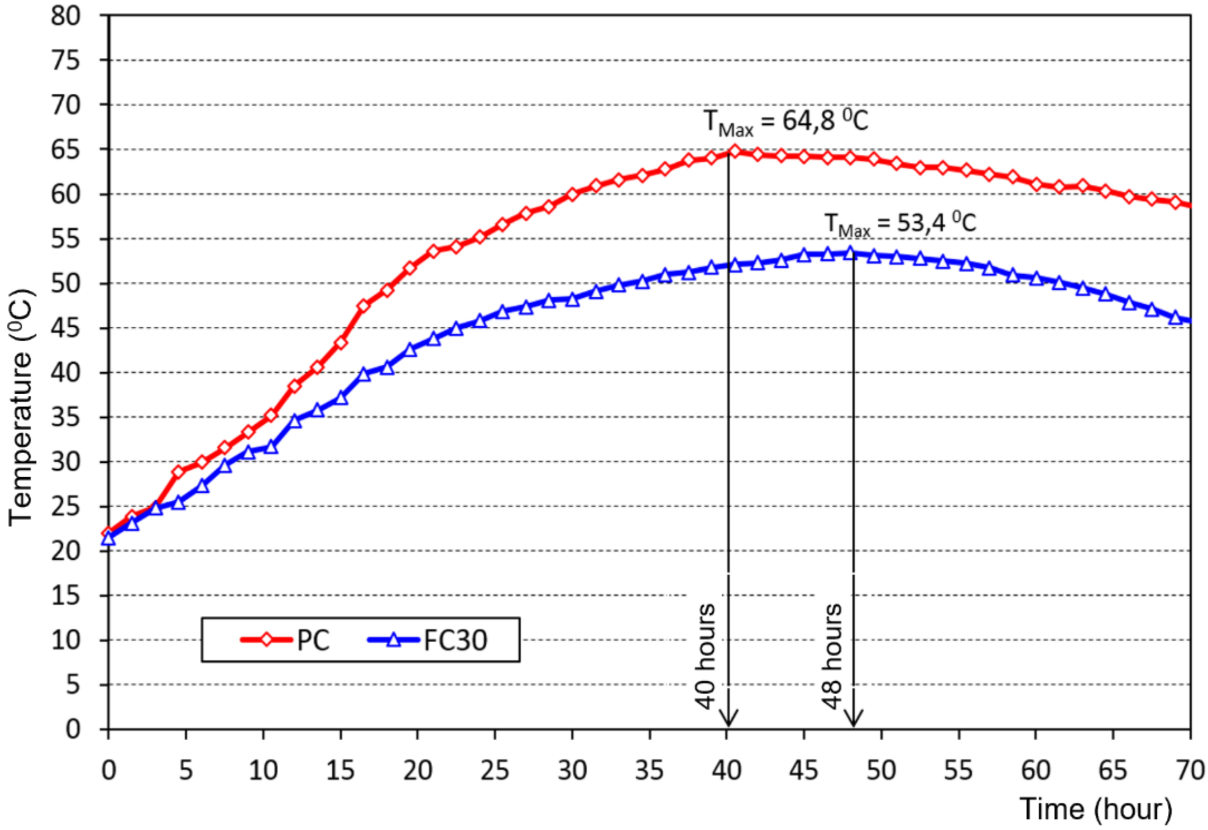


Fig. 6. Temperature development in the control concrete and fly ash concrete specimens

3.5. Mechanical performance

3.5.1. Compressive strength development

The compressive strength results reveal a clear age-dependent pattern. At 7 days, the characteristic compressive strength of the fly ash concretes was found to range from 32.30 to 35.46 MPa, which corresponds to 84.2–92.5% of that of the control concrete. At 14 days, this increased to 37.84–40.86 MPa (88.1–95.2% of the control concrete). By 28 days, however, the difference had narrowed considerably, with the characteristic strengths of FC15, FC20, FC25 and FC30 reaching 46.57, 45.92, 45.09 and 44.29 MPa respectively, compared to 47.14 MPa for the control concrete. At

56 days, the pozzolanic contribution became more pronounced. FC15 and FC20 slightly exceeded the control concrete; FC25 was nearly equivalent; and only FC30 remained lower. The age-dependent development of characteristic compressive strength is summarised in Fig. 7.

This development pattern confirms the dual role of fly ash in pavement concrete. Within the first 28 days, the reduced cement content determines the strength response and the pozzolanic reaction has not advanced sufficiently to compensate for the initial reduction in clinker. After 28 days, however, the continued reaction of the fly ash refines the matrix and contributes to strength gain. This leads to faster strength development at later ages than in the control concrete. From a pavement design perspective, this is an important finding. It shows that fly ash contents of 15–25% can preserve or even slightly improve later-age compressive strength, while delivering the fresh-state and durability benefits discussed earlier. In contrast, 30% fly ash appears to be close to the upper practical limit of this material system when aiming to maintain a balanced mechanical response.

3.5.2. Flexural strength

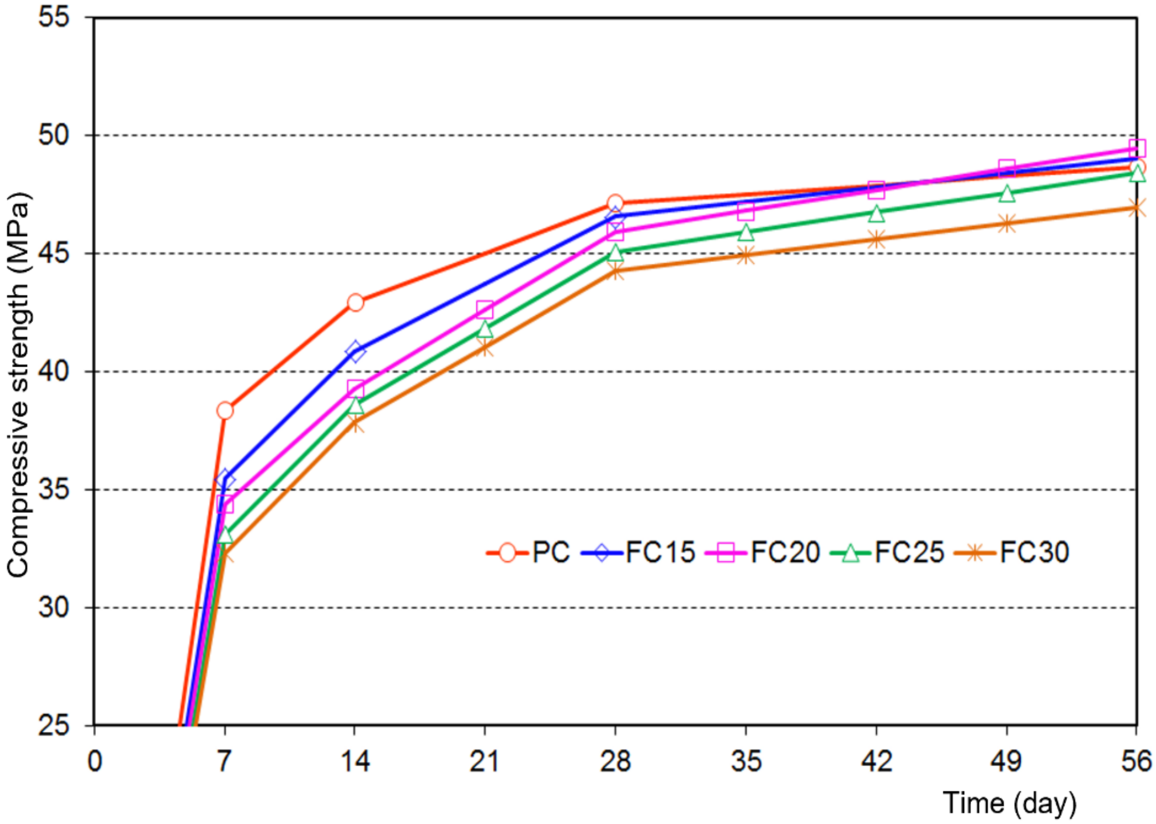


Fig. 7. Development of characteristic compressive strength with curing age

Flexural strength is the most important mechanical property for rigid pavements, and the experimental results were encouraging. After 28 days, the characteristic flexural strength of the fly ash concretes ranged from 4.67 to 4.88 MPa, compared with 5.01 MPa for the control concrete. While this was slightly lower than the control concrete, all fly ash mixtures exceeded the design requirement of 4.5 MPa for the targeted pavement class. Furthermore, one-way ANOVA was used to evaluate the differences in flexural strength among FC15, FC20, FC25 and FC30. The analysis showed that the variation among the fly ash mixtures was not statistically significant at a 95% confidence level ($P(F) = 0.098 > 0.05$), indicating that the reduction in flexural strength within this replacement range was modest rather than structurally significant. From a pavement engineering perspective, this result is significant because the performance of slabs is primarily governed by flexural resistance rather than compressive strength alone. Within the investigated material system, the modest variation in flexural strength indicates that the reduction in clinker content was largely offset by fly ash's subsequent contribution to matrix development. Consequently, bending capacity remained above the design threshold throughout the 15–30% replacement range. The 28-day characteristic flexural strengths are compared in Fig. 8.

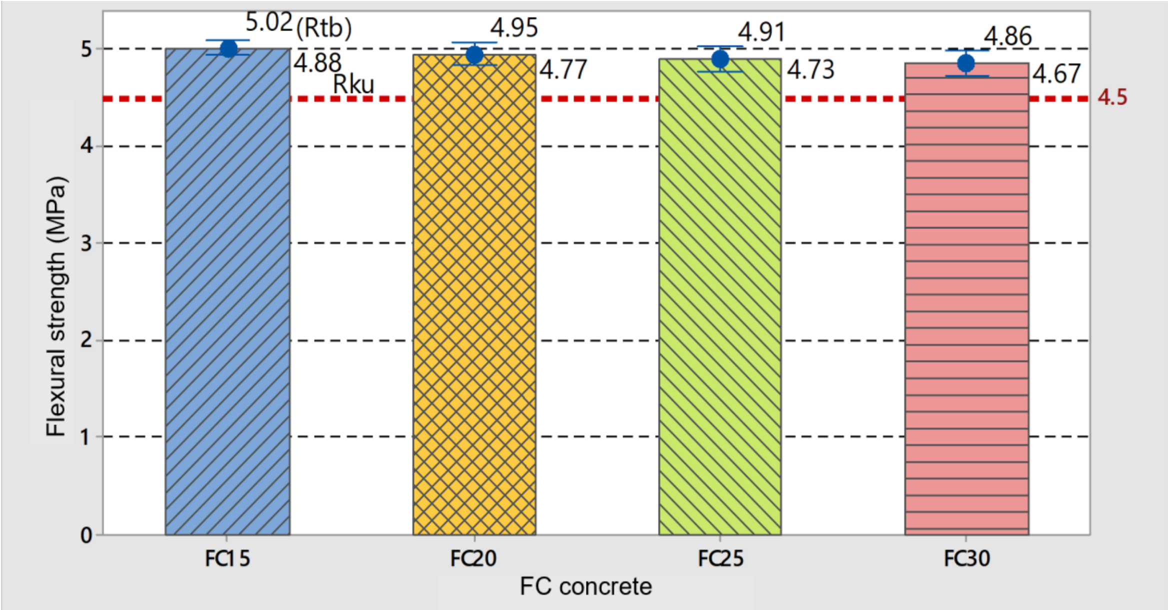


Fig. 8. Characteristic flexural strength of the control and fly ash concretes at 28 days

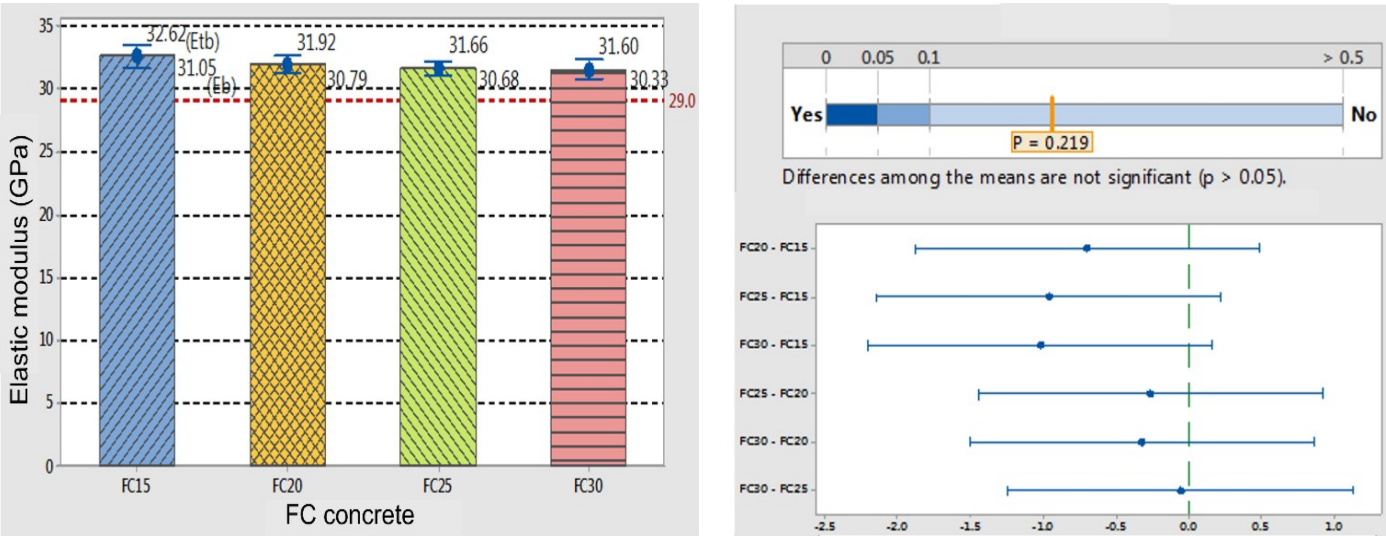


Fig. 9. Static elastic modulus of the control and fly ash concretes at 28 days

The results also enabled a practical relationship to be established between flexural and compressive strength:

$$R_{ku} = 0.71 R_n^{1/2} \quad (13)$$

Where R_{ku} is the flexural strength and R_n is the compressive strength, both in MPa. This expression is consistent with the general form recommended in ACI 318-19 [34], confirming that the flexural response of the investigated fly ash concretes remained mechanically coherent with their compressive strength level. Equally importantly, the R_{ku}/R_n ratio remained almost unchanged at 0.104–0.105 for the fly ash concretes compared to 0.106 for the control concrete. This indicates that the concrete's ability to mobilise flexural resistance relative to its compressive capacity was essentially preserved.

3.5.3. Elastic modulus

The elastic modulus results showed less sensitivity to fly ash content than the compressive or flexural strength results. The characteristic modulus for the fly ash concretes ranged from 30.33 to 31.05 GPa, compared with 31.11 GPa for the control concrete. Even the lowest value remained above the 29 GPa design requirement for the intended pavement application. Therefore, the modest reduction observed at 25–30% fly ash is not structurally critical within the investigated range. The corresponding 28-day elastic-modulus results are presented in Fig. 9.

A correlation was established between elastic modulus and compressive strength in the following form:

$$E_b = 20600\left(\frac{R_n}{10}\right)^{1/3} \quad (14)$$

where E_b and R_n are in MPa. This expression confirms that the elastic behaviour of the fly ash concretes in question is primarily governed by compressive strength and aggregate skeleton, rather than fly ash content alone. This is an important finding for pavement engineering, as it suggests that moderate fly ash replacement does not compromise slab stiffness to the same extent as it affects early-age strength. Consequently, fly ash contents of up to 25% can be considered structurally acceptable in terms of both modulus and flexural strength within the current material system. This interpretation is consistent with the role of the elastic modulus in the design of rigid pavements, where the stiffness is strongly influenced by the aggregate skeleton and less directly by the content of the fly ash itself. Therefore, the present results suggest that, within the investigated range, fly ash modifies the cementitious phase without causing a disproportionate loss of slab stiffness.

3.6. Durability-related properties

3.6.1. Abrasion resistance

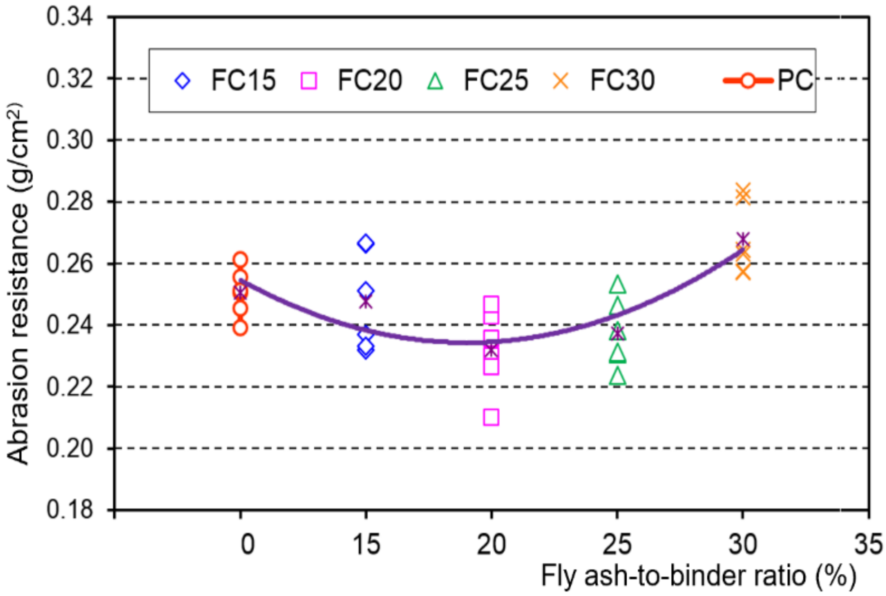


Fig. 10. Abrasion loss of the control and fly ash concretes

The abrasion test results suggest that a moderate amount of fly ash replacement improves the wear resistance of concrete surfaces. The lowest abrasion loss was recorded for FC20 at 0.207 g/cm², followed by FC25 at 0.217 g/cm², which were both lower than the value for the control concrete of 0.236 g/cm². FC15 also performed slightly better than the control concrete. In contrast, FC30 showed the highest abrasion loss among the fly ash mixtures, at 0.250 g/cm². This pattern suggests that abrasion resistance benefits from matrix refinement at moderate levels of fly ash replacement, but that this benefit is no longer sufficient at 30% replacement. At this level, the reduction in matrix strength appears to offset the favourable densification effect. As no microstructural characterisation was conducted in the present study, this interpretation should be regarded as mechanistic. This pattern suggests that abrasion resistance benefits from the denser matrix produced by fly ash at moderate replacement levels, but deteriorates once the reduction in strength becomes more pronounced. The abrasion-loss results for all mixtures are compared in Fig. 10.

This result is particularly relevant for rigid pavements because abrasion resistance is directly associated with long-term surface wear under traffic. Therefore, the results reinforce the view that a 15–25% fly ash content offers the most balanced combination of strength and durability in the present study. At 30% replacement, while the abrasion resistance remained within an acceptable range, the advantage over the control concrete was lost.

3.6.2. Water permeability

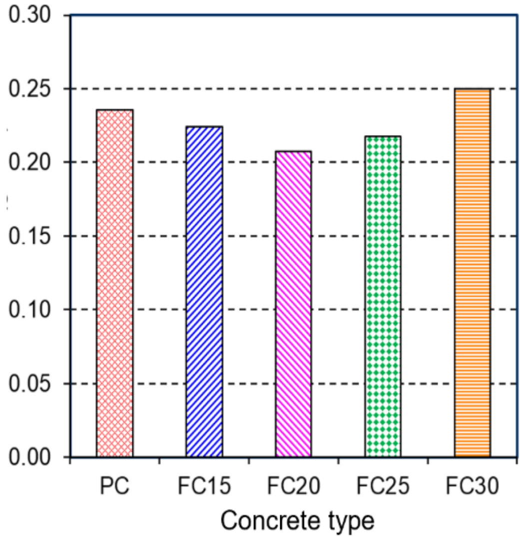


Fig. 10. (continued)

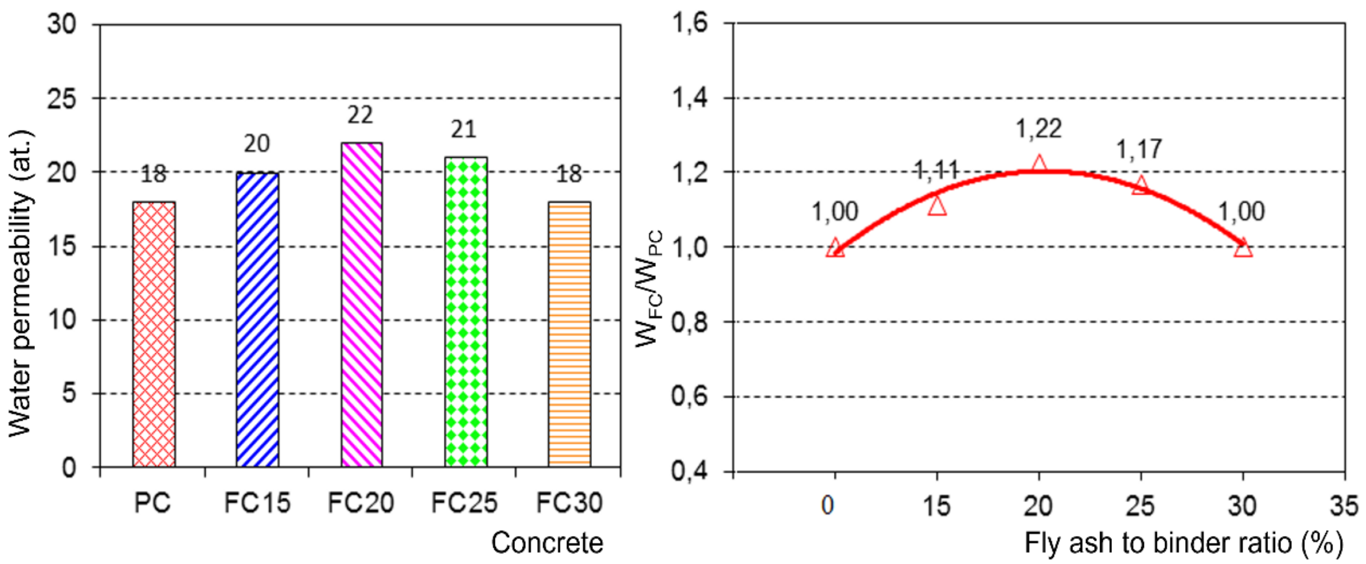


Fig. 11. Water permeability grades of the control and fly ash concretes

The water permeability results show a similar trend. The permeability grade increased from 18 for the control concrete to 20, 22 and 21 for FC15, FC20 and FC25, respectively, before returning to 18 for FC30. Thus, moderate fly ash replacement improved resistance to water penetration by 11–22% relative to the control concrete, but the 30% mixture provided no further improvement. This is consistent with the expected pore-refining effect of fly ash, which enhances compactness and reduces connectivity between capillary pores when the replacement level remains within a suitable range [8]. The corresponding permeability grades are presented in Fig. 11. From a pavement perspective, improved impermeability is closely related to long-term durability, as it minimises the ingress of water and other potentially harmful substances into the concrete matrix. The present results therefore suggest that the densification benefit of fly ash is most effective at a replacement level of 15–25%. However, when the replacement level exceeds 30%, the reduced cement content appears to offset this benefit to some extent, resulting in a permeability grade comparable with that of the control concrete.

3.7. Integrated discussion

The results show that the calibrated K-based mix design procedure provides a consistent approach from material-level calibration to engineering-scale performance verification. Using the efficiency factor enabled the cement and fly ash contents to be adjusted rationally while maintaining the equivalent cementitious contribution required by the design concept. Consequently, the designed fly ash concretes not only satisfied isolated laboratory indicators, but also achieved a consistent performance profile relevant to rigid pavement applications.

The main trade-off observed in this study is clear. Increasing the fly ash content improved workability and delayed setting. It also lowered heat evolution and enhanced selected durability-related properties. However, it reduced early-age strength, and at high replacement levels it slightly reduced flexural strength and elastic modulus. Within this balance, the 15–25% replacement range appears to be the most favourable for the material system under investigation. Within this range, the concrete retained flexural strength above the design threshold and modulus above the required level. It also demonstrated improved abrasion resistance and impermeability and achieved compressive strength at later ages that was comparable to or better than that of the control concrete. The 30% mixture was still technically usable, but the balance of advantages was less favourable, particularly in relation to compressive strength, abrasion resistance and permeability. Overall, the results support the use of Class F fly ash in pavement concrete under Vietnamese conditions, provided mixture proportioning is guided by a calibrated efficiency factor rather than direct cement replacement.

4. Conclusions

This study establishes that the efficiency factor k of Class F fly ash cannot be treated as a constant when designing a pavement concrete mix. Instead, k varies systematically with the fly ash-to-binder ratio, and to a lesser extent with the water-to-binder ratio. The calibrated results provide a practical design basis for Vietnamese materials, with k decreasing from 0.70 to 0.40 for fly ash contents of 15–35% and from 0.40 to 0.27 for 35–70%. For pavement applications, the recommended ranges were narrowed to 0.55–0.52 for 15–20% fly ash, 0.52–0.48 for 20–25% and 0.48–0.44 for 25–30%. These results confirm that locally calibrated *k*-values are essential for the incorporation of fly ash into pavement concrete within a rational design framework.

By incorporating the calibrated efficiency factor into an eight-step mix design procedure, the study goes beyond parameter calibration to provide a practical proportioning method for rigid pavement concrete. The proposed framework enables cement reduction while maintaining the necessary equivalent cementitious contribution of the binder system. In this respect, the study's main contribution is both methodological and material-based: it translates the efficiency-factor concept into a practical design tool, rather than leaving it as an isolated analytical coefficient.

Experimental validation demonstrates that fly ash improves the fresh state and thermal behaviour of pavement concrete, while preserving key structural requirements within a moderate replacement range. Increasing the content of fly ash enhances workability and slump retention, prolongs setting time and reduces early-age heat evolution. For FC30, the peak temperature decreased by 17.6% and occurred eight hours later than in the control concrete. However, fly ash reduced the early-age compressive strength. This drawback diminished with age, though, and the 56-day compressive strength of mixtures containing 15–20% fly ash exceeded that of the control concrete. The 25% mixture remained essentially comparable. Crucially, in terms of pavement performance, all of the fly ash mixtures investigated satisfied the target flexural strength and elastic modulus requirements, with characteristic flexural strengths of 4.67–4.88 MPa and elastic moduli of 30.33–31.05 GPa at 28 days.

The results relating to durability indicate that the beneficial effect of fly ash is most pronounced at moderate replacement levels. The 15-25% fly ash range showed the most significant improvements in abrasion resistance and water impermeability, whereas the 30% mixture no longer offered a clear advantage over the control concrete. Overall, these findings suggest that a 15–25% fly ash content provides the most balanced properties for the investigated material system, offering improved workability and thermal response, as well as adequate mechanical performance and favourable durability. Accordingly, this study provides a basis for the practical use of Pha Lai Class F fly ash in rigid pavement concrete in Vietnam that is validated by experimentation. Therefore, the present conclusions should be understood as laboratory-validated findings for the investigated material system and intended rigid pavement application, rather than as recommendations for generalised implementation based on field verification. Future work should extend this framework to field-scale validation, long-term pavement performance and the use of a broader range of fly ash sources.

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