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Laboratory assessment of fly ash in compressive strength, abrasion-resistant and low-carbon concrete for slope erosion control

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Abstract: Concrete is essential for landslide prevention and slope stabilization, requiring high durability and abrasion resistance. This study evaluates fly ash as a cement replacement to improve abrasion resistance, maintain M35 (35 MPa) strength, and reduce carbon emissions for sustainable construction. The methodology includes material characterization and testing of concrete properties such as compressive strength, abrasion resistance, and water permeability. Experimental results show that the 90-day compressive strength meets the M35 standard, ranging from 39.9 to 41.1 MPa. Water permeability resistance improves from 10 to 12 atm with fly ash addition. The lowest abrasion loss (4.6%) and minimal wear depth (0.5 cm) occur at 30% fly ash replacement after six test cycles (72 hours). Carbon emissions are reduced by 9.5% to 46.8%, depending on the replacement level. The study identifies the optimal mix as 30% fly ash replacement (F30P1.1), which achieves M35-grade concrete, the best abrasion resistance, and a significant 28.4% reduction in CO_2 emissions compared to concrete without fly ash. These findings have practical implications for the construction industry, particularly in the context of sustainable materials and environmental benefits.

Keywords: Experimental results, fly ash material, abrasion resistance, slope protection.

1. Introduction

Concrete is one of the most widely used materials worldwide, particularly in Vietnam, across the construction, transportation, and geotechnical engineering sectors. Concrete is crucial in engineering solutions for landslide prevention, slope stabilization, and mitigating damage in steep mountainous areas. Concrete provides high strength, low permeability, and high abrasion resistance, preventing soil and rock erosion on slopes, and enhancing slope stability to mitigate landslides [1, 2]. In Hong Kong, the use of concrete in slope protection has driven the development of various specialized concrete structures, particularly retaining walls, to reinforce and safeguard landslide-prone areas. These structures function as conventional retaining walls and create protective corridors, thereby protecting infrastructure at the slope base [3, 4]. Improving the abrasion resistance of concrete is essential for structures exposed to debris-laden flows, as surface wear can accelerate structural degradation

[5, 6, 7]. For slope protection applications, concrete must meet stringent requirements for compressive strength, impermeability, and high abrasion resistance. These structures are constantly subjected to rainfall, erosive flow, and impact from soil and rock debris. Therefore, ensuring abrasion resistance is a key consideration in both material selection and structural design [4].

Various technologies have been developed to improve the abrasion resistance and compressive strength of concrete. Optimal mix design is a practical approach. This can be done by adding fly ash and silica fume [6–13], fine sand and recycled concrete [7, 14, 15], or repair mortars [16–18]. Among these options, partial cement replacement with fly ash is practical. Adding fly ash helps maintain compressive strength and reduce surface abrasion. It also lowers emissions and supports environmental protection. Research shows that replacing 15–25% of cement usually gives the best balance between abrasion resistance and compressive strength [7, 8, 11]. In exceptional cases, such as shotcrete or self-compacting concrete, the level can be increased to 25–30% for better workability and erosion resistance [10, 12, 13]. However, when the replacement exceeds 30–35%, strength often decreases. Higher levels can increase porosity and reduce abrasion resistance [9]. These effects are linked to the microstructural role of fly ash. At moderate levels, fine particles fill voids and trigger pozzolanic reactions, making the concrete denser. At higher levels, cement dilution dominates, leading to weaker concrete. The quality of fly ash also matters. Coarse particles, high LOI, or replacement above 40–50% often cause significant strength loss after 28 days and increase abrasion [19, 20].

Research on the abrasion resistance and compressive strength of concrete in Vietnam is still limited [10, 11, 14]. Among the available studies, fly ash has shown promising results. In Hanoi, high-fly-ash self-compacting concrete with up to 60% replacement achieved about 1.29% lower abrasion loss compared with conventional concrete [10]. In southern Vietnam, research on rural road concrete with 0–35% fly ash replacement reported lower early-age strength. However, the best long-term performance was found at 15% replacement. A range of 15–25% was identified as suitable for rigid pavements by balancing strength and abrasion resistance [11]. These results suggest that fly ash improves durability through pore structure refinement and offers practical benefits for Vietnam's infrastructure. Other studies also examined limestone dust as a partial replacement for fine sand in pavement concrete. Substituting about 40% of fine sand significantly improved abrasion resistance [14]. Although this work did not involve fly ash, it highlights the potential of alternative mineral additives in enhancing durability.

A key advantage of using fly ash in concrete is the reduction of carbon emissions. Cement production contributes about half of the total emissions in concrete manufacturing [21]. To reduce carbon emissions, studies have developed green concrete by partially replacing cement with industrial by-products such as fly ash, blast furnace slag, or recycled aggregates [21–24]. This approach reduces cement consumption, improves resource efficiency, and supports sustainability. In many cases, it also maintains or even enhances the mechanical properties of concrete [22–24].

In the Vietnamese context, research on fly ash concrete is still limited, particularly concerning compressive strength and abrasion resistance, and has not been integrated with environmental assessment. This paper aims to determine the optimal fly ash replacement ratio that preserves compressive strength while improving abrasion resistance. In addition, the study quantifies the carbon emissions from concrete production and evaluates the potential reductions achieved through partial cement replacement with fly ash. The findings are expected to provide valuable guidance for professionals and support future transitions toward more sustainable concrete practices.

2. Materials and Methods

2.1. Materials

The concrete mix consists of commonly available materials in Vietnam. The cement used is PC cement (Portland cement without mineral additives) to control the fly ash content in the concrete precisely. The fly ash used is Class F, sourced from the Pha Lai Thermal Power Plant in Hai Duong Province. The coarse aggregate is crushed limestone extracted from the Hang Nang quarry in Ngoc Lap Commune, Yen Lap District, Phu Tho Province. The fine aggregate is natural sand from the Lo River, stored at the screening and crushing station of the Hang Nang quarry. The sand is carefully preserved by Tu Lap Construction Co., Ltd., located in Ngoc Lap Commune, Yen Lap District, Phu Tho Province. The superplasticizer used is GP4 from Gia Phong, ensuring enhanced and sustained workability during concrete placement.

2.2. Research Methodology

The laboratory experiments comprise two main groups: (1) experiments to determine material properties and (2) experiments to evaluate concrete properties, including unit weight, slump, compressive strength, impermeability, and abrasion resistance. As presented in Table 1, these tests were performed in strict compliance with Vietnamese and international standards at Laboratory LAS–XD 175, Vietnam Academy for Water Resources, and at the Geotechnical Laboratory, VNU University of Science, Hanoi, Vietnam.

Table 1. Materials and concrete properties experiments

Experiments		Standars
Experiments for Materials	Properties of sand and crushed stone	TCVN 7572: 2006
	Properties of cement	TCVN 2682:2020
	Properties of Fly-ash	TCVN 10302:2014; ASTM C311
Experiments for Concrete	Slump	TCVN 3106:2022
	Density of mixing material	TCVN 3108:2022
	Density of cubic concrete	TCVN 3115:2022
	Compressive strength	TCVN 3118:2022
	Water impermeability	TCVN 3116:2022
	Abrasion resistance	ASTM C1138-05

Table 2. The superplasticizer ratio corresponding to the Water-to-Binder (W/B) and Fly-Ash-to-Binder (F/B) ratios

	F/B					
W/B	0	10	20	30	40	50
0.58	0.7					
0.57		0.9				
0.55			1.0			
0.53				1.1		
0.51					1.2	
0.48						1.3

(The superplasticizer ratio = 0.7-1.3 l/100 kg Binder)

The water, admixtures, and fly ash proportions in the concrete mix were meticulously adjusted to meet the research objective of developing M35-grade concrete with a high fly ash replacement ratio. The materials of concrete can be classified and measured either by weight (W): (i) the binder, consisting of cement (W_c) and fly ash (W_F); (ii) the mortar, comprising the binder, superplasticizer (W_P), water (W_w), and sand (W_S); and (iii) the concrete, composed of the binder, mortar, and crushed stone (W_{stone}). Based on the binder weight, the investigated fly ash replacement levels include 0%, 10%, 20%, 30%, 40%, and 50%. To ensure consistent compressive strength, it is crucial to determine the fly ash-to-binder (F/B) and water-to-binder (W/B) ratios. According to Decision No. 3986/QĐ-BNN-XD (October 12, 2018, in Vietnam) [25], maintaining a constant W/B ratio while increasing F/B in 10% increments leads to a linear decrease in compressive strength. Therefore, this study adopts a mixed design approach where a reduction in the W/B ratio offsets the increase in F/B, ensuring strength retention and a better understanding of the concrete mix design process.

The mix design was developed based on practical experience, relevant literature, and a guide in the ACI 211.1-91 standard (ACI 211.1-91, 2002) [26]. The specific mix proportions and ratios are presented in Table 2 and Fig. 1, reinforcing the credibility of our research. Additionally, Fig. 1 illustrates the calculated superplasticizer dosages required to achieve target workability across different water-to-binder (W/B) ratios. These values were determined based on preliminary water-reducing efficiency tests, ensuring consistency in slump among all mixtures. This comprehensive approach reinforces the reliability and practical relevance of the proposed mix design.

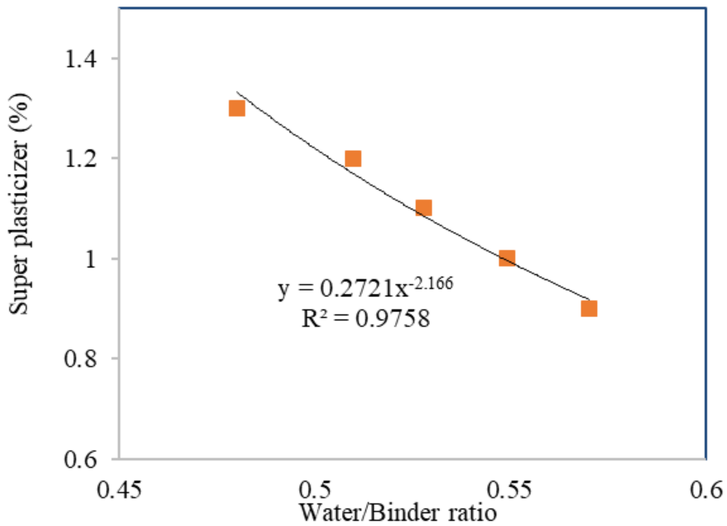

Fig 1. Relationship between superplasticizer and the W/B ratio

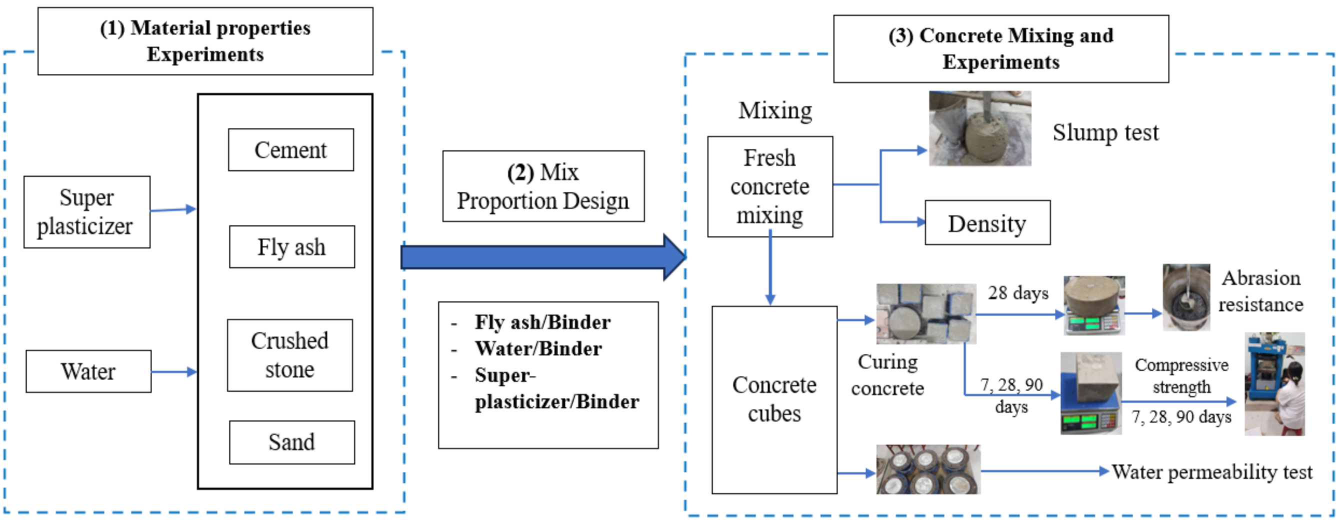

Fig 2. Experimental setup for materials and concrete

The fly ash replacement ratios in concrete for studying the properties of the blended binder and concrete are 0%, 10%, 20%, 30%, 40%, and 50% by mass. This research, which includes each mix design with nine specimens for compressive strength testing at 7, 28, and 90 days, six specimens for permeability testing, and two specimens for abrasion resistance testing. The experimental procedures and property determination methods are illustrated in Fig. 2, highlighting the relevance and interest of our work.

2.3. Determine carbon emission

This paper also assesses the environmental impacts of different concrete mix designs incorporating various levels of fly ash, using the Life Cycle Assessment (LCA) method. The LCA method, as presented in the IPCC guidelines, has been widely adopted in many countries [27–32]. The life cycle stages of concrete products typically include: (1) raw material extraction and concrete production, (2) concrete application in construction, (3) the service life of the structure, and (4) demolition and material disposal. This study focuses only on the first stage, which involves quantifying carbon emissions associated with material use and concrete mixing. Fig. 3 illustrates the concrete production process, consisting of: (i) extraction and processing of raw materials used in concrete production, including cement, aggregates, water, and a small amount of supplementary binders. Cement production is a major contributor to carbon emissions due to the calcination of limestone and clay; (ii) transportation of raw materials from extraction sites to concrete production facilities; and (iii) casting and manufacturing of concrete products, which includes mixing raw materials, pouring the mixture into molds, and curing it to achieve the desired strength and durability. Both transportation and concrete production consume energy sources such as diesel, gasoline, and electricity, which contribute to carbon emissions. According to the carbon emission inventory results for specific concrete models in Vietnam by Toan et al. [33], the transportation stage accounts for only 3–5% of the total carbon emissions from concrete. Moreover, all material groups were transported from the same locations using the same type of truck; therefore, carbon emissions from transportation are approximately equal across all concrete mixes and do not affect comparative results. For this reason, emissions from transportation are excluded from this study. Table 3 presents the emission calculation formulas based on IPCC guidelines, while the emission factors used are detailed in Table 4.

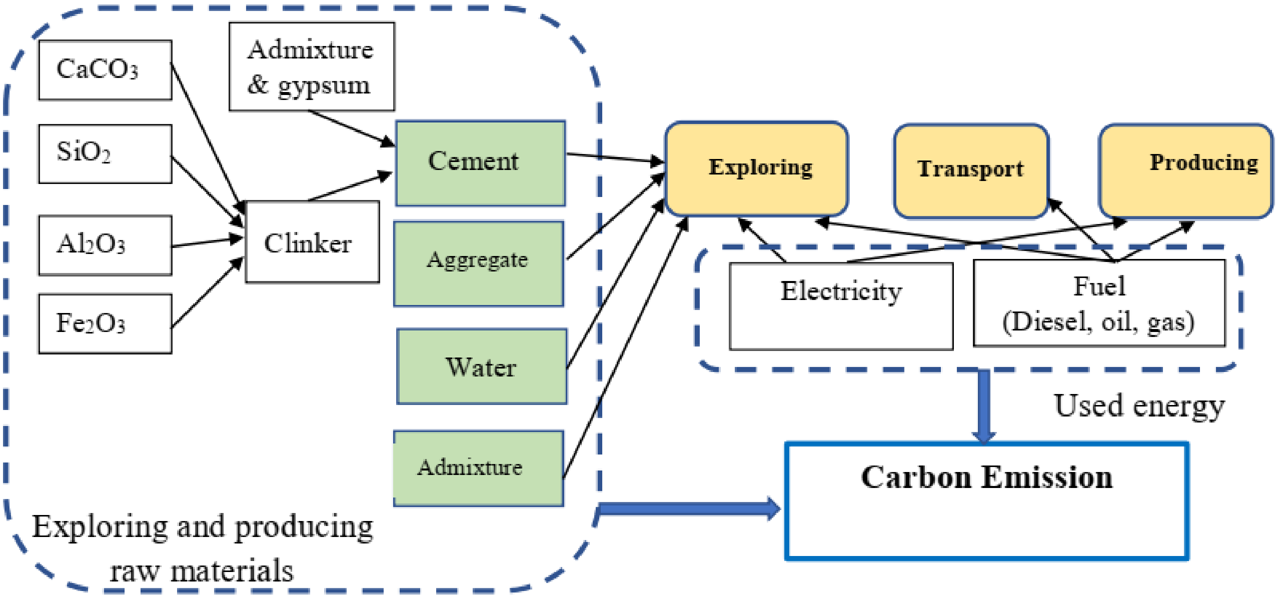

Fig 3. Concrete production process and carbon emission sources [27]

Table 3. Carbon emission calculation formulas in concrete production [28]

Carbon Emissions from Materials	$CO_2M = \sum (M_i \times f(CO_2)_{Mi})$	CO_2M Carbon emissions from using materials (kg CO_2) M_i Mass of material (i) used in concrete production (kg) $f(CO_2)_{Mi}$ Emission factor of material (i) (kg CO_2/kg material)
Transportation and Fuel Consumption	$CO_2T = \sum M_i \times d \times f(CO_2)_T)$	CO_2T Carbon emissions from transportation (kg CO_2) $f(CO_2)_T$ Emission factor for transportation (kg CO_2/kg·km)
Carbon Emissions from Concrete Mixing	$CO_2P = \sum (Mc \times f(CO_2)P)$	CO_2P: Carbon emissions from mixing (kg CO_2) Mc: Mass of concrete produced (kg or m^3); $f(CO_2)P$ Emission factor for concrete casting (kg CO_2/kg concrete or kg CO_2/m^3 concrete)

Table 4. Emission factors used for calculation

No.	Materials	Unit	Emission Factors	Resouces
1	PC40 Cement	$kgCO_2/kg$	0.82100	Calculated
2	Fly ash. F	$kgCO_2/kg$	0.0196	Korea LCI DB [29] Kim et al. [28]; Kwon et al [30]
3	Aggregate (crushed stone)	$kgCO_2/kg$	0.00706	
4	River sand	kg CO_2/m^3	0.00135	
5	Water	$KgCO_2/kg$	0.00034	ICE V3.0 [31] Craig [32]
6	Superplasticizer	$kgCO_2/kg$	0.25000	Kim et al. [28]; Kwon et al [20]
7	Concrete mixing	$kgCO_2/kg$	0.00072	ICE V3.0 [31] Craig [32]

3. Results

3.1. Experimental results of material properties

Table 5. Results of properties test for Cement

No.	Properties	Unit	Test Value	Requirement
1	Density	g/cm^3	3.15	-
2	Fineness (residue on 90μm sieve)	%	4.0	≤ 10
3	Standard consistency	%	29.0	-
4	Volume stability	mm	0.9	≤ 10
5	Setting time - Initial setting time - Final setting time	 minute minute	 135 185	 ≥ 45 ≤ 375
6	Compressive strength - 3-day strength - 28-day strength	 MPa MPa	 27.5 49.5	 ≥ 21 ≥ 40

Table 6. Results of properties test for Fly-ash

Components	Unit	Test Value
LOI	%	2.21
SiO_2	%	59.72
Fe_2O_3	%	5.75
Al_2O_3	%	24.25
CaO	%	1.40
MgO	%	1.35
SO_3	%	0.04
K_2O	%	4.11
Na_2O	%	0.22

Factors	Unit	Tests Value	TCVN 10302:2014. Type F
$SiO_2 + Al_2O_3 + Fe_2O_3$	%	89.72	≥ 70
SO_3	%	0.04	≤ 3.0
LOI	%	2.21	≤ 5 (level d)
Water content	%	1.2	≤ 3.0
Fine size. < 45µm	%	17.6	≤ 18 (level d)
6. Water weight (comparing with reference sample)	%	97	≤ 105

Table 7. Results of properties test for Sand

No.	Properties	Unit	Value	Requirement
1	Specific weight	g/cm^3	2.66	-
2	Unit weight	kg/m^3	1450	-
3	Void ratio	%	45.2	-
4	Fineness Modulus	-	2.8	≥ 2.0
5	Silt and clay content	%	1.65	≤ 3.00
6	Water content	%	0.7	-

Sieve Diameter (mm)	Cumulative retained percentage (%)	Requirement (%)
5	0.0	-
2.5	8.4	0 ÷ 20
1.25	25.1	15 ÷ 45
0.63	59.6	35 ÷ 70
0.315	88.2	65 ÷ 90
0.14	98.3	90 ÷ 100
<0.14	100.0	

Table 8. Results of properties test for crushed limestone

No.	Properties	Unit	Value
1	Specific gravity	g/cm^3	2.77
2	Dry bulk density	g/cm^3	2.74
3	Saturated bulk density	g/cm^3	2.75
4	Loose bulk density	kg/m^3	1412
5	Dense bulk density	kg/m^3	1630
6	Water absorption	%	0.40
7	Flakiness and Elongation Index	%	7.9
8	Crushing value in saturated condition	%	14.6
9	Abrasion resistance	%	15.2

Sieve Diameter (mm)	Cumulative retained percentage (%)	Requirement (%)
40	(%)	(%)
20	0.0	0
10	4.0	0 ÷ 10
5	56.3	40 ÷ 70
<5 mm	99.5	90 ÷ 100

All materials used in this study were sampled and tested for key properties before use. The detailed results are as follows:

The physical and mechanical properties of PC But Son cement are presented in Table 5. The test results not only meet the requirements of TCVN 2682:2020 (Portland Cement – Technical Requirements) but also align perfectly with our research objectives, providing a solid foundation for our further discussions. Table 6 presents the results of the chemical composition analysis of the fly ash, as assessed according to TCVN 10302:2014. The quality of Pha Lai fly ash not only meets the requirements specified in TCVN 10302:2014 ("Fly ash – Pozzolanic mineral admixture for concrete, mortar, and cement"), but also is highly suitable for the research objectives, providing a solid foundation for our work. Table 7 presents the results of the properties for the natural river sand the physical and mechanical property requirements for hydraulic concrete as specified in TCVN 7570:2006. The test results confirm that the sand is not just suitable, but crucial for achieving our research objectives. Table 8 indicates the properties of crushed stone with Dmax = 20mm, which meet the physical and mechanical requirements specified in TCVN 7570:2006 (Aggregates for Concrete and Mortar – Technical Requirements), ensuring compliance with hydraulic concrete standards and suitability for research requirements. Fig. 4 illustrates the grain size distribution curves of the sand and crushed stone used in the study, which were determined through sieve analysis to evaluate their suitability for concrete production.

The GP4 superplasticizer, a high-range water-reducing and retarding admixture that complies with ASTM C494 Type G, is produced by Gia Phong Company and widely applied in concrete structures requiring high workability or slump retention under hot climate conditions. As presented in Table 9, GP4 achieves a water reduction of up to 25%, with a recommended dosage ranging from 0.7 to 1.3 liters per 100 kg of cementitious materials.

Table 10 presents the mix proportions of the experimental cases considered in this study. For each case, the quantities and ratios of cement, fly ash, water, superplasticizer, sand, and gravel were calculated and determined following the procedure described above. With these material proportions, the mixes are expected to achieve the research objectives of ensuring adequate compressive strength, improving abrasion resistance, and reducing CO_2 emissions.

3.2. Concrete compressive strength

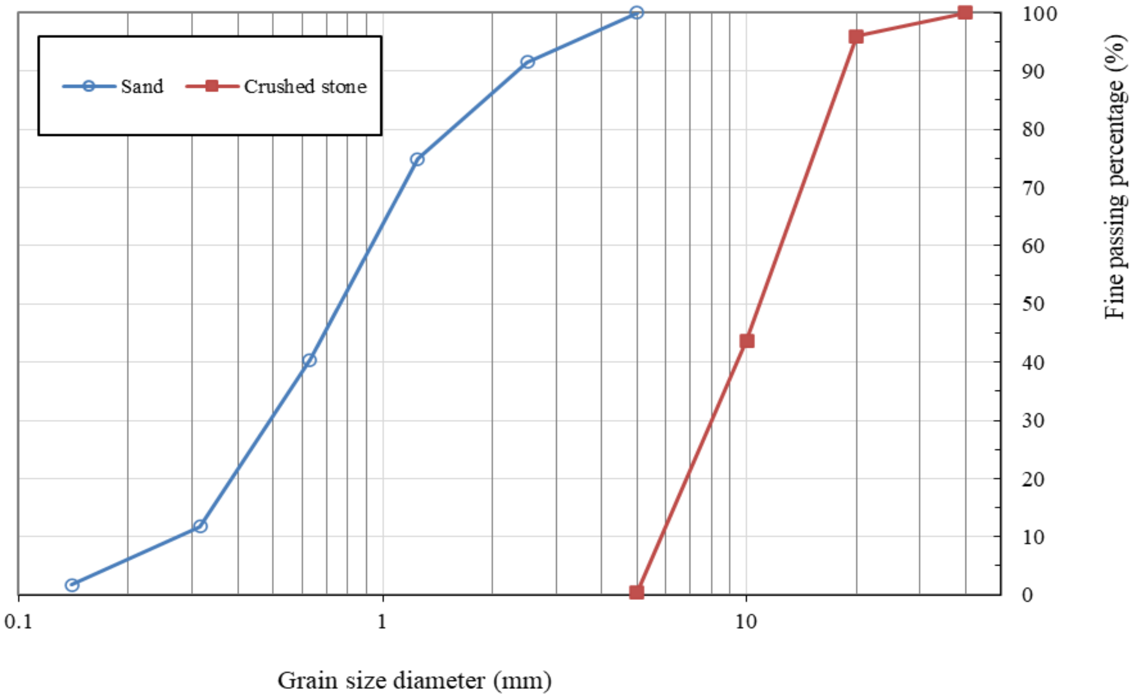

Fig 4. Grain size distribution curves of sand and crushed stone used in this study

Table 9. Results of properties test for Superplasticizer

No.	Properties	Unit	Value
1	Color	-	Light brown
2	Density	kg/lít	1.1 ± 0.02
3	Solid content	%	38 ± 2
4	Chloride content	%	< 0.01
5	pH	-	7 ± 1

Table 10. Material component for $1m^3$ concrete

No.	Concrete Test cases (*)	Cement	Fly ash	Waster	Super plasticizer	Sand	Crushed stone	Sand/ (Sand+ crushed stone)	W/ B	F/B
		kg	kg	kg	liter	kg	kg			
1	$F_0P_{0.7}$	356	0	208	2.49	702	1135	0.39	0.58	0%
2	$F_{10}P_{0.9}$	320	36	203	3.20	702	1135	0.39	0.57	10%
3	$F_{20}P_{1.0}$	284	72	195	3.56	687	1159	0.38	0.55	20%
4	$F_{30}P_{1.1}$	248	108	188	3.92	671	1181	0.37	0.53	30%
5	$F_{40}P_{1.2}$	213	143	181	4.27	655	1204	0.36	0.51	40%
6	$F_{50}P_{1.3}$	178	178	171	4.63	660	1213	0.36	0.48	50%

Note: (*) F_iP_j is the case of concrete with the (i %) Fly ash; and the Superplasticizer is (j %) of Binder.

This study determined the required material quantities based on the selection of materials, material mix proportions, design ratios, W/B (Water/Binder ratio), F/B (Fly Ash/Binder ratio), and the fly ash replacement percentage. Table 11 presents six cases corresponding to fly ash replacement ratios of 0%, 10%, 20%, 30%, 40%, and 50%, with W/B ratios varying as 0.58, 0.57, 0.55, 0.53, 0.51, and 0.48, respectively. With this mixed design, the expected compressive strength is approximately 35 MPa, meeting the target design strength. The experiment results for concrete properties are presented in Table 11, Figs. 5 and 6.

At the age of 7 days, the compressive strength of concrete ranges from 19.5 MPa to 30.3 MPa. As the fly ash content increases, the compressive strength gradually decreases, with a reduction ranging from 1.11 to 1.56 times compared to the control sample without fly ash. The primary reason for this decline is that replacing a portion of cement with fly ash reduces the total cement content in the mixture, leading to an increase in the water-to-cement ratio (W/C). In the early stages of hydration, fly ash has not yet participated in the pozzolanic reaction to form calcium silicate hydrate (C-S-H), which plays a crucial role in developing concrete strength. Therefore, as the amount of fly ash replacing cement increases, the 7-day compressive strength of concrete tends to decrease significantly (Table 11 and Figs. 5 and 6).

At 28 days, the compressive strength of concrete ranges from 29.5 MPa to 36.0 MPa. As the fly ash content increases, the strength decreases slightly (1.04–1.22 times lower than the control), but the reduction is smaller than that observed at 7 days. This indicates that the adverse effect of cement replacement with fly ash diminishes over time. With prolonged curing, the pozzolanic reaction of fly ash consumes calcium hydroxide (CH) to form additional calcium silicate hydrate (C-S-H), which gradually enhances the binding capacity of the paste. At the same time, the filler effect of fine fly ash particles contributes to pore refinement and reduces permeability. These combined mechanisms compensate for the initial strength loss and explain why the strength gap between fly ash concrete and the control mix narrows at 28 days.

At 90 days, the compressive strength of the concrete samples shows minimal variation, ranging from 39.9 MPa to 41.1 MPa. This indicates that concrete with a higher fly ash content has lower early-age strength, but its strength development rate increases significantly over time. With prolonged curing, the pozzolanic reaction of fly ash becomes more active, generating a substantial amount of calcium silicate hydrate (C-S-H), significantly enhancing the concrete's strength. By 90 days, the strength differences among the samples are no longer significant. Thus, long-term curing can mitigate the initial strength reduction associated with high fly ash content, allowing sufficient time for fly ash to develop its pozzolanic activity fully.

Table 11. Experimental results for fresh and hardened concrete mixtures

No.	Concrete cases	Test Mortar	Slump	Mixing Density	Density of cubic samples	Compressive strength of cubic samples			Water impermeability
					R28	R7	R28	R90	R90
		liter	cm	g/cm³	g/cm³		MPa		atm
1	$F_0P_{0.7}$	587	9.5	2.40	2.39	30.3	36.0	40.2	10
2	$F_{10}P_{0.9}$	587	10	2.39	2.39	27.3	34.7	41.1	12
3	$F_{20}P_{1.0}$	579	10	2.40	2.38	26.7	32.8	40.6	12
4	$F_{30}P_{1.1}$	570	10.5	2.40	2.39	26.2	32.3	40.8	12
5	$F_{40}P_{1.2}$	562	10.5	2.39	2.38	22.6	30.0	39.9	12
6	$F_{50}P_{1.3}$	559	10	2.39	2.37	19.5	29.5	39.9	12

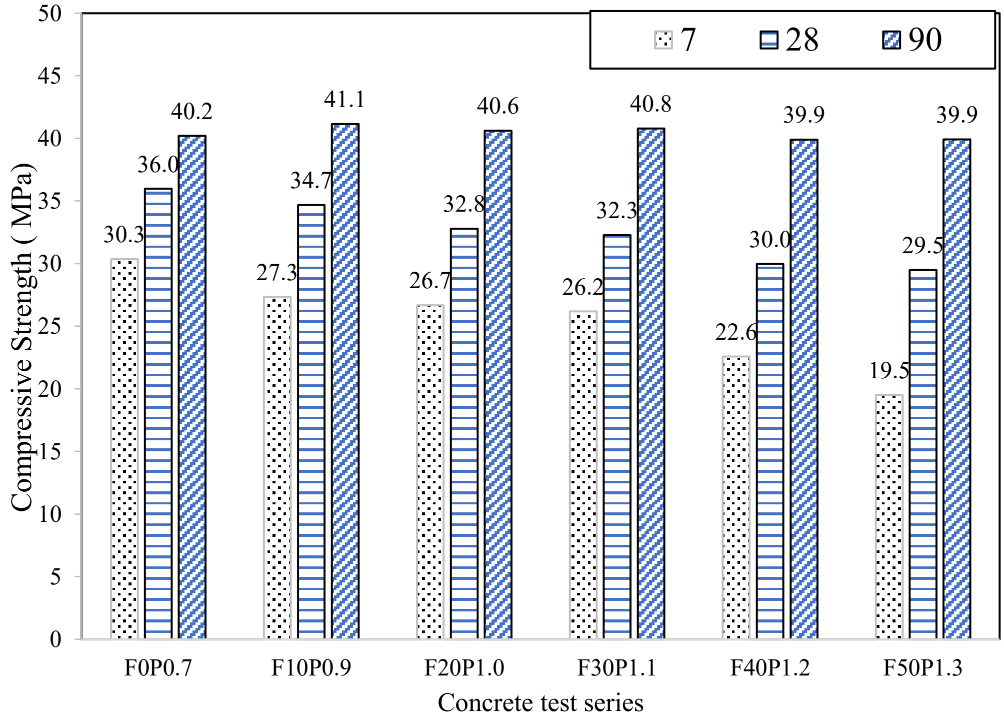

Fig 5. Compressive strength of concrete samples at different time (days)

3.3. Abrasion resistance

Abrasion resistance is a key indicator of concrete durability under flowing water with soil and rock particles. In this study, specimens were tested according to ASTM C1138 for up to 72 hours. Abrasion resistance was evaluated using water abrasion loss (%), defined as the ratio of mass loss after testing to the initial mass of the standard specimen: abrasion loss (%) = (mass loss / initial mass) × 100%. The results (Figs. 7 and 8) show that abrasion loss decreased with the increase of fly ash replacement up to 30%, reaching the lowest value of 4.72% for mixture F30P1.1, and then slightly increased again at higher replacement levels (F40P1.2 and F50P1.3). This can be explained by the presence of reactive SiO_2 in fly ash, which reacts with hydration products on the surface of aggregate particles to form additional C–S–H. These products enhance strength, densify the interfacial transition zone (ITZ), and improve the bonding between the cement paste and aggregates. Furthermore, when a high amount of fly ash is used together with a reduced water-to-binder ratio, the overall density of concrete (i.e., higher solid content) increases, thereby improving abrasion resistance. However, once the fly ash content exceeds a certain threshold, further addition reduces the "barrier effect" (due to excess fly ash particles), which lowers abrasion resistance even though the overall density continues to increase.

The findings of this study are consistent with previous research on the role of fly ash in improving abrasion resistance [7-13]. Several studies have shown that abrasion resistance often decreases at moderate replacement levels due to the dilution effect, where the reduction of cement content weakens the paste–aggregate bonding, but improves at higher replacement levels as the pozzolanic reaction of fine fly ash particles refines pore structure and densifies the matrix [7, 12]. Research in both structural and infrastructural applications further confirms that optimized fly ash mixtures can provide adequate strength while enhancing durability in pavements, sidewalks, and slope protection works [9–11]. In addition, the synergistic effect of combining fly ash with silica fume has been shown to significantly increase abrasion and chemical resistance, especially under aggressive or acidic conditions [8, 13]. Taken together, these findings support the international consensus that the abrasion resistance of fly ash concrete is governed by a balance between dilution at lower replacement levels and pozzolanic activity at higher or optimized levels, which is consistent with the trends observed in this study.

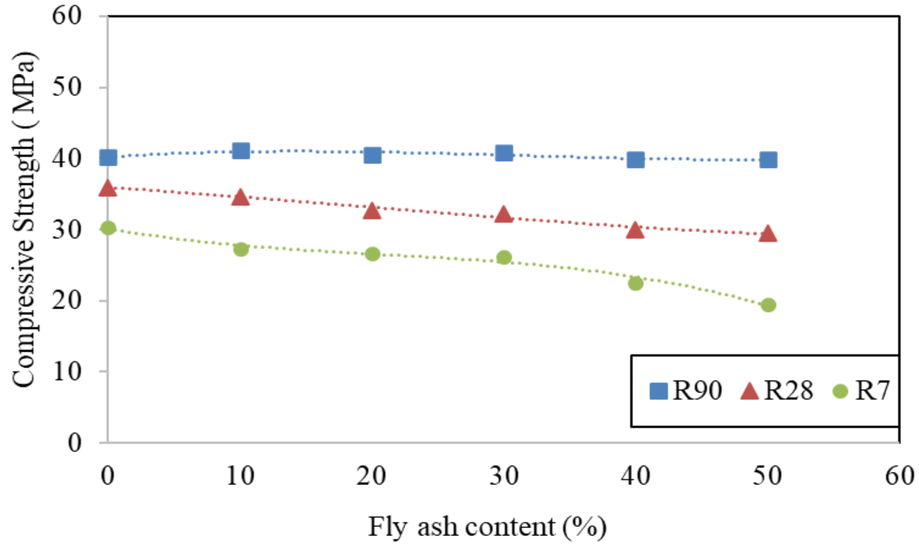

Fig 6. Relationship between compressive strength and the of fly ash component

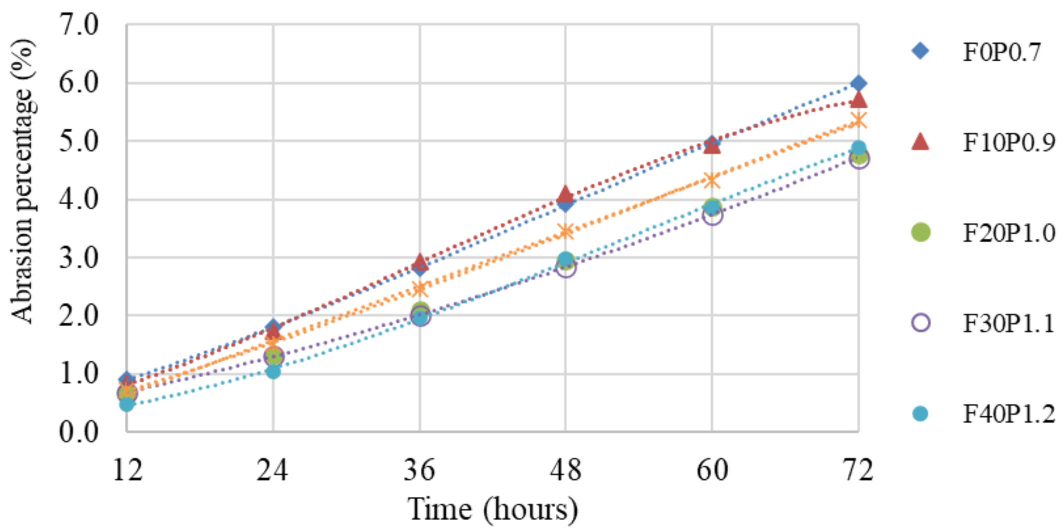

Fig 7. Water abrasion test results

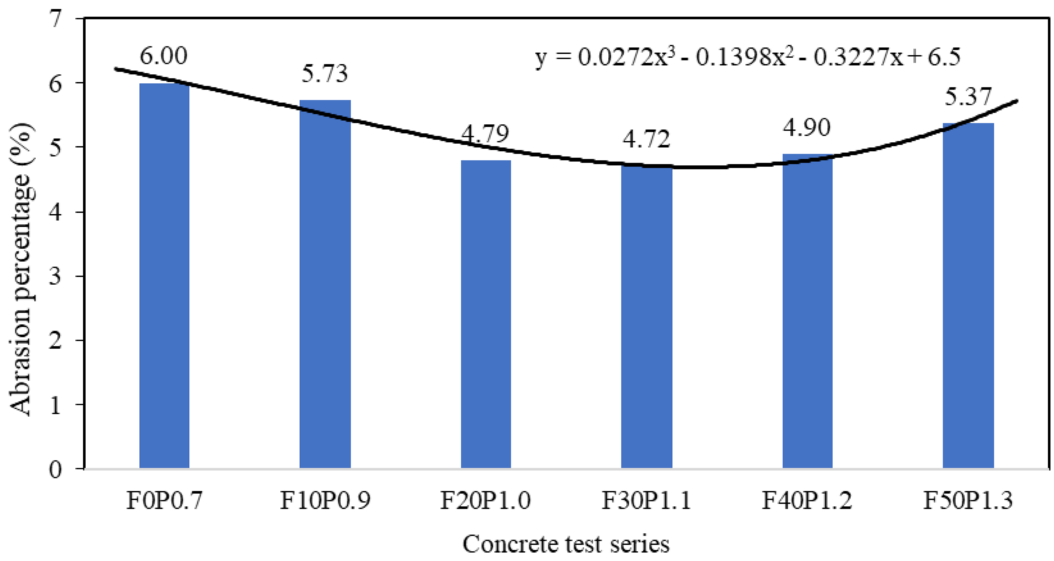

Fig 8. Abrasion resistance of concrete cases after 72 hours

3.4. Carbon emission

Carbon emissions were assessed using the Life Cycle Assessment (LCA) method, with the focus placed solely on material consumption since raw material sources and mixing processes were identical across all mixtures.

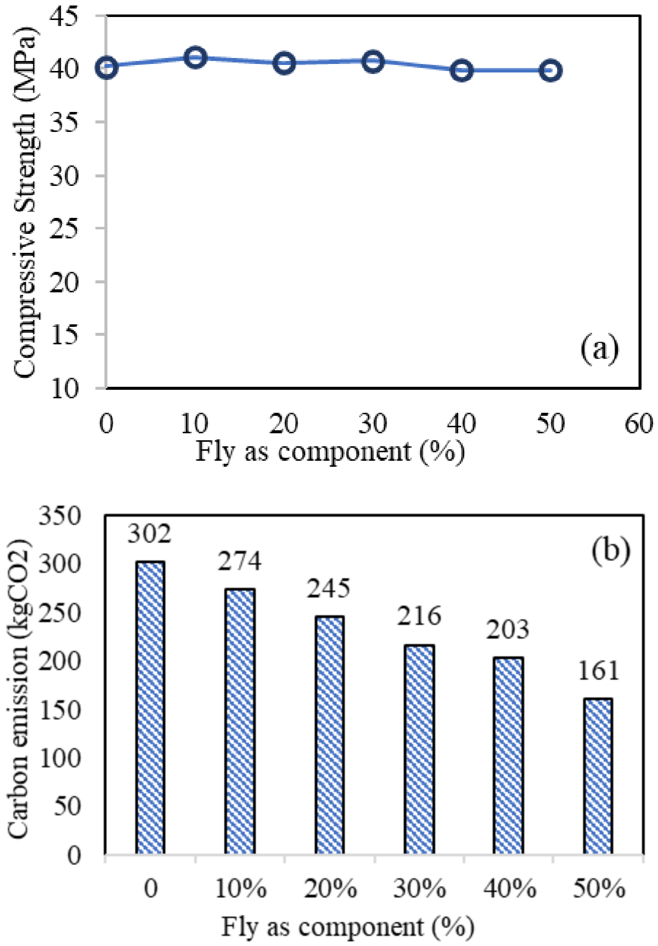

Fig 9. Effect of fly ash content on compressive strength (a) and carbon emissions (b)

Figs. 9a and 9b illustrate the relationship between compressive strength and carbon emissions at different fly ash replacement ratios. after 90 days. As shown in Fig. 9a, the compressive strength of all mixtures fluctuates within a narrow range of 39–42 MPa, indicating that incorporating fly ash up to 50% does not significantly compromise the mechanical performance of the concrete. In contrast, Fig. 9b shows a pronounced decline in carbon emissions as the fly ash content increases. Specifically, mixtures with 10%, 20%, 30%, 40%, and 50% fly ash achieve reductions of 9.48%, 18.93%, 28.39%, 32.81%, and 46.81%, respectively, compared to the control sample. These results demonstrate the clear advantage of fly ash in reducing the environmental burden while maintaining adequate compressive strength.

The findings of this study are consistent with previous research on reducing carbon emissions through cement substitution. For example, study [23] investigated a range of concretes from normal to ultra-high strength incorporating fly ash, slag, or their combination in Vietnam. The results indicated that replacing 20–40% of cement with fly ash or slag reduced emissions by about 9.14–16.28% in normal to medium-strength concrete and up to 40.6% in high-strength concrete. Similarly, the present study shows that increasing the fly ash replacement level to 30% achieves a 28% reduction in emissions while maintaining stable compressive strength. Although slag was not included in this research, the data demonstrate that fly ash alone is sufficient to significantly lower carbon emissions in normal-strength concrete. This suggests that, in practice, adopting a 30–40% fly ash replacement rate may provide an optimal balance between technical performance and environmental benefits. Furthermore, consistent with [23], our results also highlight the importance of extended curing in promoting the pozzolanic reaction, which both sustains mechanical strength and maximizes the emission reduction benefits from reduced cement use.

4. Discussion

Fly ash plays a pivotal role in improving abrasion resistance while maintaining sufficient compressive strength. At a replacement level of 15–30%, the pozzolanic reaction and filler effect of fly ash refine pore structure, reduce permeability, and enhance surface durability, which aligns with findings from Sherwani et al. [7], Lv et al. [13], and Vietnamese case studies [10, 11]. However, when the replacement exceeds 35–40%, the dilution of cementitious content results in reduced strength and increased abrasion loss, as also noted in international studies [9, 19]. Compared to silica fume, which exhibits superior reactivity even at low dosages [13], fly ash provides a more practical and cost-effective solution for large-scale slope protection applications in Vietnam.

With respect to compressive strength, the results show that fly ash replacement is strongly influenced by the aggregate-to-binder ratio (F/B), water-to-binder ratio (W/B), and superplasticizer dosage (Table 2; Fig. 1). A moderate F/B increases packing density, while excessive values raise porosity and reduce strength. Similarly, lowering W/B improves strength but reduces workability if too low, underscoring the need for balanced mix design. These findings align with previous studies, which reported that an optimal W/B reduces porosity, enhances abrasion resistance, and ensures durability and workability in fly ash concrete [5, 8, 22].

In terms of sustainability, the partial replacement of cement with fly ash substantially reduces CO_2 emissions, since cement production accounts for nearly half of the carbon footprint of concrete [21]. The present study shows that a replacement level of 30–40% can achieve up to ~28–35% emission reduction while maintaining compressive strength around 40 MPa, which is consistent with recent Vietnamese evaluations combining fly ash and slag [23]. Other studies have also highlighted the broader potential of industrial by-products in reducing carbon intensity without compromising performance [22, 24, 25].

Thus, based on the variation trend of the abrasion resistance curve, the maintenance of compressive strength, and the reduction of carbon emissions, the 30% fly ash replacement level is confirmed as the most suitable choice. Lower replacement levels initially reduce abrasion resistance, while higher levels beyond 35–40% lead to strength loss and increased abrasion. At 30%, the balance among mechanical performance, durability, and environmental sustainability is optimized, making it ideal for hydraulic concrete and slope protection applications.

5. Conclusions

Concrete mixtures were prepared with fly ash replacing cement at 10%, 20%, 30%, 40%, and 50%, with the corresponding water-to-binder ratios decreasing from 0.58 to 0.48, and the superplasticizer dosage increasing from 0.7% to 1.3%. Compressive strength results showed a significant reduction at early ages (7 and 28 days) with increasing fly ash content, but only a slight decrease at 90 days (from 41.1 MPa to 39.9 MPa), ensuring that all mixtures met the M35-grade requirement.

Fly ash also improved abrasion resistance, while abrasion resistance followed a non-linear trend—initially decreasing at low replacement levels and improving as the content approached its most effective range. The mixture with 30% fly ash replacement (W/B = 0.53) exhibited optimal performance, maintaining compressive strength, reducing abrasion loss (4.7%, 1.28% lower than the control), and achieving a notable 28.4% reduction in carbon emissions.

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