Mechanical Properties and Environmental Impact of a Sustainable Ultra-High-Performance Concrete using High-Content Fly Ash

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Abstract. This research aims to develop a sustainable Ultra-High-Performance Concrete (UHPC) by using high-volume Class F fly ash to replace cement at ratios of 20%, 40%, and 60% by weight to reduce cement usage primary source of CO_2 emission, combined with mixed-sized steel fibers at 2% by volume. All mixtures incorporated 8-mm limestone aggregates and were cured under standard water curing conditions. The investigation of mechanical properties included compressive strength, splitting tensile strength and flexural strength. The evaluation encompassed carbon emissions and the cost evaluation of each mixture in comparison to a reference UHPC. Experimental results revealed that at 28 days, mixtures containing fly ash at 60% ratio exhibited the lowest compressive strength at 117.0 MPa but could reduce carbon dioxide emissions by up to 38% when compared to the reference mixture Regarding splitting tensile strength, the mixture incorporating 20% fly ash achieved the maximum value of 22.1 MPa, whereas the flexural strength of the mixture using 40% fly ash provided the highest value of 22.7 MPa, which exceeded the reference mixture. The findings demonstrate that utilizing an of fly ash combined with mixed-sized steel fibers facilitates the production of a sustainable UHPC with satisfactory mechanical properties and reduces costs.

1 Introduction

Ultra-High-Performance Concrete (UHPC) has attracted widespread attention due to its superior properties compared to normal concrete. Physically, it exhibits high flow which facilitates effective mold filling, possesses a compressive strength exceeding 120 MPa, and a tensile strength greater than 5 MPa, alongside enhanced durability [1, 2]. These attributes render UHPC particularly suitable for structures requiring high strength and an extended service life. [1]

However, conventional UHPC is manufactured using a cement content of approximately 800–1,000 kg/m³, characterized by a low water-to-cement ratio achieved with superplasticizers, silica fume, fine aggregates, and steel fibers to mitigate brittleness. The

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utilization of such high cement dosages, coupled with steel fibers, results in production costs significantly higher than those of conventional concrete. Given that UHPC relies on a low water-to-cement ratio, it is associated with substantial carbon dioxide emissions, attributed to the substantial cement dosage utilized in its manufacture [2].

Consequently, current attention is focused on the development of more sustainable UHPC by utilizing pozzolanic materials, such as fly ash (FA) or ground granulated blast-furnace slag (GGBFS), as partial cement replacements. This serves to lower production costs and environmental impact while retaining mechanical properties comparable to those of conventional UHPC [3-5]. Additionally, incorporating longer steel fibers into the matrix yields superior performance compared to shorter fibers at an equivalent dosage [6]. The properties of UHPC strongly depend on its constituents and the type of fibers used.

This research aims to develop a sustainable UHPC by utilizing high contents of Class F fly ash to substitute cement at ratios of 20%, 40%, and 60% by weight, incorporated with mixed-sized steel fibers, to assess the effects of this replacement on mechanical properties and environmental impact. All mixtures incorporated 8-mm limestone aggregates and were cured under standard water curing conditions. The investigation involved testing compressive strength at ages of 1, 3, 7, 28, and 90 days, while splitting tensile strength and flexural strength were evaluated at 28 days. Additionally, the evaluation encompassed carbon footprint and the production costs of the constituent materials in comparison to a conventional UHPC (as a reference).

2 Materials and methods

2.1 Materials

The materials employed in this investigation were primarily locally sourced in Thailand. Cement (C) was a hydraulic cement conforming to Thai Industrial Standard TIS 2594 [7]. Fly ash (FA) was classified as Class F according to ASTM C168. Sand (S) was fine river sand, while coarse aggregate (CA) was limestone with a maximum size of 8 mm. The superplasticizer (SP) was the polycarboxylate type, and water (W) was tap water. Silica fume (SF) was of the undensified type. Straight mixed-sized steel fibers (MST), with diameters ranging from 0.18–0.35 mm and lengths of 12–14 mm, were utilized for the mixtures containing fly ash, whereas straight single-sized steel fibers (SST), with a diameter of 0.16 mm and a length of 6 mm, were employed in the reference mixture. The chemical compositions of C, SF, and FA are presented in Table 1, and the particle size distributions of the binders (C, SF, and FA) are illustrated in Fig. 1. It can be observed that FA exhibited the largest particle size, followed by C, whereas SF possessed the finest size.

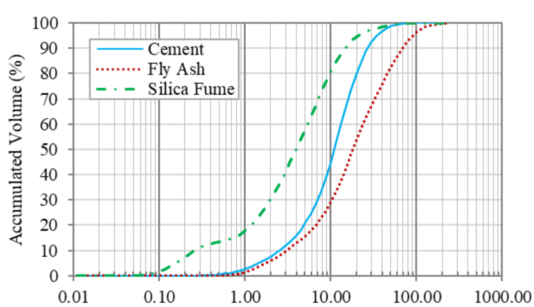

Fig. 1. Particle size distribution of cement, fly ash, and silica fume.

Table 1. Chemical compositions (%) of C, SF, and FA.

Composition	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	Na_2O	SO_3	K_2O	TiO_2	LOI
C	13.32	2.73	3.54	74.37	0.89	0.28	0.50	0.49	0.26	0.12
SF	94.80	0.15	0.03	0.88	0.70	0.20	0.96	1.98	-	0.01
FA	53.03	16.97	6.22	15.69	0.78	0.35	4.09	1.27	0.98	0.01

2.2 Mix proportioning

The mix design of the UHPC developed in this research incorporates high-volume Fly Ash (FA) to substitute cement at ratios of 20%, 40%, and 60% by weight, accompanied by a relatively low silica fume content. The water-to-cement ratio (W/C) was maintained at 0.20, falling within the typical range for UHPC of not exceeding 0.25 [2]. To enhance ductility and crack resistance, steel fibers reinforcement was incorporated at 2% by volume, consistent with the recommended range of 1–3% [3, 8]. Workability was assessed via the flow test in accordance with ASTM C1437, with values targeted within the range of 200–250 mm to ensure adequate workability. The developed UHPC was compared with conventional UHPC regarding mechanical properties and environmental impact, with the mixed proportions and flow presented in Table 2. The flow test conducted without the use of a flow table, wherein the test proceeded by allowing the UHPC mixture to flow freely under gravity, and four measurements were recorded to determine the average flow value.

Table 2. Mixing compositions (by weight).

<table>
<tr><th>Mix</th><th>C</th><th>SF</th><th>FA</th><th>S</th><th>CA</th><th>SST</th><th>MST</th><th>W</th><th>SP</th><th>Binder*</th><th>Flow (mm)</th></tr>
<tr><td>Ref.-SST</td><td>1.00</td><td>0.35</td><td>-</td><td>1.10</td><td>-</td><td>0.17</td><td>-</td><td>0.23</td><td>0.01</td><td>1.35</td><td>246</td></tr>
<tr><td>FA20-MST</td><td>0.80</td><td rowspan="3">0.80</td><td>0.20</td><td rowspan="3">0.52</td><td rowspan="3">0.48</td><td rowspan="3">-</td><td rowspan="3">0.16</td><td rowspan="3">0.20</td><td rowspan="3">0.04</td><td rowspan="3">1.08</td><td>238</td></tr>
<tr><td>FA40-MST</td><td>0.60</td><td>0.40</td><td>225</td></tr>
<tr><td>FA60-MST</td><td>0.40</td><td>0.60</td><td>210</td></tr>
</table>

*Binder is C+SF+FA.

2.3 Specimen preparations

All specimens were prepared under ambient laboratory conditions. The initial phase involved preparing the dry constituents cement, fly ash, silica fume, and sand which were premixed, along with the liquid phase consisting of water and superplasticizer. The mixing process commenced by introducing the dry materials and the initial portion of the prepared liquids into the mixer, blending until a homogeneous consistency was achieved. Subsequently, the first portion of coarse aggregates (for mixtures containing stone) was added; once combined, the remaining prepared dry materials and liquids were introduced into the mixer and blended until uniform. Thereafter, the remaining coarse aggregates (for mixtures containing stone) were incorporated and mixed until fully integrated. In the final stage, steel fibers were added and mixed until a uniform and homogeneous mixture was obtained. The mixture was then subjected to a flow test, followed by casting into prepared molds and covering with plastic sheets to prevent moisture loss. After 24 hours, the specimens were demolded and subjected to water curing until reaching the designated testing ages.

2.4 Testing of mechanical properties

All mixtures were evaluated for mechanical properties, including compressive strength, splitting tensile strength, and flexural strength, according to the specified testing ages. Compressive strength testing was conducted at ages of 1, 3, 7, 28, and 90 days utilizing 50×50×50 mm cube specimens in accordance with ASTM C109 for the reference mixture and 100×100×100 mm specimens conforming to BS 1881-116 for mixtures containing fly ash and coarse aggregates. Splitting tensile strength testing at 28 days employed cylinders specimens with a diameter of 100 mm and a height of 200 mm, following ASTM C496. For flexural strength testing at 28 days, prism specimens measuring 75×75×280 mm were utilized in accordance with ASTM C78. Details regarding all testing configurations are summarized in Table 3, and the testing illustrations are depicted in Fig. 2.

Fig. 2. Test results: (a) compressive strength, (b) splitting tensile strength and (c) flexural strength.

Table 3. Details of the mechanical tests.

Tests	Specimen size (mm)	Specimen age (mm)	Standard
Compressive strength	50x50x50 cube	1, 3, 7, 28, and 90	ASTM C109
	100x100x100 cube	1, 3, 7, 28, and 90	BS1881-116
Splitting tensile strength	ø100x200 cylinder	28	ASTM C496
Flexural strength	75x75x280 prism	28	ASTM C78

2.5 Carbon footprint

The assessment of carbon footprint is a method used to evaluate the environmental impact caused by material production processes. In this study, the carbon footprint of each UHPC mixture was defined as the total CO_2 emissions generated from all constituents per unit volume [9]. Furthermore, the carbon index (CI) was derived by normalizing the carbon footprint with the corresponding 28-day compressive strength, thereby facilitating a strength-adjusted comparison of environmental performance among mixtures. In this assessment, only the emission factors associated with material production were considered, while those related to transportation and mixing processes were excluded, as presented in Table 4.

2.6 Cost evaluation

The cost evaluation (THB/m^3) was performed based the unit cost factor (THB/kg) of the constituent materials, as summarized in Table 4. This approach enables a quantitative assessment of the production cost of each UHPC mixture according to the mix proportions and current market prices (SST, MST, W and SP). The normalized cost evaluation (NCE), expressed in units of THB /m^3/MPa, was determined from the ratio of the production cost (THB/m^3) to the 28-day compressive strength (MPa) of each mixture.

Table 4. Unit cost and emission factor (EF) of each material.

Material	C	SF	FA	W	SP	S	CA	SST	MST
Unit cost	3.1 [10]	18.6 [10]	1.6 [10]	0.0	111.0	0.9 [10]	0.3 [10]	90.0	50.0
EF	0.724[7]	0.014[11]	0.009[2]	0.0003[11]	0.72[11]	0.01[11]	0.0459[12]	1.4965[11]	1.4965[11]

Remark: Unit costs in THB/kg; Numbers in the parentheses are the references; Emission factors in kg-CO_2-e/kg.

3 Results and discussion

The developed UHPC formulations are designated as FA20%-MST2%, FA40%-MST2%, and FA60%-MST2%, aimed at mitigating carbon dioxide emissions and material costs particularly regarding cement, silica fume, and steel fibers, which represent costly constituents as well as comparing mechanical properties against the Ref.-SST2% mixture, representing a conventional UHPC.

3.1 Compressive strengths

Based on the test results illustrated in Fig. 3, it was observed that the average compressive strength of UHPC at the early age of 1 day for mixtures FA20-MST, FA40-MST, and FA60-MST exhibited a distinct reduction compared to the Ref.-SST mixture (64.3 MPa), decreasing by approximately 49%, 64%, and 70%, respectively. A similar trend was observed during testing at 3 days, wherein mixtures FA20-MST, FA40-MST, and FA60-MST continued to yield compressive strength values lower than that of the Ref.-SST mixture (99.7 MPa). Nevertheless, the FA20-MST mixture achieved a compressive strength of 96.7 MPa, which is comparable to the Ref.-SST mixture, suggesting that fly ash influences compressive strength primarily during the initial period not exceeding 3 days. Regarding testing at 7 days, the FA20-MST mixture yielded the maximum compressive strength of 117.5 MPa, surpassing the Ref.-SST mixture (110.2 MPa), whereas mixtures FA40-MST and FA60-MST exhibited lower values compared to the Ref.-SST mixture.

At a testing age at 28 days, the FA20-MST and FA40-MST mixtures yielded compressive strengths of 149.7 and 135.1 MPa, respectively, surpassing the Ref.-SST mixture, which yielded 129.3 MPa. Conversely, the FA60-MST mixture maintained the lowest compressive strength at 117.0 MPa. However, upon extending the testing duration to 90 days, the observed trend reversed; the Ref.-SST mixture achieved the maximum compressive strength of 158.4 MPa, whereas mixtures FA20-MST, FA40-MST, and FA60-MST exhibited reductions of approximately 4%, 8%, and 14%, respectively.

The decline in compressive strength may be attributed to the reduced cement content within the mixture, which serves as the primary constituent in the hydration reaction producing calcium silicate hydrate (C-S-H) gel, a critical factor for early-age compressive strength [13]. However, as the testing age extended, the compressive strength of UHPC exhibited an improving trend owing to pozzolanic reactions or the secondary hydration of unreacted cement or fly ash particles, resulting in additional gel formation that enhances the strength of the UHPC.

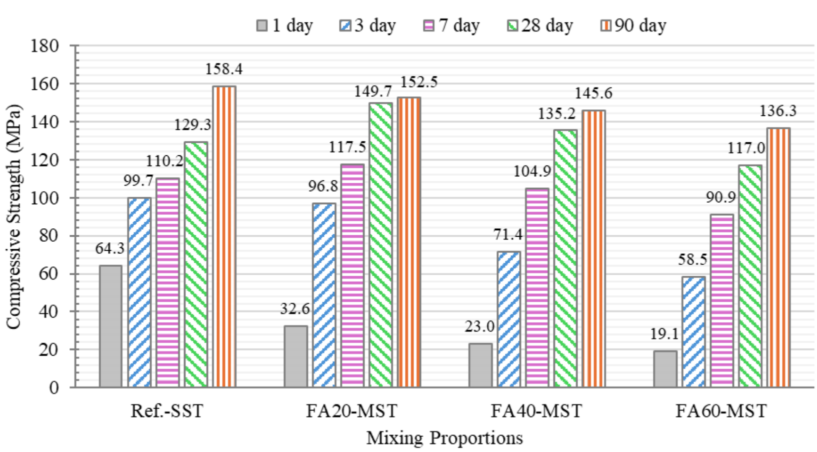

Fig. 3. Compressive strength of each mix.

3.2 Splitting tensile strengths

Based on the test results illustrated in Fig. 4 (a), it was observed that the average splitting tensile strength of the UHPC mixtures FA20-MST and FA40-MST reached 22.1 MPa and 20.2 MPa, respectively. These values surpassed that of the Ref.-SST mixture, which yielded 17.3 MPa. In contrast, the FA60-MST mixture exhibited the lowest splitting tensile strength, representing a reduction of approximately 7% compared to the Ref.-SST mixture. This demonstrates that utilizing FA at ratios of 20% and 40% in conjunction with mixed-sized steel fibers which possess greater lengths than those in the control mixture positively contributes to the mechanical properties of UHPC [6]. Nevertheless, the FA60-MST mixture is still considered to exhibit satisfactory performance, considering the reduced cement content and the results being comparable to the reference mixture.

3.3 Flexural strengths

According to the test results presented in Fig. 4 (b), it was found that the average flexural strength of UHPC mixtures FA20-MST and FA40-MST reached 22.7 and 21.7 MPa, respectively, surpassing the Ref.-SST mixture. This indicates that utilizing FA at an optimal proportion effectively enhances UHPC performance, potentially attributed to the pozzolanic reaction filling voids and increasing the structural density [13]. Furthermore, the employment of increased steel fiber lengths positively influences flexural strength [6]. whereas excessive FA content may have an adverse impact on UHPC performance.

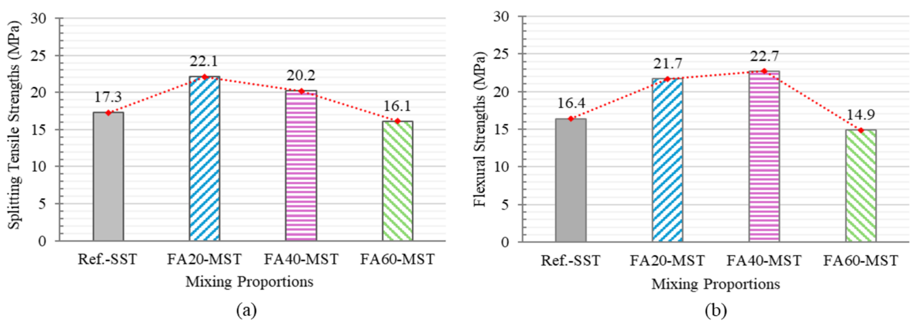

Fig. 4. Test results: (a) splitting tensile strengths and (b) flexural strengths.

3.4 Carbon footprint

Fig. 5 (a) demonstrates that the CO_2 emissions of UHPC decrease as the fly ash content within the mixture increases. Specifically, the Ref.-SST mixture exhibited the highest CO_2 emissions of 935 kg CO_2e/m^3, whereas mixtures FA20-MST, FA40-MST, and FA60-MST showed reductions of approximately 8%, 25% and 38%, respectively. This is attributed to the fact that fly ash possesses a CO_2 emission factor of 0.0090 kg CO_2e/kg, which is significantly lower than that of cement, which reaches as high as 0.7240 kg CO_2e/kg, as presented in Table 4.

As illustrated in Fig. 5 (b), it was found that the carbon index of UHPC mixtures FA20-MST, FA40-MST, and FA60-MST amounted to 5.76, 5.30, and 4.97 kg $CO_2e/m^3/MPa$, respectively, representing a decrease from the Ref-SST mixture, which exhibited a value of 7.23 kg $CO_2e/m^3/MPa$. This demonstrates that the incorporation of fly ash at mix proportions of 20%, 40%, and 60% can reduce the Carbon Index by approximately 20%, 27%, and 31%, respectively.

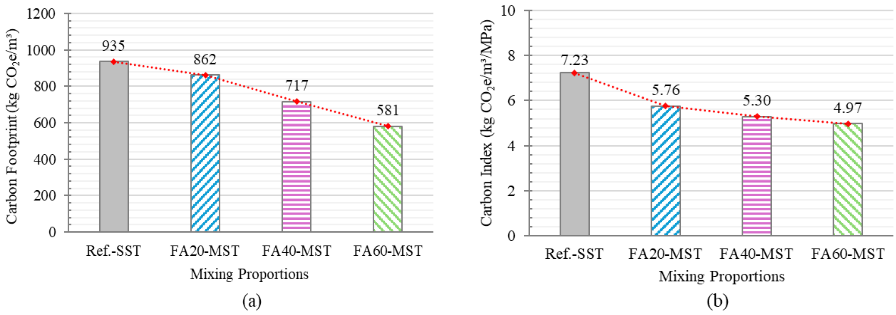

Fig. 5. Environmental performance: (a) carbon footprint and (b) carbon index.

3.5 Cost evaluation

Based on the evaluation results presented in Fig. 6 (a), it was observed that the FA60-MST mixture incurred a total material cost of 16,568 THB/m³, representing a reduction of approximately 30% relative to the reference mixture, Ref-SST, which exhibited the highest cost of 23,695 THB/m³. Furthermore, mixtures incorporating fly ash at ratios of 20% and 40% demonstrated cost reductions of approximately 28% and 29%, respectively, in comparison to the reference. This is attributed to the pricing of fly ash at merely 1.6 THB/kg, which is lower than that of Portland cement, priced at approximately 3.1 THB/kg. Moreover, the mixed-sized steel fibers are approximately 40% less expensive than single-sized steel fibers, thereby contributing to the overall reduction in the cost of UHPC.

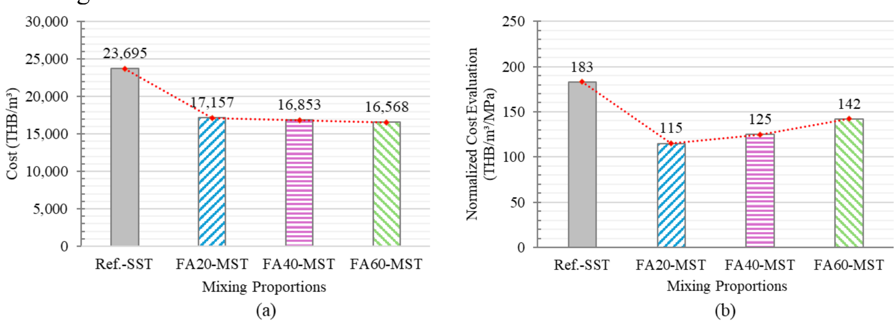

Fig. 6. Cost evaluation: (a) unit cost and (b) normalized cost.

The normalized cost evaluation (NCE) of UHPC, as depicted in Fig. 6 (b), revealed that the cost of mixtures incorporating fly ash exhibited a declining trend corresponding to the reduction in fly ash content. Specifically, the FA20-MST mixture achieved the lowest NCE of 115 THB/m³/MPa, representing a reduction of approximately 37% compared to the reference Ref-SST mixture, which exhibited the highest value of 183 THB/m³/MPa. Meanwhile, mixtures FA40-MST and FA60-MST yielded NCE values of 125 and 142 THB/m³/MPa, respectively, corresponding to reductions of approximately 32% and 22% relative to the reference mixture.

4 Conclusions

1) The compressive strength of UHPC with 2% mixed-sized steel fibers exhibited a declining trend corresponding to the increased fly ash content. Specifically, at 28 days, it yielded values of 149.7, 135.2, and 117.0 MPa at fly ash of 20%, 40%, and 60%, respectively.

Nevertheless, the compressive strength for all mixed proportions increased with curing age.

2) The splitting tensile strength of UHPC exhibited a declining trend corresponding to the increase in fly ash content. Specifically, mixtures with fly ash at levels of 20%, 40%, and 60%, reinforced with 2% mixed-sized steel fibers, yielded 28-day strengths of 22.1, 20.2, and 16.1 MPa, respectively. Notably, the mixtures containing 20% and 40% fly ash exhibited values surpassing that of the reference mixture, which possessed a strength of 17.3 MPa.

3) Regarding flexural strength, it was observed that 40% fly ash content achieved the maximum 28-day value of 22.7 MPa, whereas the 20% and 60% fly ash contents yielded 21.7 and 14.9 MPa, respectively. Nevertheless, the mixtures containing 20% and 40% fly ash exhibited flexural strengths surpassing the reference mixture (16.3 MPa) by approximately 1.32 and 1.38 times, respectively.

4) Regarding the carbon footprint of UHPC, greenhouse gas emissions exhibited a downward trend corresponding to the increasing fly ash content. Specifically, mix proportions containing 60%, 40%, and 20% fly ash demonstrated reductions in carbon dioxide emissions of approximately 38%, 23%, and 8%, respectively, relative to the reference mixture, which possessed a value of 935 kg CO_2e/m^3. This includes the carbon index, which declined by approximately 31%, 27%, and 20%, respectively, compared to the reference mixture's value of 8.75 kg CO_2e/m^3/MPa.

5) Upon increasing the fly ash replacement level in the UHPC mixture, it was observed that the material cost exhibited a declining trend corresponding to the increase in fly ash content. Specifically, the mixture containing 60% fly ash incurred the lowest cost of 16,568 THB/m³, representing a reduction of approximately 30% relative to the reference mixture, which possessed the highest cost of 23,965 THB/m³. However, the Normalized Cost Evaluation revealed that utilizing 20% fly ash yielded the lowest value of 115 THB/m³/MPa, corresponding to a decrease of approximately 37% from the control mixture.

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