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Integrated analysis of flexural strength and environmental impact performance of fly ash concrete

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ABSTRACT

Amid the increasing emphasis on sustainable construction materials, this study investigated the incorporation of fly ash (FA) as a partial replacement for Portland composite cement (PCC) in concrete. The effects of FA incorporation on flexural strength and environmental performance were evaluated using mixtures containing 0%, 15%, 30%, and 45% FA by weight of PCC. Flexural strength was measured at 28 and 90 days, while environmental performance was assessed through life cycle assessment (LCA) using six impact parameters: abiotic depletion potential (ADP), acidification potential (AP), eutrophication potential (EP), global warming potential (GWP), ozone depletion potential (ODP), and photochemical ozone creation potential (POCP). An acceptance criterion based on flexural strength was established to assess the feasibility of FA substitution. Although increasing FA content reduced flexural strength compared with the reference concrete, all FA mixtures retained more than 75% of the reference strength, satisfying the acceptance criterion and confirming their suitability as partial PCC replacements. Environmentally, FA incorporation increased ADP but consistently reduced AP, EP, GWP, ODP, and POCP, indicating a trade-off between greater abiotic resource use and lower impacts in other categories. Integrated multi-criteria analysis identified the M-45FA mixture as having the highest overall eco-structural efficiency, highlighting FA's strong potential as a sustainable supplementary cementitious material.

Keywords: fly ash, flexural strength, acceptance criterion, environmental impact, sustainable concrete, multi-criteria performance.

INTRODUCTION

The rapid expansion of the construction sector over recent decades has substantially increased the demand for building materials, particularly concrete, which remains the most widely used structural material worldwide. Driven by sustainability concerns, the global construction industry is increasingly adopting circular economy approaches to minimize environmental impacts and improve resource efficiency (Nurfaidah et al., 2026). However, large-scale concrete production requires extensive consumption of natural resources and is associated with significant carbon emissions, primarily from cement manufacturing. The cement industry represents approximately 8% of total global anthropogenic CO_2 emissions (Andrew, 2019). This estimate is consistent with the review by Barbhuiya et al. (2025), which cited several previous studies reporting a similar contribution from cement production. This environmental burden has intensified the search for supplementary cementitious materials capable of reducing the ecological footprint of concrete while maintaining its structural performance.

Among the most promising alternatives is fly ash (FA), a coal combustion by-product originating from thermal power generation processes. Global FA production amounts to hundreds of millions of tonnes annually, yet a considerable proportion is still disposed of in landfills, creating environmental concerns such as soil, water, and air contamination (Yao et al., 2015). Owing to the high content of reactive silica, alumina, and iron oxides, FA exhibits significant pozzolanic activity, making it a suitable partial replacement for Portland cement in concrete mixtures (Chindaprasirt and Rattanasak, 2017). The incorporation of FA into concrete therefore offers dual benefits: reducing cement consumption and valorizing industrial waste. Such an approach aligns with sustainable development principles by promoting resource efficiency, minimizing waste generation, and mitigating environmental impacts (Firoozi et al., 2025).

Prior studies have demonstrated that the addition of FA has the potential to enhance the long-term performance of concrete through pozzolanic reactions that refine pore structure, densifiy the microstructure, and improve the cementitious matrix (Bui et al., 2018; Yang et al., 2018). Yao et al. (2015) reported that FA improves workability, reduces the heat of hydration, and enhances durability by promoting a denser and less permeable internal structure. In terms of mechanical performance, (Upadhyay et al., 2014) observed that strength development becomes more pronounced at later ages and at optimum replacement levels, although excessive FA contents may adversely affect early-age strength. Regarding flexural strength, recent studies have shown that concrete containing moderate levels of FA can maintain satisfactory flexural performance (Ahmed et al., 2025; Nkomo et al., 2022). Nevertheless, higher replacement levels generally lead to reductions in flexural strength, unless compensated by additional strengthening mechanisms, such as fiber reinforcement (Sai et al., 2025). These findings highlight the need to identify FA replacement levels that balance mechanical performance and material sustainability.

Flexural strength is a critical design parameter for rigid pavements, as it directly reflects the tensile stresses induced by wheel loads and governs cracking resistance and structural durability. In Indonesia, the General Specifications for Road and Bridge Construction Works issued by the Ministry of Public Works (2025) designate flexural strength as the primary criterion for evaluating pavement concrete quality. Therefore, assessing the flexural performance of FA modified concrete is essential for ensuring compliance with structural and service-life requirements.

To evaluate the suitability of FA as a partial cement replacement, performance-based assessment methods are necessary. The strength activity index (SAI) is widely accepted for quantifying the effectiveness of supplementary cementitious materials (Donatello et al., 2010; ASTM C311/C311M, 2018b). In this study, this concept was adapted into an acceptance criterion (AC) to directly compare the flexural performance of concretes containing 0%, 15%, 30%, and 45% FA at 28 and 90 days, thereby assessing the feasibility of FA as a sustainable cement substitute.

Beyond mechanical performance, the sustainability of concrete should also be assessed from an environmental impact perspective. The use of supplementary cementitious materials (SCMs) has been recognized to reduce waste accumulation and carbon emissions associated with cement production (Syamsuriani et al., 2026). Life cycle assessment (LCA) facilitates a comprehensive framework for this purpose by quantifying key impact categories, including abiotic depletion potential (ADP), acidification potential (AP), eutrophication potential (EP), global warming potential (GWP), ozone depletion potential (ODP), and photochemical ozone creation potential (POCP). Collectively, these indicators capture resource consumption and the broader environmental burdens associated with concrete production (Kim et al., 2016; Olsson et al., 2024). In particular, LCA has been extensively adopted as a robust and standardized tool for analyzing the environmental performance of concrete incorporating supplementary cementitious materials, including FA, across a range of mixture designs and life cycle scenarios (Allo et al., 2026; Orozco et al., 2023). Recent reviews have further emphasized the importance of integrating material performance into LCA to ensure meaningful comparisons among concrete mixtures and to better guide sustainable material selection (Ersan et al., 2022).

Importantly, higher mechanical performance does not necessarily imply greater environmental efficiency, as improved flexural strength may be accompanied by increased environmental burdens. However, alternative cementitious materials, including FA, offers significant potential for reducing these impacts while maintaining satisfactory mechanical performance when used at optimal replacement levels (Guo et al., 2024). Therefore, an integrated analysis of structural performance and environmental impact is essential for identifying mixtures that provide optimal mechanical performance at minimal ecological cost. Accordingly, this study investigated the flexural performance and environmental impact of concrete, with the objective of attaining a minimum criterion of 75% of the reference mixture's flexural strength at 28 days.

MATERIALS AND METHODS

Materials

In this study, the materials consisted of water, PCC, FA, fine aggregate and coarse aggregate. PCC is commonly utilized as a binder in Indonesia (Caronge et al., 2025). The PCC used in this study was composite portland cement produced by one of the national cement manufacturers in Indonesia and complied with the Indonesian National Standard (SNI 7064, 2014), which is the mandatory standard for PCC products in Indonesia. The FA used in this study was a by-product of coal combustion from a coal-fired power plant located in Punagaya Village, Jeneponto Regency, South Sulawesi Province. The chemical compositions of the PCC and FA, which were determined using X-ray fluorescence (XRF) spectroscopy, were presented in Table 1. Based on its chemical composition, the FA can be classified as Class F in accordance with ASTM C618 (2019), as the combined content of SiO_2, Al_2O_3, and Fe_2O_3 exceeds 70% and the CaO content is relatively low. Also the specific gravities of the FA and PCC cement were tested and presented in Table 2.

The fine and coarse aggregate used in this study were locally sourced crushed stone derived from river rocks in Gowa Regency, South Sulawesi. The physical properties of both aggregates were tested in accordance with the applicable standards, and the results were presented in Table 3. Furthermore, both the fine and coarse aggregates satisfied the grading requirements specified in ASTM C136-06 (2006) based on the sieve analysis results.

Mix design

Four concrete mixtures were prepared with FA replacing PCC at levels of 0% (Reference), 15% (M-15FA), 30% (M-30FA), and 45% (M-45FA) by dry weight of PCC. Water additional was added to meet the slump target of 140 mm. For each mixture, three specimens (n = 3) were cast for each curing age. The freshly mixed concrete was poured into beam molds (400 × 100 × 100 mm), compacted to ensure proper consolidation, and left undisturbed for 24 h under laboratory conditions under standard room temperature conditions. After demolding, the specimens were submerged in water and cured for 28 and 90 days. The detailed mix proportions are presented in Table 4.

Testing method

Flexural strength

The flexural performance was evaluated through the Third-Point Loading method based on ASTM C78/C78M (2018) utilizing a testing apparatus with a maximum load capacity of 1000 kN. The load was applied gradually until failure occurred. Figure 1 presents the setup of concrete beam specimens for flexural strength. The flexural strength value was calculated using the Equation 1. For every mixture and curing period, flexural strength testing was performed on three specimens, and the average result was reported.

$$fr = \frac{P \cdot L}{b \cdot d^2} \tag{1}$$

where: fr is flexural strength (MPa), P is the maximum load (N), L is the span length (mm), b is the width of the specimen (mm), and d is the depth of the specimen (mm).

Acceptance criterion

This study established an acceptance criterion, AC based on the flexural strength test results (AC_{fr}), to evaluated the potential of utilizing FA as a partial PCC replacement. AC_{fr} as shown in Equation (2) was calculated by comparing the flexural strength value of FA mixture with the

Table 2. Specific gravity of FA and PCC cement

Material	Specific gravity	Test standard
PCC	3.13	(ASTM C118, 2017)
FA	2.48	(ASTM C118, 2017)

Table 1. Chemical composition of PCC and FA used (XRF test results)

Component (%)	Oxide (%)							
	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	LOI	Others
PCC	19.51	5.50	3.39	62.87	0.81	1.78	4.07	2.07
FA	43.84	10.09	24.29	7.19	0.54	4.80	8.59	0.66

Table 3. Physical properties of fine and coarse aggregates

Material	Fineness modulus	Apparent gravity	Bulk specific gravity on dry	Bulk specific gravity SSD	Water absorption	Test standard
Fine aggregate	2.30	2.53	2.42	2.49	1.84%	(ASTM C128, 2015)
Coarse aggregate	4.67	2.61	2.47	2.54	1.62%	(ASTM C127, 2001)

Table 4. Mix proportions for each variation (kg/m³)

Mixture	Water			PCC	FA	Fine aggregate	Coarse aggregate
	Initial	Additional	Total				
Reference	234	0	234	486	0	624	915
M-15FA	234	11.092	245.092	413.1	72.9	624	915
M-30FA	234	31.624	265.624	340.2	145.8	624	915
M-45FA	234	42.480	276.480	267.3	218.7	624	915

flexural strength value of the reference mixture. The criterion was calculated by modifying the SAI formula (ASTM C311/C311M, 2018), requiring that the AC value reach a minimum of 75% (ASTM C618, 2019). A similar acceptance parameter-based flexural strength was also reported by Suwindu et al. (2025), who evaluated two AP were AP_{UPV} and AP_{FR}.

$$AC_{fr} = \frac{fr\ of\ FA\ mixture}{fr\ of\ reference\ mixture} \times 100\% \quad (2)$$

Environmental impact

Environmental parameters

The environmental performance evaluation incorporated multiple impact parameters, namely ADP, AP, EP, GWP, ODP, and POCP were compiled from established and reputable scientific literature. The environmental burden for the respective concrete mixture was then subsequently quantified by applying the characterization factors for PCC, water, FA, coarse aggregate, and fine aggregate (Table 5) to the corresponding mass of each constituent in the mix design. A previous study by Caronge et al. (2017) reported that PCC classified as equivalent to CEM Type II/A-M cement.

Environmental impact calculation

The environmental impact performance of the concrete was assessed using a life cycle assessment (LCA)-based aggregation approach adapted

Figure 1. Setup for flexural strength test of concrete

Table 5. Inventorying of data environmental impact

Sources	Material (1 kg)	ADP kg Sb eq	AP kg SO_2 eq	EP kg PO_4 eq	GWP kg CO_2 eq	ODP kg CFC-11 eq	POCP kg C_2H_4 eq
Zhang et al., 2022	PCC	2.70E-07	3.77E-04	1.60E-04	4.81E-01		
Calderón-Morales et al., 2024	PCC					1.87E-02	2.38E+01
Roh et al., 2020	Water	1.76E-06	1.95E-07	3.34E-08	1.02E-04	2.78E-15	1.64E-09
Kurda et al., 2018	FA	3.37E-04	5.53E-05	8.23E-06	8.77E-03	5.58E-09	3.22E-06
Roh et al., 2020	Coarse aggregate	1.04E-05	1.13E-05	2.10E-06	6.46E-03	1.75E-11	2.25E-07
Xing et al., 2023	Fine aggregate	7.61E-09	5.47E-06	1.54E-06	4.00E-03	2.19E-10	3.57E-07

from the methodologies of Kim et al. (2016) and Wałach et al. (2018) to examine the environmental impact characteristics. As shown in Equation 3, this approach establishes a consistent and standardized framework for comparing mixture performance across multiple environmental impact categories while maintaining uniform system boundaries and data sources.

$$E = \sum_{n=i}^{i} Ni.Wi \tag{3}$$

where: E refers to the environmental impact, Ni is the reference environmental impact value for category i, and Wi is the weighting parameter associated with category i (kg/m^3).

Environmental performance assessment based on flexural strength

The suitability of FA as a partial replacement material into concrete mixtures was evaluated not only in terms of its effect on flexural strength, but also by assessing the balance between mechanical strength efficiency and environmental impacts. To provide a more holistic assessment, the average flexural strength of each mixture was related to six environmental indicators (ADP, AP, EP, GWP, ODP, and POCP). Specifically, each indicator was normalized by the corresponding average flexural strength, enabling simultaneous evaluation of mechanical performance and environmental burden. A similar performance-based environmental assessment was reported by Bakka' et al. (2024), who evaluated concrete sustainability using the inverse relationship, expressed as the ratio of flexural strength to each environmental impact indicator. As presented in Equations 4–9, this integrated framework facilitates the identification of the optimal FA replacement level by balancing structural performance with sustainability considerations.

$$EP_{ADP/frn} = \frac{ADP_{mix}}{frn} \tag{4}$$

$$EP_{AP/frn} = \frac{AP_{mix}}{frn} \tag{5}$$

$$EP_{EP/frn} = \frac{EP_{mix}}{frn} \tag{6}$$

$$EP_{GWP/frn} = \frac{GWP_{mix}}{frn} \tag{7}$$

$$EP_{ODP/frn} = \frac{ODP_{mix}}{frn} \tag{8}$$

$$EP_{POCP/frn} = \frac{POCP_{mix}}{frn} \tag{9}$$

where: EP_{ADP}/fr_n is the ADP-based environmental performance index (kgSb/MPa), ADP_{mix} is the total abiotic depletion potential of the concrete mixture per m^3 (kgSb), EP_{AP}/fr_n is the AP-based environmental performance index (kgSO$_2$/MPa), is the total AP_{mix} is the acidification potential of the mixture per m^3 (kgSO$_2$), EP_{EP}/fr_n is the EP-based environmental performance index (kgPO$_4$/MPa), EP_{mix} is the total eutrophication potential of the mixture m^3 (kgPO$_4$), EP_{GWP}/fr_n is the GWP-based environmental performance index (kgCO$_2$/MPa), GWP_{mix} is the total global warming potential of the mixture m^3 (kgCO$_2$), EP_{ODP}/fr_n is the ODP-based environmental performance index (kgCFC-11/MPa), ODP_{mix} is the total ozone depletion potential of the mixture m^3 (kgCFC-11), EP_{POCP}/fr_n is the POCP-based environmental performance index (kgC$_2$H$_4$/MPa), $POCP_{mix}$ is the photochemical ozone creation potential of the mixture m^3 (kgC$_2$H$_4$), and fr_n is the flexural strength at age n (MPa), with $n = 28$ days in this study.

RESULTS AND DISCUSSION

Flexural strength

As shown in Figure 2, a continuous decrease in flexural strength was observed with increasing FA content at both curing ages. At 28 days, the reference mixture produced the maximum flexural strength value (4.23 MPa), followed by M-15FA (4.05 MPa), M-30FA (3.76 MPa), and M-45FA (3.41 MPa). A similar trend was also identified at 90 days, with corresponding values of 4.82, 4.36, 4.04, and 3.89 MPa. Despite the reduction in absolute strength, all FA mixtures exhibited notable strength development between 28 and 90 days.

The outcomes of this study align with the findings reported in previous investigations. Islam et al. (2024) reported that FA replacement up to an optimal level can maintain flexural performance, whereas excessive replacement levels resulted in strength deterioration owing to increased porosity and the reduction of the active cementitious phase. Comparable findings were reported by Ahmed et al. (2025), who noted that higher FA contents may require additional reinforcement to offset strength loss. Likewise, Songkhla et al. (2025) and Zhang et al. (2025) found that FA at an optimum dosage enhanced the interfacial transition zone, enabling flexural strength comparable to control concrete, although strength declines at excessive replacement levels. According to the General Specifications for Road and Bridge Construction (Ministry of Public Works, 2025), the minimum required flexural strength for concrete pavement (trial mix) is 4.9 MPa for normal traffic roads, 4.2 MPa for low-traffic roads with a maximum axle load (MST) of 8 tons (AADT 50–500), and 3.9 MPa for low-traffic roads with a maximum axle load of 5 tons (AADT<50). Referring to the quantitative data illustrated in Figure 2, the findings of this study showed that at 28 days, concrete with 15% FA meets the minimum flexural strength requirement of 3.9 MPa, making it suitable for road applications with a maximum MST of 5 tons (AADT < 50). Meanwhile, the other mixtures do not meet the minimum criteria for pavement applications in accordance with the specifications.

Evaluation of the Acceptance criterion for flexural strength (AC_{fr}) demonstrated a clear trend of decreasing values with increasing FA content. At 28 days, AC_{fr} values were recorded at 95.8% for M-15FA, 89.0% for M-30FA, and 80.7% for M-45FA. A similar trend was also identified at 90 days, where the values slightly decreased to 90.5%, 83.9%, and 80.7%, respectively. These results indicate that higher FA substitution levels trend to reduce the flexural capacity of concrete.

Environmental performance

Influence of FA on ADP and flexural strength efficiency ($EP_{ADP/fr}$)

Figure 3 depicted the evolution of ADP and $EP_{ADP/fr}$ with increasing FA replacement levels of 0%, 15%, 30%, and 40%. The left and right y-axes represented ADP and $EP_{ADP/fr}$ respectively, for FA content replacement levels. ADP increased

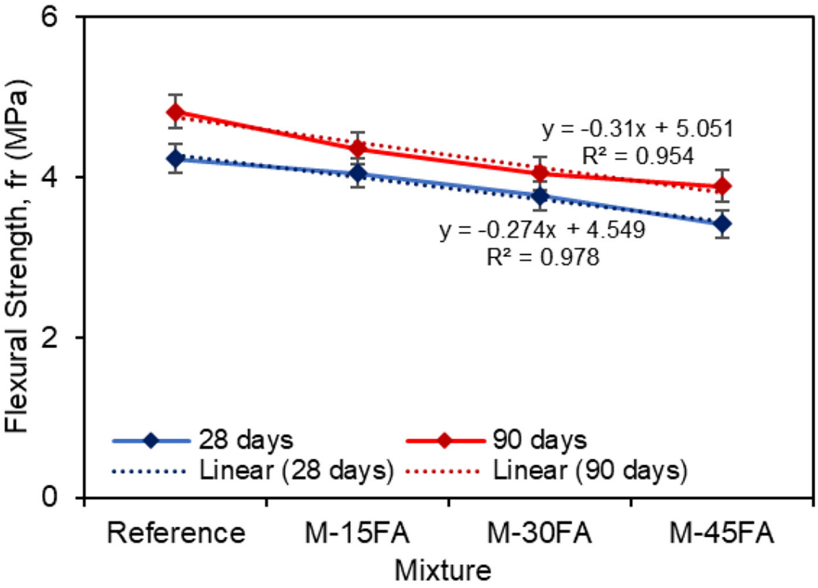

Figure 2. Flexural strengths graph of concrete mixtures

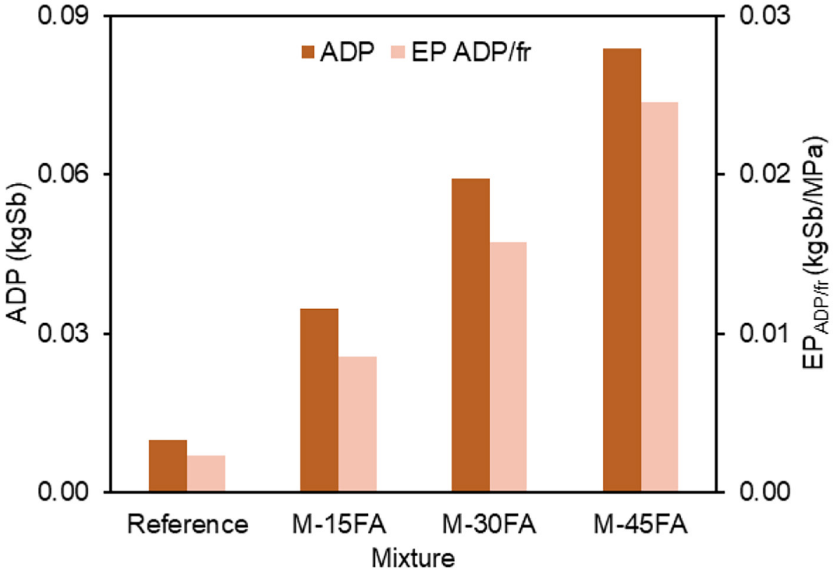

Figure 3. Correlation between ADP and $EP_{ADP/fr}$ in concrete mixtures

from 0.010 kg Sb (reference) to 0.035 kg Sb (M-15FA), 0.059 kg Sb (M-30FA) and 0.084 kg Sb (M-45FA). These values correspond to increases of 244.11%, 488.92%, and 732.50%, respectively, relative to the reference mixture.

A similar trend is observed for the environmental performance indicator expressed as the ADP-to-flexural strength ratio ($EP_{ADP/fr}$). This parameter increases from 0.002 kg Sb/MPa in the reference mixture to 0.009 kg Sb/MPa, 0.016 kg Sb/MPa, and 0.025 kg Sb/MPa for M-15FA, M-30FA, and M-45FA, respectively, representing increases of 259.21%, 561.69%, and 931.96%. The increased in $EP_{ADP/fr}$ indicates that the abiotic resource depletion impact per unit of flexural strength becomes progressively higher with increasing FA content.

Influence of FA on AP and flexural strength efficiency ($EP_{AP/fr}$)

Figure 4 showed that increasing the proportion of FA consistently reduces the Acidification Potential (AP). The AP value decreases from 0.197 $kgSO_2$ for the reference mixture to 0.174 kg SO_2 for M-15FA, 0.150 kg SO_2 for M-30FA, and 0.127 kg SO_2 for M-45FA. These correspond

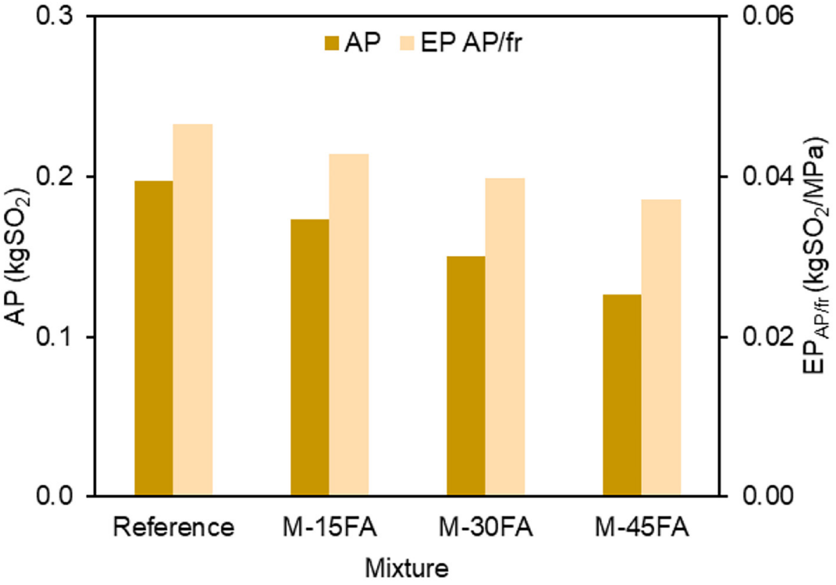

Figure 4. Correlation between AP and $EP_{AP/fr}$ in concrete mixtures

to reductions of 11.90%, 23.80%, and 35.71%, respectively, compared with the reference mixture. This trend indicates that FA incorporation is effective in mitigating acidification-related environmental impacts, primarily due to the reduced clinker content and the associated emissions from cement production.

In line with the decrease in AP, the environmental performance indicator expressed as the AP-to-flexural strength ratio ($EP_{AP/fr}$) also shows a declining trend. The $EP_{AP/fr}$ value decreased from 0.047 in the reference mixture to 0.043 kg SO_2/MPa, 0.040 kg SO_2/MPa, and 0.037 kg SO_2/MPa for M-15FA, M-30FA, and M-45FA, respectively. These represented reductions of 8.04%, 14.38%, and 20.30%, respectively, relative to the reference mixture. This indicates that the acidification impact per unit of flexural strength becomes progressively lower as the FA content increases.

Influence of FA on EP and flexural strength efficiency ($EP_{EP/fr}$)

Figure 5 showed that increasing the proportion of FA consistently reduces the Eutrophication Potential (EP). The EP value decreases from 0.081 kg PO_4 for the reference mixture to 0.070 kg PO_4 for M-15FA, 0.059 kg PO_4 for M-30FA, and 0.047 kg PO_4 for M-45FA. These correspond to reductions of 13.72%, 27.43%, and 41.15%, respectively, relative to the reference mixture. This trend indicates that FA incorporation is effective in mitigating eutrophication-related environmental impacts, primarily due to the reduced clinker consumption and the associated emissions from cement production.

In line with the decrease in EP, the environmental performance indicator expressed as the EP-to-flexural strength ratio ($EP_{EP/fr}$) also shows a declining trend. The $EP_{EP/fr}$ value decreased from 0.019 kg PO_4/MPa in the reference mixture to 0.017 kg PO_4/MPa, 0.016 kg PO_4/MPa, and 0.014 kg PO_4/MPa for M-15FA, M-30FA, and M-45FA, respectively. These represented reductions of 9.93%, 18.47%, and 27.06%, respectively, compared with the reference mixture.

Influence of FA on GWP and flexural strength efficiency ($EP_{GWP/fr}$)

Figure 6 showed that increasing the proportion of FA consistently reduces the GWP. The GWP value decreases from 242.197 kgCO_2 for the reference mixture to 207.772 kg CO_2 for M-15FA, 173.352 kg CO_2 for M-30FA, and 138.924 kg CO_2 for M-45FA. These correspond to reductions of 14.21%, 28.43%, and 42.64%, respectively, relative to the reference mixture. This trend confirms that FA incorporation is highly effective in reducing greenhouse gas emissions associated with concrete production, primarily due to the reduced clinker content and lower energy consumption during cement manufacturing. In line with the decrease in GWP, the environmental performance indicator expressed as the GWP-to-flexural strength ratio ($EP_{GWP/fr}$) also shows a declining trend. The $EP_{GWP/fr}$ value decreases from 57.265 kg CO_2/MPa in the reference mixture to

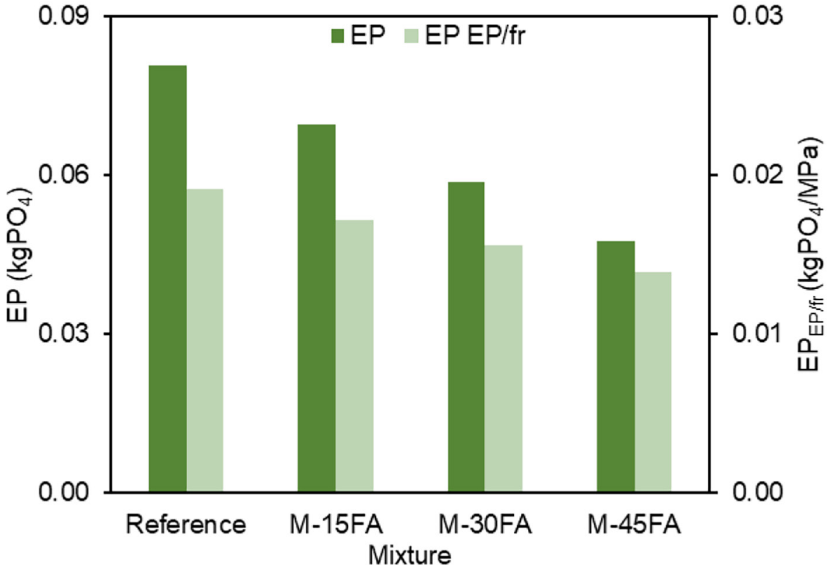

Figure 5. Correlation between EP and $EP_{EP/fr}$ in concrete mixtures

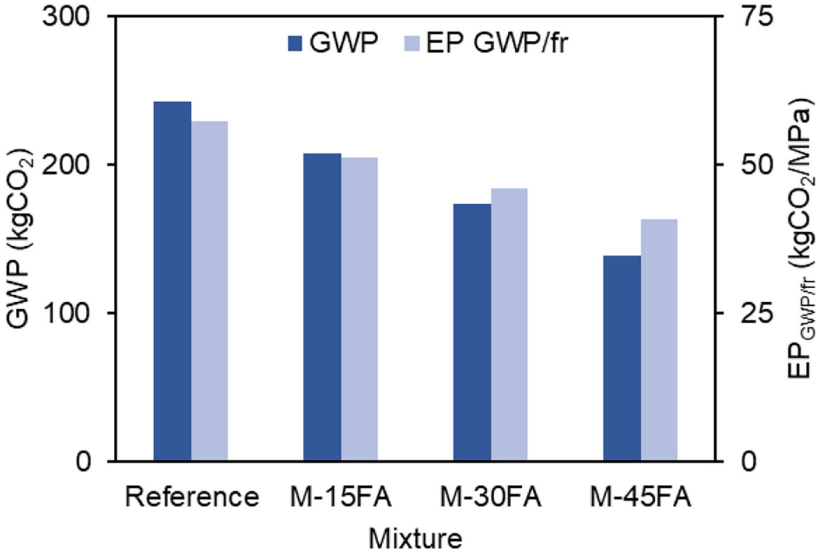

Figure 6. Correlation between EP and $_{EP/frn}$ in concrete mixtures

51.280 kg CO₂/MPa, 46.052 kg CO₂/MPa, and 40.717 kg CO₂/MPa for M-15FA, M-30FA, and M-45FA, respectively. These represent reductions of 10.45%, 19.58%, and 28.90%, respectively, compared with the reference mixture.

Influence of FA on ODP and flexural strength efficiency (EP$_{ODP/fr}$)

Figure 7 shows that increasing the proportion of FA substitution consistently reduces the Ozone Depletion Potential (ODP). The ODP value decreases from 9.088 kg CO₂ for the reference mixture to 7.725 kg CO₂ for M-15FA 6.362 kg CO₂ for M-30FA, and 4.998 kg CO₂ for M-45FA. These correspond to reductions of 15%, 30%, and 45%, respectively, relative to the reference mixture. This downward trend confirms that FA incorporation is effective in mitigating ozone depletion impacts, primarily through reduced clinker consumption, lower demand for virgin raw materials, and decreased energy requirements during cement production. In line with the decrease in ODP, the environmental performance indicator expressed as the ODP-to-flexural strength ratio (EP$_{ODP/fr}$) also shows a declining trend. The EP$_{ODP/fr}$ value decreases from 2.149 kg CO₂/MPa in the reference mixture to approximately 1.907 kg CO₂/MPa for M-15FA, followed by further reductions

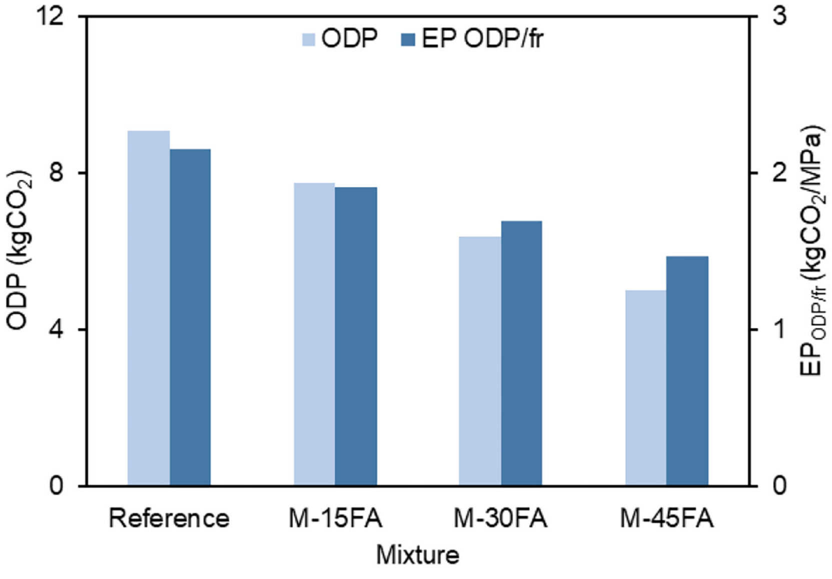

Figure 7. Correlation between ODP and EP$_{ODP/frn}$ in concrete mixtures

to 1.690 kg CO_2/MPa for M-30FA and 1.465 kg CO_2/MPa for M-45FA. In percentage terms, these represent decreases of 11.27%, 21.354%, and 31.82%, respectively, compared with the reference mixture.

Influence of FA on POCP and flexural strength efficiency ($EP_{POCP/fr}$)

Figure 8 shows that increasing the proportion of FA substitution consistently reduces the Photochemical Ozone Creation Potential (POCP). The POCP value decreases from 11566.800 kg C_2H_4 for the reference mixture to 9831.781 kg C_2H_4 for M-15FA, 8096.761 kg C_2H_4 for M-30FA, and 6361.741 kg C_2H_4 for M-45FA. These correspond to reductions of 15%, 30%, and 45%, respectively, relative to the reference mixture. This trend indicates that FA incorporation is effective in mitigating photochemical ozone formation, primarily through reduced clinker consumption and lower energy demand during cement production, both of which are major contributors to photochemical smog formation. In line with the decrease in POCP, the environmental performance indicator expressed as the POCP-to-flexural strength ratio ($EP_{POCP/fr}$) also shows a declining trend. The $EP_{POCP/fr}$ value decreases from 2734.839 kg C_2H_4/MPa in the reference mixture to 2426.578 kg C_2H_4/MPa, 2150.953 kg C_2H_4/MPa, and 1864.537 kg C_2H_4/MPa for M-15FA, M-30FA, and M-45FA, respectively. These represent reductions of 11.27%, 21.35%, and 31.82%, respectively, compared with the reference mixture.

Multi criteria performance of environmental impact

A comprehensive multi-criteria assessment was conducted to evaluate the overall performance of concrete by integrating structural and environmental considerations. Such an approach enables more balanced and informed decision-making by simultaneously accounting for mechanical efficiency and environmental sustainability (Pandjab et al., 2026). Accordingly, multi-criteria performance was assessed from effect of FA on six impact categories and flexural strength-to-impact efficiency ($EP_{ADP/fr}$, $EP_{AP/fr}$, $EP_{EP/fr}$, $EP_{GWP/fr}$, $EP_{ODP/fr}$, and $EP_{POCP/fr}$). To facilitate direct comparison among indicators with different units and magnitudes, all values were converted into dimensionless form through an internal normalization procedure. Figure 9 presents the resulting radar chart of the normalized criteria for all mixtures, providing a clear visual framework for identifying the optimal trade-off between structural and environmental impact performance.

As illustrated in Figure 9, the radar chart area followed the order M-45FA (1.82) > Reference (1.53) > M-30FA (1.48) > M-15FA (1.30). Because the evaluated parameters were based on the inverse relationship between environmental impact and flexural strength, a larger enclosed area indicates lower environmental impact per unit of mechanical performance and, consequently, higher overall eco-efficiency. Accordingly, M-45FA demonstrated the most favorable combined structural and environmental

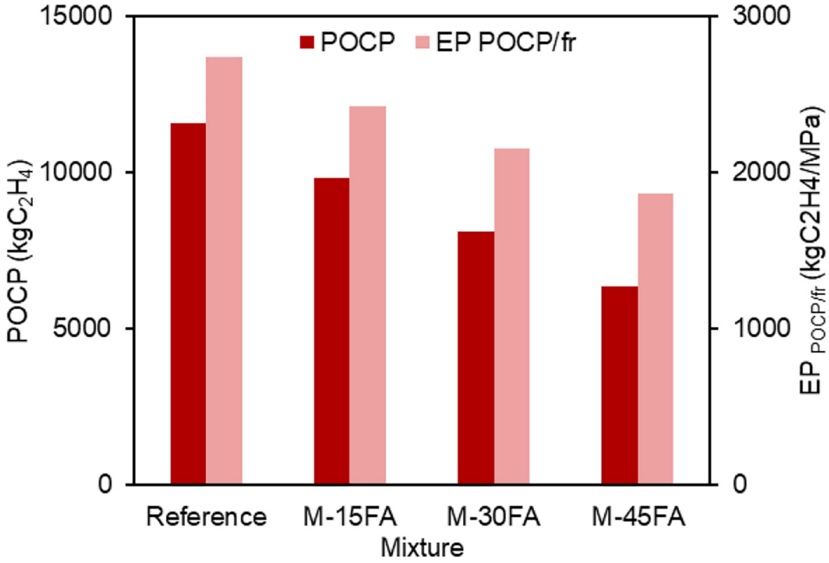

Figure 8. Correlation between POCP and $EP_{POCP/frn}$ in concrete mixtures

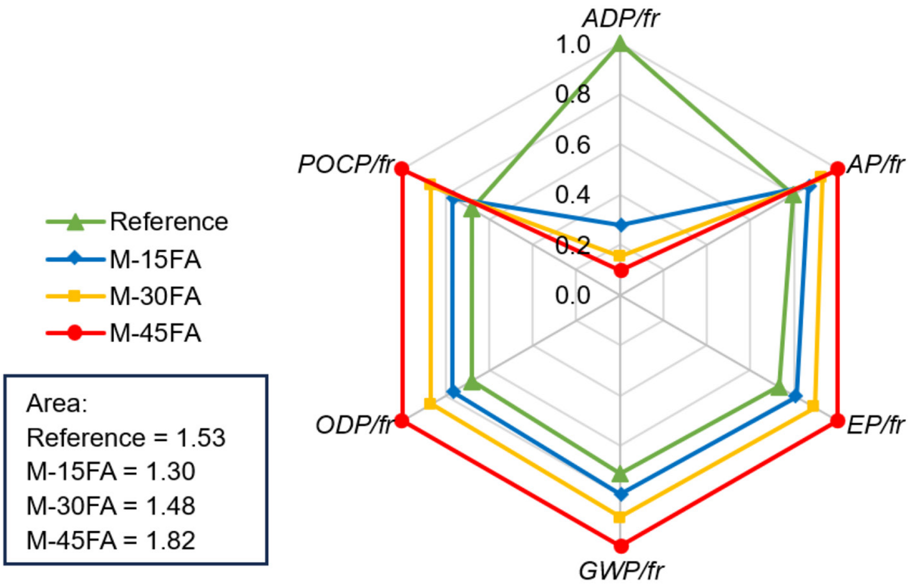

Figure 9. Multi-criteria performance

performance, followed by the reference mixture and M-30FA, while M-15FA exhibited the lowest overall efficiency. These findings confirm that FA incorporation, particularly at a 45% replacement level, offers the most effective balance between flexural performance and environmental sustainability.

CONCLUSIONS

The present study evaluated the flexural strength and environmental impact performance of concrete incorporating fly ash as a partial PCC replacement. The findings obtained from the experimental program supported the following conclusions:

1. Increasing FA content reduces flexural strength at both 28 and 90 days, although all mixtures continue to gain strength over time, and the AC_{fr} values surpassing 75% for FA-modified concrete waste indicated that FA was suitable to be used as a partial replacement for PCC.
2. FA substitution increases ADP but consistently reduces AP, EP, GWP, ODP, and POCP, indicating a trade-off between higher abiotic resource depletion and lower impacts in other environmental categories.
3. Based on the multi-criteria performance, the M-45FA mixture exhibited the highest eco-structural efficiency, as indicated by the largest radar chart area, followed by the reference mixture, M-30FA, and M-15FA.

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