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Polymer-Modified Fly Ash Concrete as a Sustainable Cementitious Composite for Low-Carbon and Durable Infrastructure

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Abstract

There is a need for sustainable cementitious composites in the construction industry which can help in reducing carbon emission and increase the durability of the constructed infrastructure. The utilization of fly ash can not only benefit the environment, but also by adding polymer modifiers, a high-performance and low-carbon composite material polymer modified fly ash concrete (PMFAC) can be produced. The study examines the engineering potential and sustainability of PMFAC by comparing its durability, resource efficiency, carbon reduction and life cycle performance. The use of fly ash helps in reducing the use of Portland cement and helps in vaporizing the industrial wastes whereas the polymer modification enhances the microstructural integrity, interfacial bonding, crack resistance and impermeability. This means that PMFAC has increased durability, longevity and reduced carbon emissions associated with its embodied concrete. The results indicate the synergistic effect of polymer–fly ash interaction on the enhancement of both structural performance and its environmental sustainability. PMFAC is thus a potential cementitious composite which can contribute towards the creation of resilient, resource efficient and low carbon infrastructure The results show the synergistic effect of polymer–fly ash on improving the structural performance and its environmental sustainability. Furthermore, PMFAC shows great promise for sustainable construction with a view to increasing the life cycle efficiency and the ability to withstand various service conditions. Fly ash and polymer modifiers work together to lower maintenance requirements, maximize material usage and to produce excellent long-term performance. These attributes are consistent with the goals of sustainability that are central to global efforts, including waste valorization, the protection of natural resources, and the shift to more environmentally-friendly and climate-resilient infrastructure systems. PMFAC is thus a potential cementitious composite which can contribute towards the creation of resilient, resource efficient and low carbon infrastructure.

Keywords: Polymer-modified fly ash concrete, cementitious composites, durability, sustainability, low-carbon infrastructure

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INTRODUCTION

With the increasing demand for sustainable infrastructure, there is a rapid development of low-carbon cementitious composites for providing enhanced durability and service life. The manufacture of conventional Portland cement is a significant contributor to greenhouse gas emissions and there is a need to use alternative materials that have less impact on the environment and yet retain structural properties. Among the various pozzolanic supplementary cementitious materials (SCMs), fly ash is the most popular one that can be used partially to replace cement. It is incorporated to minimize clinker consumption, minimize carbon emissions in the embodied energy and to encourage the beneficial use of industrial by-products [1]. Moreover, secondary hydration reactions by fly ash will be helpful in matrix densification and for long-term durability [2]. The modification of cementitious composites by polymers has proved to be an effective technique to improve their properties. Polymers – like Styrene–Butadiene Rubber (SBR), Acrylics, Polyvinyl Acetate (PVA), and Epoxy – can be used to enhance the interface bonding, lower porosity and increase the crack resistance by forming the polymer film in the cement matrix [3]. Its changes improve durability, impermeability and overall structural integrity. Polymer modified fly ash concrete (PMFAC) is a combination of fly ash concrete and the advantages of polymer modified concrete. The synergistic effect between fly ash particles and polymer networks leads to better microstructural densification, strengthening of the interfacial transition zone (ITZ) and the limitation of microcrack propagation which leads to better durability and lower carbon footprint [4]. Hence, this study considers PMFAC as a sustainable cementitious composite for low-carbon and durable infrastructure, considering composite mechanisms, durability enhancement and sustainability performance with conventional cementitious concrete system.

MATERIALS AND METHODS

Materials

The main binder used was ordinary Portland cement (OPC, 53 Grade) as per IS 12269:2013. The specific gravity of the cement was about 3.15, and the cement was the main source of calcium silicate hydrates (C–S–H) which are the products of strength development. The coal fired thermal power plant (TPP) fly ash was used as Supplementary Cementitious Material (SCM) in class F. The fly ash had a combined SiO_2 + Al_2O_3 + Fe_2O_3 content of >70% which met the ASTM C618 requirements. Its pozzolanic activity results in secondary hydration reactions, matrix densification and improvement of the durability in the long term [5]. Styrene Butadiene Rubber (SBR) latex was chosen to be used as polymer modifiers because of its high film forming properties, flexibility and compatibility with cementitious matrix. Previous research has shown that SBR creates a polymer network throughout the hydrated cement paste, which can improve the bond between the cement and the reinforcement, reduce permeability and increase the crack resistance of the cement paste [6]. Polymer was kept within 5–15% of the binder weight to give optimum strength and durability. The fine aggregate used was locally available river sand which satisfies the Zone II grading requirements and the coarse aggregate was crushed granite of nominal maximum size 20 mm. The potable water used was free from impurities for mixing and curing purposes.

Mix Composition

Polymer modified fly ash concrete (PMFAC) mixtures were made by substituting 30–50% of OPC by fly ash and 5–15% SBR latex by the total amount of binder. To achieve the proper workability and strength development, a w/b ratio varying between 0.35 and 0.45 was used. The mix proportions selected were based on previous investigations which indicated that the durability and carbon emissions were improved at these replacement levels [7]. The use of fly ash decreased the requirement for clinkers, and the embodied carbon, while the polymer material enhanced the cohesion of the matrix and the characteristics of the interfacial transition zone (ITZ). Conventional concrete (CC) was used as the base mix for comparison. In Figure 1, we have shown the flow chart of the material preparation. We have also explained various mix proportions of polymer for our polymer modified fly ash concrete and represented in Figure 2.

Performance Evaluation

Mechanical, durability and sustainability indicators were used to evaluate the performance of PMFAC. Mechanical tests were carried out to determine the mechanical performance in terms of compressive strength, split tensile strength, flexural strength as per the relevant ASTM and IS standards [8]. The durability properties were investigated using water absorption, permeability resistance, chloride penetration resistance and crack-healing efficiency which directly affect the long-term serviceability [9]. Besides, the sustainability evaluation was carried out using cement reduction

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potential, fly ash utilization efficiency, embodied carbon mitigation and projected service-life enhancement. Special attention was focused on gaining insight of synergistic influence between polymer film formation and pozzolanic reactions caused by fly ash on the improvement of composite microstructure, reduction of pore connectivity and improvement of overall durability. This integrated assessment helped identify PMFAC as a sustainable, high-performance cementitious composite for low carbon infrastructure applications [10].

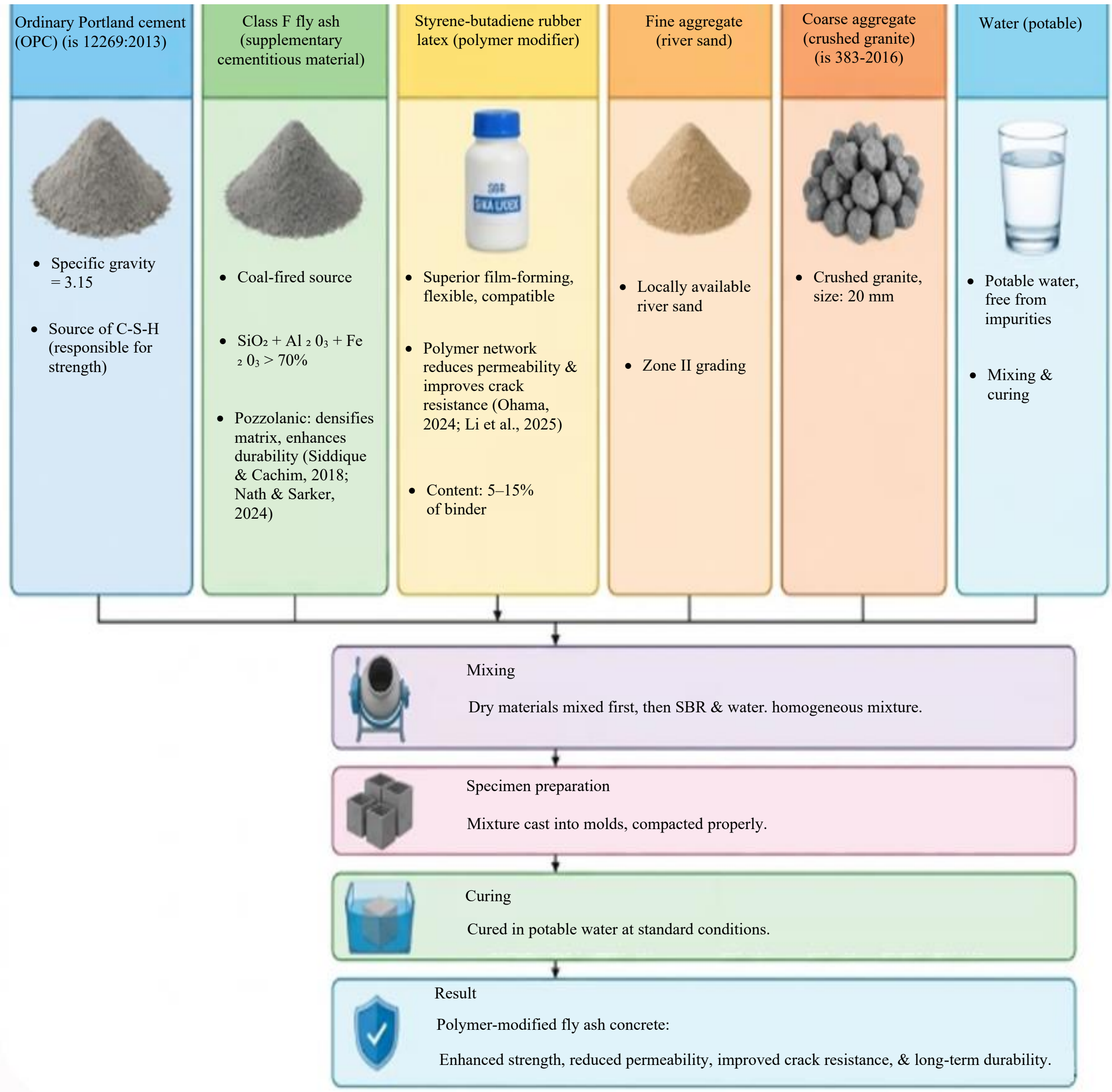

Figure 1. Flow chart of specimen preparation.

Mix Optimization and Mechanical Strengths

The mix proportions formulated in Table 1 evaluate the synergistic effects of fly ash replacement (up to 50%) and SBR latex modification (up to 15%) at reduced water-to-binder ratios. As presented in Table 2, the 28-day mechanical properties show continuous improvement with higher SBR and fly ash contents. The peak performance was achieved by PMFAC-50-15, exhibiting a compressive strength of 56.8 ± 0.9 MPa, a split tensile strength of 52.8 ± 0.08 MPa, and a flexural strength of 6.95 ± 0.10 MPa. This represents a 33.3% increase in compressive strength compared to Conventional Concrete (CC), which is further reflected by an elevated Ultrasonic Pulse Velocity (UPV) of 4.88 km/s, indicating a dense, high-quality matrix.

Mix proportions of polymer-modified fly ash concrete (PMFAC)

Design parameters

- Fly ash replacement (of OPC): 30%, 40%, 50%
- SBR latex content (of total binder): 5%, 10%, 15%
- Water-to-binder (w/b) ratio: 0.35, 0.40, 0.45
- Binder = OPC + fly ash
- Quantities are per 1 m^3 of concrete

Notation

OPC = Ordinary Portland cement (kg/m^3)
FA = Fly ash (kg/m^3)
SBR = SBR latex (kg/m^3)
W = Water (kg/m^2)
FA/OPC = Fly ash replacement (%)
SBR/Binder = SBR latex content (%)
w/b = Water-to-binder ratio
FA = Fine aggregate (river sand) (kg/m^3)
CA = Coarse aggregate (20 mm) (kg/m^3)

Mix ID	FA/OPC (%)	SBR/ Binder (%)	w/b Ratio	Binder (kg/m^3)			SBR Latex (kg/m^3)	Water (kg/m^2)	Aggregates (SSD, kg/m^2)	
				OPC	Fly ash	total binder			Fine aggregate (river sand)	Coarse aggregate (20 mm)
PMFAC-30-5	30	5	0.35/0.40/0.45	490	210	700	35	245/280/315	650	1180
PMFAC-30-10	30	10	0.35/0.40/0.45	490	210	700	70	245/280/315	650	1180
PMFAC-30-15	30	15	0.35/0.40/0.45	420	210	700	105	245/280/315	650	1180
PMFAC-40-5	40	5	0.35/0.40/0.45	420	260	700	35	245/280/315	650	1180
PMFAC-40-15	40	10	0.35/0.40/0.45	420	260	700	70	245/280/315	650	1180
PMFAC-40-15	40	15	0.35/0.40/0.45	420	280	700	105	245/280/315	650	1180
PMFAC-50-5	50	5	0.35/0.40/0.45	350	350	350	35	245/280/315	650	1180
PMFAC-50-15	50	10	0.35/0.40/0.45	350	350	700	70	245/280/315	650	1180
PMFAC-50-15	50	15	0.35/0.40/0.45	350	350	700	105	245/280/315	650	1180

Figure 2. Various mixing proportions.

Note:

- Three w/b ratios (0.35, 0.40, 0.45) may be used with each mixed ID to obtain required workability and strength.
- Aggregate quantities are kept constant for all mixes for comparison (adjust as per specific gravity, grading, and mix design method).
- SBR latex is calculated as a percentage of total binder (OPC + Fly Ash).
- Adjustments in water may be made slightly in practice to achieve target slump.

Durability and Microstructural Mechanics

The physical durability parameters detailed in Table 3 directly mirror the strength enhancements. SBR modification significantly refined the pore network, decreasing water absorption from 5.84% (CC) to 2.86% (PMFAC-50-15) and reducing sorptivity by 50%. Rapid Chloride Permeability Testing (RCPT) demonstrated a sharp drop in total charge passed from 3250 Coulombs to 1210 Coulombs, corresponding to a Chloride Resistance Index of 150.

The microstructural analysis in Table 4 clarifies the mechanism governing these macro-property improvements. Polymer film formation combined with pozzolanic activity reduced total porosity from

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16.8% to 8.2% and refined the average pore diameter from 135 nm down to 54 nm. Furthermore, the Interfacial Transition Zone (ITZ) thickness was reduced by 61.4% (from 44 μm to 17 μm), accompanied by a 46% increase in relative C–S–H content and a substantial decline in microcrack density.

Life-Cycle and Environmental Assessment

From an eco-efficiency standpoint (Table 5) replacing 50% OPC with fly ash lowers embodied CO_2 emissions by up to 41.2% (238 $\mathrm{kg\ CO_2/m^3}$ for PMFAC-50-15 vs. 405 $\mathrm{kg\ CO_2/m^3}$ for CC) and reduces total embodied energy. Furthermore, due to enhanced transport properties and dense microstructure, the predicted service life of the PMFAC-50-15 composite is doubled to 100 years.

Table 1. Mix proportions of conventional concrete (CC), fly ash concrete (FAC), and polymer-modified fly ash concrete (PMFAC) incorporating varying levels of fly ash replacement and SBR latex content.

Mix ID	OPC (kg/m³)	Fly Ash (kg/m³)	SBR Latex (% Binder)	Water/Binder Ratio
CC	450	0	0	0.45
FAC30	315	135	0	0.45
FAC40	270	180	0	0.40
FAC50	225	225	0	0.40
PMFAC-30-5	315	135	5	0.40
PMFAC-40-10	270	180	10	0.38
PMFAC-50-15	225	225	15	0.35

Table 2. Mechanical properties of concrete mixtures at 28 days showing the influence of fly ash incorporation and SBR polymer modification on compressive strength, split tensile strength, flexural strength, and ultrasonic pulse velocity (UPV).

Mix ID	Compressive strength (MPa)	Split tensile strength (MPa)	Flexural strength (MPa)	UPV (km/s)
CC	42.6 ± 1.1	3.65 ± 0.08	4.82 ± 0.11	4.25
FAC30	46.2 ± 1.3	3.94 ± 0.09	5.20 ± 0.12	4.38
FAC40	48.5 ± 1.0	4.15 ± 0.08	5.48 ± 0.10	4.45
FAC50	47.8 ± 1.2	4.08 ± 0.07	5.36 ± 0.11	4.41
PMFAC-30-5	52.4 ± 1.1	4.68 ± 0.10	6.18 ± 0.12	4.65
PMFAC-40-10	55.3 ± 1.0	5.02 ± 0.09	6.62 ± 0.11	4.79
PMFAC-50-15	56.8 ± 0.9	5.28 ± 0.08	6.95 ± 0.10	4.88

Table 3. Durability characteristics of concrete mixtures including water absorption, sorptivity, rapid chloride permeability test (RCPT), and chloride resistance performance, demonstrating the effect of pore refinement and polymer film formation.

Mix ID	Water absorption (%)	Sorptivity (mm/min½)	RCPT (coulombs)	Chloride resistance index
CC	5.84	0.168	3250	100
FAC30	4.92	0.142	2680	115
FAC40	4.45	0.128	2420	121
FAC50	4.32	0.121	2280	124
PMFAC-30-5	3.68	0.105	1780	132
PMFAC-40-10	3.12	0.092	1425	142
PMFAC-50-15	2.86	0.084	1210	150

Table 4. Comparative Microstructural characteristics of conventional concrete, fly ash concrete, and polymer-modified fly ash concrete indicating changes in porosity, pore size distribution, interfacial transition zone (ITZ), C–S–H formation, and microcrack density.

Parameter	CC	FAC40	PMFAC-40-10
Total Porosity (%)	16.8	12.5	8.2
Average Pore Diameter (nm)	135	92	54
ITZ Thickness (µm)	44	29	17
Relative C-S-H Content (%)	100	118	146
Microcrack Density (No./mm²)	12.4	7.5	3.2

Table 5. Sustainability assessment of concrete mixtures based on cement reduction, embodied carbon emissions, embodied energy consumption, and projected service-life extension achieved through fly ash utilization and polymer modification.

Mix ID	Cement reduction (%)	CO_2 emission (kg CO_2/m^3)	Embodied energy (MJ/m^3)	Predicted service life (years)
CC	0	405	3250	50
FAC30	30	320	2860	62
FAC40	40	285	2620	70
FAC50	50	252	2440	75
PMFAC-30-5	30	305	2790	82
PMFAC-40-10	40	270	2550	92
PMFAC-50-15	50	238	2320	100

Fly ash incorporation increases durability, and polymer modification enhances strength, crack resistance and long-term performance by densifying the matrix and by creating better bond between the polymer and the aggregate. Figure 3 presents a comparative performance analysis of CC, FAC, and PMFAC, demonstrating substantial synergistic gains in mechanical, durability, and crack-arresting properties for the polymer-modified system.

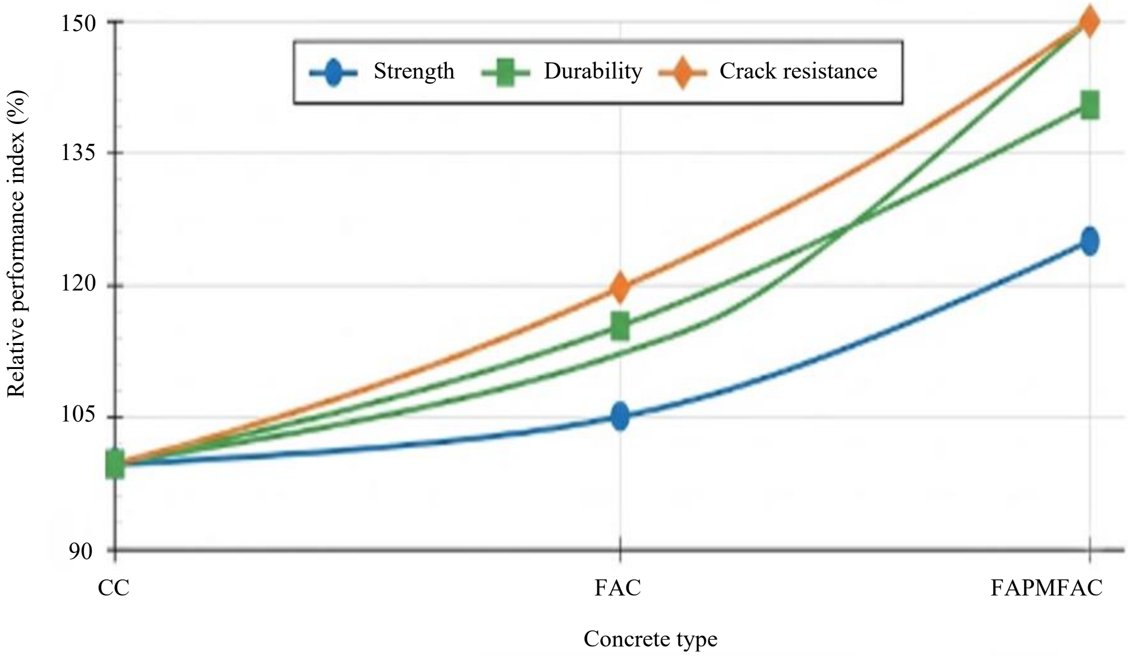

Figure 3. Comparative performance of conventional concrete (CC), fly ash concrete (FAC), and polymer-modified fly ash concrete (PMFAC).

Microstructural comparison of different concrete systems			
Feature	Conventional concrete (control mix) (0% fly ash, 0% SBR)	Fly ash concrete (FAC) (30–50% fly ash, 0% SBR)	Polymer-modified fly ash concrete (PMFAC) (30–50% fly ash, 5–15% SBR)
Matrix composition	C–S–H gel from OPC hydration is the primary binding phase; higher $Ca(OH)_2$ content.	Reduced $Ca(OH)_2$, additional C–S–H gel formed by pozzolanic reaction of fly ash with $Ca(OH)_2$,	Dense matrix of C–S–H gel with polymer film network embedded; lower $Ca(OH)_2$ content than control.
Fly ash role	Not applicable.	Acts as micro-filler; participates in secondary pozzolanic reactions producing C–S–H gel; refines pore structure.	Acts as micro-filler and reacts pozzolanically; contributes to dense matrix in synergy with polymer network.
SBR polymer role	Not applicable.	Not applicable.	Forms continuous 3D polymer film throughout the hydrated matrix; fills pores and coats particle surfaces.
Pore structure	• Higher capillary porosity • Larger pore size and wider distribution • Greater pore connectivity	• Reduced total porosity • Finer pore size distribution • Lower pore connectivity compared to control	• Significantly reduced porosity • Very fine and discontinuous pores • Minimal pore connectivity
Interfacial transition zone (ITZ)	• Relatively porous and weak • Visible microcracks and CH crystals • Poor bonding between aggregate and paste	• Improved ITZ due to fly ash micro-filling • Reduced CH crystals at ITZ • Better aggregate-paste adhesion compared to control	• Dense and compact ITZ • Polymer film strengthens ITZ • Very good aggregate-paste adhesion
Microstructure morphology (SEM observation)	Loose matrix, visible capillary pores, hexagonal $Ca(OH)_2$ crystals, and microcracks.	Denser matrix with fewer $Ca(OH)_2$ crystals; fine C–S–H gel fills pores.	Dense matrix with polymer film coating; pores filled by C–S–H and polymer, very few microcracks.
Crack resistance (micro-level)	Microcrack iniitate and propagate easily, no crack-bridging mechanism.	Reduced microcrack initiation; improved due to refined pores and better ITZ.	Polymer film acts as crack-bridging medium; artress micro-crack propagation effectively.
Stress transfer mechanism	Weak stress transfer due to porous ITZ and higher pore connectivity.	Improved stress transfer by refined structure and stronger ITZ.	Efficient stress transfer through dense matrix and strong polymer–pozzolan synergy.
Key microstructural benefits	• Simple hydration products • Higher porosity and permeability	• Denser matrix • Reduced porosity and permeability • Improved durability	• Highly compact matrix • Strong ITZ and aggregate bonding • Reduced permeability • Superior crack resistance
Overall microstructural performance	★☆☆☆☆ (Low)	★★★☆☆ (Moderate)	★★★★★ (Excellent)
Impact on mechanical and durability performance	Lower strength, higher permeability, poorer durability.	Improved strength and durability due to refined microstructure.	Significantly improved strength, toughness, and long-term durability.

Figure 4. Micro structural comparison of different concrete systems.

RESULTS AND DISCUSSION

Polymer–Fly Ash Composite Mechanism

The use of fly ash and SBR polymer brought about significant changes in the microstructure of the Cementous matrix. The fly ash particles served as micro-fillers and involved in secondary pozzolanic reactions and formed additional calcium silicate hydrate (C–S–H) gel, which further compacted the matrix. At the same time, the SBR polymer created a three-dimensional film network in the hydrated matrix. This filled the capillary pores, enhanced the interfacial transition zone (ITZ), and increased the adhesion between the aggregates and cement paste. The combination of the polymer network and pozzolanic reaction products led to a decrease in pore connectivity and enhancement of stress transfer mechanisms. Additionally, the polymer film served as a crack-bridging material that was able to slow the propagation of the microcracks and improve fracture resistance. The combination of these microstructural changes resulted in enhanced mechanical properties and durability of PMFAC as compared to traditional concrete systems. As illustrated in Figure 4, the incorporation of SBR latex and fly ash leads to a significantly denser matrix, characterized by reduced total porosity, a refined interfacial transition zone (ITZ), and improved crack-bridging mechanics.

Mechanical and Durability Performance

Mechanical and durability properties have been improved significantly after incorporation of polymer and fly ash during the normalization process of the performance evaluation. Compressive strength values were improved from 100 indexes of conventional concrete to 126 indexes of PMFAC, and the flexural strength was improved to 135. The improvements are attributed to the increased cohesion of the matrix, and the increase in the properties of the ITZ, as well as the efficiency of the load transfer between the composite structure. Even greater enhancement was seen for properties related to durability. The permeability of water was considerably decreased because of pore refinement and the formation of polymer film, resulting in the impermeability index of 148. Crack resistance also improved (index value of 155), showing good resistance to crack initiation and propagation. The decreased moisture and aggressive ion ingression should enhance chloride-induced corrosion resistance and chemical deterioration resistance, thus prolonging the service life of the material.

Sustainability Benefits

Using 30–50% fly ash in place of OPC significantly lower the use of clinker and consequently the CO2 emissions. The possible use of fly ash is a way to promote the principle of circular economy, which means using industrial waste as a value-added construction material. Furthermore, the PMFAC's durability and longer lifespan minimize maintenance activities and resource usage across the lifecycle of the infrastructure, further contributing to its environmental benefits. The results overall indicate that PMFAC is a high performing cementitious composite where polymer modification and the incorporation of fly ash are synergic for the enhancement of strength, durability and sustainability. The material is thus a potential solution for resilient and low carbon infrastructure. As illustrated in Figure 5, polymer modification and fly ash incorporation systematically improve multi-property performance indicators, achieving relative gains ranging from 26% in compressive strength to 48% in water impermeability relative to the control mix. As illustrated in Figure 6, the normalized performance indices highlight the synergistic benefits of combined fly ash replacement and polymer modification, showing steady performance enhancements across compressive strength, durability, impermeability, and overall sustainability relative to conventional concrete.

Legal and Policy Governance Framework for PMFAC in Low-Carbon and Durable Infrastructure Development

The development of polymer modified fly ash concrete (PMFAC) has resulted in a sustainable cementitious composite, contributing to the sustainable development of low carbon and durable infrastructure by utilizing fly ash while simultaneously improving the performance characteristics with the use of polymers. The United Nations Framework Convention on Climate Change commits States to take steps to reduce greenhouse gas emissions and to advance sustainable development. Reducing embodied carbon in construction materials through the partial use of fly ash in PMFAC is in line with the international climate mitigation strategies, given that the cement production process is responsible for about 7–8% of the global CO_2 emissions. The Paris Agreement further reinforced the goals of the UNFCCC by calling for Parties to work towards limiting global warming and introducing nationally determined contributions (NDCs) to reduce GHG emissions. This commitment is directly supported using PMFAC, which helps to reduce emissions from construction work and promotes climate resilient infrastructure [11].

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Normalized performance evaluation of different concrete systems				
Property (category)	Performance indicator (units)	Conventional Concrete (control mix) index (baseline)	Polymer-modified concrete (PMFAC) (30–50% fly ash, 5–15% SBR) index	Improvement of PMFAC over control (%)
Compressive strength (mechanical)	Compressive strength (index)	100	126	↑+26%
Flexural strength (mechanical)	Flexural strength (index)	100	135	↑+35%
Crack resistance (durability)	Crack resistance (index)	100	155	↑+55%
Water permeability (durability)	Impermeability index (higher value = better) (index)	100	148	↑+48%
Chloride resistance (durability)	Chloride penetration resistance index (higher value = better) (index)	100	142	↑+42%
Chemical resistance (durability)	Chemical resistance index (higher value = better) (index)	100	138	↑+38%
Durability index (overall)	Overall durability index (composite metric) (index)	100	151	↑+51%

Figure 5. Normalized performance evaluation of different concrete systems.

Note:

- Conventional concrete (without fly ash and polymer) is taken as the baseline with an index value of 100.
- Fly Ash Concrete values represent normalized indices based on experimental results and are relative to the control mix.
- Higher index values indicate better performance for all listed properties.
- Improvements are calculated as: [(Modified Index - Control Index) / Control Index] * 100.

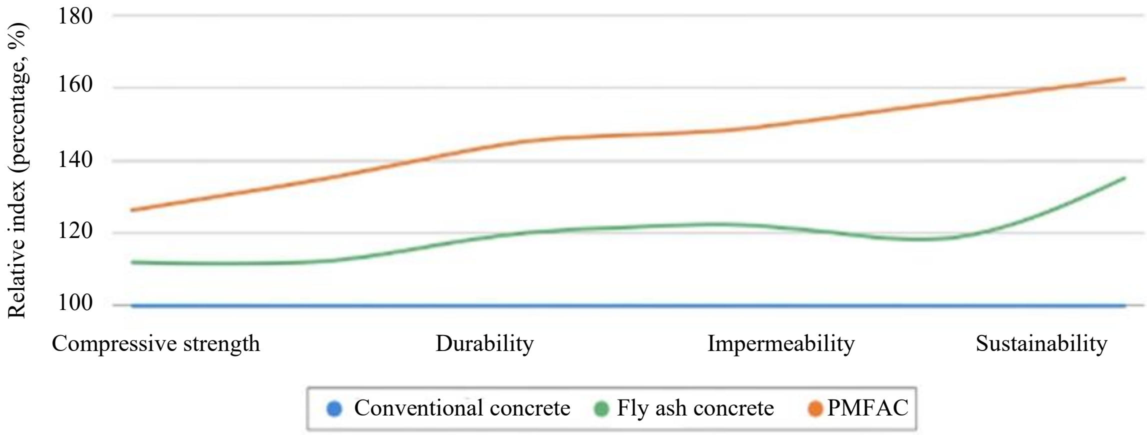

Figure 6. Normalized performance indices illustrate the synergistic effects of fly ash and polymer modification on concrete properties.

PMFAC is supported by an extra policy framework, the 2030 Agenda for Sustainable Development and the Sustainable Development Goals (SDGs). In particular, SDG 9 (Industry, Innovation and Infrastructure), SDG 11 (Sustainable Cities and Communities), SDG 12 (Responsible Consumption and Production), SDG 13 (Climate Action) encourage the adoption of new sustainable technologies, efficient use of resources, industrial innovation and low carbon infrastructure systems. These are all achieved by PMFAC's work in converting fly ash waste into a valuable resource for building construction, minimizing the need for landfill disposal, saving natural materials and resources and improving the durability of infrastructure assets. Also supporting sustainable development for PMFAC are the Rio Declaration on Environment and Development (1992) which codified internationally accepted principles of sustainable development, precaution, intergenerational equity and environmental responsibility. United Nations Conference on Environment and Development. Principle 8 of the Rio Declaration calls for States to reduce unsustainable patterns of production and consumption, and Principle 16 involves the internalization of environmental costs. These principles are reflected in the use of fly ash in construction materials, as it helps to reduce the amount of industrial waste produced and to minimize the environmental impact of cement production. PMFAC is also congruent to international frameworks, which promote the circular economy and resource efficiency. United Nations Environment Programme (UNEP) promotes sustainable material management and construction based on resource efficiency as one of the solutions to mitigate the environmental impact of the built environment [12]. Likewise, Global Alliance for Buildings and Construction highlights the use of low-carbon building materials, Life Cycle Assessment and decarbonization of the construction industry as key actions to achieve global climate targets. PMFAC helps directly achieve the goals of the circular economy and sustainable material flows by allowing the beneficial reuse of fly ash, which contributes to less demand for virgin raw materials. On the international level of standards setting, entities – like the International Organization for Standardization (ISO) and the International Code Council (ICC) – support sustainable construction with environment management standards, life-cycle assessment standards and sustainable building standards. The ISO 14001 standard advocates environmental management systems, and the ISO 14040 and ISO 14044 standards outline principles of life-cycle assessment of products and materials. In addition, the New Urban Agenda (2016) endorsed at the United Nations Conference on Housing and Sustainable Urban Development (Habitat III) calls for countries to create resilient, efficient and environmentally sound urban infrastructure. It is in this context that PMFAC contributes to the implementation of the New Urban Agenda by offering longer-lasting and low-carbon construction solutions that can help to make urban infrastructure more resilient and limit environmental impacts throughout the infrastructure's lifecycle [13].

Figure 7 illustrates the connection between international environmental agreements (such as the United Nations Framework Convention on Climate Change (UNFCCC), the Paris Agreement, and the Rio Declaration) and their contribution to the Sustainable Development Goals (SDGs) (especially SDGs

9, Industry, Innovation and Infrastructure; 11, Sustainable Cities and Communities; 12, Responsible Consumption and Production; 13, Climate Action; and 15, Life on Land). There are institutional mechanisms under the UN Environment Programme (UNEP) that enable the implementation of these global commitments and sustainability initiatives including circular economy frameworks and ISO standards. Together these policy and governance instruments promote material innovation such as Polymer-Modified Fly Ash Concrete (PMFAC).

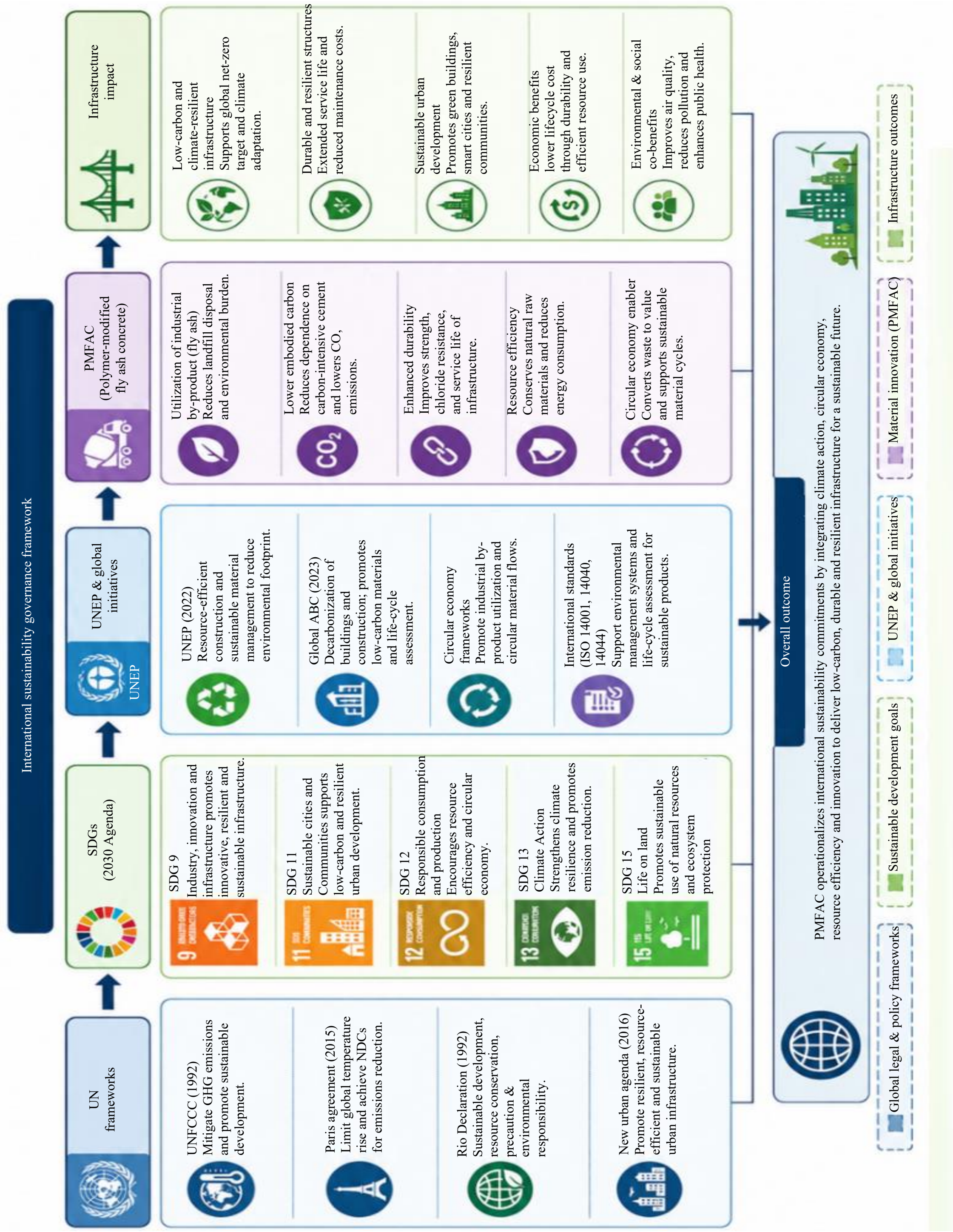

Figure 7. International sustainability governance framework.
Source: The framework is based on UNFCCC (1992), Rio declaration (1992), Paris agreement (2015), UN (2015, 2017), UNEP (2022, 2023), Global ABC (2023) and ISO (2006a, 2006b, 2015) reports.

Statutory

In India, Environment (Protection) Act 1986 is the basic statute for environmental management and pollution control in India. The Ministry of Environment, Forest and Climate Change has issued various Fly Ash Utilization Notifications under this Act, of which the latest is the Fly Ash Notification, 2021 which seeks to ensure effective utilization of fly ash produced by thermal power plants. The notification encourages the utilization of fly ash in construction work, road construction, embankment and infrastructural development which will provide a conducive climate to the adoption of PMFAC. The use of polymer modified fly ash as an SCM directly contributes to meeting the above and reduces the environmental impact of fly ash disposal. The Energy Conservation Act, 2001 and Energy Conservation Building Code (ECBC) further promote energy efficient and low carbon buildings [14]. The manufacture of ordinary Portland cement is one of the largest contributors of greenhouse gas emissions in the construction industry and the use of fly ash in PMFAC in lieu of a considerable amount of cement reduces the embodied carbon and is in line with the national energy-efficiency goals. Similarly, the National Building Code (NBC), 2016 encourages the use of sustainable building materials, efficient use of resources, durability and life cycle performance, which is increased by using polymer modified fly ash concrete [15]. The exceptional durability, low permeability, and resistance to chemical attack of PMFAC help to ensure a longer service life and fewer maintenance needs, aiding in sustainable infrastructure development. In terms of policy, PMFAC is quite aligned with India's climate governance strategy, including the National Action Plan on Climate Change (NAPCC) and India's ambition of achieving Net Zero by 2070 [16]. This material contributes to various national sustainability goals such as promoting the circular economy, reducing reliance on virgin raw materials, lowering industrial waste disposal, conserving natural resources, and reducing carbon emissions from cement production. Moreover, PMFAC helps build climate-resilient infrastructure by making it more durable, less likely to need repairs or rebuilds, and less impactful on the environment throughout the infrastructure life cycle.

The policy governance approach of PMFAC is institutionalized through constitutional, statutory, regulatory, and judicial instruments that work together to realize sustainable development, protection of the environment, resource efficiency and climate resilience. The Constitution of the Indian Republic of 1973 provides a fundamental justification for promoting Environment friendly Building Materials in Article 21, Article 48A and Article 51A (g). The right to life guaranteed in Article 21 has been judicially interpreted to include the right to a clean and healthy environment, Article 48A mandates protection and improvement of the environment by the State and Article 51A(g) lays a fundamental duty on citizens to protect and improve natural resources and ecological balance. These constitutional provisions provide a solid normative background for the implementation of PMFAC as an environmentally friendly alternative to conventional concrete. The judiciary has done a lot to enhance the principles of sustainable development and environmental governance, which are relevant to PMFAC. In M.C. Mehta v. Union of India [17], the Court reiterated the importance of balancing industrial development with environmental protection, thus promoting environmentally-friendly technological advancements. In Subhash Kumar v. State of Bihar [18], the Supreme Court held that environmental quality is part of the Right to Life of Article 21. Later, in the case of Vellore Citizens' Welfare Forum v. Union of India [19], the principles of Sustainable Development, the Precautionary principle and the Polluter Pay principle were added to Indian environmental jurisprudence. These principles help in the use of industrial by-products, like fly ash in construction materials, thereby reducing the environmental degradation and industrial waste. Additional support from the judges is provided on the case of Narmada Bachao Andolan v. Union of India [20] that Sustainable Development became a guiding principle in striking a balance between developmental needs and environmental conservation, adding to the legitimacy of using innovative materials, like PMFAC, in infrastructure development projects.

CONCLUSIONS

In this study, the engineering performance, durability characteristics and sustainability potential of polymer modified fly ash concrete (PMFAC) with the use of Class F fly ash and Styrene–Butadiene Rubber (SBR) latex has been assessed. The combined effect of the pozzolanic reaction caused by fly ash and the polymer film formation significantly enhanced the microstructure and durability of the cementitious composite. Fly ash incorporation led to further secondary C–SH formation, a decrease in CH and a decrease in the pore size. At the same time, the SBR polymer created a three-dimensional network in the hydrated matrix, thereby improving the interfacial transition zone and aggregate–paste bond. These microstructural changes greatly decreased the connectivity of pores and propagation of microcracks. Based on the test results, it is observed that the best overall performance for all the mixtures tested is the one with PMFAC with 40–50% fly ash and 10–15% SBR latex. The compressive strength of the conventional concrete was 42.6MPa, which rose to 56.8MPa, and the flexural strength rose from 4.82MPa to 6.95MPa. The water absorption was reduced by about 51% and chloride permeability reduced from 3250 Coulombs to 1210 Coulombs reflecting a significant improvement in durability. Microstructural analysis revealed that the total porosity decreased from 16.8% to 8.2% and the average pore diameter and density of microcracks also decreased. The enhanced interfacial transition zone led to better efficiency of the transfer of stress and helped provide greater fracture resistance and crack-arresting properties. Sustainability wise, up to 50% Portland cement was replaced by fly ash, which resulted in about 41% reduction in the embodied carbon emissions of the concrete structures and the service life was extended from 50 years to nearly 100 years. Additionally, the use of industrial by-products aligns with circular economy principles and helps conserve resources. It is concluded that overall, PMFAC is a very promising Low Carbon Cementitious Composite with the potential to enhance the mechanical properties, durability and environmental aspects at the same time. Results indicate that PMFAC can be an effective material solution for developing resilient and sustainable infrastructures. For the future, studies with long-term field performance, life-cycle assessment, SEM, XRD, FTIR, and TGA should be conducted to further demonstrate the engineering potential of this material.

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