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Multi-criteria analysis of impact strength in concrete with PET bottle waste additives

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Abstract: This study investigated the impact strength properties of M25 grade concrete at both the initial and ultimate cracking stages after incorporating waste polyethylene terephthalate (PET) bottles as an additive. Various concrete mixes with PET waste components, such as fibres, caps, cap rings, and labels, were tested at different percentages (1%, 2%, and 3% by volume of cement). To identify the optimal mixture for impact strength and explore alternative options, the analytical hierarchy process (AHP), a multi-criteria decision-making tool, was employed. The results demonstrated significant improvements in impact strength with the inclusion of PET fibres and cap rings, while PET caps and labels contributed only marginally to the enhancement. The optimal mixture was achieved with a 2% addition of PET

fibres (3 mm × 60 mm), as larger fibres led to matrix debonding. The AHP tool effectively identified the best mix, consistent with the experimental findings. This study highlights the potential of using PET waste in concrete to promote sustainable production while maintaining structural integrity.

Keywords: impact strength properties; drop hammer test; PET waste; decision making; MCDM; AHP.

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1 Introduction

Researchers are currently exploring sustainable concrete production by substituting traditional components with recycled PET bottle waste. This emerging field aims to enhance concrete's strength, crack resistance, and fresh properties through fibre

reinforcement. Previous studies have shown promising outcomes by introducing PET as a fibrous material with a binding agent (Gayake and Desai, 2022). The behaviour of concrete when subjected to projectiles is influenced by various factors, including penetration depth, crater diameter, and crack propagation (Zhang et al., 2005). Drop weight tests have demonstrated significant enhancements in the first crack and failure strengths of fibre-reinforced concrete compared to plain concrete, highlighting the positive impact of different fibre types (Rahmani et al., 2012; Alavi Nia et al., 2012). The addition of PET-aggregate to concrete has improved its toughness, emphasising the potential for substantial enhancements in concrete toughness using large-flake PET-aggregate (Saikia et al., 2013). Geogrid-reinforced slabs with oil palm shells and plain self-compacting concrete (SCC) have displayed excellent crack resistance (Muda et al., 2013) and improvements in mechanical properties and impact resistance (Mastali et al., 2016). Maintaining consistent impact energy in each test has revealed that an increased drop weight results in higher impact strength (Zhang et al., 2017).

Hooked end fibres have improved post-cracking performance in sisal fibre-reinforced concrete, making it suitable for shear and impact loads (Jaiskarun and Unnikrishnan, 2017). Waste plastic PET aggregate exhibited lower compressive strength but enhanced impact resistance (Saxena et al., 2018). The addition of recycled PET aggregate to concrete significantly improved impact resistance (Dave et al., 2018). Polyvinyl alcohol fibres have effectively reinforced impact resistance and tensile properties (Zhang et al., 2019). Alterations in impact resistance, without affecting other properties, were observed with increased coarse aggregates, fly ash, and hybrid fibres (Banyhussan et al., 2019). Higher fibre content has improved impact resistance in fibre-reinforced concrete (Naraganti et al., 2019) while also enhancing compressive and flexural strength (Mahakavi et al., 2019). The inclusion of carbon fibres has transformed the failure pattern of coral concrete from brittleness to relatively good ductility (Liu et al., 2019). The addition of 10% high reactivity metakaolin (HRM) has significantly affected the mechanical properties and impact resistance of high-strength concrete (HSC), with the combination of 5% Silica fume and 5% HRM performing even better and offering economic advantages (Shabbar, 2020). The reduction in impact strength with temperature has been closely associated with flexural strength, with the reduction linked to the percentage weight loss specific to the concrete type and test conditions (Al-Ameri et al., 2021).

Higher-strength concrete, being more brittle, has experienced fewer drop failures under impact load compared to ordinary concrete (Saleem et al., 2021). The addition of PET waste fibre has improved the crucial properties of HSC, with a recommended volume fraction of up to 1.5% (Arici, 2022). Zhang et al. (2023) explored concrete slab structures with varying strengths have shown a greater susceptibility to directional fractures when impacted by rectangular hammers compared to square and circular hammers. Khalid et al. (2018) investigated synthetic plastic waste as fibre reinforcement in concrete, finding that increased fibre content improved tensile strength and first crack load, with ring-shaped fibres outperforming others. Meza and Siddique (2019) examined flexural behaviour of recycled PET bottle fibres in concrete, demonstrating improved performance but reduced workability. Additionally, Foti (2013) explored PET bottle fibres' adherence to concrete, suggesting their potential for structural reinforcement. Foti (2011) investigated using PET fibres to enhance concrete ductility and reduce costs. The performance of steel-concrete composite beams with flexible shear connectors is analysed in terms of structural efficiency and behaviour under various load conditions,

providing insights into their design and application in construction (Balasubramanian and Baskar, 2018). Additionally, the flexural fatigue behaviour of fibre-reinforced polymer concrete composites under non-reversed loading is examined, highlighting the durability and mechanical performance essential for infrastructure applications (Bedi and Singh, 2020). In addressing environmental concerns, the recycling of plastic waste as coarse aggregate in concrete as investigated by Baral et al., (2022) to promote sustainable development through innovative waste management solutions. Gayake and Desai (2024a) explore the potential use of waste polyethylene terephthalate (PET) bottle caps as aggregates in concrete. Their study presents innovative solutions for incorporating these waste materials into concrete, offering both environmental and economic benefits by reducing waste and enhancing material properties.

In contemporary times, decision-making plays a pivotal role in achieving optimal results with conflicting criteria and target goals. To address this, advanced multi-criteria decision making (MCDM) tools have been developed. The analytic hierarchy process (AHP) is a widely recognised and robust decision-making tool that has been extensively used in various fields, including engineering, management, economics, and environmental science, to solve complex problems that involve multiple criteria and alternatives. AHP operates based on fundamental principles that include concepts like pair-wise comparisons, the establishment of a hierarchical structure, and the utilisation of numerical weights to represent individual preferences. These tools have gained popularity in civil engineering applications too, enabling performance analysis based on technology, economic factors, and environmental impact. The goal is to promote sustainability in material design for construction. MCDM methods assist in determining concrete mix components by evaluating various inputs and alternatives before making the final choice (Noryani et al., 2018; Martinez et al., 2018). Further advancing sustainability, a multi-criteria decision-making tool for sustainable concrete production using waste PET bottle cap aggregates is developed, emphasising the potential for utilising waste materials in construction (Gayake and Desai, 2024b).

Few of the studies illustrates a cohesive approach to sustainable construction materials through advanced optimisation and machine learning techniques. Wang et al. (2024) employ explainable machine learning to optimise recycled aggregate concrete (RAC), balancing environmental and performance criteria, thus promoting transparency in selecting optimal RAC mixtures. Similarly, Atasham ul Haq et al. (2024) emphasise the reuse of low-quality construction waste and industrial byproducts in recycled concrete, offering a framework that prioritises structural integrity while addressing resource scarcity. Wang et al. (2023) extend these ideas with a review of machine learning, deep learning, and swarm intelligence applications to predict and enhance sustainable concrete properties, underscoring artificial intelligence's role in precise material design and control. In a related domain, Sun et al. (2023) review mass transport in concrete under stress, highlighting the impact of moisture, ion, and gas transport on durability, which is crucial for predicting concrete lifespan. Also, Li et al. (2023) examine intelligent optimisation in the design of a drilling bit, demonstrating resource-efficient engineering principles that can inform concrete applications under heavy mechanical stress. Li et al. (2023) examine how higher binder content enhances the splitting tensile strength and modulus of elasticity in SCC. They propose a predictive equation, aiding in the optimisation of SCC formulations for improved structural performance. Together, these studies demonstrate a convergence towards intelligent, sustainable design in construction materials, using machine learning and optimisation to

reduce environmental impact while improving durability and efficiency across applications. Sharma and Senthil (2022) and Singh and Kaur (2022) explore the use of waste materials, like rubber and silica fume, in concrete to enhance impact resistance and durability. Both studies highlight how these additions can improve concrete's toughness, contributing to more sustainable construction practices without sacrificing performance.

The limited availability of literature on the impact strength properties of PET waste-added concrete underscores the need for the proposed methodology and its adoption in this study. This research is addressing a significant knowledge gap by exploring the impact resistance of concrete containing PET waste, and the methodology being employed is a valuable contribution to the field. It has the potential to provide valuable insights and fill a critical research void in sustainable construction materials. So, present study primarily focuses on assessing the resilience of concrete to impact incorporating PET bottle waste. Various proportions of PET waste (1%, 2%, and 3%) in relation to the weight of cement are investigated and compared against standard M25 grade concrete. To evaluate the impact strength of PET modified concrete, a drop weight hammer test is conducted. The analytical hierarchy process (AHP) is then employed to select the most suitable mixture among tested combinations. AHP's structured and hierarchical approach aids in systematic decision-making by breaking down criteria and alternatives, facilitating quantitative assessment of factors like impact strength. This method's efficacy lies in handling complexity, ensuring transparency, and reducing subjectivity in the selection of experimental PET modified concrete mixtures.

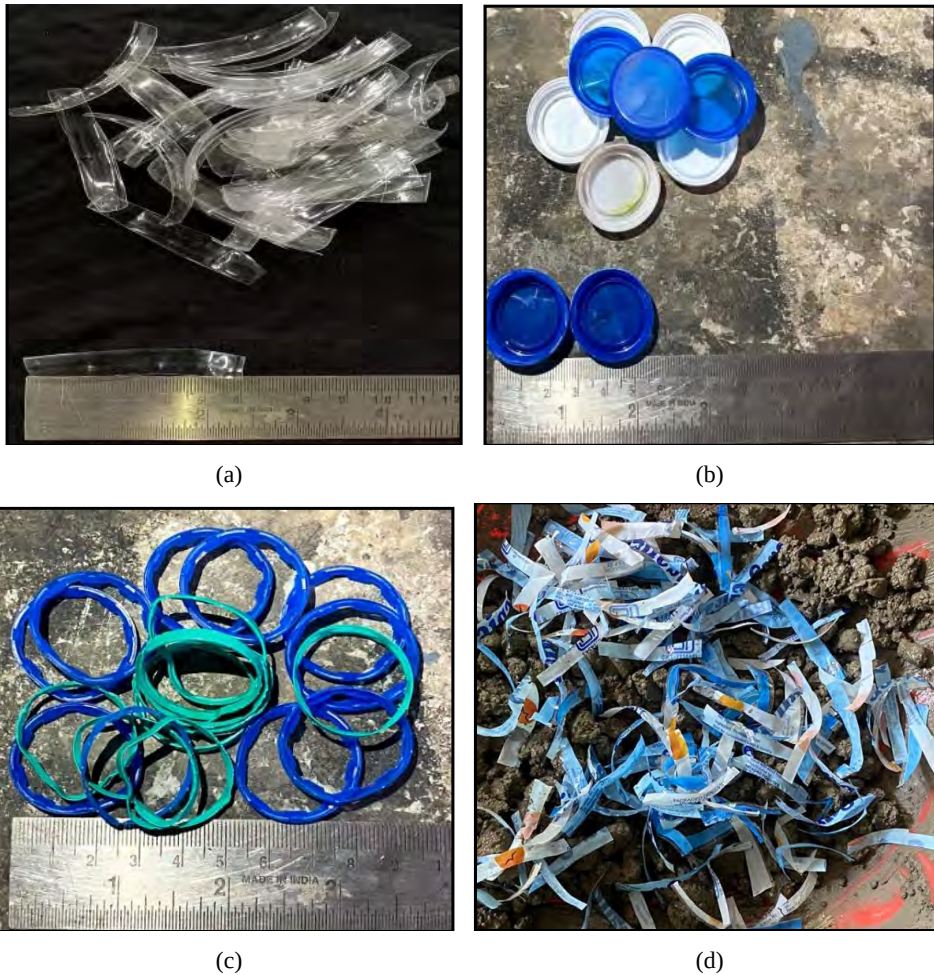
2 Materials and methodology

2.1 Materials

In the experimentation, PPC 53 grade cement, conforming to the IS 1489 Part 1 – (1991) standard with locally available river sand in the region passing through IS 4.75 mm sieve with a specific gravity of 2.62 was utilised. Crushed stones from a local source were sieved to a size that passed through a 20 mm sieve but were retained on a 10 mm sieve, following IS 383-1970 (1971) standards, with a specific gravity of 2.72 were adopted for study. PET, commonly used for beverage containers, is collected from local restaurants and hotels as waste packaged drinking water bottles. The collected waste underwent a separation process, with the bottle caps being cleaned and dried in an enamel tray for 24 hours. The PET bottle body and labels (PL) were cut into fibres (PF) of varying widths, with a length of 60 mm. Additionally, the PET bottle caps (PC) and cap rings (PR) were directly added into the mix based on the weight of cement during the study as shown in Figure 1.

2.2 Mix design

In formulating the concrete mix design, all combinations utilised the same type of Portland pozzolana cement (PPC) of 53 grade, along with river sand as the fine aggregate. The experimentation mix design for M25 concrete was developed and applied based on the results of previous tests on the core raw materials. This design follows the guidelines of IS10262:2009. The specific quantities of ingredient materials and mix proportions, as per the designed plan, are detailed in Table 1.

Figure 1 Patterns of PET bottle (a) fibres (b) cap (c) cap rings (d) labels (see online version for colours)

2.3 Methodology

The experimental process involved conducting drop-weight tests to determine the impact strength of PET-modified M25 grade concrete. These tests were carried out after a complete 28-day immersion curing period. The concrete mixes consisted of varying percentages (1%, 2%, and 3%) of PF, PR, PC, and PL, added in proportion to the weight of the cement in each mix. Six different concrete mix variations were tested, as outlined in the provided Table 2. All mix proportions for M25 grade concrete were prepared in accordance with the Indian Standard Code. The impact strength and its variations were thoroughly studied, using the specified criteria, and then compared using the AHP tool to rank the most suitable mixture among all the combinations tested.

Table 1 Mix proportion of M25 concrete

Mix type	Designation	Cement (kg/m ³)	Quantity of ingredient		Water/cement ratio
			Fine aggregate (kg/m ³)	Coarse aggregate (kg/m ³)	
M25 control	M25-C	383.2	800.94	1087.75	0.5
	Proportion	1	2.09	2.83	0.5

Table 2 Designation chart of experimental study

Sr. no.	Classification	Mix type	Designation	% addition of plastic waste (gms)			No. of specimens
				1%	2%	3%	
1	M25 concrete	Controlled	M25-C	0	0	0	3
2	M25 + PF	3 mm × 60 mm	3PF60	4.27	8.54	12.80	9
3	M25 + PF1	6 mm × 60 mm	6PF60	4.27	8.54	12.80	9
4	M25 + PR	Ring	PR	5.00	10.00	15.00	9
5	M25 + PC	Cap	PC	3.00	6.00	12.00	9
6	M25 + PL	3 mm × 60 mm	3PL60	6.00	12.00	24.00	9
7	M25 + PL1	3 mm × 60 mm	6PL60	6.00	12.00	24.00	9

2.4 Specimen preparations and test setup

Following the guidelines of IS 10262, an experimental batch of M25 grade concrete was prepared using a manual mixing method in an enamel tray. To enhance result reliability, three specimens were produced for each concrete batch. The moulds were diligently cleaned, securely tightened with binding wire around the periphery, and uniformly coated with oil on the inner surface before pouring the concrete, ensuring easy demoulding as shown in Figure 2. After 24 hours, the moulds were removed, and the specimens were cured in water at a constant room temperature of $27 \pm 2^\circ\text{C}$ for a period of 28 days. These specimens were 150 mm in diameter with a thickness of 63.5 mm, and they were cast without layers and compacted using a tamping rod and levelled at the top using a trowel.

2.5 Impact test setup

The impact resistance of PET modified concrete was evaluated through a drop-weight test in accordance with ACI committee 544.9R guidelines. Figure 3 illustrates the setup of the drop-weight test apparatus used in the study. Cylindrical disk specimens measuring 150 mm in diameter and 64 mm in thickness were utilised. During the test, a 13 kg weight was repeatedly dropped from a height of 380 mm to hit a 64 mm diameter steel ball in contact with the top surface of each specimen. The number of blows needed to initiate the first crack was recorded, and the test was continued to observe the number of blows required for complete fracture of the specimen. The energy absorption capacity of each specimen was determined using equation (1).

$$E_{\text{impact}} = N \times m \times g \times h \tag{1}$$

where

N is the blow count at a initial crack and failure stage

m is a mass in kg

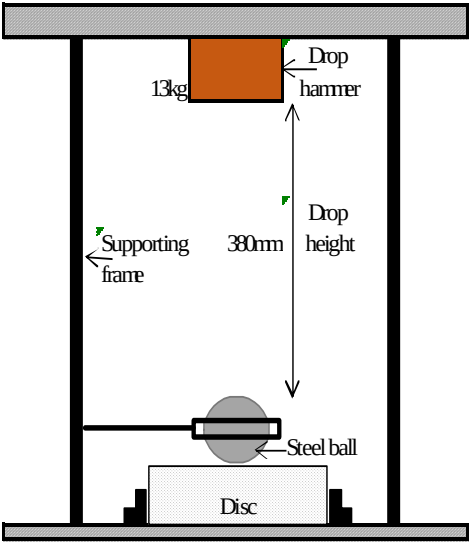
g represents gravitational acceleration (9.81 m/s^2) and

h is the height of free fall of the hammer.

Figure 2 Mould preparations (a) before casting (b) cast specimens (see online version for colours)



Figure 3 Drop weight test setup (see online version for colours)



3 Results and discussion

3.1 Impact resistance of PET modified concrete at initial and final crack

Table 3 in this study presents the results of impact resistance testing for concrete modified with PET waste. Various mix compositions were tested, and the data reveals significant insights into the effect of PET waste on the material's impact resistance. These findings are critical for understanding how PET waste can be incorporated into concrete mixtures for practical applications. The results presented in Figure 4 clearly indicate that the optimum addition of PET waste for all mix types is 2%. Beyond this percentage, the impact resistance of the concrete decreases. This suggests that a specific balance between PET waste and conventional concrete components is essential to achieve the desired improvement in impact resistance. Two specific mix compositions, namely 3PF60 and PR, exhibited the maximum number of blows required to initiate the first crack, which was 11 blows. Among these, mix 3PF60 also displayed the highest impact energy of 1066 J, with a total of 22 blows observed before complete failure. This superior impact resistance can be attributed to the effective bonding of elongated PET fibres within the concrete matrix. These fibres act as reinforcement, preventing the hard matrix from easily crushed under impact, thereby enhancing the material's resistance to mechanical stress.

Observing the initial crack energy (E_i) across various mixes with PET waste additions, it is evident that the effect of PET on initial crack resistance varies between mixes. For M25-C, E_i remains consistent at 339 J regardless of PET content, indicating that small PET additions do not impact initial crack resistance for this mix. However, in mixes like 3PF60 and 6PF60, E_i values are highest at 1% and 2% PET content, with values decreasing at 3% PET (e.g., from 436 J to 339 J in 6PF60), showing that higher PET content may reduce the resistance to initial cracking. The PR mix also shows a similar trend, where E_i increases with PET addition up to 2% (533 J) but slightly reduces at 3% (388 J). Overall, these observations suggest that certain mixes can benefit from moderate PET additions for increased crack resistance, but excessive PET may reduce initial crack energy in most cases.

For failure energy (E_f), which reflects the mix's capacity to withstand impact up to the point of failure, the effects of PET additions are more pronounced. In mixes like 3PF60, E_f reaches its peak at 2% PET with a high value of 1,066 J, while at 3% PET, it declines to 533 J, indicating a significant loss in energy absorption at higher PET levels. Similarly, in 6PF60, E_f peaks at 872 J for 1% PET but decreases at higher PET percentages. PR and PC mixes exhibit a consistent trend where E_f increases with PET addition up to a certain limit, but excessive PET (3%) results in lower values, suggesting reduced impact resistance. In mixes such as 6PL60, E_f benefits from PET up to 2%, reaching 872 J, but then declines at 3% PET. These trends highlight that PET additions in moderate amounts (typically around 1–2%) enhance the mix's ability to absorb energy, while further increases in PET content can lead to reduced failure resistance across most mixes.

On the contrary, the mix containing PC (Plain Concrete) showed a decrease in impact resistance with an increased proportion of PET waste. This decline in impact strength can be attributed to the increased porosity within the concrete, resulting from the higher PET content, which weakens its ability to withstand impact forces effectively. Additionally, the width of the PET fibres also played a crucial role in the impact resistance of the

concrete. For example, the wider 6mm PET fibres in mix 6PF60 negatively impacted the impact energy. These wider fibres exhibited poor inter facial bonding with the concrete matrix, reducing the material’s capacity to absorb impact forces. This observation emphasises the importance of both the quantity and geometry of the PET waste in concrete mix design.

Figure 4 (a) Final and (b) initial impact resistance of pet modified concrete (see online version for colours)

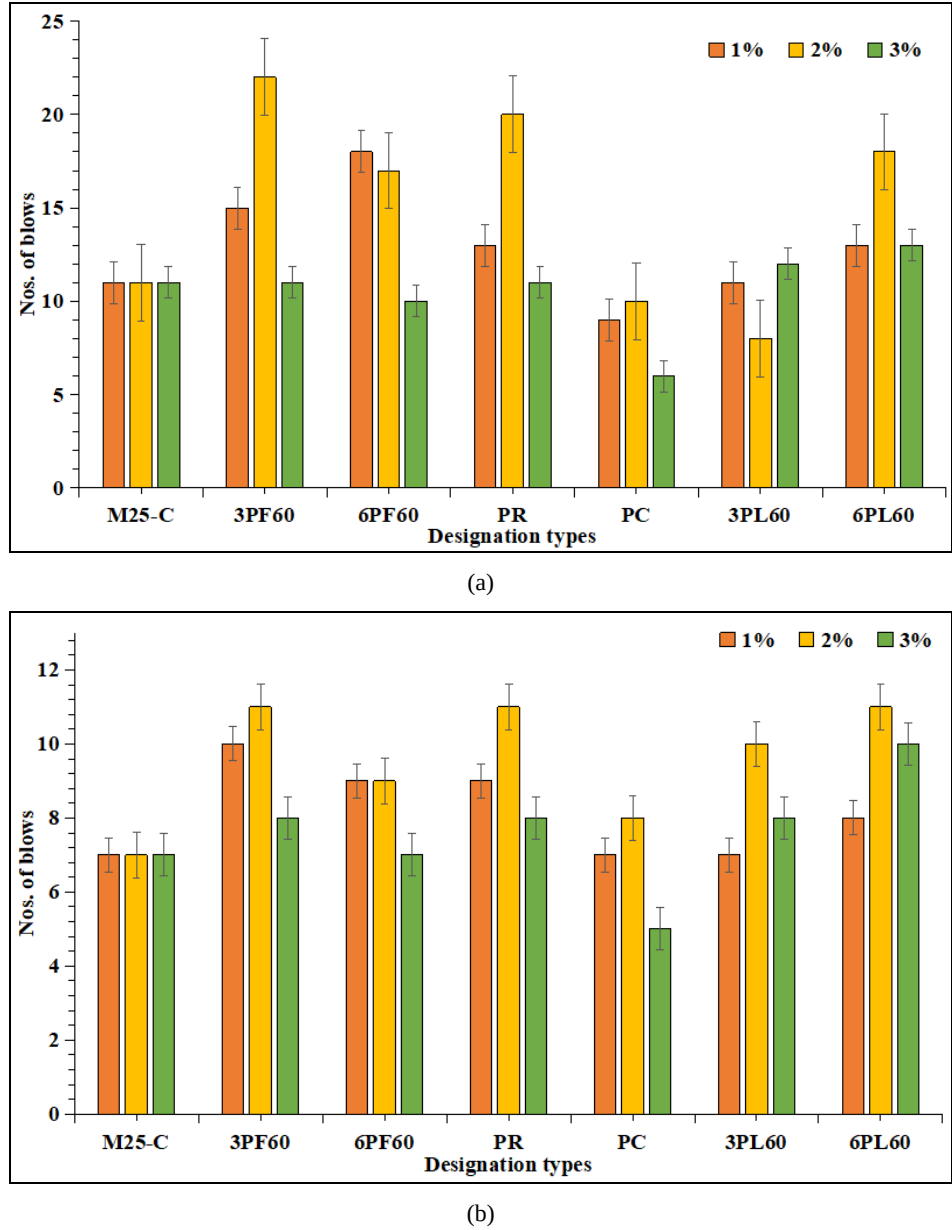


Table 3 Impact resistance and ductility index for various mixes

Designation	Percentage of PET waste addition						Energy absorbed in 'J'						Ductility index Di = (Ef/Ei)		
	Initial crack blow nos.			Failure blow nos.			Initial crack (Ei)			Failure (Ef)					
	1%	2%	3%	1%	2%	3%	1%	2%	3%	1%	2%	3%	1%	2%	3%
	7	7	7	11	11	11	339	339	339	533	533	533	1.571	1.571	1.571
M25-C	7	7	7	11	11	11	339	339	339	533	533	533	1.571	1.571	1.571
3PF60	10	11	8	15	22	11	485	533	388	727	1066	533	1.500	2.000	1.375
6PF60	9	9	7	18	17	10	436	436	339	872	824	485	2.000	1.889	1.429
PR	9	11	8	13	20	11	436	533	388	630	969	533	1.444	1.818	1.375
PC	7	8	5	9	10	6	339	388	242	436	485	291	1.286	1.250	1.200
3PL60	7	10	8	11	8	12	339	485	388	533	388	582	1.571	0.800	1.500
6PL60	8	11	10	13	18	13	388	533	485	630	872	630	1.625	1.636	1.300

Figure 5 (a) Initial (b) final energy absorbed of pet modified concrete (see online version for colours)

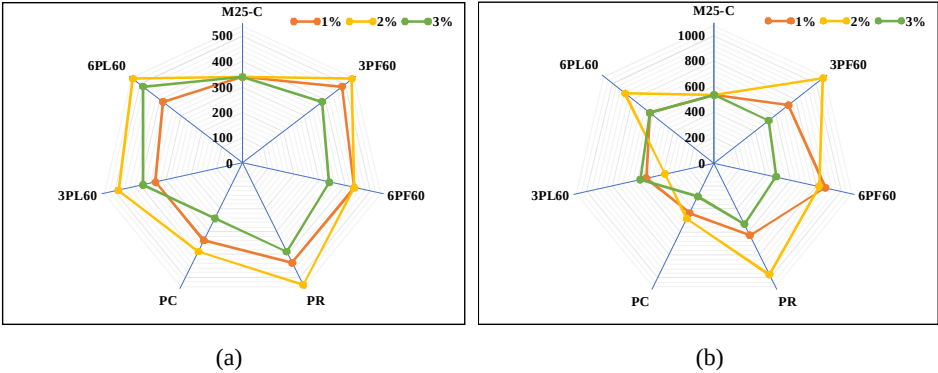


Figure 6 Crack pattern for tested disc specimens for (a) fibres (b) cap (c) cap rings (d) labels (see online version for colours)



Table 4 Ranking of concrete mixes using AHP

M25-C	3PF60-1%			3PF60-2%			3PF60-3%			6PF60-1%			6PF60-2%			6PF60-3%			PR-1%			PR-2%			PR-3%			PC-1%			PC-2%			PC-3%			3PL60-1%			3PL60-2%			3PL60-3%			6PL60-1%			6PL60-2%			6PL60-3%			Product of the row	Weight																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																											
	1	1.364	2.000	1.000	0.733	0.500	1.000	0.611	0.647	1.100	0.846	0.550	1.000	1.222	1.100	1.833	1.000	1.375	0.917	0.846	0.611	0.846	0.556	1.000	1.222	1.100	1.833	1.000	1.375	0.917	0.846	0.611	0.846	0.556	1.000	1.222	1.100	1.833	1.000	1.375	0.917	0.846	0.611	0.846	0.556	1.000	1.222	1.100	1.833	1.000	1.375	0.917	0.846	0.611			0.846	0.556	1.000	1.222	1.100	1.833	1.000	1.375	0.917	0.846	0.611	0.846	0.556	1.000	1.222	1.100	1.833	1.000	1.375	0.917	0.846	0.611	0.846	0.556	1.000	1.222	1.100	1.833	1.000	1.375	0.917	0.846	0.611	0.846	0.556	1.000	1.222	1.100	1.833	1.000	1.375	0.917	0.846	0.611	0.846	0.556	1.000	1.222	1.100	1.833	1.000	1.375	0.917	0.846	0.611	0.846	0.556	1.000	1.222	1.100	1.833	1.000	1.375	0.917	0.846	0.611	0.846	0.556	1.000	1.222	1.100	1.833	1.000	1.375	0.917	0.846	0.611	0.846	0.556	1.000	1.222	1.100	1.833	1.000	1.375	0.917	0.846	0.611	0.846	0.556	1.000	1.222	1.100	1.833	1.000	1.375	0.917	0.846	0.611	0.846	0.556	1.000	1.222	1.100	1.833	1.000	1.375	0.917	0.846	0.611	0.846	0.556	1.000	1.222	1.100	1.833	1.000	1.375	0.917	0.846	0.611	0.846	0.556	1.000	1.222	1.100	1.833	1.000	1.375	0.917	0.846	0.611	0.846	0.556	1.000	1.222	1.100	1.833	1.000	1.375	0.917	0.846	0.611	0.846	0.556	1.000	1.222	1.100	1.833	1.000	1.375	0.917	0.846	0.611	0.846	0.556	1.000	1.222	1.100	1.833	1.000	1.375	0.917	0.846	0.611	0.846	0.556	1.000	1.222	1.100	1.833	1.000	1.375	0.917	0.846	0.611	0.846	0.556	1.000	1.222	1.100	1.833	1.000	1.375	0.917	0.846	0.611	0.846	0.556	1.000	1.222	1.100	1.833	1.000	1.375	0.917	0.846	0.611	0.846	0.556	1.000	1.222	1.100	1.833	1.000	1.375	0.917	0.846	0.611	0.846	0.556	1.000	1.222	1.100	1.833	1.000	1.375	0.917	0.846	0.611	0.846	0.556	1.000	1.222	1.100	1.833	1.000	1.375	0.917	0.846	0.611	0.846	0.556	1.000	1.222	1.100	1.833	1.000	1.375	0.917	0.846	0.611	0.846	0.556	1.000	1.222	1.100	1.833	1.000	1.375	0.917	0.846	0.611	0.846	0.556	1.000	1.222	1.100	1.833	1.000	1.375	0.917	0.846	0.611	0.846	0.556	1.000	1.222	1.100	1.833	1.000	1.375	0.917	0.846	0.611	0.846	0.556	1.000	1.222	1.100	1.833	1.000	1.375	0.917	0.846	0.611	0.846	0.556	1.000	1.222	1.100	1.833	1.000	1.375	0.917	0.846	0.611	0.846	0.556	1.000	1.222	1.100	1.833	1.000	1.375	0.917	0.846	0.611	0.846	0.556	1.000	1.222	1.100	1.833	1.000	1.375	0.917	0.846	0.611	0.846	0.556	1.000	1.222	1.100	1.833	1.000	1.375	0.917	0.846	0.611	0.846	0.556	1.000	1.222	1.100	1.833	1.000	1.375	0.917	0.846	0.611	0.846	0.556	1.000	1.222	1.100	1.833	1.000	1.375	0.917	0.846	0.611	0.846	0.556	1.000	1.222	1.100	1.833	1.000	1.375	0.917	0.846	0.611	0.846	0.556	1.000	1.222	1.100	1.833	1.000	1.375	0.917	0.846	0.611	0.846	0.556	1.000	1.222	1.100	1.833	1.000	1.375	0.917	0.846	0.611	0.846	0.556	1.000	1.222	1.100	1.833	1.000	1.375	0.917	0.846	0.611	0.846	0.556	1.000	1.222	1.100	1.833	1.000	1.375	0.917	0.846	0.611	0.846	0.556	1.000	1.222	1.100	1.833	1.000	1.375	0.917	0.846	0.611	0.846	0.556	1.000	1.222	1.100	1.833	1.000	1.375	0.917	0.846	0.611	0.846	0.556	1.000	1.222	1.100	1.833	1.000	1.375	0.917	0.846	0.611	0.846	0.556	1.000	1.222	1.100	1.833	1.000	1.375	0.917	0.846	0.611	0.846	0.556	1.000	1.222	1.100	1.833	1.000	1.375	0.917	0.846	0.611	0.846	0.556	1.000	1.222	1.100	1.833	1.000	1.375	0.917	0.846	0.611	0.846	0.556	1.000	1.222	1.100	1.833	1.000	1.375	0.917	0.846	0.611	0.846	0.556	1.000	1.222	1.100	1.833	1.000	1.375	0.917	0.846	0.611	0.846	0.556	1.000	1.222	1.100	1.833	1.000	1.375	0.917	0.846	0.611	0.846	0.556	1.000	1.222	1.100	1.833	1.000	1.375	0.917	0.846	0.611	0.846	0.556	1.000	1.222	1.100	1.833	1.000	1.375	0.917	0.846	0.611	0.846	0.556	1.000	1.222	1.100	1.833	1.000	1.375	0.917	0.846	0.611	0.846	0.556	1.000	1.222	1.100	1.833	1.000	1.375	0.917	0.846	0.611	0.846	0.556	1.000	1.222	1.100	1.833	1.000	1.375	0.917	0.846	0.611	0.846	0.556	1.000	1.222	1.100	1.833	1.000	1.375	0.917	0.846	0.611	0.846	0.556	1.000	1.222	1.100	1.833	1.000	1.375	0.917	0.846	0.611	0.846	0.556	1.000	1.222	1.100	1.833	1.000	1.375	0.917	0.846	0.611	0.846	0.556	1.000	1.222	1.100	1.833	1.000	1.375	0.917	0.846	0.611	0.846	0.556	1.000	1.222	1.100	1.833	1.000	1.375	0.917	0.846	0.611	0.846	0.556	1.000	1.222	1.100	1.833	1.000	1.375	0.917	0.846	0.611	0.846	0.556	1.000	1.222	1.100	1.833	1.000	1.375	0.917	0.846	0.611	0.846	0.556	1.000	1.222	1.100	1.833	1.000	1.375	0.917	0.846	0.611	0.846	0.556	1.000	1.222	1.100	1.833	1.000	1.375	0.917	0.846	0.611	0.846	0.556	1.000	1.222	1.100	1.833	1.000	1.375	0.917	0.846	0.611	0.846	0.556	1.000	1.222	1.100	1.833	1.000	1.375	0.917	0.846	0.611	0.846	0.556	1.000	1.222	1.100	1.833	1.000	1.375	0.917	0.846	0.611	0.846	0.556	1.000	1.222	1.100	1.833	1.000	1.375	0.917	0.846	0.611	0.846	0.556	1.000	1.222	1.100	1.833	1.000	1.375	0.917	0.846	0.611	0.846	0.556	1.000	1.222	1.100	1.833	1.000	1.375	0.917	0.846	0.611	0.846	0.556	1.000	1.222	1.100	1.833	1.000	1.375	0.917	0.846	0.611	0.846	0.556	1.000	1.222	1.100	1.833	1.000	1.375	0.917	0.846	0.611	0.846	0.556	1.000	1.222	1.100	1.833	1.000	1.375	0.917	0.846	0.611	0.846	0.556	1.000	1.222	1.100	1.833	1.000	1.375	0.917	0.846	0.611	0.846	0.556	1.000	1.222	1.100	1.833	1.000	1.375	0.917	0.846	0.611	0.846	0.556	1.000	1.222	1.100	1.833	1.000	1.375	0.917	0.846	0.611	0.846	0.556	1.000	1.222	1.100	1.833	1.000	1.375	0.917	0.846	0.611	0.846	0.556	1.000	1.222	1.100	1.833	1.000	1.375

Figure 7 AHP followed for ranking of a suitable mix

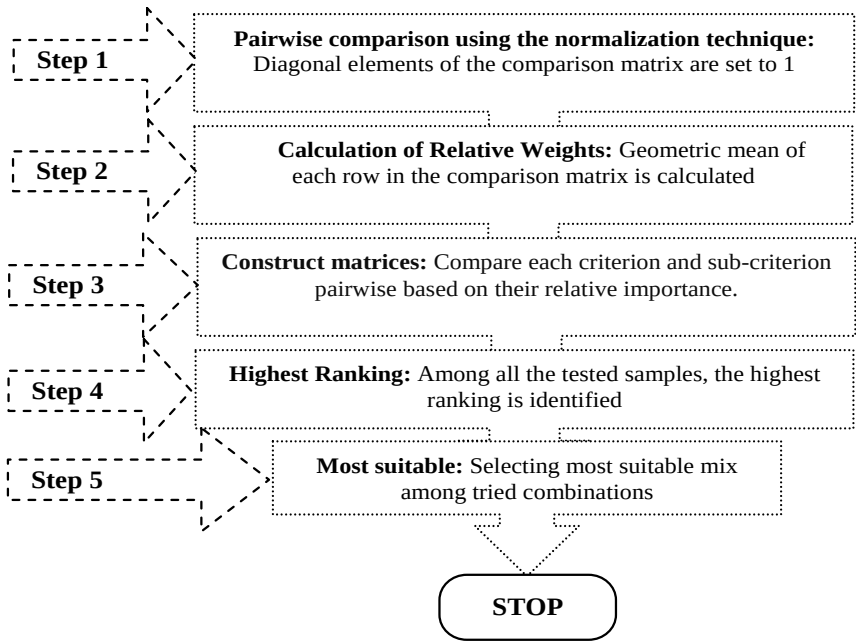
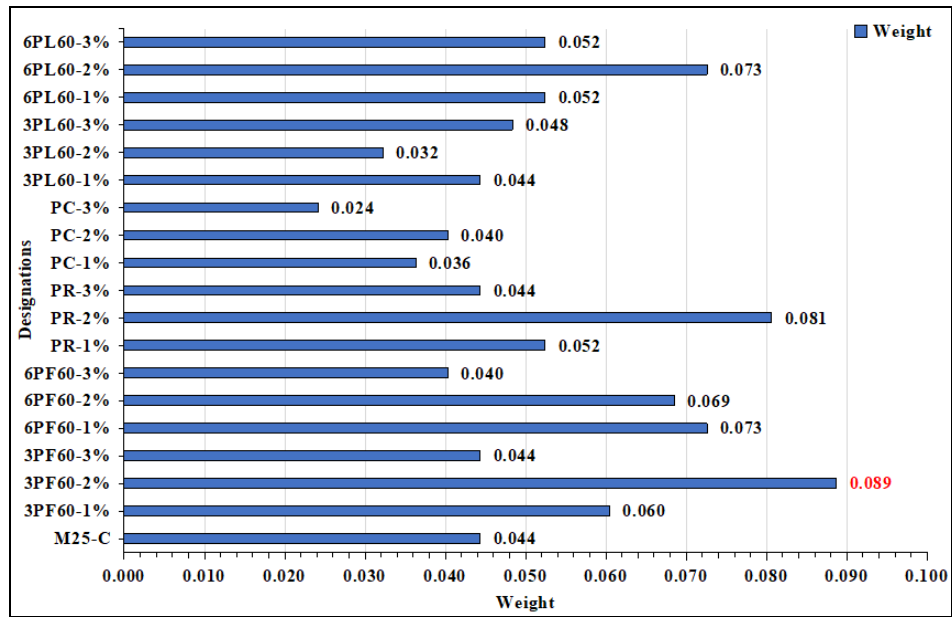


Figure 8 Ranking of mixes (see online version for colours)



Furthermore, the study introduces the ductility index (D_i), which quantifies the material's capacity to deform under stress before ultimate failure. The D_i is calculated as the ratio of the ultimate energy absorbed (total energy at failure) to the initial energy absorbed at the

first crack. This index is significant because it reflects not only the concrete's strength but also its ability to undergo deformation, or ductility, before failure. A higher D_i value indicates that the concrete can absorb and dissipate greater energy, enhancing its overall impact resistance and structural resilience. In this study, the traditional concrete (control mix) displayed a D_i value of 1.571, indicating a relatively brittle response under impact. In contrast, the 3PF60 mix achieved the highest D_i value of 2 among all tested variations, highlighting its superior ductility and enhanced energy absorption capacity. This means the 3PF60 mixture can absorb a significantly higher amount of energy before failure compared to the control mix. The tested disc specimens after final failure are depicted in Figure 6.

Although the 6PF60 mix also showed a D_i value of 2, the nature of failure in this mix was different. The specimens failed by crushing, indicating weaker bonding between the PET waste and the concrete matrix. This demonstrates that the 6PF60 mix had a higher capacity to absorb energy but failed in a more brittle manner, which may not be desirable in certain applications. The results for the PC mix were particularly noteworthy, as its D_i value was even lower than that of the control mix, indicating that the addition of PET waste to this mixture did not enhance its impact strength. This further underscores the need for careful consideration of the mix composition to achieve the desired material properties. In conclusion, the findings in Table 3 emphasise the significance of proper PET waste proportion, fibre width, and their bonding with the concrete matrix in determining impact resistance and ductility. The 3PF60 mix, with 2% PET waste and effective fibre-matrix bonding, emerges as the most suitable mixture among those tested for enhanced impact resistance and ductility. These insights provide valuable guidance for the utilisation of PET waste in concrete mix design, contributing to more sustainable construction practices.

3.2 Ranking of tried mixes for selecting suitable combination of PET waste

The AHP tool is crucial for selecting the best concrete mix parameter from available options. It prioritises and helps choose the optimal decision from accessible alternatives. Using a hierarchical structure, AHP places the goal at the top, criteria at the second level, and alternatives at the bottom. It is widely used for complex decision-making. AHP determines the best priority among alternatives and resolves conflicts in decision-making, allowing for ranking while satisfying objectives. The following steps given in Figure 7 were followed to identify the mix weights for all experimented mixes.

- 1 Pairwise comparison using experimental data of impact strength values for attributes 'i' and 'j' through normalisation with matrix size $M = 19$.
- 2 Geometric mean calculation and normalisation for relative weights using equation (2) and equation (3).

$$\text{Geometric mean } (GM_j) = \left[\prod_{j=1}^M b_{ij} \right]_{1/M} \quad (2)$$

$$\text{weight of each attribute} = W_j = \left[GM_j / \sum_{j=1}^M GM_j \right] \quad (3)$$

Table 4 presents the ranking of concrete mixes based on the impact energy absorbed at the final failure of the disc. Each impact energy value is assigned a standardised weight

and compared with all other results using pairwise comparison, ensuring that the diagonal elements of the matrix are set to 1. The highest weight value is obtained for 3PF60-2%, which is 0.089 as shown in Figure 8. The optimal percentage of PET waste to be added is found to be 2%, and the mix with PF of size 3 mm × 60 mm exhibits the highest impact energy, earning the top rank among all other tested mixes. These results align with the experimental findings, demonstrating that adding 2% of PET waste to the concrete enhances impact strength and produces sustainable concrete.

4 Conclusions

This experimental investigation was conducted with the primary objective of augmenting the impact strength of concrete through the incorporation of discarded PET bottles. Furthermore, the study aimed to advance sustainable concrete production by efficiently utilising this waste material, thus offering ecological advantages. The following key conclusions have been drawn from the study:

- 1 The disparity in the number of blows required for initial crack and final crack formation in the controlled concrete was not statistically significant. This can be attributed to the inherent brittleness of non-fibrous concrete, which results in lower resistance to impact loading.
- 2 The impact resistance to initial crack showed improvement with an increase in PET waste content up to 2%. Beyond this percentage, a decrease in strength was observed. Among all the PET waste variations, 3PF60 exhibited the best performance, followed by 6PF60, PR, and 6PL60. Notably, the inclusion of PC demonstrated an enhancement in resistance to both initial and final cracks compared to the controlled concrete.
- 3 The addition of PL did not substantially enhance impact strength but did contribute to improved ductility observed in the failed specimens.
- 4 The application of the MCDM tool facilitated pairwise comparisons, leading to the identification of 3PF60 with a 2% addition of PET waste as the most suitable PET waste for enhancing the impact resistance of concrete. And therefore, 3PF60 at 2% addition of PET waste is the best suggested mix among all tried 18 mixes.

This study has successfully showcased the positive impacts of integrating PET waste into concrete, resulting in increased structural impact strength. This approach not only addresses the issue of PET waste reduction but also plays a role in mitigating pollution caused by discarded plastic bottles in both terrestrial and aquatic environments.

5 Scope for future studies

Expanding on the experimental findings of this study, several avenues for future research could further enhance the application and understanding of PET waste in concrete.

- 1 Optimisation of PET fibre geometry and proportion: further studies could focus on optimising the shape, size, and distribution of PET fibres to achieve even greater improvements in impact resistance and ductility. Varying fibre geometries and

studying their bonding characteristics within the concrete matrix could yield insights into maximising material performance.

- 2 Long-term durability of PET-enhanced concrete: investigate the long-term durability of concrete with PET waste under different environmental conditions, such as exposure to moisture, temperature variations, and chemical agents. This would help determine the structural viability and resilience of PET-incorporated concrete over time.
- 3 Exploration of hybrid reinforcement approaches: future studies could explore combining PET waste with other sustainable materials, such as recycled steel fibres or natural fibres, to enhance both the mechanical properties and environmental benefits of concrete.

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