

Influence of fly ash and polypropylene fiber on raveling resistance, sound absorption, and environmental impact of porous concrete

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ABSTRACT

This study investigates the influence of fly ash (FA) and polypropylene (PP) fiber on raveling resistance, sound absorption, and environmental impact of porous concrete. Four mixtures were prepared, including a reference mix (RM), a PP fiber-reinforced mix (M1), and two mixes incorporating FA at 15% (M2) and 30% (M3) substitution levels. Durability was assessed by the raveling resistance, sound absorption coefficient (SAC) by an impedance tube, and environmental performance by embodied energy (EE) and carbon footprint (CF), with efficiency indices calculated. Results indicate that PP fibers decreased the mass loss by 42% compared to RM and improved SAC values up to 0.92 at 630 Hz, reflecting enhanced raveling resistance and mid-frequency absorption. In contrast, FA substitution reduced EE from 2571.8 MJ/m³ (RM) to 2369.0 MJ/m³ (M3) and lowered CF from 452.9 to 363.9 kgCO₂-eq/m³, representing up to 19.6% environmental improvement, but increased mass loss and reduced SAC when combined with PP fibers. Overall, PP fibers primarily enhanced durability and acoustic efficiency, whereas FA provided clear environmental benefits, though trade-offs emerged when used together.

Keywords: porous concrete, fly ash, polypropylene fiber, raveling resistance, sound absorption properties, environmental efficiency index.

INTRODUCTION

Noise pollution has emerged as one of the most critical environmental challenges in modern urban societies, largely due to rapid industrialization, increasing traffic density, and the intensification of human activities. Prolonged exposure to high noise levels has been linked to negative health impacts, including stress, sleep disturbances, and cardiovascular diseases, while also reducing the quality of life in residential and urban environments (Arenas et al., 2022).

To address this issue, porous concrete has recently gained attention as a multifunctional material that can simultaneously serve as a road pavement (Mikhailenko et al., 2022; Shafabakhsh and Ahmadi, 2016) and a noise absorption fence (Wang and Zhao, 2015). The acoustic efficiency

of porous concrete is largely governed by its pore ratio, tortuosity, thickness, and internal acoustic impedance, which collectively determine its ability to absorb and attenuate sound waves across various frequencies. The sound absorption coefficient (SAC) of porous concrete has been studied by Kapicová et al. (2024), Su et al. (2023), and Zhang et al. (2020; 2020), highlighting its importance as a key acoustic parameter in evaluating porous concrete performance.

Another crucial factor in porous concrete is mechanical performance, particularly in relation to the stability of its pore network under long-term service conditions. Mechanical abrasion and environmental weathering can cause aggregate dislodgement and mass loss, thereby reducing durability. The Cantabro test, widely applied to assess raveling resistance, has been emphasized

as an essential durability evaluation method by Gaedicke et al. (2014), Sandoval and Peralisi (2023), and Sherfenaz et al. (2025).

From a materials perspective, fly ash (FA), a by-product of coal combustion, has been widely studied as a partial substitute for cement due to its pozzolanic activity and significant environmental benefits (Chen and Wang, 2022; Sai Giridhar Reddy et al., 2017). The use of FA in concrete has been reported by Ekaputri et al. (2024), Khankhaje et al. (2023), and Saboo et al. (2019), demonstrating its potential to enhance performance while reducing environmental impact. In addition, polypropylene (PP) fibers have been introduced in concrete technology to improve tensile strength, crack resistance, and overall toughness. In porous concrete, PP fibers can enhance the binding capacity between aggregates and cement paste, mitigating aggregate dislodgement and improving long-term durability under mechanical and environmental stresses (Liu et al., 2022).

Equally important in evaluating the feasibility of porous concrete noise barriers is the consideration of environmental impacts through embodied energy and carbon footprint assessment. Embodied energy refers to the cumulative energy required to extract, process, and manufacture construction materials, while carbon footprint accounts for the associated greenhouse gas emissions (Asdrubali et al., 2017). Cement production is known to be energy-intensive and a significant source of CO₂ emissions, whereas FA, as an industrial by-product, has substantially lower embodied energy values (Chen and Wang, 2022). The substitution of cement with FA therefore reduces both energy consumption and environmental impact. Similarly, although PP fibers possess relatively high embodied energy, their low dosage in concrete mixtures minimizes their overall effect, while simultaneously extending the service life of porous concrete by improving durability.

In light of the above, this study seeks to explore the potential of porous concrete as a noise absorption fence by incorporating FA and PP fibers into its mixture. The study aims to establish correlations between mass loss as raveling resistance derived from the Cantabro test, acoustic properties measured through impedance tube testing, and environmental performance assessed via embodied energy and carbon footprint analysis, complemented with the efficiency indicator that integrates durability and environmental

impact. By bridging mechanical durability, acoustic efficiency, and sustainability evaluation, this investigation contributes to advancing the development of multifunctional porous concrete materials. The novelty of this study lies in the simultaneous integration of durability, acoustic performance, and environmental assessment into a unified framework, offering new insights into the design and optimization of porous concrete for noise barrier applications.

MATERIALS AND METHODOLOGY

Materials

Coarse aggregate

Crushed stone derived from the mechanical crushing of boulders and stones sourced from the Jeneberang River in South Sulawesi, Indonesia, was utilized as coarse aggregate in all mixtures. The aggregate exhibited a bulk specific gravity (SSD) of 2.52, a water absorption capacity of 1.47%, and an abrasion resistance of 26.03%.

Blended cement and fly ash

The primary cementitious material in all of the mixtures in this investigation was blended cement made by a national cement manufacturer using SNI 7064-2014 (Indonesian National Standard for Portland Composite Cement) (SNI 7064, 2014). The physical properties of blended cement had blaine fineness of 383 m²/kg. It achieved a 28-day compressive strength of 40.11 N/mm². The initial and final setting times were 132.4 and 197 minutes, respectively, within the acceptable range of 45–375 minutes. Furthermore, the cement exhibited a normal consistency of 25.14%, an air content of 11.6%, and a specific gravity of 3.03.

The fly ash used in this study was acquired from one of the power plants operating in the province of South Sulawesi, Indonesia. The fly ash particles used in this study were able to pass the 200-sieve test. Table 1 shows the chemical compounds on the blended cement and fly ash used in this study.

Mix design

Table 2 presents the composition of four mixes formulated in this investigation. The reference mix (RM) was formulated using a combination of

Table 1. Chemical compounds of binders

Compound	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	CaO	SO ₃	MgO	LOI
Blended cement	18.41	5.17	3.16	61.81	1.83	1.01	4.63
Fly ash	58.69	17.11	10.29	5.09	0.60	4.49	0.73

Table 2. Mix design composition

Mix ID	Coarse aggregate (kg)	Blended cement (kg)	Fly ash (kg)	Water (kg)	PP fiber (kg)
RM	1526.85	381.71	0.00	133.60	0.00
M1	1526.85	381.71	0.00	133.60	1.14
M2	1526.85	324.46	57.26	133.60	1.14
M3	1526.85	267.20	114.51	133.60	1.14

cement, water, and coarse aggregate, aiming for a target compressive strength of 8 MPa. The second mix (M1) utilized polypropylene fiber. The third mix (M2) and fourth mix (M3) employed PP fiber with fly ash as a substitute for blended cement. Fly ash was utilized as a substitute for cement at 15% and 30% in M2 and M3, respectively.

Raveling resistance test

The raveling resistance of concrete was assessed using the Cantabro test, which provides a quantitative measure of material durability through the evaluation of mass loss. This method has been widely employed to simulate the mechanical abrasion and wear mechanisms that occur under actual service conditions, such as traffic loading and environmental exposure (Thomas et al., 2016). The test was carried out with a Los Angeles abrasion device consisting of a rotating drum, where specimens were placed without steel balls to isolate the effect of abrasion from impact forces. The drum was rotated at a controlled speed of 30–33 revolutions per minute (rpm) for a fixed number of cycles. The percentage of mass loss in porous concrete was calculated using Equation 1.

$$\text{Mass loss (\%)} = \frac{w_1 - w_n}{w_1} \quad (1)$$

where: w_n is the mass of the specimen after the n rotation (kg), and w_1 is the initial mass of the specimen before testing (kg).

Sound absorption properties

Sound absorption was evaluated using the impedance tube method in accordance with ISO 10534-2, a standard widely recognized for precise acoustic characterization (Standardization, 2001). The experimental setup as shown in

Figure 1, consisted of a cylindrical tube where the specimen was tightly fitted at the middle part of tube. Sound waves ranging from 100–3000 Hz were transmitted (Zhang et al., 2020a; 2020b), and the sound level was measured using two noise intensity meter positioned 5 cm each before and after the specimen. The sound absorption coefficient (α_0) was calculated using Equation 2, where values near unity indicate high absorption.

$$\alpha_0 = \frac{4 \cdot 10^{\Delta L/20}}{(1 + 10^{\Delta L/20})^2} \quad (2)$$

where: α_0 represents the sound absorption coefficient, and ΔL is the difference between the maximum and minimum noise intensity pressure (dB).

Environmental assessment

The environmental performance of the porous concrete mixtures was evaluated through the calculation of embodied energy (EE) and carbon footprint (CF). Embodied energy refers to the total primary energy required throughout the life cycle of material production, encompassing raw material extraction, processing, transportation, and manufacturing (Asdrubali et al., 2017). In parallel, the carbon footprint represents the greenhouse gas (GHG) emissions associated with these processes, expressed in terms of CO₂-equivalent emissions (Chen and Wang, 2022). The embodied energy and carbon footprint of each mixture was calculated using Equations 3–4, where the values of raw materials were sourced from published databases and are summarized in Table 3.

$$EE_{\text{mix}} = \sum_{i=1}^n (w_i \times EE_i) \quad (3)$$

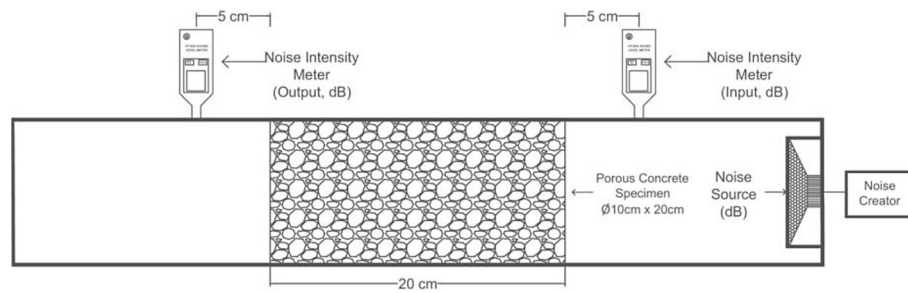


Figure 1. Sound absorption testing setup

$$CF_{\text{mix}} = \sum_{i=1}^n (w_i \times CF_i) \quad (4)$$

where: EE_{mix} is the total embodied energy of mix- i (MJ/m^3), CF_{mix} is the total carbon footprint of mix- i ($\text{kgCO}_2\text{-eq}/\text{m}^3$), EE_i is the embodied energy value of each material (MJ/kg), CF_i is the carbon footprint value of each material ($\text{kg CO}_2\text{-eq}$), and w_i is the weight of each material in 1 m^3 (kg).

To further capture the efficiency of environmental performance, an environmental efficiency index (EEI) was introduced by normalizing the durability performance against environmental impact values. This efficiency metric was expressed as the ratio of mass loss derived from raveling resistance test to embodied energy or carbon footprint of mixtures.

RESULTS AND DISCUSSIONS

Visual observation

Figure 2 displays the visual appearance of porous concrete. There is no evidence of coarse aggregate segregation, paste bleeding, or exterior cracks in any of the specimens, as determined by visual examination. During the pouring and compacting processes, it was discovered that the paste had the ability to retain the coarse aggregate and PP fiber in the appropriate manner, regardless of

whether or not it included FA, which further prevented any faults from forming.

Raveling resistance

Figure 3 shows the mass loss, which reflects the raveling resistance obtained from the Cantabro test of porous concrete specimens over the course of 250 rotations. At 50 rotations, all mixtures (RM, M1, M2, and M3) demonstrated comparable resistance to mass loss, remaining below 25%. The respective mass loss percentages were 22.0% for RM, 12.7% for M1, 13.9% for M2, and 19.0% for M3. These results suggest that, in the early stages of abrasion, the incorporation of polypropylene fibers and FA substitution had a minor yet positive effect on reducing the rate of mass loss, with M1 and M2 exhibiting slightly improved performance compared to the reference mixture.

However, as the number of rotations increased, particularly at the 100-rotation mark, more pronounced differences in mass loss patterns began to emerge. As shown in Figure 4, M3, which included the highest level of FA substitution (30%), experienced substantial mass loss, reaching 70.4%. This decline sharply contrasted with the more stable performance of the other mixtures: RM exhibited a mass loss of 32.6%, M1 recorded 19.6%, and M2 had 28.5%.

As the number of rotations reached 250, the deterioration of all mixtures continued, with M3 undergoing the most severe damage, losing up to 97.2% of its mass. By comparison, the reference

Table 3. Embodied energy and carbon footprint of materials

Material	Coarse aggregate	Blended cement	Fly ash	Water	PP fiber
Energy (MJ/kg)	0.069	6.461	3.921	0.002	77.24
Carbon footprint ($\text{kgCO}_2\text{-eq}$)	0.0041	1.17	0.362	0	3.1
Reference	(Chen and Wang, 2022)	(Chen and Wang, 2022)	(Chen and Wang, 2022)	(Kurda et al., 2018)	(Liu et al., 2022)

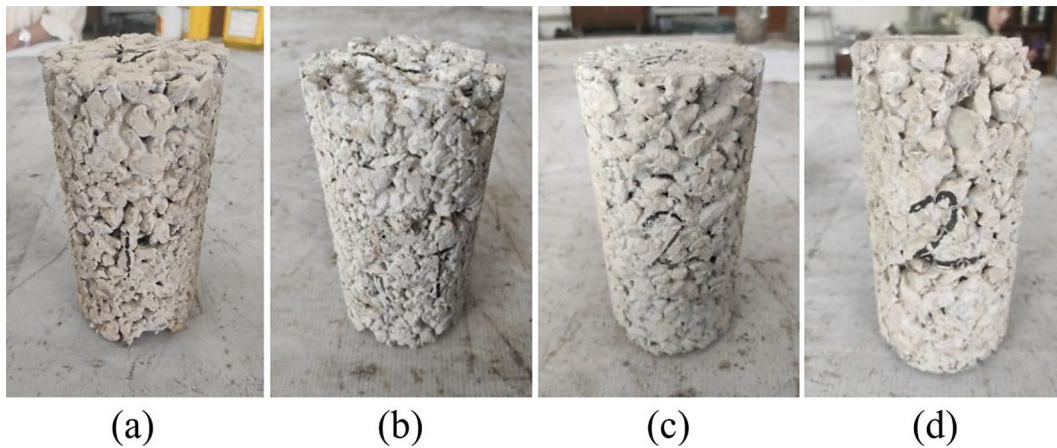


Figure 2. Visual of specimen for each mixture: (a) RM, (b) M1, (c) M2, and (d) M3

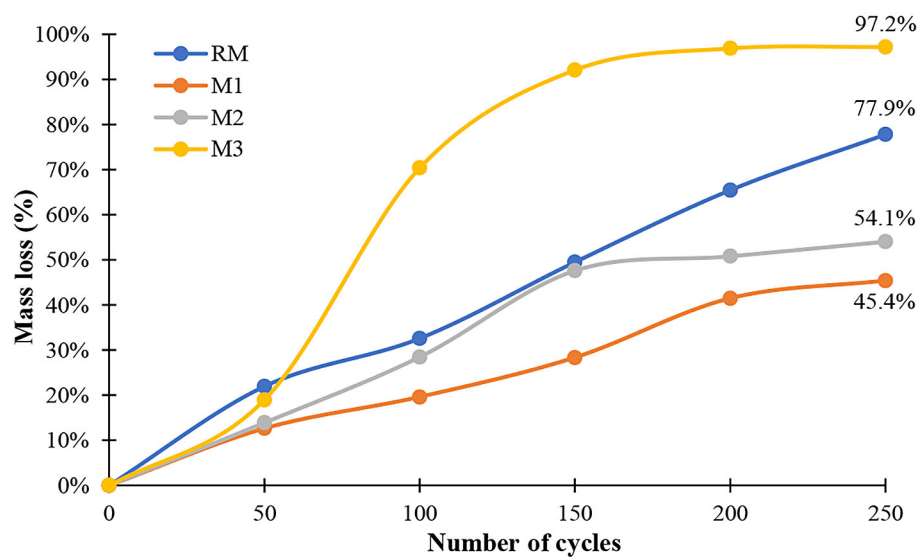


Figure 3. Mass loss of porous concrete for each mixture

mixture showed a mass loss of 77.9%, while M1 and M2 demonstrated superior durability, with mass losses of 45.4% and 54.1%, respectively.

The mass loss findings for M2 and M3, elevating the proportion of cement substitution with FA resulted in a consistent reduction in the raveling resistance of porous concrete. A plausible rationale for this decrease in raveling resistance is that the quantity of calcium hydroxide in the cement paste becomes inadequate to bind the pozzolanic silica (Tural et al., 2024), potentially resulting in diminished bonding strength between the cement paste and coarse aggregate.

Sound absorption coefficient

Figure 5 illustrates the sound absorption coefficient (SAC) of the mixtures (RM, M1, M2, and

M3) across the frequency range of 100–3000 Hz. The results indicate that all mixtures achieved relatively high absorption in the mid-to-high frequency domain, with notable peaks between 630 Hz and 2000 Hz. The highest SAC values were recorded at 0.985 for M1 at 800 Hz, 0.874 for M2 at 630 Hz, 0.903 for M3 at 630 Hz, and 0.876 for RM at 630 Hz. In comparing the mixtures, M1, which incorporated polypropylene fiber, demonstrated the most favorable acoustic response overall, especially at mid-to-high frequencies. Conversely, M2 and M3, which included fly ash as a cement substitute at 15% and 30% respectively, generally exhibited lower SAC values than M1 and in several cases also lower than RM. For example, at 100 Hz, the SAC of M2 (0.035) and M3 (0.119) was below that of RM (0.109), whereas M1 remained lower at 0.085. Despite

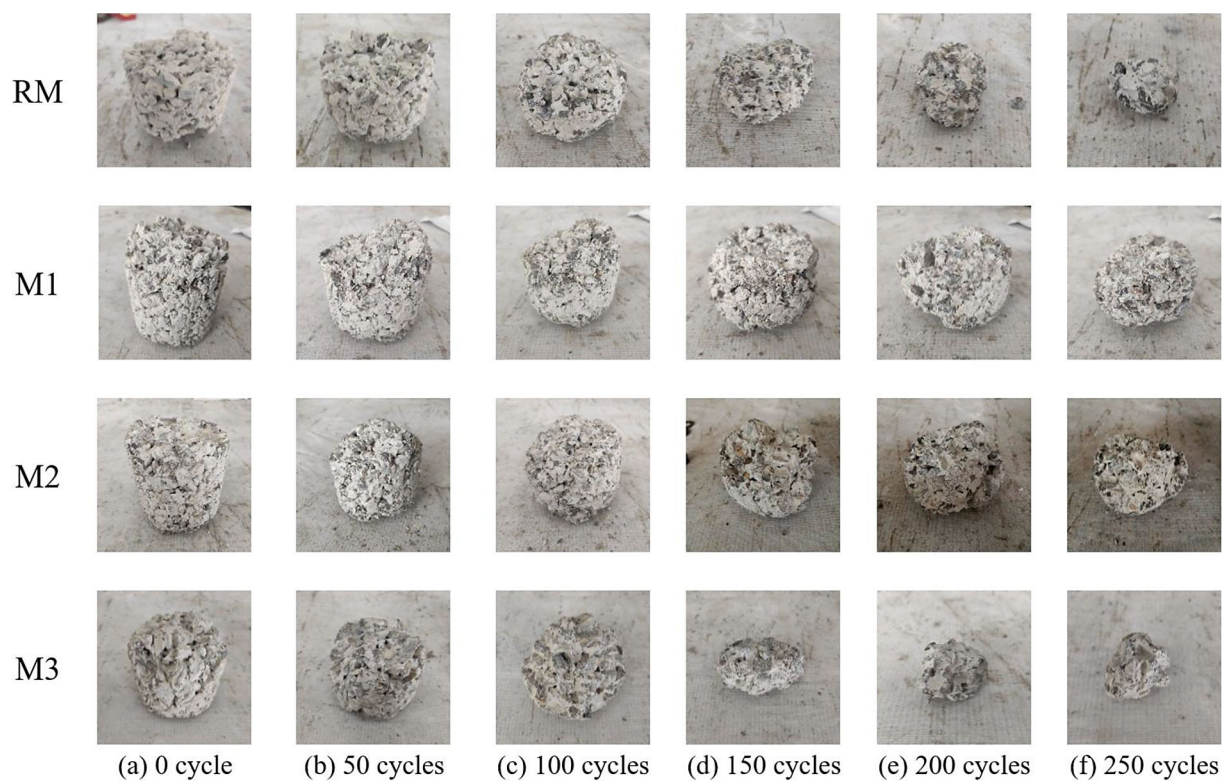


Figure 4. Degradation of porous concrete specimen over time

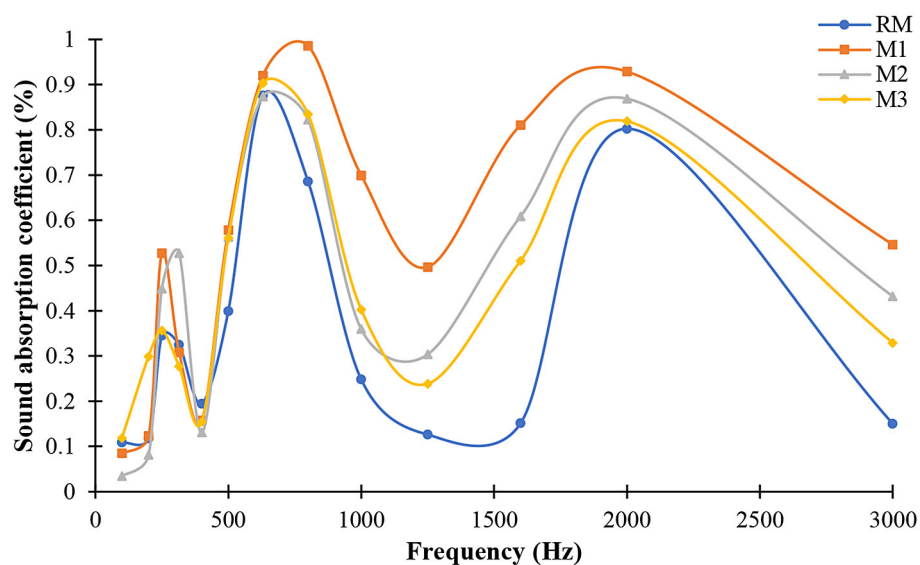


Figure 5. Sound absorption coefficient

these differences, all mixes achieved comparable peak SAC values above 500 Hz, where the performance gap narrowed. It is also worth noting that the porosity values of the mixtures, reported as 28.33% for RM, 33.71% for M1, 30.77% for M2, and 29.96% for M3, followed a similar trend with SAC, reinforcing the relationship between mixture composition and acoustic behavior.

A key observation is that the addition of PP fiber alone in M1 significantly enhanced SAC, as evidenced by its superior performance at critical frequency ranges such as 800 Hz (0.986) and 630 Hz (0.920), compared to RM at the same frequencies (0.686 and 0.876, respectively). This improvement can be attributed to the role of PP fibers in increasing the heterogeneity of the

concrete matrix and facilitating multiple internal reflections of sound waves, thereby improving dissipation. However, when PP fiber was combined with FA in M2 and M3, the SAC values decreased compared to M1. The combination appears to reduce the efficiency of acoustic energy absorption, suggesting that while PP fibers enhance sound absorption, the simultaneous incorporation of FA counteracts this effect by modifying the pore structure and diminishing effective pathways for sound dissipation through the filler action of FA (Bright et al., 2023).

Environmental assessment

Figure 6 presents the results of the environmental assessment in terms of carbon footprint (CF), embodied energy (EE). The reference mix recorded a total CF of 452.86 kgCO₂-eq/m³ and EE of 2571.85 MJ/m³. Incorporation of PP fiber in M1 slightly increased the CF to 456.39 kgCO₂-eq/m³, representing a rise of 0.78% compared

to RM, while EE also rose to 2659.90 MJ/m³, equivalent to an increase of 3.42%. In contrast, the partial replacement of cement with FA in M2 reduced the CF to 410.14 kgCO₂-eq/m³ (a decrease of 9.42%) and EE to 2514.53 MJ/m³ (a decrease of 2.23%). The most notable improvement was observed in M3, with CF declining to 363.87 kgCO₂-eq/m³ (a reduction of 19.63%) and EE decreasing to 2369.05 MJ/m³ (a reduction of 7.88%) relative to RM. These results clearly indicate that the synergistic use of FA and PP fiber contributes to mitigating environmental burdens across the mixtures.

Figure 7 shows environmental efficiency indexes (EEI-CF and EEI-EE). When comparing the EEI values, the introduction of PP fiber alone in M1 markedly reduced EEI-CF and EEI-EE to 0.00099 and 0.00017, respectively, compared to 0.00172 and 0.00030 in RM. This indicates an apparent improvement in environmental efficiency despite the higher CF and EE totals, suggesting

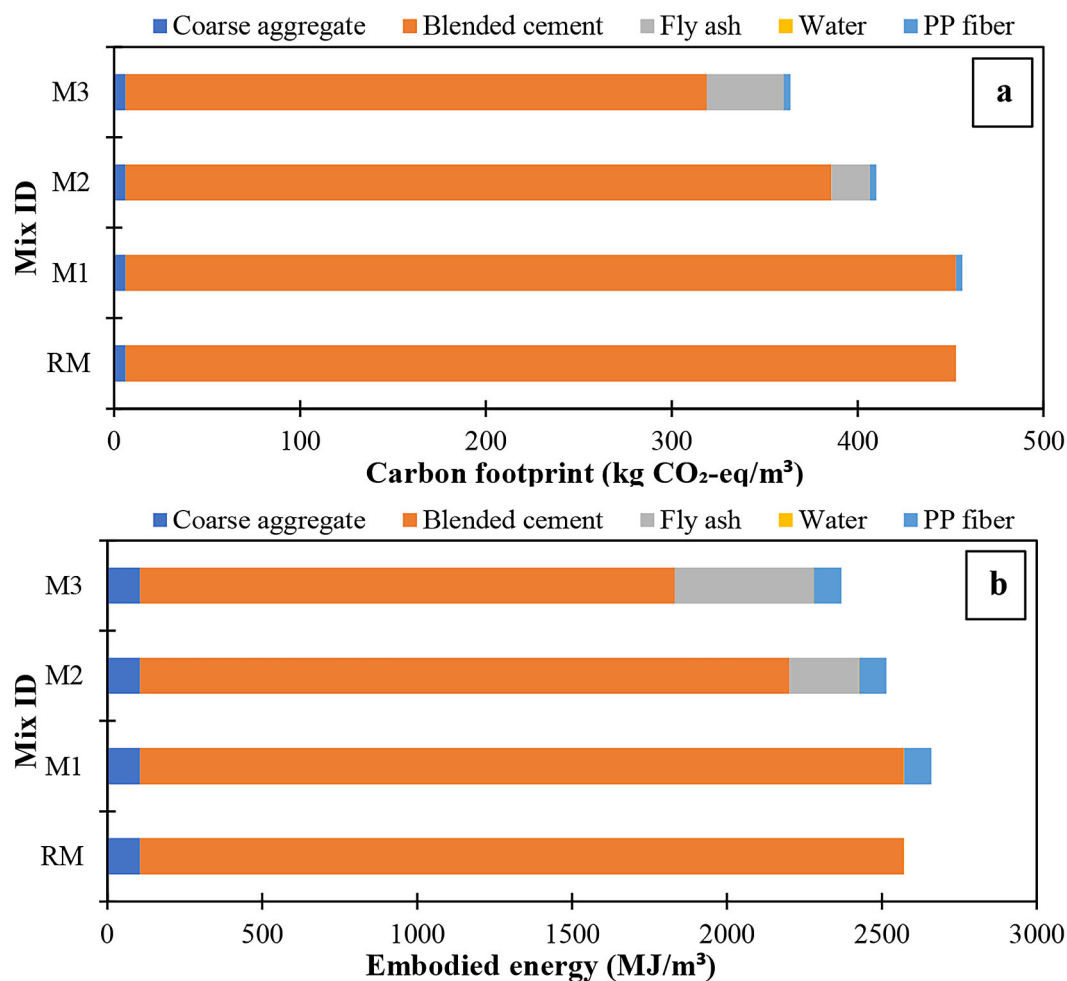


Figure 6. (a) embodied energy, and (b) carbon footprint of porous concrete

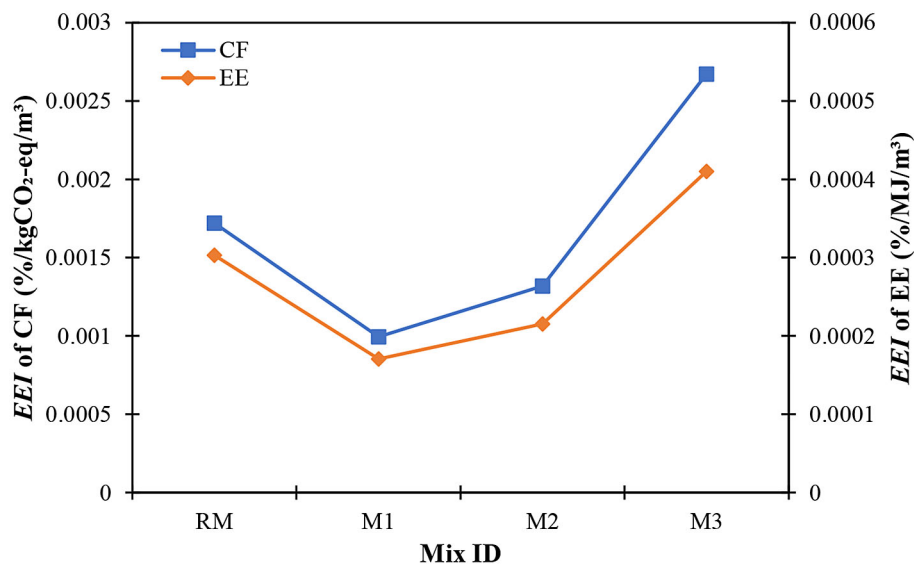


Figure 7. Environmental efficiency index of porous concrete

that PP fibers enhance performance sufficiently to offset the added energy demand. However, in M2, EEI-CF and EEI-EE increased moderately to 0.00132 and 0.00022. Conversely, M3 exhibited the highest EEI-CF (0.00267) and EEI-EE (0.00041), implying that while its absolute CF and EE values were lowest, the efficiency index penalized the larger cement reduction combined with PP fiber, possibly due to the disproportionate weighting of energy-intensive fibers.

The observed trends can be explained by material-level mechanisms. The increase in CF and EE with PP fiber addition (M1) originates from the high production energy and carbon intensity of synthetic polymers, which outweighed the savings achieved through enhanced durability and performance (Yin et al., 2016). On the other hand, the substitution of cement with FA in M2 and M3 significantly reduced both CF and EE, as cement is the most carbon- and energy-intensive constituent in concrete production (Chen and Wang, 2022; Meshram and Kumar, 2022; Shen et al., 2015; Worrell et al., 2001).

CONCLUSIONS

Based on the experimental results and analyses, several key findings can be highlighted:

1. The addition of polypropylene fibers significantly improved durability, reducing Cantabro mass loss by up to 42% compared to the reference mix.

2. PP fibers enhanced acoustic performance, with the sound absorption coefficient reaching 0.92 at 630 Hz, indicating superior mid-frequency absorption.
3. Fly ash substitution at 15–30% reduced embodied energy from 2571.8 MJ/m³ (RM) to 2369.0 MJ/m³ (M3) and lowered carbon footprint from 452.9 to 363.9 kgCO₂-eq/m³, achieving up to 19.6% improvement in environmental performance.
4. Despite these environmental benefits, FA substitution decreased durability, as indicated by increased Cantabro mass loss relative to the fiber-only mix, and reduced SAC values in the 630–800 Hz range (0.83–0.87).
5. The combination of PP fibers and FA minimized environmental burdens but introduced trade-offs, lowering both raveling resistance and acoustic efficiency.
6. Overall, PP fibers provided mechanical and acoustic benefits, whereas FA contributed to environmental sustainability.

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