FIBRE-REINFORCED CEMENT AS A SOURCE OF MICROPLASTICS AND THEIR POST-RELEASE BEHAVIOUR

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The construction industry consumes vast amounts of plastics, but has in recent decades embraced the circular economy principles increasingly. Nevertheless, these materials degrade throughout their life cycle, and represent a non-negligible source of microplastics, contributing to one of today's major environmental challenges. In this study we investigated the generation and properties of microplastics released from cementitious composites reinforced with polypropylene (PP) and recycled polyethylene terephthalate (rPET) fibres. The two degradation scenarios (simulated wear and demolition) produced distinct particle size ranges, spanning from long fibres to fine fragments. Cement adhesion to the fibres, governed by their surface morphology and functionalisation, was identified as a factor capable of altering key properties such as the contaminant-dependent density. Complementary leaching experiments showed further that functionalised fibres exhibit a high potential for releasing organic substances. Overall, our findings highlight the need to consider multiple aspects of microplastics derived from fibre-reinforced cement when assessing their environmental implications.

DOI
https://doi.org/10.18690/um.fkkt.1.2026.9

ISBN
978-961-299-130-2

Keywords:
microplastics,
fibre-reinforced cement,
construction materials,
circular economy,
environmental impact

University of Maribor Press

1 Introduction

Plastics have transformed modern life, becoming indispensable due to their versatility, processability, low weight, and, above all, affordability. These properties have not only contributed to technological progress and improved quality of life but, in some cases, even reduced environmental impacts by lowering energy consumption and substituting other problematic materials (Hinton et al., 2022). In 2022, global plastic production exceeded 400 Mt (Plastics Europe, 2024), and projections estimate it may reach around 590 Mt by 2050 (*Global Plastic Production*, 2023). The scale of industry, dominated by short-lived products, remains tied strongly to fossil fuel dependence, the generation of vast and poorly managed waste streams, and the resulting pollution of ecosystems worldwide (Hinton et al., 2022). Because of this pervasive and persistent contamination, researchers refer increasingly to the present era as the "plastic age" (Porta, 2021; Stoett et al., 2024).

Within the framework of sustainable development, the circular economy has emerged as one of the central strategies. Beyond reducing environmental burdens, it also emphasises the recognition of plastic waste as a secondary resource for new products, thereby decreasing the demand for virgin raw materials (Shamsuddoha & Kashem, 2024). Among the industries where such circular solutions are particularly promising, construction stands out, due to its massive plastic demand and long product lifespans. Although progress remains slow and the development, as well as implementation of secondary raw materials, are limited (Awoyera & Adesina, 2020), the share of post-consumer recycled plastics has increased substantially, rising by 70% between 2018 and 2022 (Plastics Europe, 2024). This trend is especially significant for construction, which already accounts for 22.9% of recycled plastic use in Europe (Plastics Europe, 2024).

The construction sector, the world's second-largest consumer of plastics (Plastics Europe, 2024), uses polymer-based materials not only as structural and protective components, but also as reinforcement or fillers in composites to improve their performance (Agarwal & Gupta, 2017). One example is the incorporation of polymer fibres into cement, which is the most commonly used material for fibre reinforcement compared to steel and glass (Ochigue et al., 2025). They improve tensile strength and crack resistance, resulting in more durable building materials, while contributing to lightweight properties and competitive costs (Concrete

Reinforcing Fibre Market Size, Share, 2025). For instance, polymeric fibres lower the amount of steel reinforcement required in concrete pipes exposed to aggressive environments such as sanitary sewers (Peyvandi et al., 2014), while also addressing the problem of steel corrosion (Prasittisopin, 2025).

Polymeric fibres incorporated into cementitious matrices can originate from both virgin and recycled plastics. The incorporation of recycled polymers into construction materials is gaining significant momentum, with the construction sector currently showing the fastest growth in recycled plastic uptake among all the industries (Plastics Europe, 2024). This trend is also driven by increasing legislative pressure to improve recycling rates and reduce waste generation (Horvat et al., 2024). The use of secondary fibres therefore represents a promising approach to achieving high-performance, yet more sustainable composites, in line with the objectives of the EU Circular Economy Action Plan, which encourages circularity and greater use of secondary raw materials in construction (European Commission, 2020). At the same time, fundamental questions remain regarding the stability and durability of these materials and potential environmental trade-offs, including the release of microplastics at various stages of the material's life cycle, from production and use to demolition and subsequent waste handling.

Despite being engineered for long-term durability, construction materials containing plastics inevitably undergo gradual degradation. Mechanical wear, UV exposure and other ageing processes facilitate the breakdown of plastics, leading to the formation and release of microplastics (Yuk et al., 2022), defined as insoluble synthetic polymer particles ranging from 1 µm to 1000 µm (*ISO 24187*, 2023). In the case of fibre-reinforced cement materials, microplastic can detach from the surface of concrete paving blocks as they undergo abrasion and weathering, subsequently entering the environment through urban runoff (Smyth et al., 2025). Furthermore, demolition activities increase microplastic release markedly, as the breaking and crushing of concrete liberate fine particles that can disperse through the air or leach into the surrounding media (Prasittisopin et al., 2023). It has been reported that demolition processes generate substantially higher levels of particulate matter than those observed during regular service life, contributing significantly to air pollution and its associated adverse health effects (Cheng et al., 2021).

Due to their widespread occurrence, persistence and potential impacts on ecosystems and human health, microplastics have become one of the most pressing environmental challenges of recent decades (Ghosh et al., 2023). However, research efforts within the field of microplastics are highly uneven across the sectors. Despite being one of the largest consumers of plastics, the construction industry has received little scientific attention, even though the Irish Environmental Protection Agency (Mahon et al., 2017) highlighted it as potentially the most hazardous sector in terms of microplastic generation. Between 2004 and 2024, construction was mentioned in only 0.6% of all microplastic-related publications (Turk et al., 2025). At the same time, the issue is largely overlooked within the construction industry itself. While much emphasis is placed on reducing CO_2 emissions and improving energy efficiency, the potential release of microplastics from building materials and their environmental and health consequences has yet to receive comparable attention (Prasittisopin, 2025). This knowledge gap underscores the urgent need for focused research to understand better how construction materials, including fibre-reinforced cement, contribute to microplastic pollution, and how such emissions can be monitored and mitigated effectively.

In this study, we examined fibre-reinforced cement incorporating virgin polypropylene (PP) and recycled polyethylene terephthalate (rPET) fibres, focusing on the formation and characteristics of the resulting microplastics. Considering the growing use of recycled materials in construction, the two fibre types were compared, to determine how the fibre origin and composition affect cement adhesion and the properties of the generated microplastics. Microplastic particles from reinforcing fibres, which may form through abrasion or demolition of construction structures, were analysed further for their morphology and density, and leaching experiments were conducted to evaluate their potential influence on water chemistry, specifically, the total organic carbon (TOC).

2 Materials and methods

2.1 Materials

The experiments were carried out using 12 mm polypropylene fibres (f-PP) functionalised specifically for incorporation into cement-based materials as an additive to concrete or mortar. These fibres are manufactured in accordance with the harmonised technical specification EN 14889-2:2007 (European Committee for Standardisation (CEN), 2006). To reflect circularity considerations and the potential use of recycled materials in cementitious matrices, parallel experiments were also performed with 12 mm polyethylene terephthalate fibres (f-rPET) produced from recycled material. These fibres represent a newer product and are not yet used widely in construction applications; consequently, they have not been surface-functionalised specifically or tailored chemically for incorporation into cementitious systems such as concrete.

Because plastic materials ultimately fragment into microplastics, several analyses were also conducted on pre-prepared microfibres. Polyethylene terephthalate microfibres (μf-rPET) were obtained from the manufacturer as precision-cut fibres of 500 μm (produced from the same material as f-rPET). In contrast, the polypropylene microfibres (μf-PP) were produced in-house by cryogenic milling of the f-PP at -196 °C using a Cryogenic Mixer Mill CryoMill (Retsch GmbH, Germany) in three high-frequency milling cycles (60 s, 30 Hz), with intermediate cooling steps (30 s, 5 Hz) between the cycles.

2.2 Preparation of the cement prisms

The cement prisms were prepared by incorporating f-PP and f-rPET (2 vol%) into the cement matrix to produce fibre-reinforced composites. The fibres were first mixed homogeneously with the dry cement, after which water was added at a water-to-cement ratio (w/c) of 0.5. The mixture was cast into moulds, sealed to prevent moisture loss, and cured under closed conditions for 28 days at 23 ± 2 °C.

2.3 Simulation of surface abrasion and demolition

The release of microplastics from fibre-reinforced cement was simulated under controlled laboratory conditions, using two approaches to represent both the use phase and later demolition. The use phase was simulated through surface abrasion using a hand rasp. The rasp was cleaned thoroughly and fixed in a vice, with paper placed underneath to collect the released particles. The sample prisms were then rubbed manually against the rasp surface. To mimic the mechanical stresses associated with the demolition and subsequent processing of construction waste, the prisms were also subjected to fragmentation using a MixMill MM20 horizontal vibration ball mill (Domel, Slovenia). The cured prisms were first broken coarsely into pieces of approximately 0.5 g using a chisel and hammer. Milling was then performed with about 2.5 g of material and a single 25 mm stainless steel ball at a frequency of 10 Hz for 30 seconds per cycle, repeated until complete homogenisation was achieved. Following both treatments, microplastic fragments were detected visually under a stereo microscope SMZ-171 (Motic, China).

2.4 Assessing the amount of cement residues adhered to the fibres

The amount of cement adhering to the fibre surface was determined using scanning electron microscopy (SEM), JSM-IT500LV (Jeol, Japan). A controlled crack was induced in the cement prism using a chisel and hammer. The main cement mass was separated carefully, and the protruding fibres were trimmed near the fracture surface using fine scissors. The extracted fibres were transferred carefully onto SEM pin stubs and analysed to assess the morphology of the (micro)fibres and extent of the adhering cementitious material. To quantify the amount of cement attached to the fibres, a custom script was developed in Mathematica. High-resolution SEM images (2000× magnification) were pre-processed and binarised so that the fibre area appeared black (value 0), while the adhering cement residues appeared white (value 1). The surface coverage of fibres by cement was calculated based on the resulting pixel matrix.

2.5 Density measurement

The density of (micro)fibres without cement residues was determined using a 50 mL metal pycnometer and isopropanol. To minimise evaporation, the overflow opening for excess liquid was sealed immediately with a small piece of adhesive tape, and the pycnometer rim was additionally secured with Parafilm. The density of each sample was calculated according to Equation (1), where ϱ is the density of the (micro)fibres, ϱ_l is the density of the liquid, m_1 is the mass of the empty pycnometer, m_2 is the mass of the pycnometer filled with the (micro)fibres, m_3 is the mass of the pycnometer containing both the (micro)fibres and the liquid, and m_4 is the mass of the pycnometer containing the liquid. In addition, the floatability of the (micro)fibres was evaluated using the sink–flow method in a demineralised water and 5% NaCl solution to simulate seawater.

$$\rho = \rho_l \times \frac{m_2 - m_1}{(m_4 - m_1) - (m_3 - m_2)} \tag{1}$$

2.6 Leaching experiment

The leaching of chemical substances from (micro)fibres was conducted in 100 mL Erlenmeyer flasks. Approximately 3 g of (micro)fibres were mixed with 60 mL of demineralised water, corresponding to the standard TCLP solid-to-liquid ratio of 1:20 (U.S. Environmental Protection Agency, 1992). The mixtures were agitated on an orbital shaker at 300 rpm for 3 hours. After agitation, the suspensions were vacuum-filtered through Sartorius filter paper (grade 393). The resulting filtrates were collected in pre-cleaned glass vials and analysed for TOC using a multi N/C 3100 analyser (Analytik Jena, Germany).

3 Results and discussion

3.1 Microplastic generation under simulated wear and demolition

The abrasion simulation produced a fine powder consisting of fragmented cementitious material and short polymer fibres, with approximate dimensions of 400 μm and smaller. In contrast, the simulation of demolition by crushing followed by milling in a horizontal vibration mill under the applied conditions produced a distinctly different product. In this case, the polymer fibres embedded in the cement matrix did not necessarily fragment to the microplastic size range during the initial crushing phase. A microscopic examination revealed fibres ranging from the original 12 mm in length down to microscopic dimensions. Additionally, numerous fibres were observed to be entangled and interconnected by larger cement fragments forming aggregates. As an example, Figure 1 shows the microscopic images of the abraded, as well as the crushed and milled materials derived from the cement prisms with f-rPET.

Based on these observations, it can be concluded that mechanical wear and demolition processes generate microplastics through fundamentally different mechanisms, resulting in various particle size distributions and shapes of the resulting fragments. Abrasion causes primarily progressive surface erosion and fibre fragmentation, while demolition results mainly in the detachment of larger fibre–

cement aggregates that may later degrade into microplastics through secondary processes. These findings highlight the importance of simulating multiple degradation pathways when assessing the potential environmental release of microplastics from fibre-reinforced cement composites.

Figure 1: Microscopic images of the material obtained by abrasion (left) and by crushing followed by milling (right) of the cement prisms reinforced with f-rPET.
Source: own.

3.2 Adhesion of cement residues on the (micro)fibres

Based on quantitative surface coverage calculations using a custom-made program in Mathematica, the cement adhered more strongly to f-PP, with an average coverage of 13.4 ± 6.0 %, compared with only 2.4 ± 0.9 % for f-rPET, which is also evident from the SEM micrographs (Figure 2). The extent of cement adhesion to fibres is governed by a combination of mechanical, physical and chemical interactions that are interlinked closely. According to the adsorption theory, good interfacial bonding requires intimate contact between the adhering substrates, and arises from a combination of mechanical interlocking, electrostatic interactions, diffusion processes and adsorption/surface reactions at the interface (Pakravan et al., 2012).

The SEM images of f-PP revealed an intrinsically very smooth surface, which would generally limit mechanical interlocking with the cementitious matrix. In this context, the importance of appropriate surface functionalisation becomes evident. The f-PP used in this study were treated specifically, in accordance with EN 14889-2:2006 (European Committee for Standardisation (CEN), 2006), to enhance compatibility with cementitious materials and promote interfacial bonding. This surface modification likely contributed to the substantially higher cement coverage observed on f-PP, as it facilitates better wetting and stronger physicochemical interactions at the interface, thereby reducing the tendency of the matrix to slip along the fibre surface.

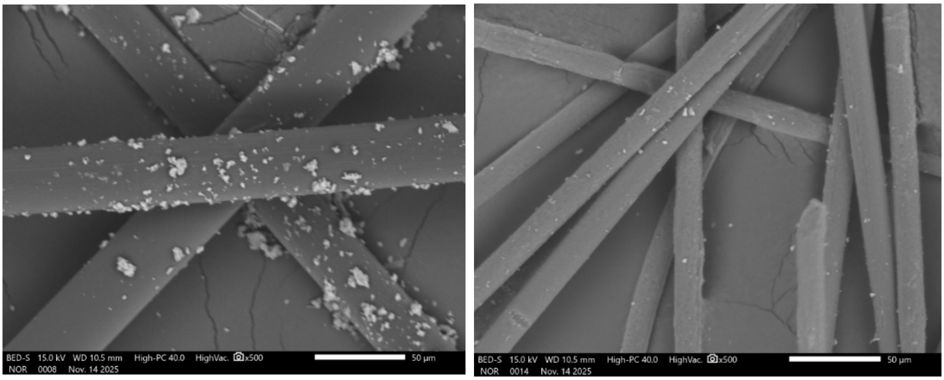

Figure 2: SEM images of f-PP (left) and f-rPET (right).
Source: own.

In contrast, the SEM images of f-rPET at higher magnification (2000×) showed a more irregular and less smooth surface. As these fibres were not functionalised specifically for cementitious applications their surface chemistry does not promote adhesion actively. It is therefore plausible that the limited cement attachment observed on f-rPET arises mainly from mechanical interlocking within these grooves and surface irregularities, rather than from tailored chemical interactions at the interface. In both cases, the cement residues were distributed unevenly along the fibre length, forming a heterogeneous pattern with localised clusters of cement particles separated by nearly clean fibre segments (Figure 2). The adhered residues also varied considerably in size, from fine particles to larger agglomerates, indicating that local microstructural conditions might influence the extent and quality of the fibre–matrix contact.

It is important to note that the strength of attachment of these residues remains unknown, and it is therefore unclear to what extent the attached particles would detach, for example, under mild mechanical stresses, such as sample handling and transport, or under environmental abrasion. This uncertainty is particularly relevant when considering the environmental behaviour of fibres and the microplastics derived from them, as the stability of cement residues on the fibre surface will affect the particle density, fragmentation pathways and, ultimately, their transport and fate in aquatic and terrestrial systems directly (Galafton et al., 2025).

3.3 Density

The density measurements obtained using the pycnometer showed satisfactory agreement with the values reported by the fibre manufacturers (Table 1), confirming the robustness of the applied pycnometry procedure and the choice of isopropanol over water as the measuring liquid. Due to the hydrophobic nature of plastics, the water did not wet the (micro)fibre surface adequately, which led to the trapping of visible air bubbles, and, consequently, to unreliable density measurements. In addition, PP has a lower density than water and therefore floated, contributing further to errors in the step where the excess liquid is displaced from the pycnometer. By contrast, isopropanol wetted the (micro)fibres effectively, reduced air entrapment, and, owing to its lower density, allowed all the (micro)fibres to sink to the bottom of the measuring vessel.

Table 1: Densities of the PP and rPET (micro)fibres compared with the data from the technical data sheets (TDS) available on the internet or provided by the manufacturer.

	Density (TDS)	Density (pycnometer method)
f-PP	920 ± 10 kg/m^3 (Treechem, n.d.)	923,9±3,1 kg/m^3
µf-PP		893,3 ± 1,3 kg/m^3
f-rPET	1370 ± 10 kg/m^3 (SwissFlock, n.d.)	1411,98 ± 12,2 kg/m^3
µf-rPET		1357,0 ± 4,9 kg/m^3

This relatively simple approach proved more suitable than advanced techniques such as gas pycnometry, where the measured densities deviated more markedly from the TDS values, or mercury intrusion porosimetry, which was not appropriate for these materials and produced unusable density data. Beyond that, the good agreement with manufacturer values is also important from the perspective of material validation, as the density is not only used as a separation parameter for microplastics (Mattsson et al., 2022), but can also support the identification of different polymer types (Barnett et al., 2021). Nevertheless, slight differences were observed between the measured densities of the microfibres and their longer counterparts. These are most likely due to residual air trapped between the individual filaments, a phenomenon that can occur for both fibre lengths, but is more pronounced in the case of microfibres because of their higher specific surface area. Air bubbles occupy volume in the pycnometer without contributing to the total mass, which leads to an apparent underestimation of the true density.

From an environmental perspective, density is a key property governing the behaviour of microplastics, as it controls their distribution within the water column largely, and, consequently, their bioavailability to aquatic organisms (L. Li et al., 2018). The sink–float method tests confirmed the expected behaviour of the tested (micro)fibres: The PP remained at the water surface, whereas the rPET sank to the bottom (Figure 3). The combination of quantitative density measurements with simple flotation experiments provides a robust, yet practical framework for evaluating the environmental behaviour of (micro)fibres, providing both precise density values and direct insight into whether the materials tend to remain at the water surface or sink into deeper layers, where they may change and ultimately accumulate in freshwater or marine sediments, potentially affecting living organisms (Alavian Petroody et al., 2023; Zidar et al., 2024).

Figure 3: Sink-float method for (micro)fibres (from left to right: f-PP, µf-PP, f-rPET, µf-rPET).

Source: own.

However, it must be recognised that cement residues adhering to the (micro)fibre surface can affect their contaminant-dependent density substantially, so (micro)fibres that would otherwise float may begin to sink when a sufficient amount of cement is attached. Due to the practical challenges of isolating enough (micro)fibres with firmly attached cement residues from the cementitious matrix, we were not able to perform reliable pycnometric density measurements on these composite particles. Nevertheless, the qualitative observations in aqueous media showed that fibres carrying cement residues may sink or remain suspended below the surface, in contrast to pristine f-PP, which floated consistently. These findings suggest that cement adhesion can modify the contaminant-dependent density significantly, and, consequently, the environmental transport and fate of fibre-derived microplastics, particularly in aquatic systems.

Once released into the environment, however, the density of microplastics agglomerate can evolve further. Processes such as mechanical abrasion, biofilm formation and other forms of biofouling, as well as weathering and the adhesion of mineral or organic matter, can increase the density of the (micro)fibres progressively. As a result, polymers with intrinsic densities lower than that of water may ultimately be found embedded in sediments. Moreover, while the difference between the density of particles and that of the surrounding water largely controls their settling, depth-related changes in temperature and salinity, and, hence, in water density, introduce additional complexity to their vertical transport (J. Li et al., 2023). Assessing the environmental fate of microplastics is therefore extremely complex, and requires integrating intrinsic material properties, such as density, with dynamic environmental processes.

3.4 Leaching experiment

Measurement of dissolved carbon is one of the commonly used approaches to assess the amounts of leachates released from plastic materials and microplastics. The leaching results are presented in Figure 4. For rPET the TOC values were higher for µf-rPET than for the corresponding f-rPET. This result reflects the larger specific surface area of the smaller particles, which generally enhances the extent of leaching. Accordingly, the leaching data are often normalised to particle surface area and reported as the mass of a released substance per unit surface area (Egea et al., 2024; Romera-Castillo et al., 2018). In contrast, this trend was not observed for PP, where the TOC values for µf-PP were lower than for the corresponding f-PP. This apparent discrepancy can be explained by the floating nature of the PP, which became more pronounced in the case of µf-PP. While the f-PP could be pushed down into the solution more easily, the µf-PP tended to accumulate as a diffuse layer at the water`s surface and adhered partially to the walls of the Erlenmeyer flasks during shaking. As a result, only a fraction of the µf-PP mass was truly in contact with the aqueous phase, thereby limiting the extent of leaching and leading to lower measured TOC values. This suggests that improved experimental design ensuring more effective contact between the (micro)fibres and the aqueous phase could facilitate more extensive leaching and yield more representative TOC measurements.

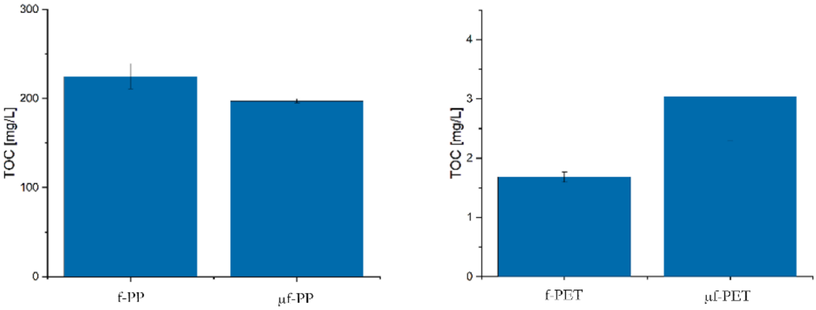

Figure 4: TOC values of the leachates for PP (left) and rPET (micro)fibres (right).
Source: own.

Also, different polymers exhibit distinct leaching behaviours. For example, Yuan et al., 2023 reported more pronounced initial leaching from PP compared with PET under comparable conditions. In addition, commercial fibres contain various additives, (e.g. surfactants, coupling agents, stabilisers), that are introduced to obtain the desired performance. f-PP designed for concrete applications require surface chemistry that promotes good interfacial bonding with the cement matrix, which is consistent with our SEM observations of higher amounts of cement residues adhering to the f-PP surface compared with f-rPET. Under intensive mixing and shaking, such additives can be released into the aqueous phase. This was also evident during filtration, where leachates from the PP (micro)fibres produced pronounced foaming, in contrast to rPET. This behaviour supports the interpretation that plastic-derived additives contributed substantially to the elevated TOC values observed for f-PP and µf-PP in the leaching experiments further.

The TOC levels are also influenced strongly by experimental conditions such as particle concentration, shaking speed, pH of the medium, exposure time and temperature, which makes direct comparison between different studies challenging. For example, leaching typically evolves over time, being most intense during the initial phase and then slowing gradually (Yuan et al., 2023). Our experiment was designed specifically to capture this early, highly dynamic stage, and was conducted under relatively aggressive conditions (high shaking speed and high (micro)fibre concentration). In this light, the higher TOC values observed in our study compared with the literature data can be interpreted as a consequence of the chosen experimental setting (Chen et al., 2024; Yuan et al., 2023). Furthermore, even after filtration, the leachate may still contain nanoplastics, that pass through the filter and are detected as part of the TOC signal together with low-molecular-weight organic leachates (Chen et al., 2024).

Although TOC is inherently a non-specific parameter and does not allow identification of individual leached compounds, it nonetheless serves as a valuable screening tool for comparing leaching behaviour between different materials (e.g., PP vs. rPET, fibres vs. microfibres) and for identifying scenarios in which plastic-derived leachates may represent a relevant contribution to organic loading in ecosystems.

4 Conclusions

In this work we examined how fibre-reinforced cementitious composites can act as a source of microplastics and associated chemical leachates throughout the use phase of the life cycle, from the production of the fibre-cement composite to degradation and demolition. We demonstrate that the characteristics of fibre-derived microplastics from cementitious composites depend strongly on the degradation pathway. Abrasion produced predominantly fine fragments, whereas the applied demolition scenario involving crushing and subsequent milling generated a much broader particle size spectrum, ranging from intact 12 mm fibres to microfibres. These contrasting outcomes highlight that different mechanical processes can lead to distinct microplastic size distributions and morphologies, even when starting from the same material.

We showed further that cement residues can adhere to polymer fibres, and that the extent of this adhesion depends on both the fibre surface treatment and surface morphology. The f-PP functionalised specifically for use in concrete exhibited markedly higher cement coverage than f-rPET. Nonetheless, the less smooth surface of f-rPET still enabled a certain degree of mechanical anchoring of cement residues, despite the lack of targeted functionalisation. This adhesion of cement residues can also modify key properties such as contaminant-dependent density and may shift fibres that would otherwise float towards suspending or sinking behaviour, thereby altering their environmental fate.

Finally, the leaching experiments indicate that, beyond particle size and surface area, the presence of additives used to enhance fibre–cement compatibility likely plays a major role in governing the leachate levels. Together, these findings emphasise that, when assessing the potential environmental impacts of fibre-reinforced cementitious materials, it is essential to consider not only the microplastics themselves, but also the attached cement residues and the functional additives necessary to achieve the required performance of the reinforcing fibres, as these components may appear subsequently in the leachate.

Acknowledgment

This work was supported by the Slovenian Research and Innovation Agency (ARIS) through research program P2-0273 and the Young Researcher Program (Grant no. 59559).

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