

Figure 4. Optical images of textile waste microfibers at (a) 30× and (b) 20× magnitude.

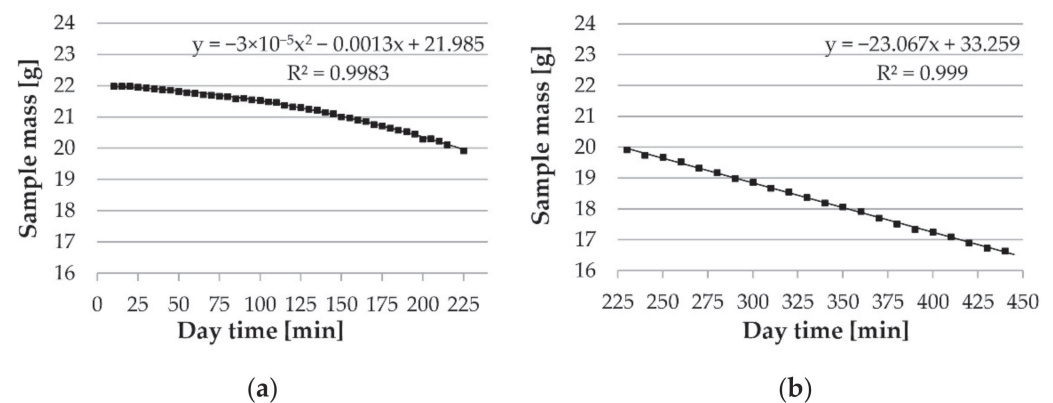


Figure 5. Water release over time by textile waste microfibers at early stage: (a) up to 225 min (3:45 h); (b) from 225 to 450 min (between 3:45 and 7:30 h).

3.2. Characterization of Composite Construction Materials Containing Textile Waste Microfibers

The three-point bending test displayed that the mechanical performance of FRCs, such as the maximum bending load (Figure 6a) and toughness (Figure 6b), gradually improved with increasing fiber content.

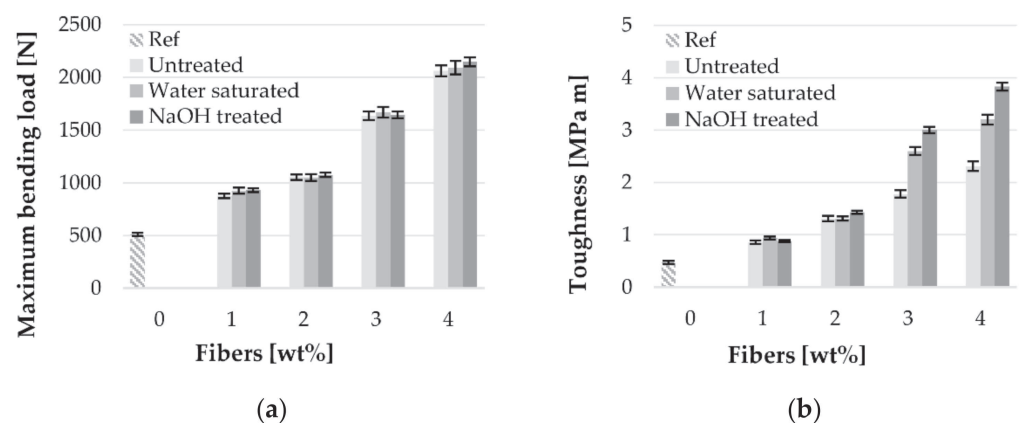


Figure 6. Improvement in three-point bending performance of FRCs when increasing microfiber content: (a) maximum bending load; (b) toughness. The error bars stand for standard deviation.

Compared to the reference value of Portland cement (0 wt% microfibers), an improvement of up to 320% in the maximum bending load was observed for FRCs containing 4 wt% microfibers. However, a more significant influence on maximum bending load enhancing was observed for fiber content, rather than for fiber treatment (Figure 6a).

By contrast, toughness was affected by both fiber content and treatment (Figure 6b). The toughness enhancement was magnified with increasing fiber contents [30,31], and NaOH treatment resulted in more efficiency for contents ≥ 3 wt%. Remarkably, a 715% enhancement in toughness was displayed by the FRC containing 4 wt% of NaOH-treated microfibers, compared with that of the reference sample with 0 wt% microfibers. The better performance of NaOH-treated microfibers was attributable to the effect of mercerization treatment, which promoted a rougher and more functionalized fiber surface [24,25,32]. Therefore, NaOH treatment resulted in increased mechanical and chemical adhesion between the constituent phases of the composite material (cementitious matrix and textile microfiber), which is known and generally sought to improve the overall mechanical behavior of FRCs [32,33]. The water-saturated microfibers behaved better than the untreated ones, likely due to a greater w_{released} over time, which promoted a differed hydration of the cementitious binder, and thus better mechanical properties. Supporting this hypothesis, the difference in performance was detected for 3 and 4 wt%, which had a higher amount of water released compared to that of 1 and 2 wt%.

These mechanical improvements were attributable to a good fiber distribution, fiber mechanical reinforcement, and crack-bridging effect [30,34,35]. Although microfibers are generally regarded as affecting the FRC strength prior to the maximum bending load (first cracking load), they can also influence the post-peak behavior, especially if they are embedded into cementitious matrices with low-grade aggregates or cement paste [34]. As reported in Figure 7f, the microfibers acted as anchors between the two matrix edges at the fracture section. This action, called crack-bridging, limits crack formation and propagation during both shrinkage (especially for microfibers) and mechanical loading [30,34,35]. During loadings, the tensile stresses are transferred from the cementitious matrix to the fiber reinforcement, which, being more ductile than the matrix, allows the FRC to have greater overall ductility and energy absorption [34]. Since the crack-bridging effect was stronger as the fibers acted in a direction perpendicular to the cross-sectional area, the microfibers exploited their maximum crack-bridging effect during the three-point bending test of the FRCs (Figure 7f) [30].

Moreover, a high specific surface area of reinforcing fibers is a main factor in enhancing the energy absorption capacity and toughness of FRCs [36]. This property allows for a better fiber-to-matrix adhesion, and thus a better mechanical behavior of the FRC. A high surface-to-volume ratio is a characteristic property of MPs. According to Zhang et al. [2], the same property is considerably higher for FMPs than, for example, spherical MPs. When present in polluted environments, the high surface-to-volume ratio leads to the absorption of persistent organic pollutants (POPs) on the MP surface. The absorption of such pollutants may increase the hazardous nature of both MPs and FMPs [2]. If consumed by biota, they may act as POP vectors, leading to bioaccumulation in such organisms. Although there is still a debate questioning whether MPs constitute significant sinks and vectors of POPs [37,38], predictions estimate that large quantities of MPs will be released into the sea in the next 30 years [39], increasing the likelihood of POP transfer from MPs to biota. The approach used in this study took advantage of the high surface-to-volume ratio of FMPs. Thus, although this property represents an increased capacity for absorbing hazardous organic chemicals if FMPs are released into the environment, in this study, their intrinsically high specific surface area-to-volume ratio was expected to promote FRC properties, accordingly. Given the evidence from Figures 6 and 7f, a decrease in crack width and crack propagation was observed as the microfiber content in FRCs increased (Figure 7). The limitation of crack opening allows the prevention of the early degradation of the material due to environmental chemical attacks, thus extending the service life of the structure in which the material is employed.

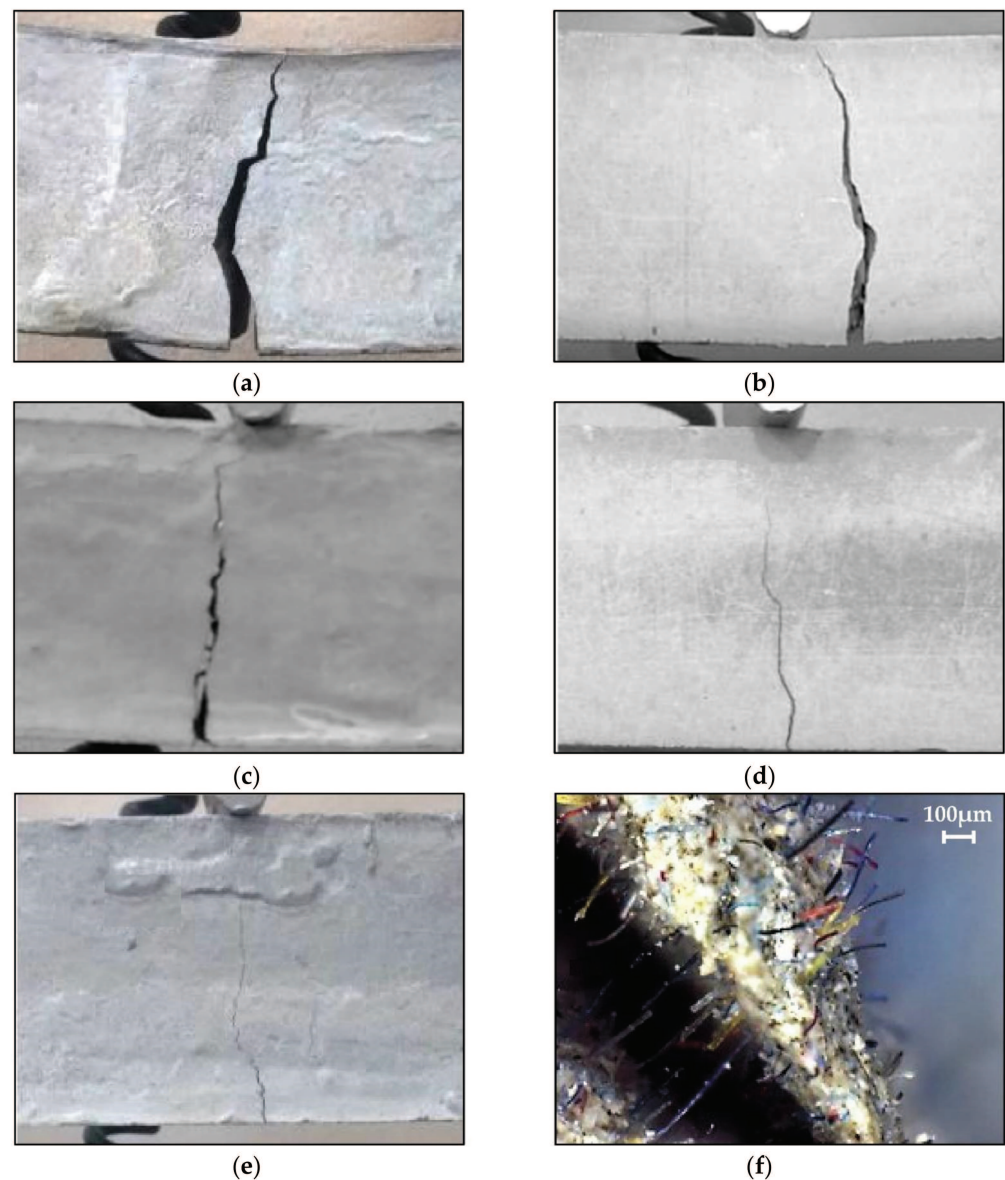


Figure 7. Reduction of crack opening during three-point bending test due to the crack-bridging effect of higher microfiber content: (a) reference unreinforced sample (0 wt% microfibers); (b) 1 wt% microfibers; (c) 2 wt% microfibers; (d) 3 wt% microfibers; (e) 4 wt% microfibers; (f) detail of the crack-bridging effect. The pictures are related to untreated microfibers, but the same results were obtained for water-saturated and NaOH-treated microfibers.

Figure 8 displays the influence of the crack-bridging effect on the linear shrinkage measurement. The use of microfibers, particularly synthetic ones, has been highlighted as the best solution to reduce hydraulic shrinkage by the standard prescriptions [30]. In this study, it was observed that the linear shrinkage of the unreinforced reference sample was positively reduced by both increasing the microfiber content and treatment type. NaOH treatment resulted in more efficiency for reduced microfiber contents (−60% at 1 wt%). However, 1 wt% water-saturated and untreated microfibers reduced it by 40% and 20%, respectively. The influence of microfiber treatment was reduced by increasing the microfiber content until becoming negligible at 4 wt%. Up to 80% linear shrinkage reduction was observed for all FRCs with 4 wt% microfibers compared with that of the reference Portland cement (0 wt%).

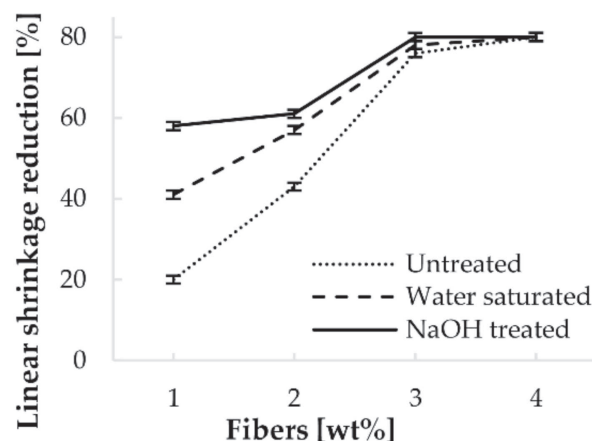


Figure 8. Reduction in linear shrinkage of FRCs compared with that of Portland cement when increasing the microfiber content of untreated, water-saturated, and NaOH-treated textile waste microfibers.

The increase in microfiber content also contributed to reduce the thermal conductivity, thereby increasing the thermal-insulating power of the final FRC (Figure 9). Indeed, textile fibers are known for their thermal insulation properties, which is the main reason they are used to manufacture clothing [40]. In particular, the addition of 4 wt% of untreated microfibers reduced the thermal conductivity of the reference unreinforced sample by 42%, almost doubling the insulating power of solely Portland cement.

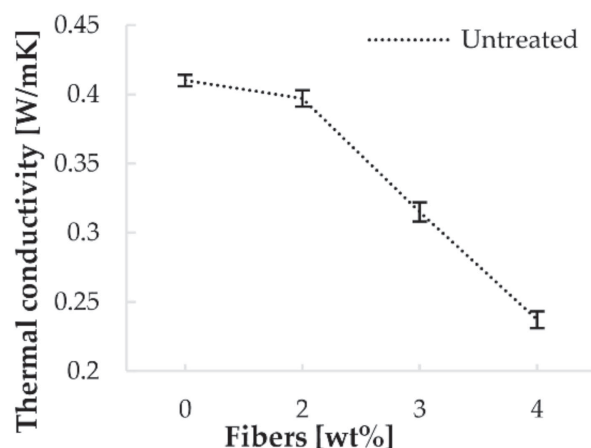


Figure 9. Improvement in power insulation of FRCs when increasing untreated textile waste microfiber content.

4. Conclusions

In recent years, the presence of microplastics (MPs) within all environmental compartments (air, water, soil, and biota) has become an emerging global issue, both for the concerning number of MPs and induced health issues in biota. The most prevalent MPs in the air are fibrous microplastics (FMPs), which can spread rapidly from one compartment to another (35% of MPs are in oceans) and have already been found within human tissues and stool. FMPs arise from the lifecycle of synthetic and blended textiles (production, use, and disposal), and their impact on the environment is expected to worsen because of the fast-fashion concept that favors mass production to a circular economic system. Among textile waste (490,000 t/year of special waste and 146,000 t/year of urban waste in Italy), processing waste fibers, including FMPs, are currently not recycled. In particular, waste microfibers from the finishing of fabrics (5000 t/year in Italy) are volatile and are therefore easily released into the environment.

For the first time, this paper proposes a viable solution to the problem of FMPs from processing textile waste microfibers by arranging for their collection directly at the process stage, before spreading into the air or soil. Their collection can occur during the finishing of fabrics using an air-filtering system, and their reuse is hypothesized as reinforcing microfibers into construction materials. Therefore, at the same time, a new mitigation technique for FMPs and the manufacturing of green fiber-reinforced cementitious composite materials (FRC) are proposed. Moreover, by considering blended textile waste microfibers and not only synthetics, this study addresses the issue of FMPs from textile waste by considering a real-like condition.

A composition of 61% pure cotton, 29% cotton blend (cotton and synthetics), and 10% synthetics resulted from the characterization of the blended textile waste microfibers. From size measurements, the synthetic microfibers (accounting for at least 10% of the textile waste microfibers involved) were classified as FMPs, following the ECHA definition.

Portland cement-based FRCs were designed, including up to 4 wt% of blended textile waste microfibers both in untreated, water-saturated, and NaOH-treated conditions. As expected, the maximum bending load and toughness linearly improved with increased microfiber contents due to the crack-bridging effect enacted by the microfibers. Additionally, the propagation of crack width appeared to be reduced. Remarkably, adding 4 wt% microfibers enhanced the maximum bending load and toughness of the reference Portland cement by 320% and 715%, respectively. Linear shrinkage and thermal conductivity also appeared to be dependent upon microfiber content. A reduction of up to 80% in linear shrinkage was displayed by FRCs with 4 wt% microfibers, compared with that of Portland cement, thus strongly preventing the crack formation from shrinkage and lengthening the nominal life of the material. Moreover, the 4 wt% microfibers also allowed a doubling of the thermal-insulating power. This enhancement stands as a significant achievement for the thermal–energetic performance of buildings and is a direct result of using intrinsically thermal-insulating textile microfibers. Concerning the microfiber treatments, NaOH-treated microfibers displayed the best performance in toughness (above 3 wt%) and linear shrinkage (below 4 wt%) due to improved chemical and mechanical adhesion with the cementitious matrix. For microfiber content lower than 3 wt%, no difference in toughness was detected between different surface conditions, the same for 4 wt% microfiber content in shrinkage. The water-saturation condition was the second most performant treatment in promoting a cement hydration process more controlled and differed over time. Water-saturation and NaOH treatment, which are generally intended to improve natural fiber properties, optimized the FRC behavior, thus promoting the use of the overall blended textile microfiber waste, including FMPs.

The viability of producing green FRCs by reusing hitherto-unrecycled-textile waste microfibers was demonstrated. The inclusion of textile waste microfibers additionally brought improved thermal-insulating and mechanical properties to Portland cement. Remarkably, considering the composition of the microfibers, the suggested solution promotes the removal of at least 4 kg of FMPs (almost the same number of FMPs falling in a day in Paris) per ton of cement paste. Hence, a mitigation of MPs from the environment and the production of green and optimized FRCs were validated.

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