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Performance of concrete reinforced with synthetic fibres obtained from recycling end-of-life sport pitches

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Abstract

Micro-plastics pollution has risen at an alarming pace over the last decades and it is now recognised as a leading environmental emergency. Indeed, only a very small fraction of annual plastic production is successfully reused, while the vast majority is either disposed of (mainly through incineration or landfilling) or dispersed into the environment. In this paper, polyolefins synthetic fibres, obtained from processing disposed artificial turf pitches aimed at paving sport facilities, are studied. Focus is set on assessing their potential for the Fibre Reinforced Concrete (FRC) technology. Mechanical performance is discussed at two fibre volume fractions, namely 3% and 5% vol., alongside environmental impact. The former is assessed in bending and reveals a significant enhancement of the post-crack energy dissipation capability, whose extent is compatible with what is usually obtained by the adoption of virgin fibres. This is especially significant in consideration of the light processing operated on the waste material. Indeed, life cycle assessment is adopted to evaluate the environmental impact of fibre reuse against fibre manufacturing from either virgin materials or plastic

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waste. It clearly appears that fibre reuse brings a double environmental benefit: on the one side, it decreases the need for new plastics and, on the other, it reduces plastic waste, whose traditional disposal technique, through incineration, entails a considerable footprint.

Keywords: Fiber Reinforced Concrete, Recycled polyolefins, Life Cycle Assessment, flexural behavior

1. INTRODUCTION

Polyolefins consist of synthetic polymers with a very complex macromolecular structure, whose properties highly depend on the manufacturing process. They include ethylene-based and propylene-based polyolefins, which represent two of the largest polymer families produced and consumed worldwide [1]. Polyolefin blends find applications in several fields that include packaging (especially food), healthcare, automotive, aerospace and civil engineering. Within the technology of Fibre Reinforced Concrete (FRC) and mortar, they constitute the randomly dispersed reinforcing phase in the cementitious matrix [2]. Polyethylene (PE) is characterized by high ductility and impact strength, while polypropylene (PP) prevents concrete from spalling at high temperature, it improves the residual strength of heated specimens [3] and offers good resistance to cyclic loading. Besides, the addition of PP fibres in concrete leads to an increase in compressive strength [4]. On the other hand, both PE and PP suffer from low stiffness and high viscous deformation when subjected to loading (creep). A general inconvenience of synthetic fibres for FRC composites consists in the lack of hydrophilicity and compatibility with the inorganic matrix. As a result, interphase adhesion with the cementitious binder is week and performance is generally inconsistent. A variety of strategies are proposed in the literature with the aim to improve compatibility between the fibres and the matrix, ranging from oxidative surface treatments [5] to inorganic nano-coatings [6, 7, 8, 9].

The use of recycled plastics in concrete is a practical approach at reducing plastic waste disposal, while improving sustainability in the construction industry [10]. This approach falls upon the European Strategy for Plastics in a Circular Economy, first adopted in January 2018 [11]. Indeed, re-usage of plastic waste helps reducing dependence on non-renewable fossil fuels for virgin plastics production, curbs CO_2 emissions and eventually promotes cross-linking across the product value chain in a circular economy approach.

In the excellent review by Gu and Ozbakkaloglu [12], recycling of plastics in concrete occurs under two major approaches: either in the form of plastic aggregates (PA) or as plastic fibres (PF). Indeed, much interest has been recently devoted in the literature to considering PA for lightweight concrete [13, 14, 15, 16]. Literature contributions considering recycled PF are less abundant [17]. In the paper by Ochi et al. [18], a procedure is outlined for producing polyethylene terephthalate (PET) fibres from end-of-life PET bottles through melting and drawing. However, the use of PET fibres obtained from disposed bottles is controversial, as fibres are reported to dissolve in the alkaline environment of the matrix after 150 days [19]. Better results are obtained with PP, as illustrated by Yin et al. [20], where performance of virgin fibres is compared with that of recycled fibres produced by extruding, spinning and stretching PP granules obtained as industrial PP waste.

In this respect, it is important to emphasize that industrial waste widely differs from general waste in that it is very homogeneous and consistent, to the extent that it is often capable of being reprocessed to become a so-called *secondary raw-material*. When this is the case, industrial scraps can no longer be labelled as waste. Furthermore, the vast majority of literature contributions deal with significant reprocessing of the plastic waste, which, unfortunately, is most often cost-ineffective.

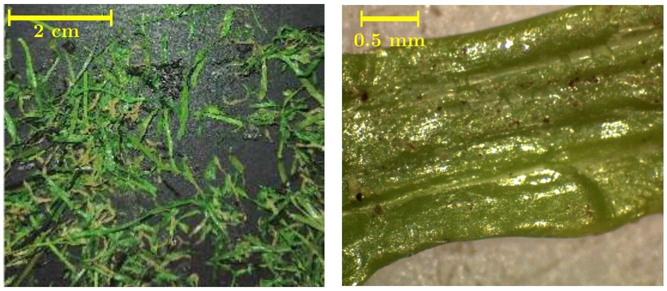
In contrast, in this work, we investigate direct incorporation of variable length fibres obtained from processing disposed artificial turf carpets for paving sport pitches. At end-of-life, carpets are mostly landfilled and therefore constitute a waste. Instead, we investigate a very simple and cost-effective fibre processing stage which demands pitch shredding and fibre gravimetric separation (mainly from sand and rubber). The fact that this is a cost-effective approach is supported by an environmental footprint analysis, which compares emission of the present process to those available in the literature regarding both virgin and reprocessed fibres. We conclude that waste recycling is very much mission-dependent, for it is economically sustainable only if the right combination of waste processing and product incorporation is identified.

2. MATERIALS AND METHODS

A single pre-mixed ordinary Portland cementitious (OPC) mortar is adopted for specimen preparation. This commercially available matrix is selected in light of its thixotropic character, that is imparted by the presence of fine-grained siliceous and carbonate aggregates (up to 500 µm) [21]. Its main physical and mechanical properties, as declared by the manufacturer [22], are reported in Table 1. This inorganic matrix is reinforced by randomly dispersed plastic fibres, which are obtained from processing disposed artificial turf (AT) carpets employed for paving sport facilities (typically five-a-side football or tennis pitches). Fibre length is heavily scattered as it ranges from 1 cm to 4 cm. Such dimensional variability is beneficial in terms of multi-level crack bridging, as documented by Khan et al. [23]. Reinforcing fibres are shown in Fig.1(a) and their surface morphology is presented in Fig.1(b). Fibres are flat, with thickness much less than width, and present large surface wrinkles along the longitudinal axis which may benefit fibre-to-matrix mechanical adhesion [6, 24].

Characteristic	**Unit**	**Value**
Max. grain size	µm	500
Permeability to water [EN 1504-2]	m	0.94
Water absorption [EN 1062-3]	$kg/m^2h^{-0.5}$	0.08
Flexural strength [EN 196-1]	MPa	4.0
Compressive strength [EN 12190]	MPa	27.0
Elastic modulus [EN 13412]	GPa	15.2
Adhesion strength (to concrete) [EN 1542]	MPa	1.1

Table 1: Cement based mortars properties (as provided by the manufacturer)



(a) (b)

Figure 1: PE-PP fibres obtained from recycling disposed artificial turf carpets (a) and surface morphology, as it appears at 10× optical magnification, with distinct longitudinal wrinkles (b)

2.1. Experimental program and specimen manufacturing

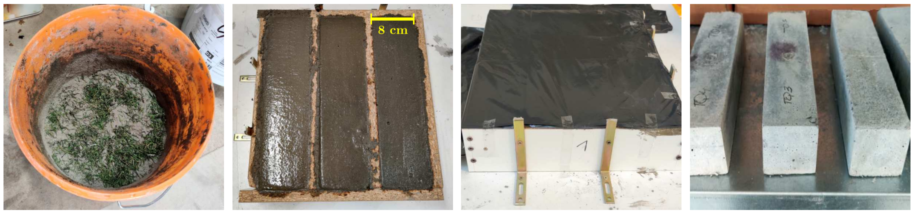
Chemical composition is characterised through differential scanning calorimetry (DSC) and Fourier transform infrared spectroscopy (FT-IR). Fibres are homogeneously dispersed in a reference pre-mixed mortar at two different fibres-to-matrix volume ratios, 3% and 5%. Mechanical performance is assessed in three-point bending tests (3PB) and the focus is set on evaluating the energy dissipation capabilities of the composite.

2.1.1. Fibres characterisation

In order to determine fibre composition, that may vary across different AT carpets, we carry out FT-IR spectrometry (Bruker Optik GmbH, Ettlingen, Germany) in Attenuated Total Reflection (ATR) mode, associated with a DSC analysis (TA DSC 2010, TA Instruments, New Castle, DE, USA). DSC results are obtained in an aluminium crucible and nitrogen atmosphere for two consecutive $-20\,^{\circ}\mathrm{C}$ to $200\,^{\circ}\mathrm{C}$ heating ramps, with heating rate $20\,^{\circ}\mathrm{C/min}$. Matching results from both analyses reveals coexistence of several polymeric compounds.

2.1.2. FRC characterisation

80×80×320 mm prismatic beams are manufactured for three-point bending (3PB) tests in wooden formworks specifically designed and manufactured. Indeed, dimensions are chosen as integer multiples of those prescribed in [25] (testing methods for both cement and lime hardened mortars for structural



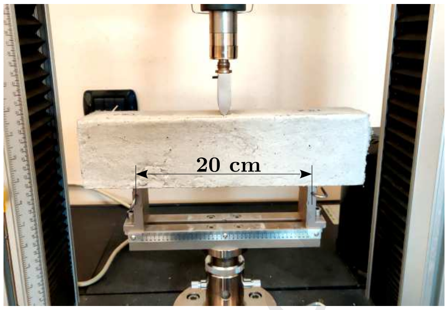
(a) (b) (c) (d)

Figure 2: Manufacturing stages of FRC specimens for three-point bending tests: fresh mixture preparation (a), wooden formwork casting (b), moist curing (c) and specimen stripping (d)

Table 2: Mechanical testing programme

Group	**Description**	**Fibres content** [kg/m^3]	**No. of specs.**
NF	*Plain cementitious beams (reference)*	—	3
AT3	*FRC beams with 3%vol. recycled AT fibres*	27.1	6
AT5	*FRC beams with 5%vol. recycled AT fibres*	45.2	6

purposes). The main manufacturing steps are illustrated in Fig.2 and hereinafter detailed. Recycled polyolefin fibres are incorporated within the solid phase (binder plus siliceous aggregates, see Fig.2(a)), by means of a low speed mechanical stirrer. Thorough mixing is crucial to obtain homogeneous fibre distribution within the matrix. Then, water is added to the mixture and further stirring is carried out in order to allow uniform hydration of the conglomerate. Fresh mortar is then cast into the lubricated formworks, compacted and then thoroughly vibrated to allow air bubbles to surface, Fig.2(b). Specimens are finally wrapped in tight polypropylene foil and left curing at 100% RH for 7 days before stripping, Fig.2(c). As in [8], hardening is completed after further 21 days at laboratory conditions (20 °C and $60-75\%$ relative humidity), Fig.2(d). The geometry of the beams and the loading configuration are schematically represented in Fig.3. Specimens are tested under displacement control in an Instron 5567 universal testing machine (UTM) equipped with a 30 kN load cell attached to the upper cross-head. A constant displacement rate of 1 mm/min is set and two fibre dosages are considered, namely 3 and 5% vol. The experimental programme is summarised in Table 2.



(b) UTM during testing

(a) Geometry [mm]

Figure 3: 3PB test set-up

2.2. LCA analysis

In order to evaluate the environmental footprint, all processes undertaken to obtain PE-PP fibres from disposed synthetic turf carpets are individually analysed and assessed in terms of environment-pollutant emissions. This allows to compare the environmental footprint of recycled fibres against virgin fibres, which are commonly used for structural applications. Several methods are available to measure and assess the environmental impact of a product and the benefits which may arise from a circular economy strategy. In particular, we mention Input-Output analysis, Design for X, Multi Criteria Decision Methods, Material Flow Analysis among many [26]. Here, emission evaluation is performed through the widely accepted life cycle assessment (LCA) method [27]. Indeed, LCA is a helpful tool to quantify the environmental pressures and benefits, the trade-offs and areas for achieving improvements by taking into account the full life-cycle of the product [28]. According to the international standards ISO 14040 [29] and ISO 14044 [30], LCA analysis refers to the quantification of the environmental benefits (or impacts) associated to a product, a system or a service throughout its life cycle [31, 32]. Assessment is performed in four steps:

1. Goal and scope declaration, where the purpose of the study and the system boundaries (SB) are defined;
2. Inventory analysis, in which input and output data are collected and analysed with regard to the functional unit (FU), that is the output under evaluation;
3. Impact assessment (LCIA), where the environmental impact of the product/system is determined;
4. Interpretation, which brings results evaluation, draws conclusions and formulates recommendations.

3. RESULTS AND DISCUSSION

3.1. Polyolefin compound characterization

DSC provides indirect information regarding the composition of the polyolefin compound. Indeed, the heat flow pattern characterises specific physical changes in the specimen, as given in Fig.4 corresponding to the second heating ramp. Two main endothermic reactions can be identified which are likely related to PE (peak around 126°C) and PP (peak around 165°C) solid-liquid transition. Although DSC cannot provide quantitative information on the relative amount of PE and PP in the compound, comparison of the specific energy developed during the heating process shows that PE seems to be the main constituent.

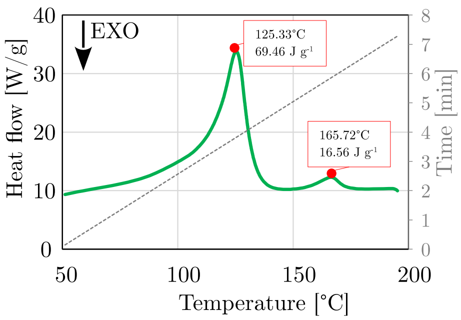


Figure 4: Heat flow pattern in the DSC analysis of AT fibres

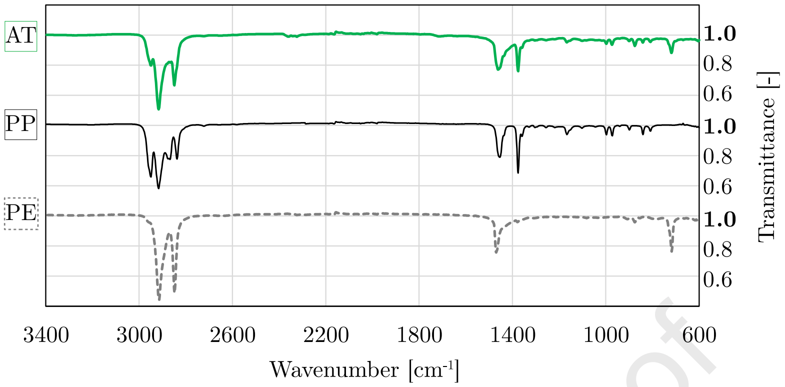


Figure 5: FT-IR spectrograph of the PE-PP compound (top), as it compares to plain PP (middle) and PE (bottom curve)

The ATR FT-IR spectrograph of the polyolefin compound is reported in Fig.5 (green, solid line), where, for better comparison, the spectrographs associated to virgin PP (black, thin solid line) and low-density PE (grey, dashed line) are also given. The strong absorbance peaks in correspondence of the wavenumbers 2914 and 2847 cm^{-1} are likely due to asymmetric and symmetric C-H stretching in CH_2 groups, which are in both PP and PE. In contrast, an extra peak appears at 2949 cm^{-1}, which is ascribed to asymmetric stretching of CH_3 groups typical of PP only. For AT fibres, strong absorbance peaks stand out at 1461 and 1376 cm^{-1}, associated to symmetric bending in CH_3 groups. This pattern is much more pronounced for plain PP as opposed to PE, see [33, Tab.2]. Other absorbance peaks observed in AT specimens at 1167, 997, 973, 841 and 808 cm^{-1} are consistent with interactions typical of plain PP, such as C-H wagging and rocking, CH_3 rocking and C-C stretching, as shown by Fang et al. [34, Tab.1]. Finally, the absorbance peak appearing around 718 cm^{-1} may be ascribed to C-H rocking, again specific to PE. On the basis of this analysis, we support the presence of both PE and PP in the polyolefin compound, although we have no definitive indication on the prevailing composition [35, 36].

3.2. Mechanical assessment of FRC beams

Fig.6 compares the mean load vs. displacement curve for each specimen group. Results are gathered in Table 3 in the form of mean (μ) ultimate load,

Figure 6: Load-deflection curve in 3PB testing of NF (no fibres), AT3 (3% vol. recycled AT fibres) and AT5 (5% vol. recycled AT fibres)

$P_{\max}$, secant elastic modulus, E_s, and energy dissipated at failure, W, alongside the relevant standard deviation ς. Specifically, W represents the area under the load-deflection curve, up to the residual load capacity $P_{\text{res}} = 0.10 P_{\max}$, while flexural stiffness is calculated as the slope of the straight line passing through the loads $0.60 P_{\max}$ and $0.90 P_{\max}$, in the uncracked ascending branch of the curve [37].

Table 3: Ultimate load, P_{max}, stress, f_u, secant modulus, E_s, and dissipated energy, W, across all tested groups. μ is the mean, $\varsigma(\cdot)$ the standard deviation, and CoV the coefficient of variation of the relevant quantity.

G	$\mathbf{P}_{\max}$ μ [kN]	ς	$\mathbf{f_u}$ μ [MPa]	ς	**CoV** $\{P_{\max}\}$ [%]	**W** μ [J]	ς	**CoV** $\{W\}$ [%]	$\mathbf{E_s}$ μ [MPa]	ς	**CoV** $\{E_s\}$ [%]
NF	7.96	0.41	4.66	0.23	5.1	2.93	0.19	6.6	602	22	3.6
AT3	7.29	0.51	4.27	0.30	7.0	12.20	2.75	22.5	581	36	6.12
AT5	6.05	1.09	3.55	0.64	18.1	17.71	5.52	31.2	518	66	12.8

Addition of fibres to the matrix produces two competing effects: on the one hand, a reduction in terms of first-cracking strength f_u is observed, most likely due to the presence of discontinuities at the matrix-to-fibre surface, air bubbles and a general reduction in the resisting matrix cross-section. In fact, the decrease in ultimate performance is mostly relevant at high fibre dosage, i.e. in the AT5 group (-24%), and it should be compared with the mild reduction encountered in the AT3 group (-8%). This outcome is in line with the findings presented in Signorini et al. [8], concerning addition of virgin PP fibres at 3% vol. dosage.

On the other hand, a seizable increase in terms of mechanical energy dissipation at failure is met, due to a shift in the pathway to failure. Indeed, plain concrete presents a typical brittle failure mechanism, which occurs as self-sustained irreversible crack propagation right after the ultimate tensile strength is attained. In contrast, FRC exhibits significant post-peak resistance and ductility, owing to the crack-bridging effect deployed by the fibres. This residual resistance is mainly a function of the force it is required to pull fibres out of the matrix. Adhesion at the matrix-to-fibre surface and subsequently friction thereat become the driving parameters in the pull-out phase, which occurs right after the first-cracking strength [7]. Specifically, for the AT3 group, recycled fibres induce a more than 4-fold increase in the energy dissipation capability with respect to the plain mortar NF. Indeed, the post-peak softening behaviour of the composite provides the main contribution to the greatly enhanced toughness of FRCs [38]. Again, this quantitative observation is coherent with what appears in the literature for virgin PP fibres in a dosage of 3% vol. [8, Fig.15], where the dissipation capability is around 3.5 times the one of plain mortar, and can be further improved with appropriate surface functionalisation [39]. As a result, ductility generally increases with the fibre volume ratio (dosage) and, for the AT5 group, it proves 6-fold higher than in the control group NF (plain matrix) and still $+45\%$ greater than in the AT3 group. This result is commonly ascribed to the possibility of averaging out stress peaks on a larger cross-sectional area, owing to tangential friction developed by the fibres which carries stress outside the peak zone [40]. Obviously, this positive inference with dosage is limited by workability considerations. At the considered fibre dosages, strength curves exhibit a steep stress drop at first cracking and then a softening response. This is in line with what it is commonly observed for FRC composites with virgin synthetic fibres at comparable dosages (see, for example, Brandt [41, Fig.6a]). Indeed, Babaie et al. [42] show very similar, if not more pronounced, stress drops at cracking for FRC with 2.5%vol. content of virgin PP macro-fibres, as well as consistent residual post-peak strength values (see [42, Fig.10b]). It is precisely this unexpected performance similarity with virgin fibres that advocates for the opportunity of replacing them with waste materials, at least in the form here analysed.

Fig.7 fits ultimate load, dissipated energy (a) and flexural secant modulus (b) data as a function of fibre dosage. For energy dissipation, an almost perfect linear correlation appears to stand ($R^2 = 1.000$) within the considered range. In contrast, flexural modulus of the uncracked fibre reinforced conglomerate decreases with dosage, although, for moderate fibre contents, a mere 3% reduction emerges. When the AT5 group is considered, flexural stiffness decreases around 14%, showing that the rule of mixtures is unable to fully account for the reduction, which is presumably also influenced by the growing importance of the interphase zone.

Data scattering, in terms of coefficient of variance (CoV), is plotted in Fig.8 against dosage, as a mean to assess test consistency. As expected, good reproducibility is met in terms of ultimate load, P_{max}, given that this performance is strongly linked to the properties of the plain matrix, with the CoV staying below 18%. Here, the monotonic increase in scattering is quite moderate. Conversely, in terms of toughness W, the distribution of the fibres in the embedding medium strongly affects the post-peak behaviour and we see wider data fluctuations. However, scattering remains under 23% for AT3 and 32% for AT5, which is unexpectedly low in consideration of the dramatic increase in energy dissipation capability and in light of the covariance effect, whereby higher performance is always accompanied by higher data scattering. Finally, when flexural stiffness E_s is considered, a pattern similar to that appearing for the ultimate load is seen (which is expected).

The results obtained projecting data scattering as a measure of workability loss are consistent with the findings presented by Grünewald and Walraven [43], although these refer to steel fibres, whose density is sensibly higher. Indeed, with due proportion, AT5 dosage lies in the interval identified by Grünewald ($40 \div 100$ kg/m^3) as the critical fibre content range that impairs the fresh properties of the composite conglomerate. In this range, fibres start to form bundles and cluster in nests during mixing, penalising the quality of their random dispersion. This strongly affects in the negative the first-cracking strength as well as flexural stiffness at the uncracked stage. Still, in contrast to steel fibres, the fact that the density of synthetic fibres is close to the matrix's helps easing some workability issues, such as segregation.

4. ENVIRONMENTAL ASSESSMENT

4.1. Goal and scope definition, system boundary and life cycle inventory

LCA is a viable and flexible method for assessing the environmental benefits connected to recycling PE-PP fibres from disposed AT carpets and to their usage as secondary raw material into a cementitious matrix (FRC). We set 1 kg of PE-PP fibres as our FU, whereby all input and outputs are expressed per kg of PE-PP fibre product, ready to be dispersed in the cementitious matrix. Impact related to the production of other constituent materials (i.e. Portland cement, gypsum and blended materials) and to the building process itself (i.e. construction, maintenance and dismantling) is outside the scope of the analysis, as it is assumed that it would take place regardless of the recycling process. Indeed, other materials and processes remain practically unaffected by the choice of the reinforcement phase: The single pre-mixed OPC mortar would actually be the same, the FRC would be adopted for the same application and the building processes are similar, independently of the mix design. Therefore, the simplified method herein adopted is considered to be a good and reliable approximation at this specific stage, also in line with other studies [44].

Fig.9 illustrates a flow chart of the process adopted to recycle PE-PP fibres from disposed AT carpets. Carpets are collected and transported to the processing plant. The transport distance is on average 300 km. After washing with water, mechanical sorting is used to separate out the single components, mainly rubber, sand and fibres. In general, AT carpets weigh around 25 $\mathrm{kg\,m^{-2}}$ and from their processing the following materials are retrieved: synthetic fibres (12.5%), bituminous membrane (2.5%), sand (50.5%) and rubber (34.5%). The processing plant has a throughput of around 300 $\mathrm{kg\,h^{-1}}$ and it works in almost closed cycle, for it recovers and cleans the process water with little losses. In fact, during cleaning, water is lost owing to surface capillarity and wettability in the range of 7% of the total amount. Processing water is first conveyed to a reservoir whence it moves into a cleaner for further use. Sludge is subsequently disposed of as waste. After drying, PE-PP fibres are shredded, compacted and packed into big bags with a approximate throughput of 1000 $\mathrm{kg\,h^{-1}}$. Auxiliary processes aimed at recovering non-plastic materials, such as bituminous membrane, sand and rubber, are considered outside the system boundary. The impact related to the collecting processes, to sorting and washing are accounted only for 12.5% (mass allocation). In this study, primary data are used, collected directly via on-site investigations and via face-to-face, telephone and email communications with an Italian company that deals with this activity. Data are relative to the collection and the treatment of artificial turf carpets in 2019. Background data, such as electricity and waste treatments, are taken from the Ecoinvent database version 3.5.

4.2. Environmental impact assessment

LCIA is the estimation of indicators of the environmental pressures in terms of e.g. climate change, summer smog, resource depletion, acidification, human health effects, etc. associated with the environmental interventions attributable to the life cycle of a product. The software SimaPro 9.0 is used for the LCIA. The impact categories include global warming potential (GWP), acidification potential (AP) (kg SO_2 eq), eutrophication potential (EP) (kg ${PO_4}^{3-}$ eq), photochemical oxidant formation potential (POFP) (kg NMVOC eq), abiotic depletion potential elements (ADP elements) (kg Sb eq), abiotic depletion potential fossil fuels (ADP fossil fuels) (MJ) and water scarcity footprint (WSF). The impacts categories are selected according to the Product Category Rule (PCR 2019:14), referring to the EN 15804 (EN 15804:2012+A2:2019) [45] for construction products and services, in order to easily compare the environmental profile with products available on the market and to pave the way for future environmental declarations, all the more necessary in the construction sector [46]. GWP (kg CO_2 eq) is calculated on the basis of the database gathering the 100-year greenhouse gas emissions reported by the Intergovernmental Panel on Climate Change method [47]. AP (kg SO_2 eq) is based on CML 2001 non-baseline method [48], while EP (kg ${PO_4}^{3-}$ eq), ADP elements (kg Sb eq), ADP fossil fuels (MJ) are based on CML 2001 baseline method [49]. POFP (kg NO_x eq) is based on Recipe 2008 method [50] and, finally, WSF (m^3 H_2O eq) is based on the AWARE method [51]. Fig.10 shows the estimated environmental impact induced by producing 1 kg of recycled PE-PP fibres from disposed AT carpets. As it can be seen, fibre recycling results in little environmental impact for the selected categories. Indeed, to produce 1 kg of fibres, the industrial plant produces 0.117 kg CO_2 eq, 0.000147 kg of kg ${PO_4}^{3-}$ eq, 1.61 MJ of ADP fossil fuels and 0.0529 m^3 H_2O eq, considering the most impactful categories.

Fig.11 lay out the major contributions to the overall impact within each category. GWP and ADP are dominated by transport from collection centers to the processing plant. EP and WSF are mainly given by shredding and packaging, especially in the form of electricity consumption by the plant. Washing and sorting also bring a significant contribution, mainly to WSF, due to the water required to clean the carpets, despite it being used in almost closed cycle. Results show that recycling PE-PP fibres from disposed AT carpets curbs CO_2 eq emissions by a striking 99%, with respect to fibre production form virgin PP granulate. Even more interestingly, CO_2 eq emissions are still reduced by a staggering 94%, when comparing with data concerning the estimated impact of fibre production from industrial and domestic recycled plastics, see [44, 52]. Indeed, the environmental benefit is mainly due to the absence of several impactful processes needed to re-compound generic recycled plastic waste and subsequent extrusion for fibre production. A specific comparison that brings similar results is possible with, for example, the commercial product emesh©, for which impact data are available from The International EPD© System.

5. CONCLUSIONS

We investigate the benefits attached to adding to a cementitious mortar matrix polyolefin fibres obtained from processing disposed artificial turf (AT) carpets used for paving sport facilities. Fibres are obtained from simple processing of AT carpets in a specifically designed plant which performs shredding and vibro-separation. No impactful thermo-chemical treatments are envisaged, which fact carries significant economic and environmental implications. Fibres come in a wide range of lengths, from 1 to 4 cm, present a variable composition and distinct signs related to the original processing and to wear. Indeed, differential scanning calorimetry (DSC) and Fourier transform infrared spectroscopy (FT-IR) indicate that recycled fibre composition is a mixture of polyethylene (PE) and polypropylene (PP). Two fibre volumetric dosages are considered, named AT3 and AT5, and mechanical performance is experimentally investigated through 3PB tests on FRC beams. It is found that fibre addition leads to a significant enhancement in the energy dissipation capability, which is entirely comparable with what is obtained from virgin fibres (such as PP) at the same dosages. Indeed, AT3 and AT5 exhibit a softening post-peak ductile response, whose energy dissipation is up to 6 times that of plain concrete. This ductility gain is in line with that obtained using virgin synthetic fibres at similar dosages [41, 42]. As well known, high fibre contents strongly impair workability of the fresh conglomerate [43, 53]. Analysis of data scattering suggests that a homogeneous distribution of the fibres in the matrix becomes difficult for contents of recycled fibres beyond 3%.

Fibre addition leads to a substantial reduction of the ultimate flexural strength, that is close to 1/3 for AT5. This result is due to the reduced concrete cross-sectional area and to discontinuities at the fibre-to-matrix interface, possibly in the form of small air pockets. Again, for AT3, this loss is very mild and it is in line with previous studies concerning virgin PP-FRC [8]. In this context, our results advocate for virgin fibre full replacement with recycled fibres, at little or no performance expense, with important economic and environmental benefits. The latter are assessed through the LCA methodology, where a detailed comparison is presented with respect to virgin PP-PE fibres for FRC systems. We show that recycling PE-PP fibres from AT carpets offers very substantial environmental benefits over virgin fibres for comparable performance. Most interestingly, this advantage extends over fibres recycled from general plastic waste. Indeed, mechanical processing of AT carpets immediately provides workable fibres, without requiring the impactful procedures associated with the processing of plastic granulates.

It is concluded that adopting synthetic fibres obtained from mechanical processing of end-of-life artificial turf carpets is a promising approach for reducing the large environmental impact of the construction sector.

FUNDING

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The Authors adhere to the Ethics in publishing of this Journal.

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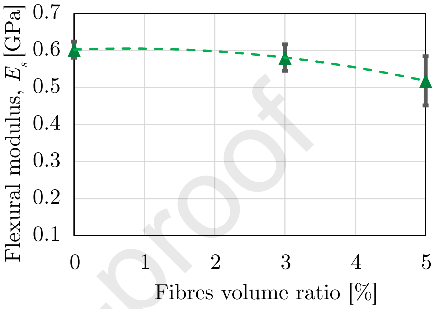

(b)

(a)

Figure 7: Curve fits for the maximum load, dissipated energy at failure and flexural stiffness as a function of the fibre dosage, with uncertainty bars

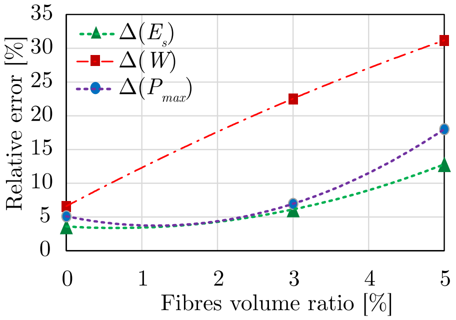

Figure 8: Coefficient of variance (CoV) of the main mechanical parameters, as a function of the fibre volume ratio. Curve-fits are also plotted.

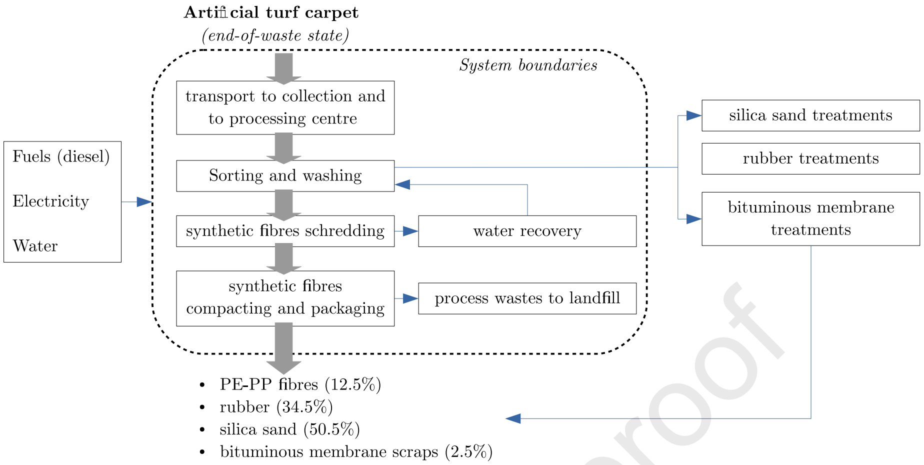

Figure 9: Flow chart for production of recycled PP-PE fibres from disposed AT carpets

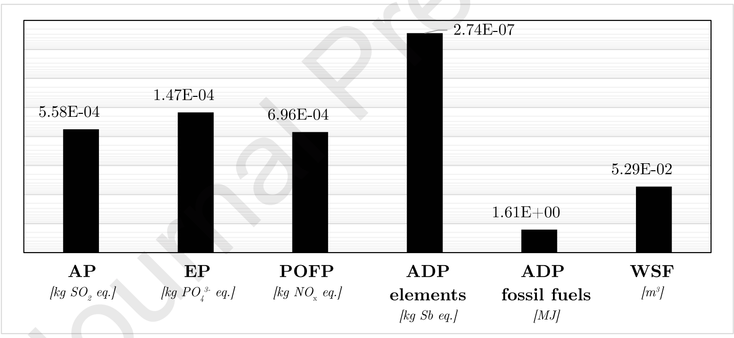

Figure 10: LCIA impact estimation for producing 1 Functional Unit (FU), that is 1 kg of recycled PE-PP fibres

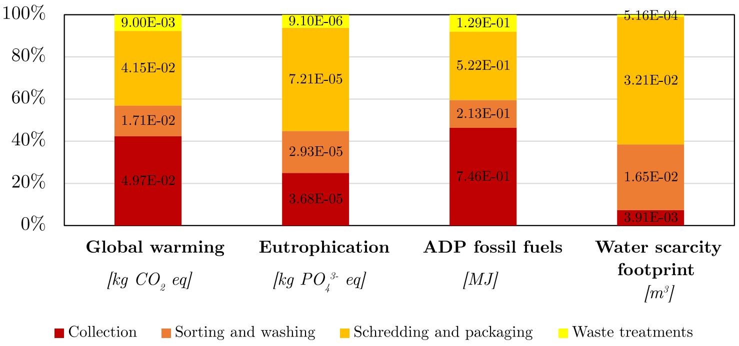

Figure 11: Contribution of the major processes to the overall impacts within th most impacted categories.

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Itemized list of the new results presented in the paper

"Performance of concrete reinforced with synthetic fibres obtained from recycling end-of-life sport pitches"

by C. Signorini, S. Marinelli, V. Volpini, A. Nobili, E. Radi and B. Rimini

- Fibres from disposed artificial turf for paving sport facilities are investigated;
- A ductile post-cracking regime in bending is achieved for FRC with recycled fibres;
- Recycled fibres favour FRC toughness to a similar extent as virgin fibres usually do;
- Life Cycle Assessment reveals a remarkable reduction of the ecological footprint;
- Impact reduction is very substantial also with respect to processing plastic waste.

Cesare Signorini: Conceptualization, Methodology, Investigation, Data Curation, Writing - Original Draft, Writing - Review & Editing; **Simona Marinelli**: Software, Investigation, Formal analysis, Data Curation, Writing - Original Draft; **Valentina Volpini**: Validation, Investigation, Writing - Review & Editing, Visualization; **Andrea Nobili**: Conceptualization, Methodology, Writing - Review & Editing, Project administration, Funding acquisition; **Enrico Radi**: Supervision, Funding acquisition; **Bianca Rimini**: Supervision, Funding acquisition.

Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Reggio Emilia, 22/07/2020

The corresponding Author, on behalf of all the Authors.

Cesare Signorini