Recycling of Waste Polyethylene Fishing Nets as Fibre Reinforcement in Gypsum-based Materials

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Abstract: Identifying new recycling initiatives for waste fishing gear is highly important, especially, if the fishing gear could end up as marine litter. The aim of this study is to investigate the potential of using recycled polyethylene (R-PE) fibres from waste fishing nets as fibre reinforcement in gypsum-based materials. The discarded fishing nets were processed by an industrial, mechanical cutting operation to create monofilament R-PE fibres. The fibre characterisation included tensile tests, geometry, morphology and leaching of anions (Cl^-, NO_3^-, SO_4^{2-}). The mechanical properties of the R-PE fibres were found to be in the same range as other commercially available synthetic fibres used in gypsum-based materials. Laboratory-scale specimens were prepared and R-PE fibres added at fractions of 0.25-2.00 wt%. Mechanical tests were carried out to determine the compressive and flexural response of gypsum-based materials. The addition of R-PE fibres resulted in a small reduction in the compressive strength and the ultimate flexural strength, but to the positive side, there was a significant increase in the post-crack performance. Based on these results, gypsum-based materials with the addition of R-PE fibres have the potential for being used as non-structural elements such as gypsum boards where increased post-crack performance and ductility is required.

Keywords: Gypsum-based materials, Mechanical properties, Fibres, Waste fishing nets, Plastic recycling

Introduction

Plastic waste is a major concern for the vulnerable marine environment and lost or otherwise discarded fishing nets are likely to be the greatest threat to marine wildlife, since they can lead to entanglements and can cause severe damage to fish, sea birds and marine mammals [1,2]. Approximately 8 million tonnes of plastic enter the ocean each year [3] and of that, fishing nets are an important fraction because of their shape and physical size. Historically, fishing gear was made of natural materials such as hemp, cotton or sisal that would decompose relatively quickly and, thus, be less detrimental to the marine wildlife if lost into the sea [4,5]. Nowadays, nets are typically made of synthetic fibres of polyethylene (PE), polypropylene (PP), polyester (PES) or nylon, which are all non-biodegradable [5]. Furthermore, waste fishing nets are often difficult to dispose of, costly to transport and take up a lot of space at landfill sites. As a consequence of outdoor- and UV-exposure together with continuous load impacts, the properties of the fishing nets can be impaired during use and can vary significantly [6].

Building materials with gypsum as main binder are widely used in the construction industry, mostly for plaster elements such as plasterboards and for protective/decorative coating and finishing of walls and ceilings [7,8]. Gypsum-based materials are generally associated with a brittle behaviour when exposed to tension [9]. Despite that the material mainly is used for non-structural elements, an adequate mechanical performance is still important. Adding fibre reinforcement to gypsum-based materials is a well-known technique for improving the post-crack performance and toughness of the composite [9,10]. Fibres of materials with various mechanical and physical properties have been used as reinforcement in gypsum-based composites, including glass [11,12], polymers such as polyamide (PA), polypropylene (PP) and polyvinyl alcohol (PVA) [13-16], and different types of natural fibres [10,17-20]. The incorporation of waste materials as fibre reinforcement is gaining increased attention in the construction industry mainly due to the reduced the need for virgin materials in the production of new fibres. The incorporation of both waste fibres [13,21-26] and different types of natural fibres [10,17-20] in gypsum-based materials have been studied with the aim of revealing new ways of producing more eco-friendly materials. These studies have shown that several types of plastic waste materials beneficially can be used to create low-cost reinforcement techniques of structural and non-structural building materials. It has also previously been demonstrated that fibres from waste fishing nets perform well in cement-based materials [27,28] and other types of materials [29,30]. Spadea *et al.* [27] found that recycled nylon fibres obtained from waste fishing nets added in fractions of up to 1.5 wt% improved the flexural strength, post-crack performance and toughness of cement-based mortars and that longer fibres resulted in superior performance. Similar tendencies were found by Orasutthikul *et al.* [28] who also studied recycled nylon fibres from waste fishing nets of different fibre length and shape (straight fibres or fibres with knots). However, when fibres were added the mortar mixture in too large fractions, the effect of the fibres was decreasing, mainly due to balling of the fibres and uneven fibre distribution. In a previous study by the

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authors, the performance of similar R-PE fibres was investigated with the aim of controlling plastic shrinkage cracking in restrained cement-based mortars overlays [31,32]. It was found that the addition of 2.0 vol% of R-PE fibres was successful in reducing plastic shrinkage cracking. This finding indicates that the R-PE fibres could improve the mechanical performance of lower-modulus materials such as hardened gypsum.

Fibres made of recycled plastics can be prepared by either mechanical recycling such as cutting or shredding operations, or by thermal reprocessing where the material is heated so that new products can be processed [33]. Although some recycled fibres used as fibre reinforcing materials have been produced by thermal reprocessing [34,35], it is more energy-efficient to produce recycled fibres by mechanical operations [27,28,36-39]. Fishing net lines most commonly consist of either twisted or braided fibres, which are easy to separate and cut into shorter fibres applicable as fibre reinforcement [5,27,28]. The R-PE fibre characteristics presented in the present study suggest that there is a great potential for using such fibres as reinforcing material in gypsum-based materials.

Experimental

Fibre Characterization

A Danish recycling company, Plastix A/S, provided the monofilament R-PE fibres obtained from waste fishing nets. Fishing nets of PE materials comprise a large fraction of the total amount of waste fishing nets collected and processed by the company. The recycling company collects waste fishing nets and reprocess them into new plastic pellets. Prior to the reprocessing, the fishing nets are separated into different polymer fractions, pre-washed, mechanically cut into shorter fibres, melted and, finally, reprocessed into new plastic pellets. However, the R-PE fibres used in the present study were obtained by the mechanical cutting operation, thus before the final melting and reprocessing.

The R-PE fibre samples provided by Plastix A/S contained a small amount of impurities such as sand and residues from the fishing operation. To analyse the influence and necessity of an additional cleaning process, the uncleaned fibres were first dry-sieved through a 0.25 mm sieve and subsequently washed in tap water to remove impurities. These were then labelled as cleaned R-PE fibres (CF), while the fibres that received no additional cleaning, were labelled uncleaned R-PE fibres (UF). Figure 1 shows samples of a) cleaned R-PE fibres, b) uncleaned R-PE fibres, and c) the impurities that were dry-sieved from the uncleaned fibre samples. Almost no difference between the cleaned and uncleaned R-PE fibres were observed by a visual examination, but the presence of the impurities was apparent when touching the uncleaned fibres. The fibre morphology was evaluated based on Scanning Electron Microscope (SEM) analysis and the geometry (length and diameter) were measured on 500 randomly chosen fibres from the cleaned fibre samples. The diameter of the fibres was determined as an average based on the length and mass of each fibre and confirmed using the SEM analysis on randomly selected fibres.

Impurities in the Uncleaned Fibre Samples

The uncleaned R-PE fibres contained a small amount of dirt from fishing operations. These impurities were separated from the uncleaned fibres by dry-sieving through a 0.25 mm sieve and were analysed to determine whether it was necessary to clean the fibres prior to using them in gypsum-based materials. Some salts, for instance, are known to accelerate the hardening of gypsum-based materials [7]. The characterization of the impurities included SEM analysis, thermogravimetric analysis (TGA), differential scanning calorimetry (DSC), and X-ray diffraction (XRD). DSC and TGA were carried out on a Netzsch STA 449 Jupiter with a heating rate of 10 °C/min from 25-800 °C.

Leaching of Fibres and Impurities

To simulate the leaching of contaminants from the R-PE fibres (uncleaned, cleaned) and the impurities separated from the uncleaned fibre samples, leaching tests were conducted. The materials were dried at 50 °C for 24 h and the test was performed following the prescriptions in EN 12457-2 (2002). Dried samples of 50 g (fibres or impurities) were immersed in 500 ml of CO_2-saturated water and placed into an agitation apparatus for 24 h. The liquid was filtered and the concentrations of anions (Cl^-, NO_3^-, SO_4^{2-}) were measured by ion chromatography (IC).

Mechanical Properties of Fibres

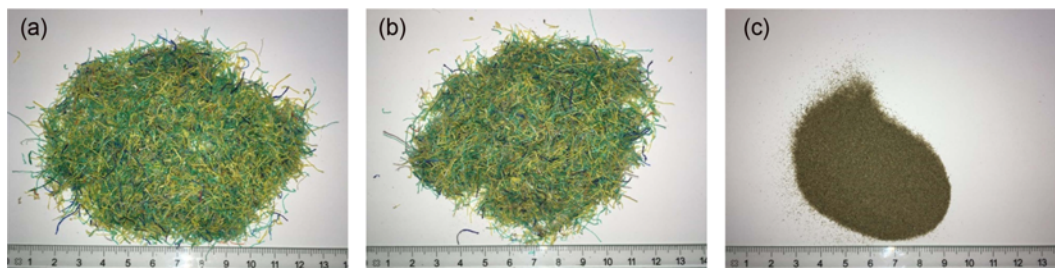The R-PE fibres received from Plastix A/S originated

Figure 1. (a) Cleaned R-PE fibres (CF), (b) uncleaned R-PE fibres (UF), and (c) impurities separated from the uncleaned fibres by dry-sieving.

Figure 2. Waste and new PE fishing nets from Euronete, used for characterisation of the mechanical properties of single fibres. Braided polyethylene (BP), Euroline (EU), and Euroline premium (EP).

from different sources of PE fishing net, so the mechanical properties were expected to vary to some extent. Since the length of the R-PE fibres from Plastix A/S were not long enough to perform tensile tests on, fibres extracted from selected known types of PE fishing nets were tested with respect to tensile strength and stiffness. The tensile properties were determined to clarify the variations in the mechanical properties of the R-PE fibres. Moreover, to get an indication of the level of deterioration and how impaired the R-PE fibres were with respect to the mechanical properties, fibres from both new (N) and recycled (R) fishing nets of equivalent types were tested, see Figure 2. Three types of fishing net that are commonly used in Denmark were selected: Braided Polyethylene (BP), Euroline (EU), and Euroline Premium (EP), all from Euronete. These three net types are all made from PE of different inherent mechanical properties (tensile strength and modulus), with Braided Polyethylene being the net with the lowest tensile strength and Euroline Premium the net with the highest tensile strength according to data sheets. Thus, these three net types were expected to represent the range of fibres present in the R-PE fibre samples from Plastix A/S. The waste nets were collected at dumpsites or received from Plastix A/S and the new nets were provided by Vonín, Strandbynet A/S. For each type of waste net, the visually most damaged and deteriorated net was chosen to represent the most conservative values for the respective fibre type. Single fibres were extracted from these fishing net lines by loosening the knots and gently separating the

single fibres from each other.

The tensile strength and tensile modulus were determined in accordance with ASTM C1557-14 [40] on single fibres with gauge lengths of 20, 25, and 30 mm. The test was carried out in an Instron 6022 instrument with a load capacity of 10 kN. Tensile load was applied in a displacement controlled loading rate of 20 mm/min to obtain a failure within 30 s. Each fibre was anchored on a piece of thick paper with WEICON PP-PE 2-component glue. Only failures on the free length of the fibre were counted as successful. Eight tests were carried out for each fibre type and gauge length. To determine the tensile modulus, E, the elongation (ΔL) over the force (F), $\Delta L/F$, was plotted against the initial length (l_0) over the cross-section area (A), l_0/A. The test setup is shown in Figure 3.

Characterisation of Gypsum-based Materials

Gypsum-based materials with the addition of R-PE were cast to determine the compressive and flexural responses. A hemihydrate of the type Miller Modelgips supplied by C. Flauenskjold was used. The mineralogical composition was characterised by XRD. The mixture consisted of the following materials: 1600 ± 2 g of hemihydrate, 700 ± 1 g of tap water, and fibre contents of 0.25 wt% to 2.0 wt% (% by weight with respect to the binder). The addition of 2.0 wt% of fibres was observed to be the maximum fibre content that could successfully be mixed into the gypsum material with the given mixture design and process. Batches reinforced with both cleaned and uncleaned R-PE fibres were prepared for three-point flexural bending tests, and batches with cleaned fibres were prepared for compression tests.

The dry mixture was primarily homogenised to ensure a homogeneous fibre dispersion. Then the mixture was hydrated by adding all the water under mechanical mixing in a Hobart mixing machine at low speed (corresponding to 140 rotations/min) for 15 s. Two types of specimens were prepared; prismatic specimens measuring $40\times40\times160$ mm^3 for three-point flexural bending tests, and cylinders measuring 60 mm$\times$120 mm for compression tests. The fresh material was cast in steel/PVC moulds and vibrated on a vibration table at 60 Hz to ensure the complete filling of the moulds and the removal of air bubbles. The moulds were covered with a metal plate on top to prevent non-uniform expansion
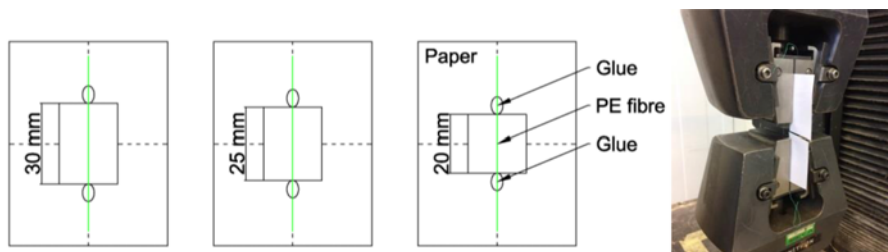

Figure 3. Test setup for tensile testing of monofilament fibres with gauge lengths of 20-30 mm.

of the specimen. The specimens were produced in sets of three replicates. Finally, the specimens were demoulded after 24 hours and air-cured for 48 hours at a temperature of 21±3 °C until testing.

Mechanical Testing of Gypsum-based Specimens

Three-point flexural bending tests were carried out on the prismatic specimens in accordance with UNI/EN 196-1 (2005) [41]. The tests were performed in an Instron 6022 hydraulic testing machine with a displacement controlled loading rate of 1 mm/min. The flexural stress is calculated from the load in accordance with UNI/EN 196-1 [41]. The ultimate flexural strength (f_{cr}) of the prismatic specimens is represented by the first peak of the flexural response, i.e. the load at which the first crack appear. The stiffness of the uncracked material, i.e. the Young's modulus (E) was estimated from the linear part of the flexural response (from the slope from 0.4 f_{cr} to 0.9 f_{cr}). The uniaxial compressive strength of cylinders with the addition of cleaned R-PE fibres was determined in accordance with UNI/EN 12390-3 (2012) [42] in a TONI Industries compression machine with a load controlled loading rate of 0.5 kN/s. After the three-point flexural bending tests, the prismatic specimens were left at laboratory conditions until 50 days after casting and the fracture surfaces of the prisms were analysed using SEM.

Results and Discussion

Fibres

Physical and Morphological Characterisation of R-PE Fibres

The R-PE fibre samples from Plastix A/S were investigated with respect to the geometry, morphology and leaching behaviour. The length and diameter of the cleaned fibre samples were measured to a mean length of 15±9 mm (varying between 1-65 mm with very few fibres longer than
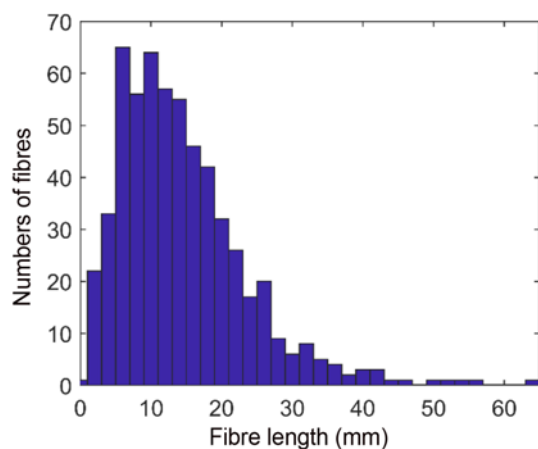
30 mm), see Figure 4, and a mean diameter of 280±30 μm. These large variations in the fibre length are due to the industrial, mechanical cutting operation, which potentially could be improved to produce fibres with more homogeneous lengths. During the washing process of the uncleaned fibre samples, it was observed that a few of the shortest fibres (length of 1-2 mm) were washed out with the impurities. Although the R-PE fibres originated from different PE fishing nets, only small variations in diameter were observed in the fibre sample.

Figure 5a-c shows SEM images of three selected cleaned R-PE fibres. There were large variations in the degree of surface deterioration of the R-PE fibres, which was expected
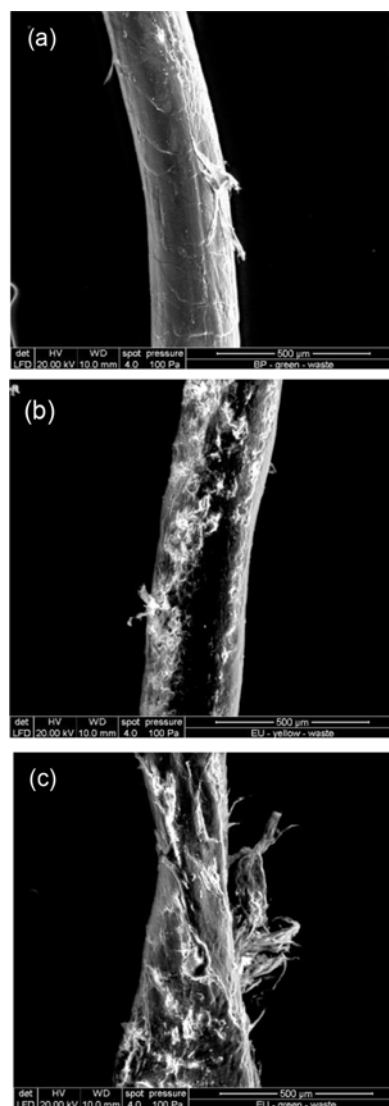

Figure 5. SEM analysis of selected cleaned R-PE fibres with different levels of deterioration; Field of view=1.27 mm; (a) little degree of surface deterioration, (b) medium degree of surface deterioration, and (c) high degree of surface deterioration.

Figure 4. Fibre length distribution for cleaned R-PE fibre sample.

to be due to factors such as different lifetimes, load history, abrasion with seabed, exposure to UV-light etc. [6]. The majority of fibres had an approximate circular cross section and a straight shape. The mechanical cutting process may also have damaged the fibres. However, most fibres investigated in SEM appeared with a smooth surface as the one showed in Figure 5a.

Impurities in Uncleaned R-PE Fibres

The uncleaned R-PE fibres contained a small amount of impurities, which by a visual inspection comprised sand, small particles/fibres of plastic and other unidentified types of dirt. These impurities were separated from the uncleaned fibre samples by dry-sieving and are shown in the SEM images in Figure 6. The SEM analysis revealed a mix of quartz grains, thin fibres, and small particles of plastic. The XRD results mainly revealed that the impurities contained quartz.

The thermal properties of the impurities were determined on two replicates and Figure 7 shows the TGA and DSC curves. The wt% of the original mass of the material as a function of the temperature is shown on the TGA curves and measured to 95-96 wt%. The DSC curve shows a small peak at 130 °C, which is the melting point for PE. Another peak can be seen at a temperature of 573 °C, which is the
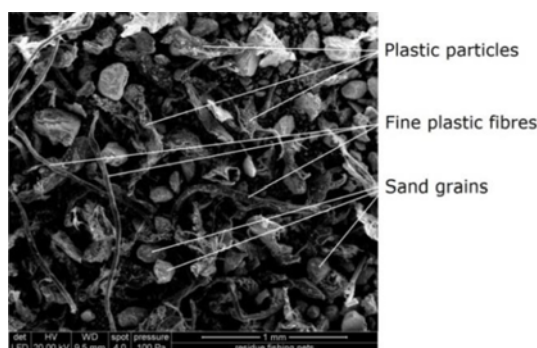
Table 1. Leaching of anions from impurities and R-PE fibres (uncleaned, cleaned)

Sample	pH (−)	Cl^- (mg/l)	NO_3^- (mg/l)	SO_4^{2-} (mg/l)
Impurities in uncleaned R-PE fibres	6.4	100.4	29.3	30.2
Uncleaned R-PE fibres	6.3	61.2	20.5	22.2
Cleaned R-PE fibres	5.9	3.7	1.2	3.9
Values found by [27] for R-fibres	8.2	2.2	5.9	3.6

temperature at which quartz undergoes a reversible change in crystal structure from α-quartz to β-quartz.

Leaching

The leaching of anions (Cl^-, NO_3^-, SO_4^{2-}) from the R-PE fibres (uncleaned, cleaned) and the impurities separated from the uncleaned fibres are shown in Table 1. The concentration of leached anions is highest for the impurities; especially chlorides due to the use of the fishing nets in sea water. It is also observed that a high concentration of anions were leached from the uncleaned R-PE fibres, and that, by simply cleaning the fibres in tap water, it was possible to decrease the content of leachable anions significantly. The concentrations were compared to the values found by Spadea *et al.* [27] who also studied the leaching behaviour of recycled nylon fibres from waste fishing nets by following the same procedure as in the present study, see Table 1. The R-nylon fibres studied by [27] were concluded to be safe to use as reinforcing material for cement-based mortars. Thus, since the leaching values for the cleaned R-PE fibres are in the same range as the R-nylon fibres found by [27] it was considered necessary to wash the fibres prior to using them as fibre reinforcement in gypsum-based materials. Furthermore, the addition of chlorides to gypsum is known to accelerate the hydration of the matrix [7,43], which is another reason for cleaning the R-PE fibres prior to using them as reinforcing material for gypsum composites.

Figure 6. SEM analysis of the impurities separated from the uncleaned R-PE fibres by dry-sieving. Field of view=2.55 mm.

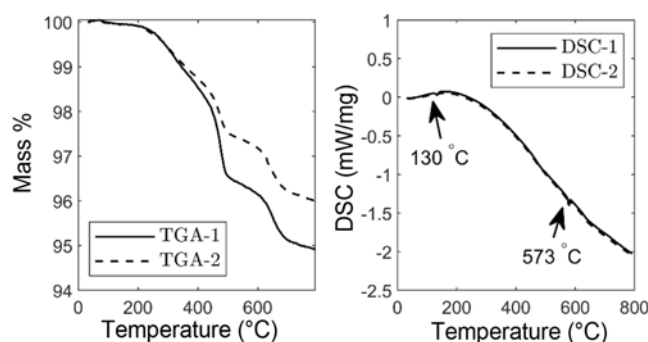**Figure 7.** TGA and DSC for the impurities in the uncleaned R-PE fibre samples (DF).

Characterisation of Tensile Properties of Fibres

The tensile properties were determined on fibres from recycled (R) and new (N) fishing nets of the types Braided Polyethylene (BP), Euroline (EU), and Euroline Premium (EP). These three selected net types were expected to cover the range of mechanical properties present in the R-PE fibre samples from Plastix A/S. The reason for testing both new and recycled fibres was to get an indication of how impaired the selected recycled fibres were compared to the equivalent new ones. Figure 8 illustrates examples of the stress-strain behaviour of R-BP and N-BP fibres with a gauge length of 20 mm exposed to uniaxial tension. Table 2 gives an overview of the mechanical properties of all fibres. Roughly, a linear stress-strain behaviour of the fibres was observed until failure. The mean tensile strength for fibres of the type Braided Polyethylene, R-BP and N-BP, was 376±60 MPa and 480±44 MPa, respectively, for fibres of the type Euroline, R-EU and N-EU, 445±69 MPa and 477±73 MPa,

Table 2. Properties of fibres from recycled (R) and new (N) PE fishing nets

Net type	Type	Tensile strength σ_t (MPa)	Peak strain ε_t (%)	Tensile modulus E (GPa)	Regression (−)
Braided polyethylene	R-BP	376±60	30±5.5	1.03±0.65	
	N-BP	480±44	30±4.1	1.53±0.70	
Euroline	R-EU	445±69	26±4.2	1.96±0.63	
	N-EU	477±73	33±6.3	2.31±0.68	
Euroline Premium	R-EP	452±81	25±5.2	1.41±0.87	
	N-EP	512±47	28±5.9	3.05±0.61	

Mean values of three gauge lengths (20-30 mm) are given for the three types of tested fishing net fibres.
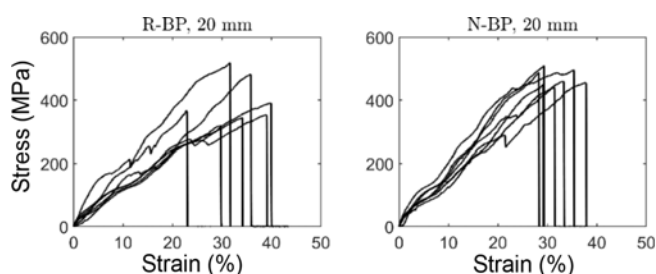
Figure 8. Tensile stress-strain behaviour of recycled (R) and new (N) fibres from the net types BP, with gauge length of 20 mm.

respectively, and finally, fibres of the type Euroline Premium, R-EP and N-EP, had a mean tensile strength of 452±81 MPa and 512±47 MPa, respectively. For the BP fibres there was a significant difference in tensile strength between the new and the recycled fibres, whereas it was less noticeable for the two other fibre types. The tensile strength was lowest for the recycled fibres independently of the fibre type with a mean value for the tensile strength for the recycled fibres of 420±50 MPa.

The tensile modulus of the fibres was derived using linear regression for the elongation over the force, $\Delta L/F$, between 20 % and 50 % of the failure load, against the initial length over the cross-section area, l_0/A. The results are given in Table 2. Due to a large standard deviation in the fibre strength-strain relationship and thereby a low regression values of 0.61-0.87, the results shall be considered as indications of the fibre stiffness.

Properties of Gypsum-based Composites

The mineralogical composition is shown on the XRD pattern in Figure 9 showing peaks corresponding to mainly hemihydrate (H) anhydrite (A) and dolomite (D).

The mechanical properties such as the compressive strength, ultimate flexural strength (f_{cr}, point A on Figure 10) and for fibre reinforced materials also the fibre efficiency factor (FEF) and the post-crack performance are important indicators of how well a building material perform, regardless that the composites mainly are intended for non-structural
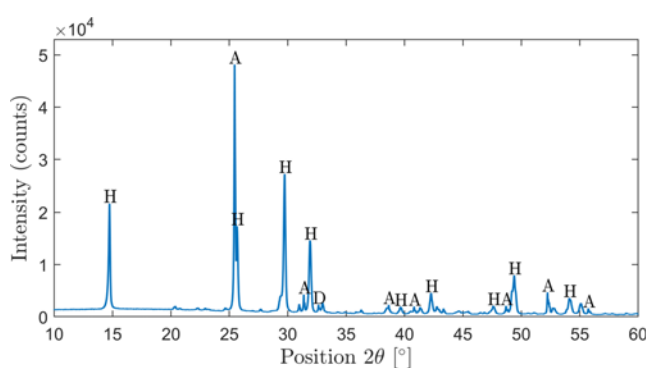
Figure 9. XRD pattern for hemihydrate (H=CaSO$_4$ 0.5H$_2$O; A=CaSO$_4$; D=CaMg(CO$_3$)$_2$).
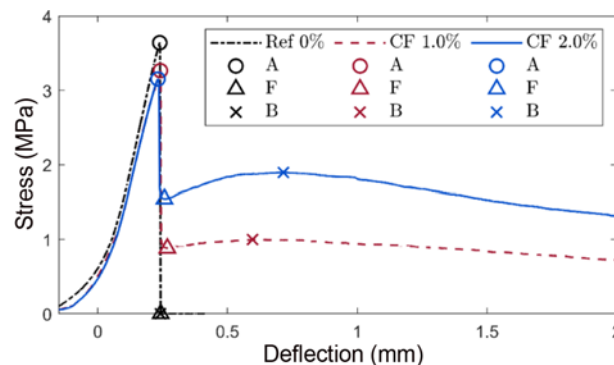
Figure 10. Flexural stress-deflection responses for gypsum-based prisms with 0.0 wt%, 1.0 wt% and 2.0 wt% of R-PE fibres (three-point flexural bending test).

elements. Examples of the flexural stress-deflection response of three selected specimens are given in Figure 10. The figure shows the reference specimen with no fibres (Ref), and specimens with the addition of 1.0 wt% and 2.0 wt% of cleaned R-PE fibres, respectively. As expected, the flexural response reveals that the Ref specimen had a brittle failure mode, since the load dropped immediately when the first crack appeared. The addition of R-PE fibres also resulted in this drop in load, but only until the internal tensile forces

were transferred to the fibres (point F, Figure 10). When the ultimate flexural strength was reached for the fibre reinforced specimens, the specimens still remained a whole with one crack appearing in the centre of the specimen where the load was applied. Thus, the addition of fibres increased the post-crack performance of the material. The maximum post-crack strength ($\sigma_{B,max}$) is marked as point B in Figure 10. The fibre efficiency factor (FEF) is calculated as the ratio of the stress at which the fibres start working (Point F in Figure 10) to the material's ultimate flexural strength (f_{cr}, point A in Figure 10) [25,44]:

$$\text{FEF} = \frac{\sigma_f}{f_{cr}}$$

Figure 11 shows the ultimate flexural strength, the maximum post-crack strength, the fibre efficiency factor (FEF), the stiffness of the uncracked composite and the compressive strength of specimens with various levels of cleaned (CF) or uncleaned (DF) R-PE fibres. From the figure, the following observations regarding the fibre influence are done: The ultimate flexural strength (f_{cr}) at which the first crack occurred is decreasing with increasing fibre content. The Ref specimen obtained an ultimate flexural strength of 3.7 MPa, whereas it decreased to 3.2 MPa for the specimens with 2.0 wt% of cleaned R-PE fibres. The maximum post-crack strength increased with increasing fibre content, i.e. it was 0.0 MPa for the Ref specimens, 0.85 MPa for specimens with 1.0 wt% of cleaned R-PE and 1.60 MPa for specimens with 2.0 wt% of cleaned R-PE. Even the addition of only 0.25 wt% of R-PE fibres resulted in a failure with fibres bridging the crack, although the post-crack performance was very limited. The specimens reinforced with cleaned fibres generally experienced a slightly larger post-crack performance than those reinforced with uncleaned fibres. Similar observations can be done for the FEF, where the addition of cleaned R-PE fibres resulted in an almost linear increase, while the uncleaned fibres showed more varying effects. The stiffness of the uncracked material is calculated as the linear part of the flexural response before the first crack appears. There is no clear indication as to whether the addition of fibres reduces the stiffness or not.
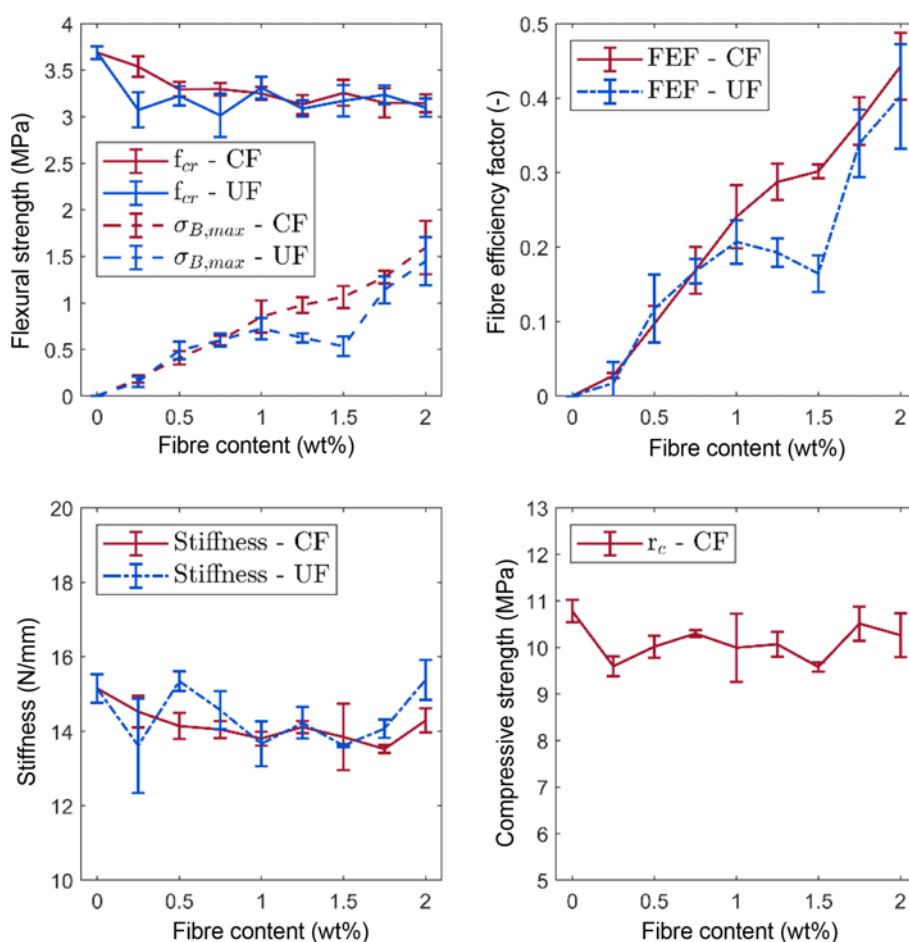

Figure 11. Ultimate flexural strength (f_{cr}); maximum post-crack strength ($\sigma_{B,max}$); fibre efficiency factor (FEF); stiffness; and compressive strength of the composites as a function of fibre content (CF: cleaned fibres, UF: uncleaned fibres).
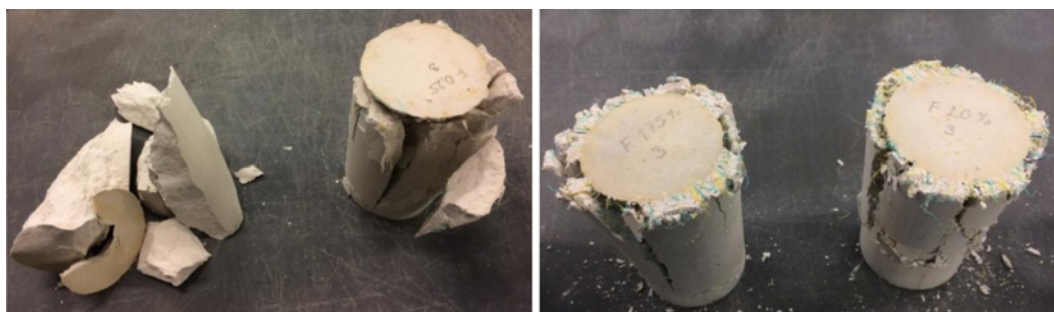
Figure 12. Compressive failure of selected cylinders with addition of 0 wt% (Ref), 0.25 wt%, 1.75 wt%, and 2.0 wt% of cleaned R-PE fibres.
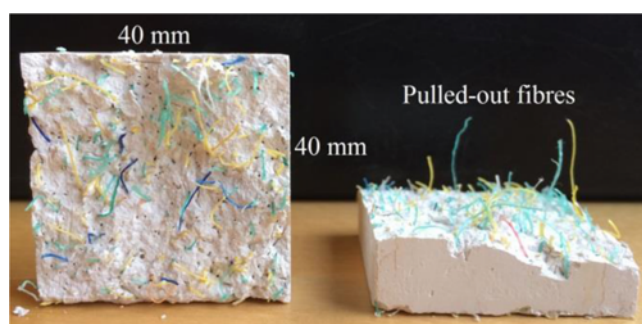

Figure 13. Fracture surface of prismatic specimens with 2.0 wt% of cleaned R-PE fibres after three-point flexural bending test.

Figure 11 also shows the compressive strength (r_c) of cylinders with cleaned R-PE fibres. Although the unreinforced Ref specimen had the highest compressive strength, there are no clear indication on whether the addition of fibres resulted in an increase or decrease of the compressive strength. Figure 12 shows four selected specimens reinforced with fibre fractions of 0, 0.25, 1.75 and 2.0 wt% (CF) after the compression test. While the unreinforced Ref specimen had a fragile failure, the failure in the fibre-reinforced specimens was more ductile even for specimens with the lowest fibre content of 0.25 wt%.

Fracture Surface Analysis and Microstructure

The mechanisms involved in the improved post-crack performance of the prismatic specimens used for the three-point flexural bending test relate to the fibre-to-matrix bonding, i.e. the pull-out of fibres for brittle materials and the fibre fracture [10]. Only fibre pull-outs and no fibre fractures were observed when examining the fracture surfaces of the prisms, see Figure 13. A large number of small holes could also be detected at the fracture surface together with fibres sticking out. This shows that fibres were pulled out of the gypsum matrix during the flexural test.

The SEM images in Figure 14 show the microstructure of the fractured surface of a composite after the three-point flexural bending test at two magnifications. During the hydration process of the gypsum material, randomly orientated small needle-shaped crystals were formed. The interfaces between the R-PE fibres and the material appeared porous with the hydrated needle-shaped crystals of plaster closely gathered around the fibres where a small gap of debonding can be seen. The fibres that were pulled out of the matrix have small particles of plaster on the fibre surface and appeared without any signs of degradation.
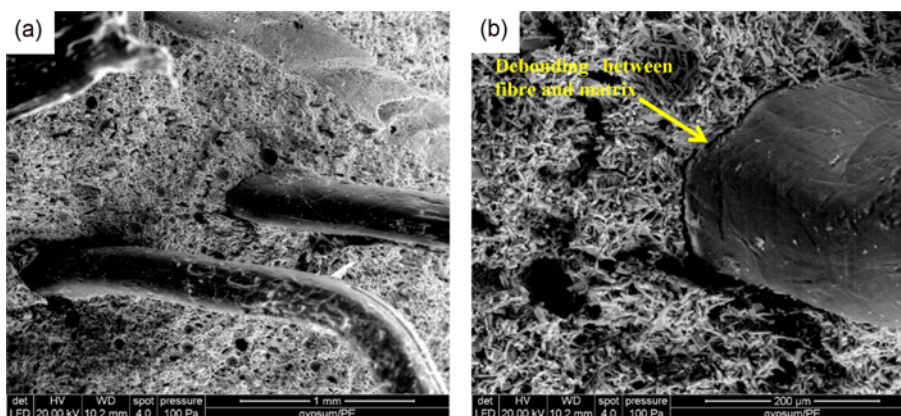

Figure 14. SEM images of the fracture surface of prismatic specimens with the addition of 2.0 wt% of cleaned R-PE fibres; (a) ×50 and (b) ×250.

Discussion

The benefits of using fibres from plastic waste materials as fibre reinforcement in brittle building materials are that waste materials can be recycled, while some mechanical properties of the composite material are improved. Although the recycling of waste fibres in gypsum-based materials would allow the production of more eco-friendly products, it is still important to consider the future recyclability of the end-of-life material. This issue of recycling fibre reinforced materials does not only concern the incorporation of waste fibres but also the use of virgin fibres in various types of composites [45]. The results of the present work are promising and the characteristics of the R-PE fibres from waste fishing nets were found to be in the same range as many other low-modulus fibres used as fibre reinforcement in gypsum-based materials. Because the R-PE fibres had previously been used for fishing operations, the uncleaned R-PE fibres contained some impurities and residues. Since these impurities had a high concentration of leachable ions (mainly chlorides), it was considered necessary to clean the fibres in tap water prior to using them as fibre reinforcement in the gypsum-based materials.

Influence of Fibres on the Mechanical Performance of Gypsum-based Materials

The major benefit of adding fibres to brittle materials is to avoid a catastrophic failure of the material by improving the post-crack performance. These positive effects of adding fibres from waste fishing nets of nylon to cement-based materials were previously reported by Spadea *et al.* and Orasutthikul *et al.* [27,28]. The fibre influence on the post-crack performance depends on their performance in providing bridging forces across the cracks [44], which is a result of the fibre-to-matrix bonding, the fibre pull-out force and the fibre properties such as the geometry, shape, surface, tensile strength and tensile modulus. One of the challenges when using waste- or natural fibre materials instead of commercially available fibres of virgin materials relates to the variations in properties [17-19,22,25]. The R-PE fibres extracted from waste fishing nets had large variations in fibre length as a result of the industrial, mechanical cutting operation. Still, the mean fibre length of 15±9 mm corresponds well with other fibres used in gypsum-based composites studied in the literature [11,13,14,18,46,47]. The fibre length is an important parameter with respect to the mechanical performance of the composites, and in particular, to the post-crack performance and fracture energy [22]. It is generally assumed that fibres of longer length are the main attributers to the gain in fracture energy [44], but longer fibres and too high fibre fractions can also lead to poor mixing and fibre bundling resulting in impaired properties of the composite material [28]. The fibre diameter of the R-PE fibres of 280±30 μm is coarser than most other synthetic fibres used in gypsum- or cement-based composites reported in the literature. However, also gypsum-based

specimens with the addition of fibres with coarser diameter in the range of 0.15-0.6 mm were studied with promising results showing significant improvements in post-crack performance [10,15,17,18,48]. The fibre aspect ratio is also a relevant property for the performance of the fibres. As a result of the varying fibre length and diameter, the aspect ratio is as well not similar for all fibres. The mean value is around *L/d*=50, which is in the low range of other tested fibre types in gypsum-based materials [25,44]. Vasconcelos *et al.* [22] studied gypsum-based composites with the addition of granulated cork and PA6 fibres obtained from recycled tyres. In the study, large variations in fibre geometry were reported. This covered fibre lengths of 0.1-12.5 mm and diameters of 7.2-34.1 μm, and, despite these variations, it was still found that the fibres were successful in improving the fracture energy of the composite. Li *et al.* (2003) [48] used cotton stalk fibres, which also had large variations in the fibre geometry (lengths of 5-20 mm and diameters of 0.5-3.0 mm). Both untreated fibres and fibres treated with styrene acrylic emulsion were used as reinforcement in gypsum-based composites, and it was found that styrene acrylic-treated fibres achieved better fibre-to-matrix bonding.

The tensile strength of the R-PE fibres of 420±50 MPa was determined by testing fibres from three types of known PE nets, which were assumed to cover the range of mechanical and geometrical properties present in the R-PE fibre samples. The material properties of the R-PE fibre samples were considered to vary due to the differences in inherent mechanical properties and in the level of deterioration due to mechanical loading and abrasion during fishing operations, exposure to UV-light etc. Furthermore, some nets were stored at dumpsites, harbors or at the recycling plant for an unknown period of time before they were processed. Some of these variables could be improved with upgraded waste management of the waste fishing gear. The tensile strength of the R-PE fibres from waste fishing nets corresponds well with the tensile strength of other synthetic fibres (especially low-modulus fibres of PP or PA) used as reinforcing materials in gypsum-based materials, where tensile strengths in the range of 300-600 MPa have been reported in the literature [15,16,44,47,49]. Eve *et al.* [44] studied the influence of virgin PA fibres of different geometries as fibre reinforcement in gypsum-based materials added in fibre fractions up to 5 wt%. The PA fibres had tensile properties comparable to those of the R-PE fibres used in the present study, although their diameter was finer (15-40 μm compared to 280±30 μm). The ultimate flexural strength of the gypsum-based material was also in the same range as the material investigated in the present study, why it was possible to compare the influence of these fibre types. Fibre efficiency factors (FEF) of approximately 0.2-0.6 were found for the studied PA fibres when added in fractions of 2 wt% [44], which is in the same range as the R-PE fibres (FEF=0.44 for 2.0 wt%). The addition of the low-modulus

R-PE fibres was found to cause a decrease in the ultimate flexural strength, which was also observed in other studies [16,44]. Zhu *et al.* [16] studied the influence of PVA and PP fibres on the mechanical properties of gypsum-based composites. The tensile properties of the PP fibres (tensile strength of 570 MPa and tensile modulus of 3.5 GPa) were slightly larger, but still comparable to the R-PE fibres used in the present study (tensile strength of 420±50 MPa and tensile modulus of 1.5±0.5 GPa), whereas the tensile properties of the PVA fibres were significantly larger (tensile strength of 1580 MPa and tensile modulus of 36 GPa). It was found that the PVA fibres performed superior with respect to improving the toughness of gypsum-based composites, compared to PP fibres, which was ascribed to the improved mechanical properties of the fibres and the good adhesion between PVA fibres and gypsum matrix [16].

The effect of adding synthetic fibres to brittle materials such as gypsum-based or cement-based composites with respect to the compressive strength has been a topic of much discussion in the literature, with some studies reporting an increase in the compressive strength [49-52], others reporting a decrease in strength [13,27,44,53,54], and yet others reporting either unclear effects or no effect at all [22,55]. In this study, the addition of R-PE fibres of up to 2 % did result in a reduction of 5 % in compressive strength and there was not observed a clear tendency with increasing fibre addition. Accordingly, these comparisons with other studies show that the addition of R-PE fibres to gypsum-based materials can achieve similar results with respect to the improvements in the post-crack performance. Thus, these R-PE fibres can be a promising alternative to other types of low-modulus synthetic fibres of virgin materials.

Conclusion

The aim of this study was to explore new ways of using fibres obtained from waste fishing nets as fibre reinforcement in gypsum-based materials. The fibres obtained from waste fishing nets of recycled polyethylene (R-PE) were characterized. The following findings regarding the R-PE fibre characteristics can be highlighted:

1. The R-PE fibre samples were obtained by an industrial, mechanical cutting operation of waste fishing nets of different types of PE. This operation resulted in fibres with large variations in length (15±9 mm). The diameter of the R-PE fibres was found to be more uniform (280±30 mm). The tensile strength was determined on selected types of known fishing nets, which were expected to cover the range of mechanical properties present in R-PE fibre samples. The mean value for the tensile strength of the recycled fibres was 420±50 MPa.
2. The characterisation of the R-PE fibres showed that the tensile strength and geometry of the fibres were in the range as other low-modulus synthetic fibres such as PP

and PA, which are used in gypsum-based materials.
3. The R-PE fibres contained a small amount of impurities from the fishing operation, which had high concentrations of leachable chlorides. These impurities were considered necessary to extract from the fibre samples and it was found sufficient to wash the fibres in tap water.

Gypsum-based specimens were produced with the aim of evaluating the influence of R-PE fibres on the mechanical performance. The compressive and flexural responses were determined on laboratory-scale gypsum-based specimens prepared with fibre additions of 0.25-2.0 wt%.

1. The flexural response of gypsum-based composites with the addition of cleaned and uncleaned R-PE fibres resulted in an increase in the post-crack performance and fibre efficiency factor (FEF), but also in a decrease in the ultimate flexural strength. The unreinforced gypsum-based specimens experienced a brittle failure, while the post-crack performance could significantly benefit from the addition of R-PE fibres.
2. Fracture surfaces from the three-point flexural bending test were analysed using Scanning Electron Microscopy (SEM) and revealed that most fibres were pulled out of the matrix. The fibres showed no sign of degradation from having been inside the gypsum composites for 50 days.
3. Although, the highest compressive strength was obtained for the unreinforced specimens, no clear indications on whether the fibre addition had a positive or negative influence on the compressive strength was found.

The R-PE fibres performed similarly to other low-modulus synthetic fibres of virgin materials used in gypsum-based materials. These results support that there is a potential in using R-PE fibres obtained from waste fishing nets as fibre reinforcement in gypsum-based materials to create a more eco-friendly material.

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