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Published in:
Marine Plastics

Link to article, DOI:
10.1007/978-3-031-31058-4_12

Publication date:
2023

Document Version
Publisher's PDF, also known as Version of record

Citation (APA):
Bertelsen, I. M. G., Lima, A. T. M., & Ottosen, L. M. (2023). Possible Applications for Waste Fishing Nets in Construction Material. In S. M. F. Grimstad, L. M. Ottosen, & N. A. James (Eds.), *Marine Plastics: Innovative Solutions to Tackling Waste* (pp. 211–241). Springer. https://doi.org/10.1007/978-3-031-31058-4_12

Chapter 12
Possible Applications for Waste Fishing Nets in Construction Material

Ida Maria Gieysztor Bertelsen, Ana Teresa Macas Lima, and Lisbeth Mølgaard Ottosen

Abstract Research on the use of recycled plastics in construction materials has increased over the last decade. The major trends and recycling applications for plastic waste in construction materials are reviewed in this chapter with a special focus on the use of discarded fishing nets as reinforcing material. The experimental part of this project included the characterization of discarded fishing nets of polyethylene with the aim of discovering new recycling alternatives for the use of fishing nets as reinforcement in different types of construction materials. The fishing net material was added either in the form of fibers or as pieces of net. The characterization of the polyethylene fibers showed that the material properties were in the same range as some commercially available fibers used in construction materials. The influence of the addition of fishing nets to construction materials was evaluated based on the mechanical performance and early-age shrinkage properties of cement-based mortars, gypsum, and earth-based adobe bricks. The results showed that the addition of fishing net fibers improved the post-crack performance of all types of tested construction materials, but the most prominent gain in mechanical properties was obtained for the earth-based adobe bricks. The addition of fibers was also found to mitigate shrinkage deformations and cracking of cement-based and earth-based materials.

Keywords Recycling of fishing nets · Construction materials · Fibre reinforcement · Mechanical properties

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S. M. F. Grimstad et al. (eds.), *Marine Plastics: Innovative Solutions to Tackling Waste*,
https://doi.org/10.1007/978-3-031-31058-4_12

12.1 Introduction

Recycling of various forms of plastic waste in construction materials has gained increasing attention in recent decades and several studies have shown that it is possible to improve the mechanical performance and different durability-related properties of construction materials by including waste plastics in the forms of fibers, aggregates, or net shapes to the material (Ahmed et al. 2021; Gu and Ozbakkaloglu 2016; Merli et al. 2020; Pablo Ojeda 2021; Sharma and Bansal 2016). Section 12.2 provides an overview of recent research on the use of waste plastic in construction materials.

The experimental work described in this chapter is described in Sect. 12.3 and was conducted as part of the two international projects funded by the European Union's Northern Periphery and Arctic Programme, Circular Ocean, and Blue Circular Economy. Arctic DTU, DTU Civil Engineering, was the Greenlandic partner in both projects. Thus, the starting point was based on the situation in Greenland, with the focus on the accessible types of waste fishing gear, which were available in large quantities at local landfill sites in towns along the Greenlandic coastline. However, it was quickly realized that the types of fishing net materials used in the entire Northern Periphery and Arctic (NPA) region were relatively homogeneous. Hence, the encountered solutions for the recycling of fishing nets in construction materials could also be implemented in other regions. Figure 12.1a shows an example of the storage of fishing nets and trawls at a landfill site in Greenland (a). The most used types of nets are made of polyethylene. Figure 12.1b shows fibers of recycled polyethylene (R-PE) obtained from discarded fishing nets by mechanical cutting operations at the Danish recycling company, Plastix A/S (b). Fishing nets often consist of bundles of monofilament fibers with a shape corresponding to those used as synthetic fiber reinforcement in construction materials. This observation led to the idea of investigating the use of fibers obtained from discarded fishing nets as fiber reinforcement with the aim of identifying possible recycling options (Bertelsen 2019).

Fig. 12.1 **a** Discarded fishing nets piled up at the landfill site in Sisimiut, Greenland. **b** Monofilament R-PE fibers from discarded fishing nets processed by a mechanical cutting operation by the Danish recycling company, Plastix A/S (Bertelsen 2019)

12.2 Aim of the Project

The aim of the project was to investigate the use of discarded fishing nets as reinforcement in construction materials by experimental testing. Fishing nets were in most cases included in the form of fibers, but some test series were carried out on the addition of net pieces as a reinforcing layer in the construction materials.

Moreover, a literature review was conducted on the use of plastic waste materials in construction materials with special focus on the use of discarded fishing nets.

12.3 Use of Recycled Plastic in Construction Materials

The potential use of recycled plastic and polymeric waste materials in construction has been widely studied in the literature. The application has gained recognition in the construction industry due to their broad applicability, low price, and sustainability aspects (Gu and Ozbakkaloglu 2016; Sharma and Bansal 2016; Siddique et al. 2008). In the recent decade, there has been an exponential increase in the number of studies as well as review studies on the topic. To confirm this, a literature search was carried out using the Scopus database. The search criteria were "Title, Author, Keywords, Abstract", and the selected keywords are shown in Table 12.1 for Search #1 and Search #2, respectively. Search #1 is focused only on review studies, while Search #2 is focused on research studies on the topic. No exclusion criteria were adopted about the publication date.

The Scopus search returned 128 results for Search #1 including "review" and 1249 results for Search #2. The results from the literature search are shown in Fig. 12.2 showing the total number of results per year. There has been an exponential increase in the number of published papers, both in terms of review papers and research papers. Note that the figures show the total number of results without exclusion.

The next step was to critically evaluate the results to allow the selection of relevant publications focusing on the use of plastic waste fractions in construction materials. The selected 42 publications were only selected from Search #1 (review papers). These are listed in Table 12.2. Review studies on asphalt materials were excluded.

Table 12.1 Search criteria used for the literature search in Scopus

Keywords	Selected hits (total hits)
Search #1: TITLE-ABS-KEY(Review AND "Plastic waste" OR "Recycled plastic" OR "Waste plastic" OR "Polymeric waste" AND "Concrete" OR "Cement" OR "Construction material")	42 (128)
Search #2: TITLE-ABS-KEY("Plastic waste" OR "Recycled plastic" OR "Waste plastic" OR "Polymeric waste" AND "Concrete" OR "Cement" OR "Construction material")	(1249)

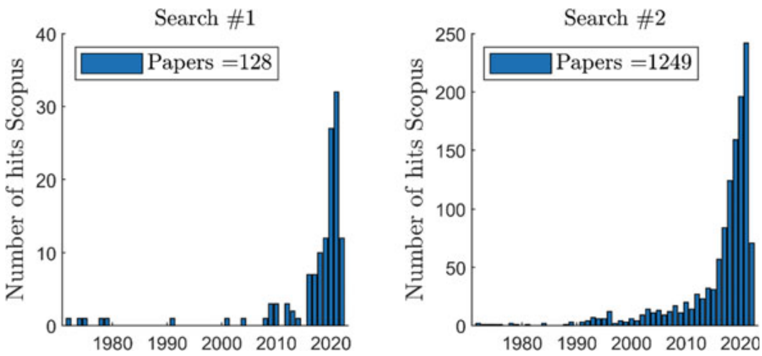


Fig. 12.2 Overview of results in Scopus search

As seen in Table 12.2, the application of plastic waste in construction materials has been studied in the form of aggregates, fibers, or other functions such as using the polymer as the binding material. Most of the review studies covered the use of plastic waste in the form of aggregates replacing material aggregates in cementitious composites. This was also found in the meta-analysis by Pablo Ojeda (2021). The reason for this could be that larger volume fractions of plastic waste can be used in the form of aggregates compared to that of fibers. In the review study by Almeshal et al. (2020), replacement levels of aggregates in cementitious composites with recycled plastic aggregates were up to 100% for mortar and up to 75% for concrete were reported, although lower replacement levels are more widely studied. However, when replacing natural aggregates with increasing additions of plastic aggregates in cementitious composites, not only does the density decrease, but also the mechanical properties such as the elasticity modulus, compressive, flexural, and tensile strength are impaired (Almeshal et al. 2020; Pablo Ojeda 2021). For most types of construction materials, a high elastic modulus and high strength properties are preferred since it creates stiffer and stronger materials resulting in higher load-bearing capacity.

Recycled plastic fibers are commonly added in much lower fractions to cementitious composites and for other reasons than plastic aggregates, which is explained in Sect. 12.3.1. Ahmed et al. (2021) conducted a review on the use of recycled fibers in cementitious composites. The maximum fiber addition reported was up to 5 wt% (weight% of fibers by mass of the other dry materials such as cement, sand, and gravel depending on the type of construction material), but for fiber-reinforced concrete, the beneficial effects of adding the plastic fibers can, depending on the fiber properties, be obtained at much lower fiber additions.

Since the fishing nets investigated in the present project already have the fiber shape with one line consisting of multifilament fibers, they were investigated with the aim of being used as fiber reinforcement.

Table 12.2 Selected review studies from Search #1 on the use of recycled plastic in construction materials

References	Year	Title	Aggregate	Fiber	Other
(Siddique et al. 2008)	2008	Use of recycled plastic in concrete: a review	x	x	
(Pacheco-Torgal et al. 2012)	2012	Properties and durability of concrete containing polymeric wastes (tyre rubber and polyethylene terephthalate bottles): an overview	x	x	
(Saikia and De Brito 2012)	2012	Use of plastic waste as aggregate in cement mortar and concrete preparation: a review	x		
(Gu and Ozbakkaloglu 2016)	2016	Use of recycled plastics in concrete: a critical review	x	x	
(Tiwari et al. 2016)	2016	Feasibility assessment for partial replacement of fine aggregate to attain cleaner production perspective in concrete: a review	x		
(Sharma and Bansal 2016)	2016	Use of different forms of waste plastic in concrete—a review	x	x	
(Alfahdawi et al. 2016)	2016	Utilizing waste plastic polypropylene and polyethylene terephthalate as alternative aggregates to produce lightweight concrete: a review	x		
(Krishna and Jagadeesh 2017)	2017	Influence of admixtures on plastic wastes in an eco-friendly concrete—a review	x		
(Sodhi and Salhotra 2017)	2017	Utilising wastes as partial replacement in concrete—a review	x		
(Babafemi et al. 2018)	2018	Engineering properties of concrete with waste recycled plastic: a review	x	(x)	
(Meng et al. 2018)	2018	Recycling of wastes for value-added applications in concrete blocks: an overview	x		
(Usman et al. 2018)	2018	Effect of recycled plastic in mortar and concrete and the application of gamma irradiation—a review	x		
(Mercante et al. 2018)	2018	Mortar and concrete composites with recycled plastic: a review	x		
(Kishore and Gupta 2019)	2019	Application of domestic & industrial waste materials in concrete: a review	x		

(continued)

Table 12.2 (continued)

References	Year	Title	Aggregate	Fiber	Other
(Law et al. 2019)	2019	A review on waste materials usage as partial substitution in self-compacting concrete	(x)	(x)	
(Frhaan et al. 2022)	2020	Relation between rheological and mechanical properties on behaviour of self-compacting concrete (SCC) containing recycled plastic fibres: a review		x	
(Sidhardhan and Albert 2020)	2020	Experimental investigation on light weight cellular concrete by using glass and plastic waste—a review	(x)		
(Gupta et al. 2020)	2020	Utilization of recycled aggregate, plastic, glass waste and coconut shells in concrete—a review	x		
(Tang et al. 2020)	2020	Advanced progress in recycling municipal and construction solid wastes for manufacturing sustainable construction materials	x		
(Faraj et al. 2020)	2020	Use of recycled plastic in self-compacting concrete: a comprehensive review on fresh and mechanical properties	x	x	
(Bahij et al. 2020)	2020	Fresh and hardened properties of concrete containing different forms of plastic waste—a review	x	x	
(Almeshal et al. 2020)	2020	Use of recycled plastic as fine aggregate in cementitious composites: a review	x		
(Goli et al. 2020)	2020	Application of municipal plastic waste as a manmade neo-construction material issues & wayforward	x		
(Kumar et al. 2020)	2020	A review on utilization of plastic waste materials in bricks manufacturing process			x
(Dadzie et al. 2016)	2020	Exploration of waste plastic bottles use in construction			x
(Mahmood and Kockal 2020)	2020	Cementitious materials incorporating waste plastics: a review	x	x	
(Park and Kim 2020a)	2020	Mechanical properties of cement-based materials with recycled plastic: a review	x	x	

(continued)

Table 12.2 (continued)

References	Year	Title	Aggregate	Fiber	Other
(Rathore et al. 2021)	2021	Influence of plastic waste on the performance of mortar and concrete: a review	x		
(Lamba et al. 2021)	2021	Recycling/reuse of plastic waste as construction material for sustainable development: a review	x		x
(Uvarajan et al. 2021)	2021	Reusing plastic waste in the production of bricks and paving blocks: a review	x		x
(Raj and Somasundaram 2021)	2021	Sustainable usage of waste materials in aerated and foam concrete: a review	x		
(Mohan et al. 2021)	2021	Recent trends in utilization of plastics waste composites as construction materials	x		x
(Abeysinghe et al. 2021)	2021	Engineering performance of concrete incorporated with recycled high-density polyethylene (HDPE)—a systematic review	x	x	
(Ahmed et al. 2021)	2021	Use of recycled fibers in concrete composites. A systematic comprehensive review		x	
(da Silva et al. 2021)	2021	Application of plastic wastes in construction materials: a review using the concept of life-cycle assessment in the context of recent research for future perspectives	x	x	
(Alqahtani and Zafar 2021)	2021	Plastic-based sustainable synthetic aggregate in Green Lightweight concrete—a review	x		
(Zulkernain et al. 2021)	2021	Utilisation of plastic waste as aggregate in construction materials: a review	x	(x)	
(Kazemi et al. 2021)	2021	State of the art in recycling waste thermoplastics and thermosets and their applications in construction			x
(Alyousef et al. 2021)	2021	Potential use of recycled plastic and rubber aggregate in cementitious materials for sustainable construction: a review	x		
(Kaliyavaradhan et al. 2022)	2022	Effective utilization of e-waste plastics and glasses in construction products—a review and future research directions	x	x	

(continued)

Table 12.2 (continued)

References	Year	Title	Aggregate	Fiber	Other
(Ferdous et al. 2021)	2021	Recycling of landfill wastes (tyres, plastics and glass) in construction—a review on global waste generation, performance, application and future opportunities	x		
(Kazemi and Fini 2022)	2022	State of the art in the application of functionalized waste polymers in the built environment			x

12.3.1 Fiber Reinforcement Used in Construction Materials

The addition of plastic fibers (virgin or recycled) to construction materials is a commonly used technique for improving different material properties such as:

- The enhancement of post-crack performance by increased ductility, impact resistance, and other mechanical properties of quasi-brittle materials such as concrete (Balaguru and Shah 1992; Bentur and Mindess 2006).
- For mitigating early-age shrinkage cracking (plastic shrinkage cracking and drying shrinkage cracking) in construction materials susceptible to shrinkage cracking (Banthia and Gupta 2006; Naaman et al. 2005). Cracks in concrete or other types of construction materials should be avoided since water and other aggressive agents can penetrate the materials through the cracks and thereby lower the durability and lifetime of the construction material.
- For improving fire safety by preventing spalling in concrete structures such as tunnel linings under fire exposure (Banthia et al. 2012; Heo et al. 2010).

Besides the addition of fibers to cement-based materials, similar fiber types have also been used to improve the performance of other types of construction materials such as gypsum plaster, bitumen, and earth-based construction materials (adobe, CEB, rammed earth) (Abtahi et al. 2010; Araya-Letelier et al. 2019; Binici et al. 2005; Eve et al. 2002). Depending on the specific application of the material, fiber characteristics play a significant role: e.g., the geometry and shape of the fiber, chemical/geometrical bonding to the matrix, mechanical strength and stiffness, and thermal properties.

12.3.2 Recycled Plastic Fibers

As shown in Table 12.2, the use of different fractions of plastic waste materials as fiber reinforcement in both cement-based materials and other types of construction materials has been widely investigated in the literature. Various types of plastic waste deriving from different sources have been studied as fiber reinforcing material in construction materials. Researchers suggested fibers from waste fractions such as:

- Carpet (nylon, polyester) (Awal and Mohammadhosseini 2016; Ozger et al. 2013; Ucar and Wang 2011; Wang 1999; Wang et al. 2000).
- Plastic bags (Ghernouti et al. 2015; Jain et al. 2021).
- Plastic bottles (mainly PET) (Borg et al. 2016; Dadzie et al. 2016; Foti 2013; Fraternali et al. 2013; Kim et al. 2008a, b; Pelisser et al. 2010; Rebeiz 1995).
- Fishing nets (Nylon or PE) (Nguyen et al. 2021; Orasutthikul et al. 2017; Park and Kim 2020b; Park et al. 2021; Spadea et al. 2015; Srimahachota et al. 2020; Truong et al. 2020).
- Different types of mixed industrial or post-consumer waste (Auchey 1998; Naik et al. 1996; Pešić et al. 2016; Yin et al. 2015).

Several studies have focused on the performance of plastic waste fibers in construction materials for various applications. The main application of plastic waste in construction materials is described below:

- for mitigating early-age shrinkage cracking in cement-based materials (Al-Tulaian et al. 2016; Auchey 1998; Bertelsen et al. 2019b; Borg et al. 2016; Kim et al. 2008a, b; Pešić et al. 2016; Serdar et al. 2015),
- for improving the mechanical performance in cement-based materials (Foti 2013; Fraternali et al. 2013; Orasutthikul et al. 2017; Pereira De Oliveira and Castro-Gomes 2011; Spadea et al. 2015),
- for improving the mechanical performance in other types of construction materials, e.g., gypsum (Parres et al. 2009; Vasconcelos et al. 2015) and earth-based materials (Bertelsen et al. 2021; Gandia et al. 2019; Prasad et al. 2012; Tavares and Magalhaes 2019).

These studies have shown that several types of plastic waste materials can be profitably employed to create low-cost reinforcement techniques for applications similarly to commercial fibers. The use of local waste fractions as resources can reduce the need for production and transportation of fibers of virgin materials and the reuse or recycling of a waste material could potentially solve disposal problems.

12.3.3 Reuse of Fishing Nets as Reinforcement in Construction Materials

The interest in reusing discarded fishing nets in construction materials is also gaining attention. Recent studies have found that the addition of nylon or PE fibers cut down from discarded fishing nets can improve the mechanical performance (Nguyen et al. 2021; Orasutthikul et al. 2017; Ottosen et al. 2019; Park and Kim 2020b; Park et al. 2021; Spadea et al. 2015; Srimahachota et al. 2020) or early-age shrinkage cracking of cementitious composites (Bertelsen et al. 2019a, c). A few studies have investigated the use of fishing nets as continuous reinforcement of cement-based materials (Mousa 2017, 2018; Bertelsen et al. 2022; Truong et al. 2020), and for soil reinforcement (Kim et al. 2008a, b; Tran 2021). More research is needed on the use of fishing nets in other types of construction materials than cement-based materials. Table 12.3 provides a more detailed overview of research studies investigating the use of discarded fishing nets as reinforcement of construction materials.

12.4 Research Program

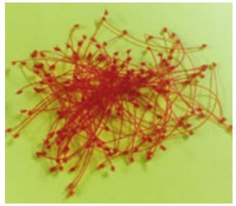
The first part of the experimental work was to characterize selected types of fibers or net materials from discarded fishing nets. The second part was to test and evaluate their use as reinforcement in different types of construction materials to explore suitable applications. The results presented in the following sections were made as part of the Ph.D. project, published in Bertelsen (2019), and as part of various student projects carried out at DTU Civil Engineering.

12.4.1 Characterization of R-PE Fibers from Discarded Fishing Nets

Fibers from different types of fishing nets were included in the experimental work, but most of the experimental activities were conducted on fibers of recycled polyethylene (R-PE) received from the Danish recycling company, Plastix A/S. An example of such fibers is shown in Fig. 12.1. The discarded nets were collected by Plastix A/S at national and international harbors. After being collected, the nets were transported to the recycling plant, sorted into the respective material fractions, pre-washed, mechanically cut into shorter fibers, and finally reprocessed to produce new plastic pellets of the recycled material. The R-PE fibers investigated in the present study were only processed into fibers by mechanical cutting operations and pre-washed. Thus, R-PE fibers were collected prior to the final reprocessing at the recycling plant.

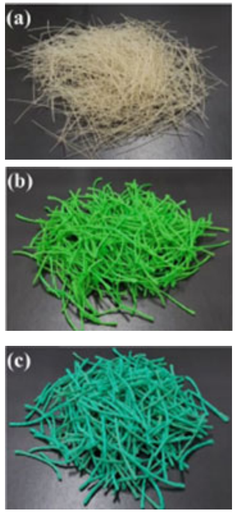
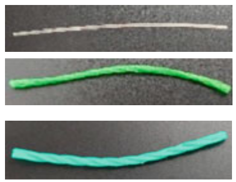
Variations in the material properties of the R-PE fibers were expected. The main reasons for these variations were the various types of PE net materials with different inherent properties, but also the ways the nets had been used and stored. The fiber characterization included measurement of the geometrical properties and shape, visual investigation of the morphology by SEM, mechanical properties, and alkali resistance; properties which are of importance when being used as fiber reinforcement in construction materials. These tests were performed on fibers from discarded fishing nets as well as from corresponding new nets to examine the degree of deterioration of the used nets.

Table 12.3 Overview of studies investigating the use of discarded fishing nets in construction materials

References	Polymer	Processing method	Image
Fibers added to cement-based mortar			
(Spadea et al. 2015)	R-Nylon fibers	Manual cutting of fibers to desired fiber length of 13–38 mm. Fiber diameter of 0.33 mm. Tensile strength of 290–350 MPa. Fiber addition of 0.5–1.5 wt% The addition of fibers increased the first-crack flexural strength and toughness of mortar prisms, while the compressive strength was reduced	
(Orasutthikul et al. 2016, 2017)	R-Nylon fibers	Manual cutting of fibers to desired fiber length of 20–40 mm. Straight fibers and fibers with knots. Commercially available fibers of PVA were included in the test program. Fiber diameter of 0.2–0.7 mm. Tensile strength of 440–975 MPa. Fiber addition of 0.5–2.0 wt% The addition of straight R-Nylon fibers to mortars improved the flexural strength, while the compressive strength decreased with increase in fiber fraction and fiber length	 

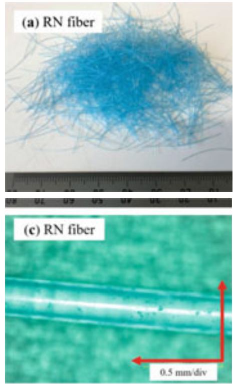
(continued)

Table 12.3 (continued)

References	Polymer	Processing method	Image
(Park et al. 2021)	N/A fibers	Collection, selection of three types of fishing nets, with different geometrical shapes (monofilament, twisted multifilament, and braided multifilament) Processing: water jetting, drying, and cutting to desired fiber length of 40 mm. Fiber diameter of 0.45–1.5 mm. Fiber addition of 0.5–1.0 wt% The mechanical behavior of waste fishing net fiber-reinforced cementitious composites subjected to direct tension, or compression were tested. As the fiber volume increased, both the compressive and first cracking strengths decreased, while the post-cracking strength increased. The multifilament fibers (twisted or braided) resulted in better post-crack performance than the monofilament fibers. This effect is attributed to the improved mechanical fiber-to-matrix bond for the multifilament fibers	
(Park and Kim 2020b)	N/A fibers	Fibers similar to those in Park et al. (2021) were used. The pull-out resistance of short fibers embedded in cement mortar was investigated by conducting fiber pull-out tests. The bundled structures of the multifilament fibers gave the best results due to the generated mechanical interaction between fiber and matrix during fiber pull-out	

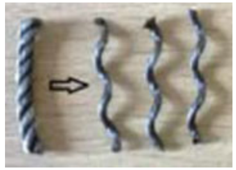
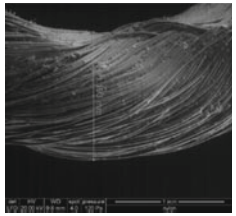
(continued)

Table 12.3 (continued)

References	Polymer	Processing method	Image
(Nguyen et al. 2021)	R-PE fibers	Processing of fibers as explained in Park and Kim (2020b) and Park et al. (2021). Fiber length of 40 mm. Fiber diameter of 0.23 mm. Fiber addition of 1, 2, and 3 vol% The compressive strength, toughness, splitting tensile strength, and biaxial flexural tests were conducted on fiber-reinforced concrete. Compressive strength decreased but other properties increased as a function of fiber proportions	
(Srimahachota et al. 2020)	R-Nylon fibers	The FN was obtained from local fishermen in Hokkaido. Processing of fibers: washed, dried, and manually cut. Fiber length of 20 mm. Fiber diameter of 0.24 mm. Tensile strength of 440 MPa. Fiber addition of 1 vol% The short fibers were added to improve the mechanical properties of cement mortar used as repair mortar of reinforced concrete (RC) beams. The tested RC beams were subjected to four-point flexural tests to study their load-carrying capacity. It was found that the fibers helped transfer stresses through cracks and distribute stresses by transforming a single wide crack into many small cracks	
(Bertelsen et al. 2019a, c)	R-PE fibers	Processing of fibers: mechanical cutting of fibers at recycling company; subsequent washing and drying. Fiber properties as described in Table 12.4. Fiber addition of 0.2–2 vol% The addition of fibers resulted in reduced plastic shrinkage cracking of cement-based mortars subjected to drying	

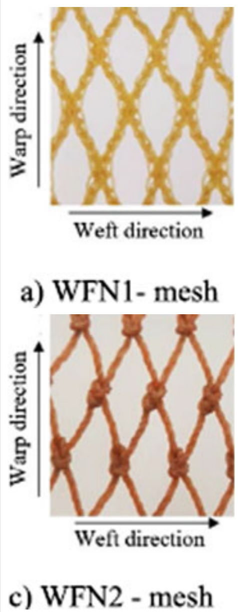
(continued)

Table 12.3 (continued)

References	Polymer	Processing method	Image
(Ottosen et al. 2019)	R-Nylon fibers	Processing of fibers: the nets were washed by soaking in tap water for 30 min repeated four times. Manual cutting of fibers to desired length of 20–40 mm. The nets were made of three twisted bundles (multifilament), which were separated and used in the test. Tensile strength of 260 MPa. Fiber addition of 0.5–2 wt% Fiber-reinforced mortar prisms were cast and subjected to three-point bending test and compression test. The compression and first-crack strength decreased with addition of fibers, but the post-crack performance increased	 
Pieces of net for continuous reinforcement in cement-based mortars			
(Mousa 2017, 2018)	R-Nylon nets	Pieces of fishing nets of multifilament threads were cut to the desired shape Net-reinforced mortar was cast with one layer of fishing net (dog bone specimens). Direct tensile tests were carried out on the dog bone specimens. The mortar with fishing net had higher displacement capacity	 

(continued)

Table 12.3 (continued)

References	Polymer	Processing method	Image
(Truong et al. 2020)	R-PE nets, two types	The WFNs used in this study were collected from the seabed nearby Dalpo Port, Ulsan, Republic of Korea. The nets were cleaned by water jet to eliminate organic and inorganic impurities and saline water. Pieces of fishing nets were cut and washed prior to use Fishing nets (WFNRC) and commercial net reinforcement (TRCC) were used as continuous reinforcements in cement-based matrix. Although the commercial TRCCs produced better mechanical resistance than the WFNRCs, the addition of four layers of W2 to cement-based matrix also produced pseudo-tensile-hardening behavior. WFNRCs containing W2 produced higher tensile and flexural resistance than those containing W1	

(continued)

Table 12.3 (continued)

References	Polymer	Processing method	Image
Fishing nets (pieces or fibers) added to earth-based materials			
(Bertelsen et al. 2019d, 2021)	R-PE fibers	Processing of fibers from fishing nets as explained in Bertelsen et al. (2019c). Fiber addition of 1–5 wt% Fiber-reinforced unfired adobe bricks consisting of clay (Greenlandic sediments) and gravel were produced as prismatic specimens The addition of fibers improved all tested properties: compressive and flexural strength, post-crack performance, linear shrinkage, and drying shrinkage cracking	
(Bertelsen et al. 2022)	R-PE nets	Nets were washed and cut into smaller pieces like the size of the mold Adobe bricks consisting of clay (Greenlandic sediments) and sand were produced with 0, 1, or 2 layers of FN While the flexural post-crack performance was improved, the flexural first-crack strength decreased from 0.53 MPa for the reference to 0.36 MPa for the bricks with two layers	

Table 12.4 Properties of R-PE fibers

	Length L (mm)	Diameter d (μm)	Tensile strength σ_t (MPa)	Stiffness E (GPa)
R-PE	15 ± 9 (1–65)	280 ± 30	380–450	1.0–2.0

Density, length, and diameter were measured on R-PE fibers in the R-PE samples, while the tensile strength and stiffness were measured on three types of selected fishing nets in Fig. 12.4 (Braided Polyethylene, Euroline, and Euroline Premium from Euronete) (Bertelsen and Ottosen 2021)

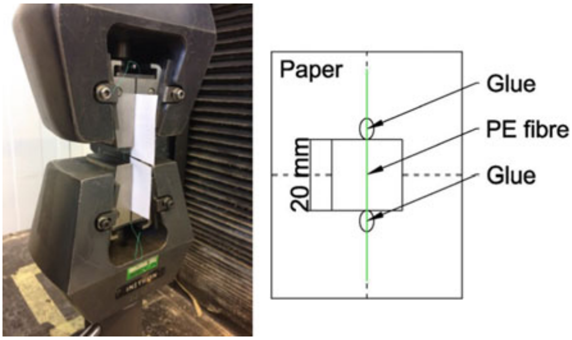


Fig. 12.3 Test setup for tensile test of fishing net fiber (Bertelsen and Ottosen 2021)

The R-PE fibers received from Plastix A/S were not long enough for performing tensile tests of single fibers as shown in Fig. 12.3. To get an indication of the variations in the mechanical properties of the R-PE fibers, fibers obtained from selected types of PE fishing nets were tested with respect to tensile strength and stiffness. Three types of fishing nets commonly used in the NPA region were selected for the mechanical testing (Braided Polyethylene, Euroline, and Euroline Premium from Euronete). These net types were chosen because of their mechanical properties, which were expected to represent the range of fibers present in the R-PE samples. For each type of fishing net, both new and used fibers were tested to get an indication of the level of deterioration. Mechanical tensile tests were performed on fibers extracted from new nets and discarded nets of the corresponding type, see Fig. 12.4.

12.4.2 Results: R-PE Fiber Characterization

The characterization of R-PE fibers is presented in this section. Table 12.4 shows relevant fiber properties for the R-PE fibers obtained by experimental testing.

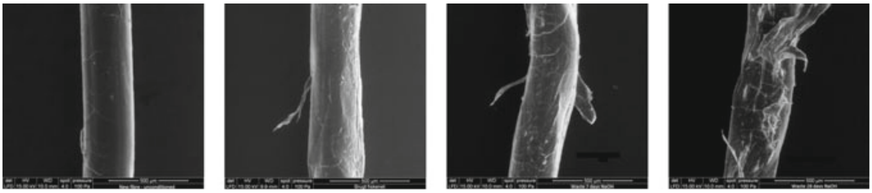
Although the R-PE fibers were reprocessed from different types of PE fishing nets, the diameter of 280 ± 30 μm was found to be consistent. As a result of the mechanical cutting operation, the fiber length varied significantly. However, this operation could be optimized to cut the fibers into the desired length. From the SEM images (Fig. 12.5), it was observed that all fibers had an approximate circular cross

Fig. 12.4 Waste and new PE fishing nets from Euronete, used for characterization of mechanical properties. "Braided Polyethylene" (BP), "Euroline" (EU), and "Euroline Premium" (EP) (Bertelsen and Ottosen 2021)

section, a relatively smooth surface, and a straight shape. However, because it had been used, and later stored, for an unknown period under different environmental conditions, the surface of the recycled fibers was rougher and more damaged than the new fibers. The alkali resistance of the PE fibers was evaluated to simulate the fibers' deterioration in a highly alkaline environment such as cement-based materials and is important for the overall durability of the material. If the fibers deteriorate and leave channels inside the material, the channels may enhance the ingress and transportation of aggressive agents into the concrete.

The effect of the exposure to the highly alkaline environment is shown in Figs. 12.5 and 12.6. The SEM images show that the R-PE fibers were influenced by the alkaline solution by having more loose parts on the fiber surface. However, no reduction in cross section area was observed during the 28 days of exposure.

The mechanical performance of the fibers was evaluated based on tensile tests of single fibers as shown in Fig. 12.3. For all the tested fiber types (Fig. 12.4), it was found that fibers extracted from new (N) fishing nets had a higher tensile strength and stiffness than fibers from corresponding recycled (R) fishing nets. Examples of the stress–strain behavior of N-PE and R-PE fibers are illustrated in Fig. 12.6



(a) New - Unconditioned *(b) Recycled - Unconditioned* *(c) Recycled – 7 days in 1M NaOH* *(d) Recycled – 28 days in 1M NaOH*

Fig. 12.5 SEM images (300×) of unconditioned new **a** and recycled **b** fibers from fishing nets of the type "Braided Polyethylene" immersed in a 1 M NaOH solution at 50 °C for 7 **c** and 28 days **d**, respectively. FOV = 1.27 mm (Bertelsen 2019)

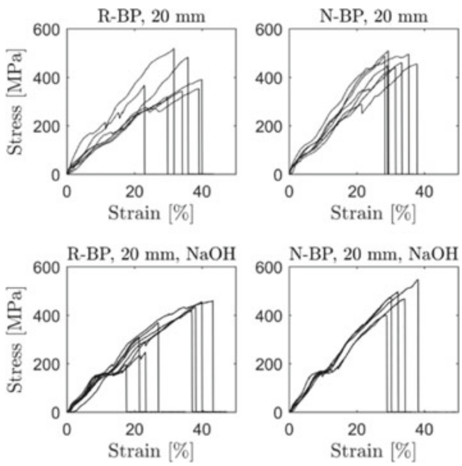


Fig. 12.6 Tensile stress–strain behavior of unconditioned and alkali-cured PE fibers from recycled (R) and new (N) nets of the type "Braided Polyethylene" (BP). Gauge lengths of 20 mm (Bertelsen 2019)

showing the strain versus the tensile stress during the test. An almost linear behavior until failure is observed for all fibers, which also followed approximately the same trend. The exposure of the fibers to a highly alkaline environment did not have any significant influence on the tensile strength.

The mechanical properties are in the same range as other low-modulus fiber types used in construction materials, such as PP fibers with tensile strength and stiffness around 150–800 MPa and 0.5–10 GA, respectively (Banthia et al. 2012; Daniel et al. 2002; Zheng and Feldman 1995). The results on the mechanical performance of the R-PE fibers indicate that they are very similar to that of PP fibers.

12.5 Applications for Discarded Fishing Nets in Construction Materials

12.5.1 Fiber Influence on Mechanical Performance of Construction Materials

The use of R-PE fibers as fiber reinforcement in different types of construction materials was investigated with the aim of obtaining a broad overview of the fiber influence on the mechanical performance and shrinkage properties of the composite materials. The tested construction materials were:

- earth-based adobe bricks (unfired clay bricks)
- gypsum-based plaster
- cement-based mortars.

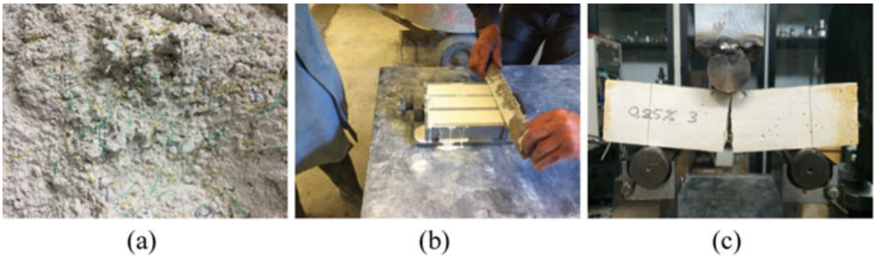


Fig. 12.7 Example of the preparation and test procedures of small-scale prisms used for the three-point bending tests shown for gypsum-based specimens. **a** Mixing raw materials and R-PE fibers; **b** casting specimens in steel molds; **c** and three-point bending testing (Bertelsen 2019)

The selected types of construction materials had very different intrinsic mechanical properties, with the cement-based mortar being the strongest and stiffest, followed by gypsum and finally the earth-based adobe bricks. Adobe bricks are unfired clay bricks made of a mixture of clay- and gravel-type soils (Houben and Guillaud 1994) and in this case made from Greenlandic fine-grained sediments. The three evaluated construction materials had different levels of R-PE added (the R-PE fibers added are those shown in Fig. 12.1).

A test program including small-scale prisms measuring 40 × 40 × 160 mm of the three mentioned types of construction materials was carried out in accordance with the standard UNI/EN 196-1 on flexural testing of small-scale prisms (UNI/EN-196-1 2005). For more details on the test program and the results, see (Bertelsen 2019). The basic steps in the casting and testing procedure are shown in Fig. 12.7 for the gypsum-based specimens including mixing (a), casting (b), and during the three-point bending testing (c).

All specimens had similar dimensions and test procedures were kept constant for all three types of materials, whereas the mixture proportions, curing time, and curing method varied depending on the requirement for the respective material. This can be seen in Table 12.5. The three-point bending tests were all performed in the same displacement-controlled testing machine with a displacement rate of 1 mm/min and an example of the test setup is shown in Fig. 12.7d.

12.5.2 Results: Influence of R-PE Fibers on Mechanical Performance of Construction Materials

The results from the mechanical testing of small-scale prisms of different types of construction materials (cement-based mortar, gypsum-based plaster, and earth-based adobe) are briefly described in this section. Selected results for the stress–strain behavior are presented in Fig. 12.8 for the respective reference specimens (no fiber addition) and specimens with the maximum amount of R-PE fiber which could be

Table 12.5 Overview of materials, mixture proportions, curing conditions, and fiber content for small-scale prisms

Material	Proportions	Curing	Fiber content (wt%)	Fiber content (vol%)
Earth-based adobe	["clay" : water : gravel] [1.0 : 0.44 : 1.0]	3 d of dry-curing inside molds + 25 d of air-curing at ~21 °C	1.00, 2.00, 3.00, 4.00, **5.00**	2.05. 4.1, 6.15, 8.2, **10.25**
Gypsum-based plaster	[gypsum : water] [1.0 : 0.44]	1 d of dry-curing inside molds + 2 d of air-curing at ~21 °C	0.25, 0.50, 0.75, 1.00, 1.25, 1.50, 1.75, **2.00**	0.44, 0.87, 1.31, 1.74, 2.18, 2.62, 3.05, **3.50**
Cement-based mortar	[cement : water : sand] [1.0 : 0.5 : 3.0]	1 d of sealed dry-curing inside molds + 27 d of wet-curing at ~21 °C	0.17, 0.33, 0.50, 0.67, 0.83, 1.00, 1.17, **1.33**	0.38, 0.77, 1.15, 1.54, 1.92, 2.31, 2.69, **3.07**

The maximum fiber content possible to mix into the respective mix proportions is written in bold

added to the respective material during mixing. For more detailed information on the results, see (Bertelsen 2019; Bertelsen et al. 2021; Bertelsen and Ottosen 2021).

First, the flexural strength of the three materials varies significantly. The mortar specimens had the highest stiffness and a flexural strength of ~8 MPa, followed by the gypsum specimens with a flexural strength of ~3.5 MPa and finally the adobe specimens, which gained the lowest flexural strength of 0.7–1.2 MPa. Secondly, the fibers improved the post-crack performance of all three materials, although the effect was poor for both the cement-based and gypsum-based specimens. A large drop in stress is seen for the mortar and gypsum specimens, whereas no drop occurs for the adobe specimens. Moreover, the flexural strength of the adobe specimen is almost doubled for the specimen with the addition of R-PE fibers, which is not the case for mortar or gypsum. Another interesting finding was that the addition of R-PE fibers to adobe bricks resulted in increased compressive strength from 2.6 to 3.5 MPa (Bertelsen et al. 2021). Again, this was not the case for the two other materials (mortar and gypsum). The findings for the cement-based mortar are quite similar to previous studies on the use of fishing net fibers added to cement-based mortar (Orasutthikul et al. 2017; Ottosen et al. 2019; Spadea et al. 2015).

12.5.3 Results: Influence of R-PE Net Pieces on Mechanical Performance of Earth-Based Adobe Bricks

Based on these results, and the assumption that it would be easier to remove the plastic fibers from the adobe material compared to the cementitious material at the

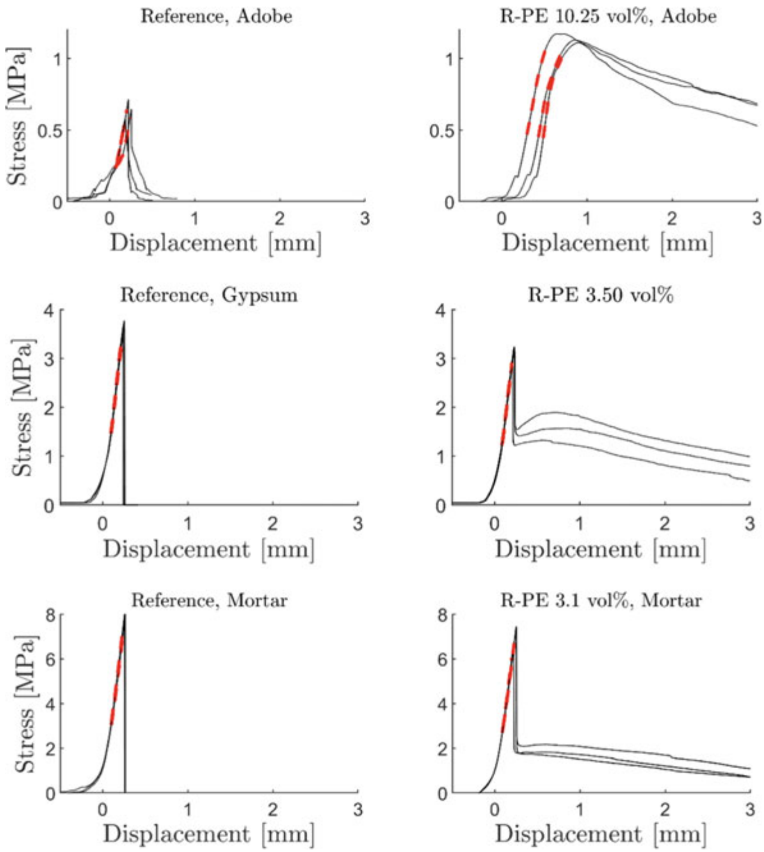


Fig. 12.8 Flexural stress-displacement behavior of prisms with no fibers (reference) or with the maximum addition of R-PE fiber, which could be mixed into the material. Note the different scales on the *y*-axis (Bertelsen 2019; Bertelsen et al. 2021)

end of life, it was decided to continue the research on the adobe material. The fishing nets were added to the adobe material either in the shape of fibers or as pieces of net cut out of the fishing net. This was done for larger-scale adobe bricks of Greenlandic fine-grained sediments as shown in Fig. 12.9. The results of the study is published in Bertelsen et al. (2022). One of the main benefits of this type of construction material in a Greenlandic context, is that it can be produced from locally available resources in Greenland, where both the fine-grained sediments and discarded fishing nets are available in large quantities along the coastal towns. The advantage of using larger pieces of fishing net as reinforcement compared to fibers is the improved recyclability of the material, where larger pieces can more easily be removed than fibers. However, the increased flexural strength was not as good as when the adobe bricks were added the reinforcement in the shape of fibers.

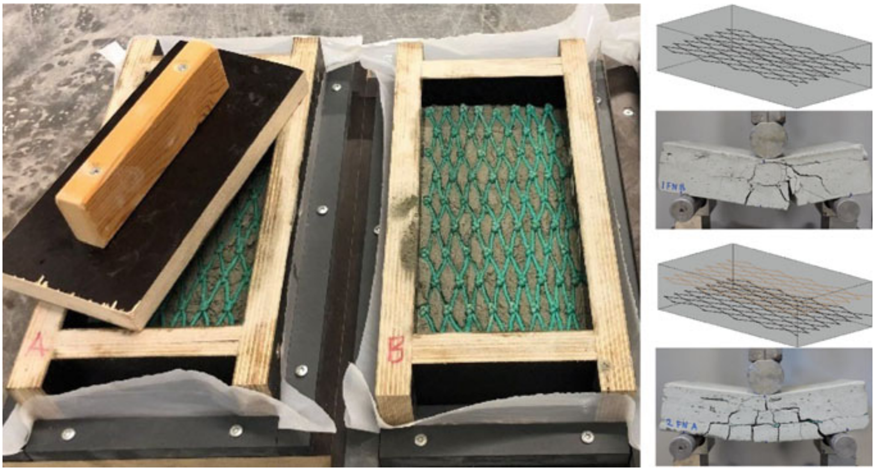


Fig. 12.9 Production of adobe bricks with one or two layers of fishing net reinforcement (Bertelsen et al. 2022)

12.5.4 Mitigation of Shrinkage Cracking in Construction Materials by Adding Fibers

Other uses of the R-PE fibers in construction materials were, for example, to mitigate shrinkage cracking in brittle materials, which tend to shrink during drying. The evaluated types of construction materials included in this part of the study were cement-based mortars and earth-based adobe material susceptible to early-age shrinkage deformations and cracking. Examples of the influence of R-PE fibers on shrinkage cracking of cement-based mortars and earth-based adobe material, are the plan views of material samples shown in Fig. 12.10. There is a clear tendency that the addition of fibers reduces the degree of shrinkage cracking. For more information, see (Bertelsen et al. 2019b, 2021).

12.5.5 Use of Fishing Net-Reinforced Adobe Bricks as Construction Material

Construction material in unfired clayey soil, such as adobe bricks, is a highly sustainable alternative to, for example, concrete or fired clay bricks, since the production procedure is very simple and requires no firing at high temperatures (Salih et al. 2020). The technique has been used for more than 9000 years and is still widely used, especially, in developing countries (Minke 2012). Adobe bricks are commonly used all types of walls in dry climates, but in harsher climates, the material is mainly intended for inner walls due to the relatively poor durability. It is common practice

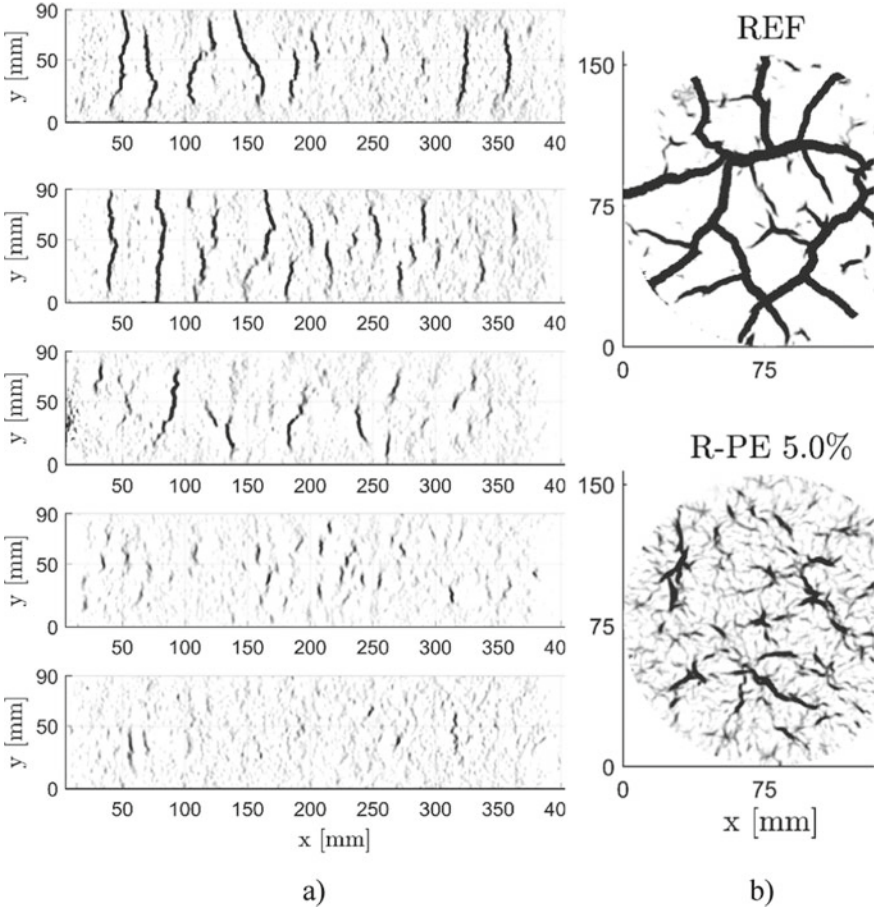


Fig. 12.10 Plan view of material samples with shrinkage cracking: **a** cement-based mortars susceptible to plastic shrinkage cracking and the influence of R-PE fibers (0% (REF) to 2.0 vol%); **b** earth-based adobe material susceptible to early-age shrinkage cracking and the influence of R-PE fibers (0% (REF) or 5.0 wt%) (Bertelsen et al. 2019d, 2021)

to reinforce adobe bricks with fibers of either natural origin or derived from waste materials (Salih et al. 2020).

The best results for the use of fishing net reinforcement from the experimental program described in this chapter were found for adobe bricks. A challenge for the implementation of adobe bricks in Greenland could be that it is a “new” type of construction material, which is not used in Greenland today. However, adobe bricks with fishing net reinforcement would not only be applicable to Greenland, but also globally where the construction technique is already used and thus more easily applicable.

12.6 Overall Conclusions

Discarded fishing nets were investigated as reinforcement in different types of construction materials. The findings showed that fishing nets, especially in the form of fibers, can improve the post-crack performance of construction materials such as cement-based mortars, gypsum, or earth-based adobe bricks. The best results were obtained for high fiber additions (up to 5 wt%) to the earth-based adobe bricks. The adobe material is a low-stiffness construction material, where the addition of fibers resulted in improvement of the mechanical properties (compressive, flexural, post-crack strength) as well as reduction in the early-age shrinkage cracking. The addition of fibers was also found to mitigate plastic shrinkage cracking in cement-based mortars. The findings in the present project were supported by those in recent studies on the use of discarded fishing nets in cement-based mortars. However, very little research is carried out on the use of fishing nets in other types of construction materials, and this needs more research. Overall, there is a great potential in reusing discarded fishing nets as reinforcement in especially low-stiffness construction materials not only in Greenland, but also globally.

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