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INFLUENCE OF RECYCLED FIBRE REINFORCEMENT ON PLASTIC SHRINKAGE CRACKING OF CEMENT-BASED COMPOSITES

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Abstract

Recycled polyethylene (R-PE) fibres from discarded waste fishing nets are used as fibre reinforcement in cement-based mortars for control of plastic shrinkage cracking. A thin, fresh mortar overlay is cast directly on top of a restraining concrete substrate and placed under controlled environmental conditions. Mortar overlays with the addition of R-PE fibres up to 2.0 vol% were tested and compared to mortar overlays with a 0.2 vol% addition of commercially available PP fibres. The cracking behaviour is monitored using a digital image correlation (DIC) technique allowing measurements of strain and displacement fields on the overlay surface. The R-PE fibres were successful in controlling the plastic shrinkage cracking of restrained mortar overlays for fibre fractions of 2.0 vol%.

Keywords: Plastic shrinkage, crack detection, plastic waste fibres, digital image correlation

1. INTRODUCTION

The amount of marine plastic litter that have been entering the marine environment has accelerated in the last two decades of the 20th century [1]. Among these are lost or otherwise discarded fishing nets one of the most troublesome fractions due to their large volume and their ability to continue to “ghost fish” while floating around [2]. It is, therefore, important to create incentives for reusing these materials. In this study, we show how recycled polyethylene (R-PE) fibres processed by mechanical cutting of discarded fishing nets can be used for controlling plastic shrinkage cracking in cement-based materials. Plastic shrinkage is the volumetric contraction of cementitious materials and occurs within the first few hours after casting, thus it happens when the material is still in a plastic state [3]. Cracking induced by plastic shrinkage deformations may occur if the tensile stresses generated in the material exceed the strength of the fresh material. A laboratory-scale test method comprising of a fresh overlay cast on top of restraining concrete substrates has been used by [4,5] for evaluation of restrained plastic shrinkage cracking of cement-based materials. The addition of low-modulus synthetic fibres to cement-based materials susceptible to plastic shrinkage cracking is a well-known technique for controlling the formation of this type of surface cracking [4]. The fibres have the ability to improve the strain capacity of the fresh material and to provide bridging forces across the cracks. Also, polymeric fibres from different types of waste fractions have shown positive results in controlling plastic shrinkage cracking [6–10]. The degree of surface cracking induced by plastic shrinkage is most frequently evaluated based on techniques such as manual microscopic measurements, which are commonly resulting in semi-quantitative measures of the degree of surface cracking; or image-based techniques such as digital image correlation (DIC) enabling more quantitative results [11,12]. In this study, a 2D-DIC technique has been used to analyse the degree of surface cracking of restrained mortar overlays and thereby to evaluate the influence of recycled and virgin fibres.

2. MATERIALS AND METHODS

The test method used for evaluation of restrained plastic shrinkage behaviour of cement-based mortar overlays using DIC was developed at the Technical University of Denmark as described in [13,14]. Each shrinkage test comprised of a concrete substrate and a fresh, thin mortar overlay with the addition of fibres.

2.1 Materials

Substrate bases measuring approximately 50 x 95 x 420 mm^3 as shown in Figure 1 were produced in accordance with UNI/EN 1339 [15] and the surface was prepared to a desired roughness using a needle hammer. The compressive strength of the substrate material was tested in accordance with UNI/EN 12390-3 [16] on cylinders and was found to 35.5 ± 6 MPa. At the time of testing, the substrate bases were wetted with tap water and placed inside moulds measuring 60 x 95 x 420 mm^3, whereupon a fresh mortar overlay with a thickness of 10 mm was poured on top of the substrate bases directly after mixing. The mixture proportions for the mortar overlay are given in Table 1. The test was carried out with three replicates of each specimen type. Two types of fibres were added to the fresh mortar overlay during the mixing process; 1) commercially available polypropylene (PP) fibres of the type Fiberflex with a diameter of 19.5 µm and a length of 12 mm; and 2) recycled polyethylene (R-PE) fibres obtained from discarded waste fishing nets with a length of 15 ± 9 mm and a diameter of 280 ± 30 µm. The geometrical variations were due to an “uncontrolled” mechanical cutting operation of the waste fishing nets. The recycled R-PE fibres were provided by a Danish recycling company, Plastix A/S that collects, sorts, washes and reprocesses waste fishing nets of difference material fractions. The fishing nets were collected from national and international harbours. The compressive strength and secant modulus of the material used for the mortar overlays was tested on cylinders measuring 60 x 120 mm (three replicates) with the two fibre types at different curing times in accordance with UNI/EN 12390-2 [16] and -13 [17].

Table 1: Mixture proportions for mortar overlay

	CEM I kg/m^3	**Sand 0-4 mm** kg/m^3	**Water** kg/m^3	**Fibres (V_f)**
Mortar overlay	700	980-1032	350	REF: 0% PP: 0.2% R-PE: 0.2-2.0%

Figure 1: Geometry of substrate bases and mortar overlay; R-PE fibres; and PP fibres

2.2 Methods

The shrinkage test was carried out inside a climate-controlled chamber (Figure 2) and the specimens were monitored using DIC. The procedure for the shrinkage tests was as follows:

Time	Procedure
t = 0 min	Mixing procedure included first dry-mixing of cement and sand, whereupon water was gradually added under continuous mixing. If fibres were added, they were added to the wet mixture. “Time zero” (t = 0 h) was being defined as the time when water was added to the dry mixture.
t = 10-15 min	Casting and vibration of the fresh mortar overlay on top of substrate bases.
t = 20-45 min	Specimens were left at ambient temperatures of 20 ± 3 °C.
t = 45 min	Specimen surfaces were covered with a white layer of chalk-based spray paint and subsequently spray painted with black dots of chalk-based paint for the DIC analysis. The chalk-based paint type was more diffusion open than other paint types such as acrylic paint and was, therefore, not affecting the water evaporation rate [13].
t = 55 min	Specimens were transferred to a climate-controlled chamber with a temperature of 32.0 ± 1.5 °C and a relative humidity of 33.5% ± 5%. Electrical fans were placed in front of the specimens to ensure a wind flow resulting in a maximum water evaporation rate of ~0.5 kg/m^2/h. A constant light source was ensured by LED panels and high-resolution optical cameras were fixed parallel to the specimen surfaces as shown in Figure 2.
t = 1 h	The DIC monitoring was initiated by capturing the first image of the specimen surface at t = 1 h, and subsequently every 15 min until t = 25 h. The technique enabled continuous monitoring of in-plane strain and displacement fields.
t = 25 h	Test finished and images imported to DIC software for processing.

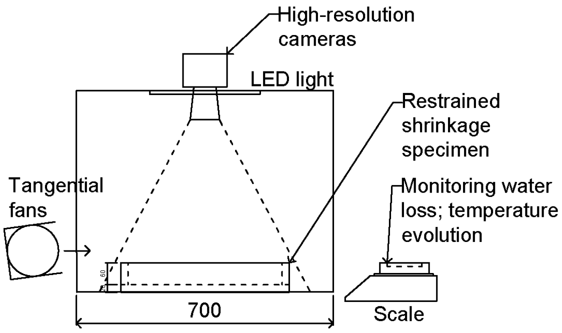

Figure 2: Plastic shrinkage test setup using DIC

After the test, the high-resolution images of the specimen surfaces were modified in ImageJ to improve the brightness and contrast and subsequently analysed using the DIC software, GOM Correlate Professional 2016. A region of interest (ROI) was defined for each specimen in the DIC software and was virtually meshed into a grid with overlapping subset elements. The subset elements were defined to have a size of 20 x 20 pixels and a point to point distance of 15 pixels with a pixel length corresponding to 0.080 mm/pixel. Finally, the DIC data was exported for further analysis and visualisation in Matlab, see also [13,14].

3. RESULTS AND DISCUSSION

3.1 Study of surface cracking using DIC

The DIC software is capable of providing information about the in-plane surface displacement and strain in each subset element, thus the plastic shrinkage behaviour of restrained mortar overlays was evaluated based on this data. The specimens tested included mortar overlays with addition of PP fibres (0.2%), R-PE fibres (0.2-2.0%) or no fibres (REF, 0%). First, we observe one of the reference overlays, REF (A), because this mixture design was expected to be susceptible to plastic shrinkage cracking under the given environmental conditions. The principal strain data in the (x,y)-directions is good for a visual presentation of the surface cracking since peaks in strain (dark colours) represent the crack locations, see Figure 3(a), which illustrates the strain level at the end of the test (t = 25 h). From this figure, it is observed that the crack openings mainly appeared in the x-direction (x-direction defined as being parallel to the longer side of the specimens of 420 mm), which is considered due to the geometry of the specimen and the wind flow in the x-direction. Actual crack widths are calculated based on the displacement data [18], which is only given for the x-direction since the main cracks appeared in this direction, see Figure 3(b). Section A-A is going through the centreline of the specimen surface parallel to the x-direction and shows the surface displacement (dotted blue line) and principal strain (red line) along the section surface; see Figure 3(c). Sudden drops in surface displacement correspond well with the opening of an actual surface crack [18] (marked with red and blue circles). For the reference specimen, REF (A), the crack widths along the selected section A-A at t = 25 h are for example 102, 317, 327, 83, 189, 51, 72 and 31 µm, which corresponds well with microscopy measurements.

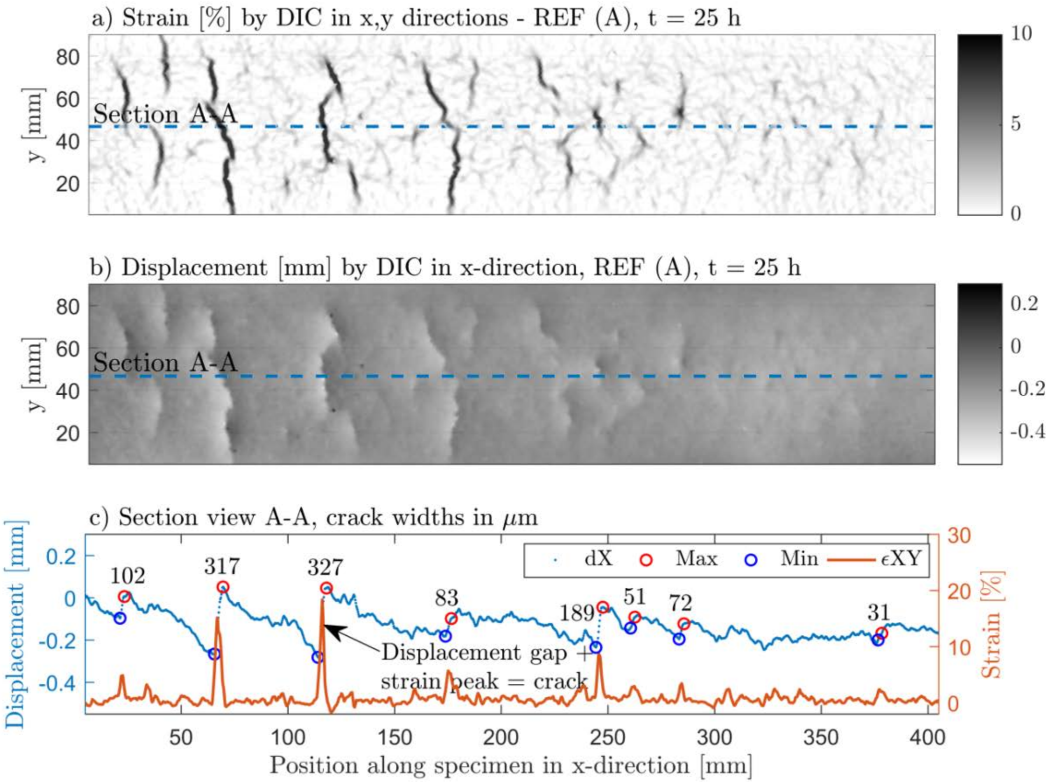

Figure 3: REF (A) specimen at t = 25 h. a) Principal surface strain in the (x,y)-direction by DIC; b) Surface displacement in the x-direction by DIC; c) Section A-A going through specimen showing surface displacement in x-direction and principal strain

3.2 Influence of fibres

The surface strains in (x,y)-direction are given for all tested specimens in Figure 4. By visual observations, it is obvious that the addition of fibres had a positive effect on the cracking behaviour of the restrained overlays. As expected, the commercially available PP fibres performed well in controlling the plastic shrinkage surface cracking when added in volume fractions as low as 0.2%. Only very few and fine cracks were visible on the specimen surface and the DIC also revealed areas with increased strain but yet not any visible cracks. Similar results with the use of PP fibres in similar fibre fractions added to restrained cementitious materials were obtained in other studies [4,5]. With respect to the R-PE fibres, which have a diameter that is approximately 15 times coarser than the PP fibres, the influence was not expected to be as good as for the PP fibres. No reduction in surface cracking was observed for the specimens added 0.2% R-PE fibres. For additions of larger fibre fractions such as 0.5% and 1.0% some improvements with respect to the amount and size of cracks were observed, and when 2.0% of R-PE fibres were added to the overlay, only very few visible surface cracks were observed. Despite the fact that 2.0% is a very high volume fraction to add to the material, it was seen that the fibres have a good effect in controlling the plastic shrinkage cracking of the restrained overlays. These results are also in agreement with other studies testing the influence of recycled fibres or fibres with similar coarse diameter, where volume fraction up to 1.5% have been studied [6–8,10,19]. For more elaborated results, please see [14].

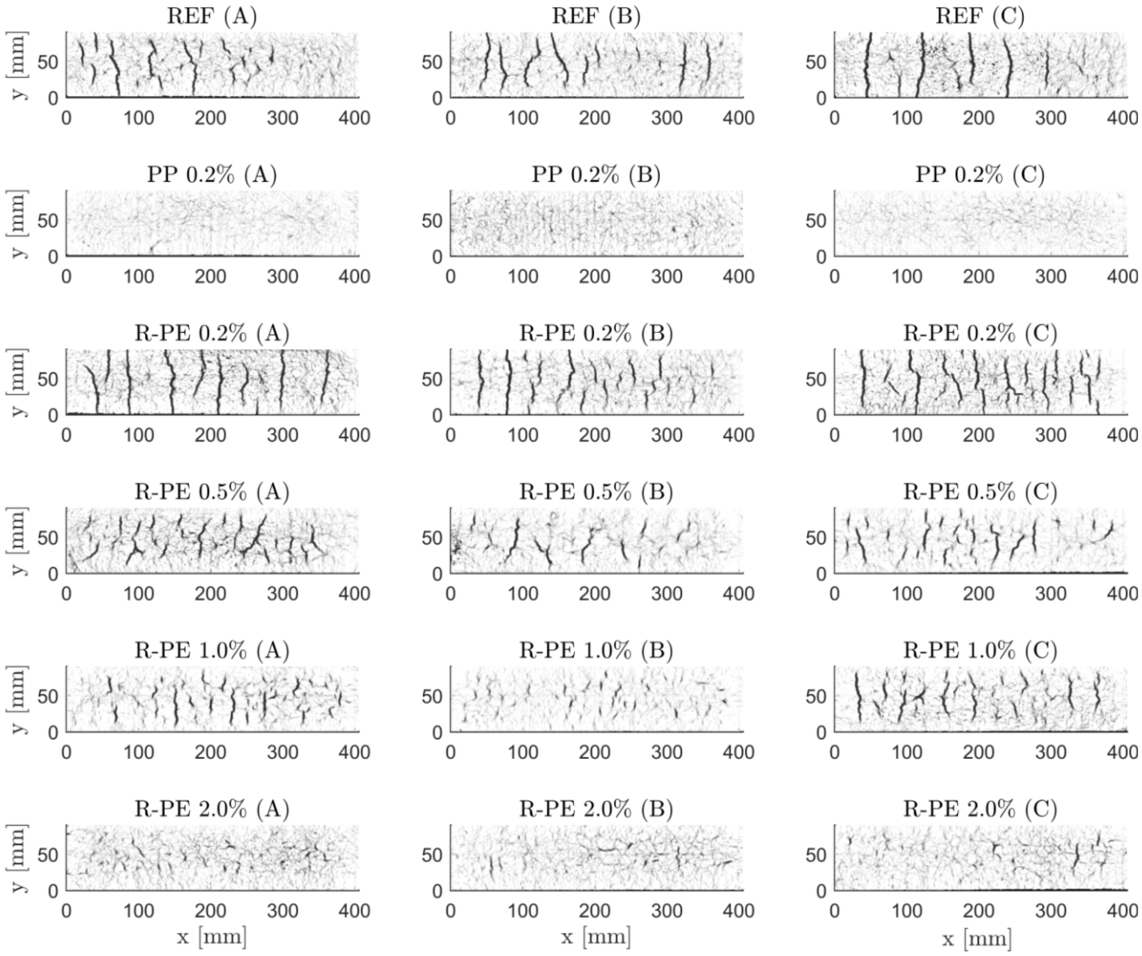

Figure 4: Principal strain for specimens at t = 25 h. White colour represents uncracked area with strain $\varepsilon_{x,y}$ = 0%; Black colour represents surface cracks with strain $\varepsilon_{x,y}$ = 5%.

3.3 Mechanical properties of mortar mixtures

As observed in Figure 4, the necessary addition of R-PE fibres for achieving a satisfactory reduction in surface cracking is 2.0% compared to only 0.2% for the commercially available PP fibres. The compressive strength and secant modulus were tested for three different mixture designs similar to the ones used for the fresh mortar overlays; A reference mortar (no fibres); 0.2% PP fibres; and 2.0% R-PE fibres, with the results being illustrated in Figure 5. The REF specimens achieved the highest compressive strength at all curing times, followed by the 0.2% PP specimen and finally by the 2.0% R-PE specimen. The development of compressive strength and secant modulus followed the same curve shape for all specimen types. The 28-days compressive strength was 52.5 MPa for the reference specimens, 49.0 MPa for the 0.2% PP specimens, and 47.1 MPa for the 2.0% R-PE specimens. These results show that the addition of 0.2% PP fibres decreased the compressive strength with 6%, while the much larger amount of 2.0% R-PE fibres decreased the 28-days compressive strength with 10%. Similar tendencies with respect to the influence of fibres were observed for the secant modulus.

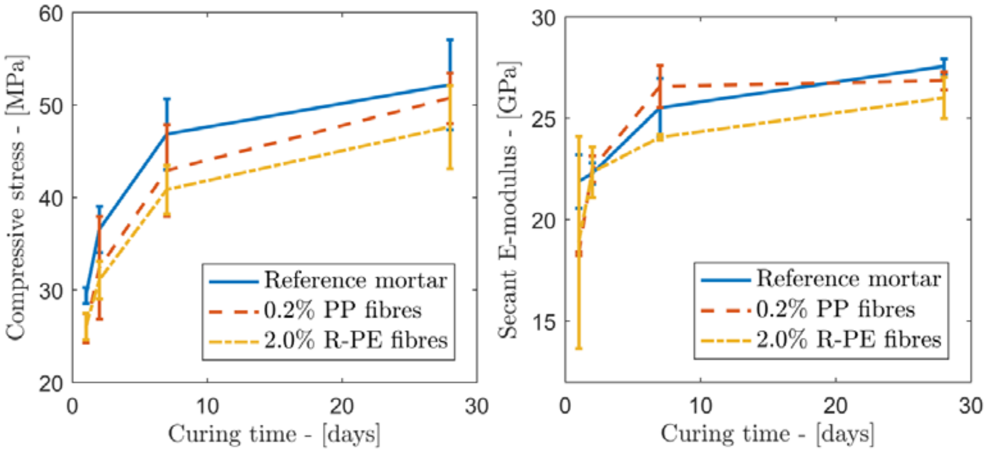

Figure 5: Compressive strength and secant modulus of mixtures used for the mortar overlay in the plastic shrinkage test. Age of wet-curing: 1 day, 2 days, 7 days and 28 days.

4. CONCLUSION

The plastic shrinkage cracking of restrained mortar overlays cast on top of concrete substrates was studied with the aim of evaluating the influence of two fibre types; commercially available PP fibres and recycled polyethylene (R-PE) fibres obtained by mechanical cutting of waste fishing nets. The surface cracking was studied by using a DIC technique enabling the detection of surface strains and displacements. The results showed that the addition of 0.2% PP fibres was successful in controlling the plastic shrinkage surface cracking, while 2.0% of R-PE fibres were necessary to add to the overlay for achieving comparable results.

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