Interaction assessment between fiber reinforcement and cement matrix containing finely ground recycled concrete

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Abstract. This work deals with adhesion enhancement between polymer macro-fibers and cement matrix (CEM I 42.5 R). Two types of fibers were used – polypropylene (PP) and polyethylene terephthalate (PET), both having approx. 0.3 mm in diameter. To achieve the increase between the two materials, fibers were surface roughened by means of an oxygen plasma treatment. Moreover, a concrete finely ground recyclate containing grains at the size of less than 0.25 mm was admixed into the cement matrix (the amount was equal to 30 wt. % of cement) to promote the required adhesion between the two materials by principle of adhesive locks. To assess the adhesion, individual fibers were pulled-out from the matrix, while a force needed to their movement was recorded. The fiber embedded length was 30 mm. It was shown, that plasma treated fibers exhibited increased adhesion with the matrix by ca. up to 20% (PP), resp. 5% (PET) than them with no surface treatment. If the concrete recyclate was used, the adhesion further increased by ca. 5–10% for both fiber types.

1. Introduction

It is obvious that production of waste is unsustainable on a global scale. More than elsewhere, the same assertion applies to the construction industry. It is reported that from 3 to 10 billion tons of construction waste is produced per year all over the world. In the Czech Republic, the amount of this waste is equal to 3.5 million tons per year. These facts justify creation of authority's and ecologist's requirements and regulations aiming to reduce production and to re-use of waste. The European Union has therefore established the prohibiting of the storage of waste from 2024 [1]. Although this ordinance has rather a political than a technical origin, it is necessary to adapt it and to re-use construction waste, concrete from demolished building including [2].

For example, Australia, Denmark, Germany, Japan, Holland and the Great Britain recycle more than 50% of waste concrete, some of them even more than 70%. On the contrary, developed countries as Italy or France less than 20%. The Czech Republic with its ca. 40% share of the concrete recycling is ranged side by side rather to worse countries from this point of view [3]. Therefore, it is necessary to find out new ways how to reuse the waste concrete and how to reach a rate of the recycling of the most progressive countries.

T. Pavlů et al. summarized that possibilities of concrete recycling rests in re-use of aggregate separated from waste concrete and in an utilization of dust emerging during this process. It was shown that recycled aggregate can be used for production of new concrete again [4]. Unfortunately, it is obvious...
that potential of this material is significantly limited due to presence of various contaminants, a random shape and a size of particles etc. [3, 5, 6].

On the contrary to the utilization of recycled aggregate, the finely ground powder seems to have good potential to be used for production of cement-based products, if processed properly from waste. As Plachý et al. remarked, the powder originated from the waste concrete contains more than 10% of unhydrated grains [6]. Therefore, the powder can be used not only as micro-aggregate but also as an active binder. To exploit potential of this material, it must be processed by a high-speed milling. This leads to unification of a particles size and to stripping of un-hydrated grains [7]. As reported in many studies, thus obtained material can be used for production of mortars, lightweight concrete blocks and so on [6, 7, 8]. Throughout scientific and technical studies, there can be found many ways to use milled dust effectively. So far, in the field of fiber reinforced cement composites, an impact of this recycled material on an adhesion between fibers and the matrix has not been unambiguously researched. A few papers have been published, but their results are not conclusive [9, 10]. In can be assumed from what is obvious, that presence of finely milled dust in cement-based materials contributes to the adhesion between the matrix and the fiber reinforcement. Nevertheless, the rate of this contributing has not been clearly quantified.

To solve this unanswered question, a set of pull out tests of polymer (PP and PET, d = ca. 0.3 mm) macro-fibers was done from two types of cement matrix: (i) reference and (ii) containing 30 wt. % of recycled concrete powder. Two types of each fibers were used – as received and surface treated via a plasma treatment.

2. Materials

2.1. Fibers

Two types of polymer fibers were used – PP (polypropylene) and PET (polyethylene terephthalate). Each type was distinguished by their surface treatment on untreated (marked PET and PP) and plasma treated (marked PET-T and PP-T). According to methodology published in our previous research [11], the treatment was done in order to roughen fiber surfaces and to increase their wettability by water (classified by a contact angle measurement). Their basic mechanical and geometric properties are summarized in the table below (Table 1). Both types were made by manufacture Spokar Inc. (Czech Republic). These fibers are primarily made for production of brushes, however, as it was confirmed earlier, they can be used as an alternative to common types of fibers designated as the reinforcement of fiber reinforced concrete [11].

|                  | Diameter [µm] | Density [kg/m³] | Young’s modulus of elasticity [GPa] | Tensile strength [MPa] | Elongation [%] | Contact angle [°] |
|------------------|---------------|-----------------|------------------------------------|------------------------|---------------|------------------|
| PET / PET-T      | 335           | 950             | 5.8                                | 238                    | 51            | 85.0/26.2        |
| PP / PP-T        | 305           | 900             | 6.1                                | 440                    | 8             | 88.3/31.1        |

2.2. Cement and finely ground recycled concrete

For purposes of experiments described in following captures, two types of matrixes were made. The first was composed only from Portland cement CEM I 42.5 R with water to cement ratio (w/c) equal to 0.4 (in the chapter of results marked as “CEM”), while the second contained moreover finely ground recycled concrete in the amount of 30 wt. % of cement (marked as REC). In this case, w/c ratio was increased to 0.41 due to a high specific surface area of the recylcate. Recycled concrete comes from old drainage channels. It was ground using the high speed milling technology. The size of grains was up to 0.25 mm. Curing and hardening of mixtures took 28 days in standard laboratory conditions.
3. Experimental Methods

3.1. Pull-out tests

For purposes of pull-out testing, samples from above mentioned mixtures were made using prismatic molds of dimensions equal to 25 × 20 × 25 mm. During samples preparation, the single fiber was placed into the each form (located in its center), while its embedded length was equal to the height of specimen, i.e. 25 mm. One of thus prepared samples is captured in the picture below (Figure 1). After 28 days of mixture curing and hardening, the pull-out tests were performed. Samples was fixed by means of self-locking chuck as a part of a loading frame Web Tiv Ravestein FP100. A free-end of the single fiber protruded from the specimen was fixed to a movable part of the device. Then, the fiber was pulled out from the specimen at the constant rate of 2 mm/min (the experiment was displacement controlled), while the response of the fiber during the pulling was recorded in the form of dependence between the fiber free-end displacement and a force resisting to the movement. The experiment was interrupted when displacement reached on 5 mm. To obtain statistically relevant data, ten measurements were realized for each type of fiber and matrix. At the whole, 40 pull-out tests were thus realized. The resulting data were evaluated using MatLab based software DiPro. In the field of fiber reinforced composites, it is in a habit to indicate the adhesion between the matrix and the fiber in the form of interface shear stress due to provide values normalized by the fiber surface area. Therefore, the shear stress was calculated from load-displacement curves at distinct stages (i) when the force reached its maximum (further marked by index “MAX”) and (ii) when displacement reached value 3.5 mm (marked as “3.5”), according to calculations given below (1),

\[ \tau_{\text{max}} = \frac{F_{\text{max}}}{C_f l_e} \quad \text{and} \quad \tau_{3.5} = \frac{F_{3.5}}{C_f l_e} \]  

(1)

where \( F_{\text{max}} \) and \( F_{3.5} \) represent the maximal force and the force necessary to reach 3.5 mm free-end displacement, respectively. \( C_f \) is a fiber circumference and \( l_e \) is the embedded fiber length.

![Figure 1](image1.png)

Figure 1. Digital image of specimen specially made for pull-out testing.

4. Results

For clarity, it is appropriate to repeat marking of fibers, matrixes and pull-out stages. Collectively, “PP” and “PET” mark the fiber type, polypropylene and polyethylene terephthalate, respectively. If used “T”, it means “surface treated”. “CEM” and “REC” mark matrixes, cement and cement with recyclate, respectively. Finally, “MAX” and “3.5” refer to the stage during pull out tests in which was the force recorded and further used to a calculation of the shear stress, in more detail in the chapters above.

Figure 2 clearly shows that the strongest adhesion was attained in the case of treated PP fibers pulled-out from the matrix containing finely ground recycled concrete. In this case, the maximal interfacial shear stress between the two materials reached almost to 0.45 MPa and to ca. 0.38 at 3.5 mm displacement of the fiber free-end. When the cement matrix and the same fibers were used, results were following: ca. 0.4, resp. 0.34 MPa. It is also worth noting that the adhesion between PP fibers and the cement matrix was practically unchanged, compared to them and the matrix containing recyclate.

Similar results were obtained also in the case of PET fibers, as shown in the Figure 3. Contrary to our assumptions, we found out that the adhesion between reference fibers and the matrix containing recyclate was rather worse than between them and the cement-only matrix. The maximal shear strength
decreased from ca. 0.31 (cement matrix) to 0.28 (matrix with recyclate) MPa, while the shear strength detected after 3.5 mm fiber free-end displacement decreased from 0.31 to 0.3 MPa. On the other hand, the adhesion was slightly increased, if treated fibers were used, especially in the case of samples made from recyclate containing matrix. Concretely, the use of the recyclate led to increase of the maximal shear stress by ca. 5–10% to ca. 0.33 MPa.

In summary, it can be concluded, that the use of finely ground concrete as an admixture to cement may improve adhesion between fibers and the matrix, but only in cases, when treated fibers are applied. If reference fibers having smooth surface were used, the utilization of the recyclate seems to be useless. Therefore, it is obvious, that the physical interaction between individual particles of the recyclate and roughened fiber surfaces plays an important role in the attainment of the required adhesion increase. Our finding corresponds with Sebiabi’s et al. work [9], who confirmed that presence of very small particles of the silicate powder can improves the adhesion between the reinforcement and the matrix. Similarly, J. Zhou et al. [12] found out, that with increasing amount of limestone powder (up to 2 wt. %) in cement composite reinforced with PVA fibers, the tensile strain capacity of the material increased. It must be however added, that both cited authors did not provide an information about fibers morphology.

![Figure 2](image2.png)

**Figure 2.** Interfacial shear stress between PP fibers and cement matrix obtained from pull-out tests.

![Figure 3](image3.png)

**Figure 3.** Interfacial shear stress between PET fibers and cement matrix obtained from pull-out tests.
5. Conclusion

The adhesion between two types of polymer fibers (polypropylene and polyethylene terephthalate) having ca. 0.3 mm in a diameter and cement matrixes was researched. The first matrix was made from Portland cement only (CEM I 42.5 R, w/c 0.4), while the second one contained 30 wt. % of finely ground recycled concrete. The influence of the recyclate use on the interfacial interaction between the two materials was assessed. Apart of that, two variants of each type of fiber was used – reference and surface roughened via plasma treatment. The adhesion was assessed via single-fiber pull out tests from samples (25 × 20 × 25 mm). It was shown, that: (i) the adhesion between reference fibers (characterized by smooth surfaces) and the matrix was not increased if used concrete recyclate, (ii) the interfacial shear stress was increased by using of the recyclate, but only if surface treated fibers were used.

Acknowledgments

This work was financially supported by Czech Technical University in Prague – SGS project SGS16/201/0HK1/3T/11 and Czech Ministry of Industry and Trade project FV20503. The authors would also like to thank to Tereza Horová for her help with this research.

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