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Short-term and creep pull-out behavior of polypropylene macrofibers at varying embedded lengths and angles from a concrete matrix

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HIGHLIGHTS

- 85 short-term and 15 creep pull-out tests are performed on polypropylene fibers.
- The embedded length and angle greatly influence the pull-out behavior.
- Post-peak pull-out is governed by the embossment profile of the fibers.
- Fiber creep is proposed to be the driving force behind pull-out creep.

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ABSTRACT

This paper reports on the short-term and creep pull-out behavior of different polypropylene fibers from a concrete matrix. 85 displacement controlled tests are carried out for two types of fibers with different embedded lengths and angles. Additionally, 15 creep tests are performed in a climate controlled room at different load ratios to study long-term loading effects. The pull-out tests show that an increase in the embedded length of the fiber increases the maximum pull-out force. More inclined fibers with respect to the load application direction initially increase the pull-out force as well, but the fibers tend to rupture more at the concrete surface, leading to a brittle failure mode. Furthermore, an oscillating post-peak behavior is observed during pull-out which is related to the embossed surface profile of the fibers. The profile is gradually abraded during the test which in turn leads to a pure-friction controlled pull-out behavior at large relative displacements. The pull-out creep tests show that the behavior strongly depends on the load ratio, with higher loads decreasing the failure time. A novel positive feedback loop mechanism is proposed to qualitatively explain the pull-out creep behavior in which the fiber creep deformations are the driving force behind pull-out creep.

1. Introduction

In fiber reinforced concrete (FRC), fibers are added to improve the concrete properties at early age and/or in the hardened state. In the latter, fibers can improve the post-cracking characteristics by bridging crack faces and taking up tensile forces [1]. The FRC performance depends on the properties and the mutual synergy of its three constituents: (1) the concrete matrix, (2) the fibers and (3) the bond between fiber and matrix [2]. Subsequently, failure of FRC elements is the result of a failure of one of these three constituents: (1) concrete crushing (2) fiber fracture or (3) fiber pull-out. Concrete crushing and fiber fracture are usually associated with brittle failure modes and should be avoided. Therefore, a well designed FRC element will fail due to fiber pull-out to ensure a semi-ductile behavior. The pull-out behavior of fibers is thus of high importance for all FRC elements. To improve the pull-out strength of fibers, several bond-improving mechanisms are reported in literature, ranging from improving mechanical anchorage in the form of crimped, embossed or hooked end fibers to the use of additives for improving the chemical bond [3–6]. The fibers used in FRC elements can be made of different materials, with steel being the most commonly used. However polymeric, glass or carbon fibers have been successfully used as well. Because of the widespread use of steel FRC (SFRC), the pull-out behavior of mostly hooked end steel fibers has been extensively investigated in the last decades [7–10]. Higher pull-out forces are recorded for hooked end steel fibers than their straight counterparts, as well as an overall improvement in pull-out behavior. Furthermore, it was observed that in the case of hooked-end steel fibers, the pull-out resistance is mainly provided by the straightening of the end hooks. Consequently, the influence

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of the embedded length of steel fibers on the maximum pull-out load is limited. On the other hand, it was found that higher embedded angles increase the pull-out force but fiber fracture became more prominent. Additionally, for angled fibers, the strength of the concrete matrix started to play a more important role as spalling was observed during pull-out. In the case of polymeric fibers, the fiber strength is lower than steel fibers and hooked end mechanical anchorage is not possible. To improve the bond strength through mechanical anchorage, polymeric fibers are often crimped or embossed. Contrary to the hooked end steel fibers, the pull-out resistance of polymeric fibers is mainly provided by friction and, as such, different researchers have found that increasing the embedded length or angle can lead to an increase in pull-out force, again at a higher probability of fiber fracture [11–13]. It is also found that during pull-out, polymeric fibers undergo a significant degree of surface abrasion. It should be noted that all reported tests considered a cement paste or mortar matrix. While considerable attention has been devoted to the short-term pull-out behavior, research on the pull-out creep behavior remains scarce. Sustained loading tests on single hooked end steel fibers have been done on concrete [14] or ECC [15] and showed that localized matrix damage near the hooked end was the dominant mechanism for time-dependent fiber pull-out in FRC. However, in the case of polymeric fibers, localized mechanical anchorage is relatively limited and the pull-out resistance is provided by friction. Based on a multi-scale approach to the tensile creep of macro-synthetic FRC, it was found that increasing the creep load causes samples to fail much earlier [16]. However, no further tests are found in literature and much work is needed to come to a better understanding of the pull-out creep mechanisms involved in the case of polymeric fibers.

2. Experimental research

2.1. Overview

In this paper, the results of short-term and creep pull-out tests of two different fiber types from a concrete matrix are considered. In the following, the fiber types are denoted as type A and type B, the latter being a newer and upgraded type A fiber. In total, 85 pull-out tests were executed with variable embedded lengths ℓ and angles θ. The number of tests per considered embedded length and angle is shown in Table 1 for both fiber types. Depending on the scatter of the first three tests, additional specimens could be cast. In some tests, the data acquisition system crashed during testing and the results were not saved and the tests omitted. Additionally, 15 pull-out creep tests are considered. All pull-out creep tests were done on fiber type B, with ℓ = 15 mm and θ = 0° with 5 different considered load ratios, ranging from 25% to 75% of the short-term pull-out strength.

2.2. Material properties

The concrete mixture uses cement CEM I 42.5R HES (350 kg/m^3) in a W/C ratio of 0.5, together with 835 kg/m^3 0/4 sand and 1099 kg/m^3 4/14 gravel. Lastly, superplasticizer Glenium 51 (1 kg/m^3) is used to improve flowability and workability. The compressive strength is determined from 3 cubes after 28 days according to the European Standard EN 12390-3 [17] and it was found that the mean compressive strength $\bar{f}_{cm,cube}$ = 43 MPa.

In this research, two different fiber types are considered, denoted as type A and B. Both fibers are virgin polypropylene (PP) embossed fibers with a repetitive diamond shaped embossment pattern. The two fiber types are produced by the same Belgian manufacturer and are commercially available in Belgium and abroad. According to the manufacturer, the equivalent diameter of type A and B is 0.95 mm and 0.9 mm, respectively. The length of both fiber types is 45 mm. The mechanical properties of type A and B are determined in a displacement controlled test according to the European Standard EN 14889-2 [18]. However, the standard was under revision at the time of testing and the adopted test parameters for type B were in accordance with the new revision of that standard, i.e. a higher testing speed of 50%/min was imposed. The test parameters and the results of the characterization tests are shown in Table 2. The coefficient of variation (cov) is shown in parentheses. In this table, the tensile strength f_t is calculated using the equivalent diameter. The maximum tensile force is shown as F_t. The strain ϵ_{f_t} is the strain measured at $\sigma = f_t$ and the Young's modulus E is the cord modulus between $\sigma = 0.1f_t$ and $\sigma = 0.3f_t$. The tensile strength of type B is 17% higher, however its stiffness is lower than that of type A. It is noted that the mechanical properties of both types are on the lower end of the spectrum for commercially available fibers.

2.3. Specimen preparation and properties

Pull-out specimens are cast in polyoxymethylene molds that allow the fiber to be accurately embedded. The concrete specimen's diameter and height are respectively 100 mm and 50 mm, and casting and compacting is done manually. After casting, the concrete is left to cure for 7 days in a climate controlled room at constant temperature (20 °C) and relative humidity (90%). The specimens are demoulded and tested 7 days after casting. It was found by different researchers [13,19] that the interfacial bond strength is fully developed after curing for 2 days. Additional curing did not increase the bond strength any further. This has been confirmed for a test on specimens of type B with ℓ = 15 mm and θ = 0° by comparing the peak load after 1 week vs. 8 weeks. The results were found to be not statistically significant at a significance level of 5%. Each specimen contains only one fiber, embedded over a length ℓ and under an angle θ as defined in Fig. 1. The free end of the fiber is clamped between two L-shaped aluminium plates. These plates are glued and bolted together to prevent fiber end slippage in the clamp. The first set of bolts are positioned 10 mm from the free surface, and 27.5 mm to the next pair (center-to-center). Fibers are clamped over a length of 80 mm, and the free length between clamp and concrete is 20 mm for the short-term specimens.

Table 1
Number of short-term tests per embedded length and angle.

	Angle θ	Length ℓ [mm]				
		10	15	20	25	30
Type A	0°	5	7	9	6	6
Type B	0°	3	6	6	5	–
	15°	–	5	–	–	–
	30°	6	5	5	–	–
	45°	–	6	–	–	–
	60°	–	5	–	–	–