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Drymix Mortar Yearbook
3D Special

Editor: Ferdinand Leopolder

Published on Occasion of
The Interdisciplinary Symposium on Printable Mortars
scalingUp3D, 27. - 28. June 2019, Austria

drymix.info

ISBN 978-3-9821114-0-7

FORMULATING 3D-PRINTING MORTARS WITH POLYMER BINDERS AND SYNTHETIC FIBERS

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Abstract

Fibers have been used in mortars and concrete for many years now, particularly to prevent cracks from developing due to deformation energy or drying shrinkage. The type of fiber to be used is selected based on the application's requirements. Synthetic fibers are available in different structures and chemical compositions with the aim of achieving high pull-out resistance via fiber surface anchorage. Based on the typical material properties, suppliers of fiber technologies develop the optimum geometry to achieve the best bonding.

The use of fibers in construction materials is current practice, particularly when it comes to short-cut fibers.

Short-cut polymer fibers are normally used to protect the mortar from shrinkage cracks and change the rheology of the mortar. In machine-applied mortars – especially extrudable mortars for 3D printing – this rheology change has to be well controlled. The addition of synthetic fibers can be expected to improve properties for the 3D-printing process in the following ways: high initial stiffness (green strength) of the freshly applied mortar strand, good cohesion during curing and a denser matrix and flexural strength of the hardened material.

Polymer binders are used to improve adhesion to the substrate and to lower the modulus of elasticity. Samples for pull-out testing were prepared to study the interaction of the polymer binder with the fiber at the interface of the lower layer of freshly prepared and partially cured mortar and to determine whether polymer-containing mortar demonstrates better adhesion to the fiber, thus increasing the pull-out force and the desired modulus of elasticity.

The study showed very strong interaction between the polymer fibers and the VAE polymer used. It was possible to increase the relative pull-out force from 1 for the reference samples to 1.48 (+50%) for the polymer-modified mortar. The polymer binder has a high affinity for the polymer fiber material, thereby enabling the production of a composite material that clearly surpasses the mechanical anchorage to the lower layer and the final tensile strength and stability of a printed structure. If composites are generated by adding polymer binder, the system can be considered to be more robust. Systems that are more robust are user friendly and facilitate better structures. Although the fine concrete formulation used as a reference can be seen as representative, it does show a direct comparison with what one could expect from the weaker interface of printed mortar layers.

1. Introduction

Macro-fibers have been used in concrete for many years now, particularly to prevent cracks from developing in the concrete due to deformation energy. Depending on the building project and its requirements, they are provided to the customer in different designs. As is usually the case with standard concrete applications, the fibers are added to the concrete as it is mixed. This can either be a wet or a dry concrete mix design (fiber-reinforced concrete or FRC). FRC's functional principle is to mechanically anchor the polymer fibers in the dense matrix of the binder or concrete.

Synthetic fibers serve the following functions:

- Lending shape to the modeled surface structures
- Achieving high pull-out resistance via mechanical anchorage.

Based on the typical material properties, suppliers of macro-fiber technologies develop the best geometry to achieve an optimum composite structure (image 1).

Due to the different handling of these concretes in use, the fibers are also influenced in their alignment in the construction material. For standard concrete, the fibers' orientation in space is three-dimensional, i.e. the fibers are spread out in all directions (x, y and z axes). Statistically, the effective range of a fiber is equivalent to that of a sphere with a diameter equal to the fiber length. Only when the spatial orientations of the spheres overlap can a load distribution be achieved – this can be obtained with a sufficiently high amount of fibers. The distribution is arbitrary and only dependent on how the mold is filled. Since, at most, half of the fiber length is effective, the sphere's radius can also be taken as the effective range.

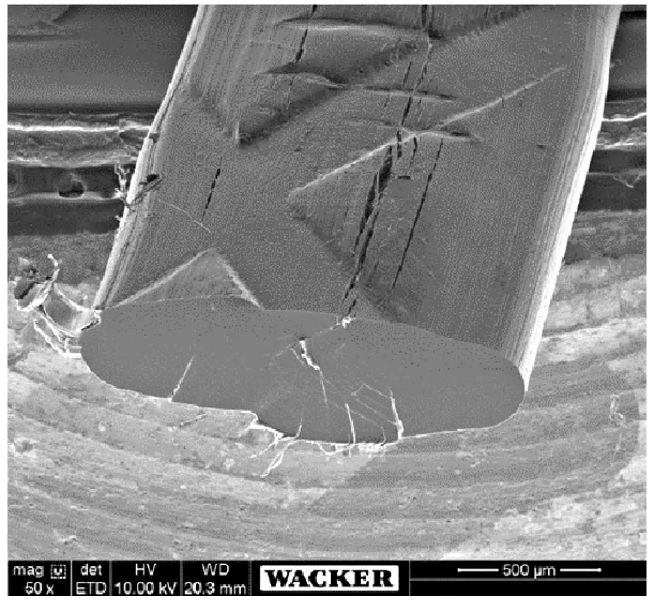

Image 1: **Cross-section and surface of a polypropylene fiber, enlarged, SEM; 60x used fiber (BarChip® 65).**

Printable concrete application primarily differs from poured concrete in its composition, especially with regard to the maximum grain size. In printing concrete, the diameter is usually less than 4 mm, while for standard casting concrete, it's above 8 mm. In practice, either an accelerator is added to the pumped concrete at the nozzle, or the formulation has already been accelerated. This is the typical procedure for dry-mix concrete; special binders are used here as well. Acceleration has technical advantages. It guarantees rapid strength development, which can occur after only a few seconds.

Fiber dosage in the concrete varies considerably, depending on the material. The following dosage can be taken as a guide value: 5 kg/m^3 for synthetic fibers.

TABLE 1. FIBER TYPE

Fiber Type	Fiber Weight in g	Typical Dosage kg/m^3 (Manufacturer Specifications)	Number of Fibers per m^3
Polymer (BarChip 65)	0.0274	5	182,482

2. Goal of the Study

The use of fibers in construction materials is current practice, particularly when it comes to short-cut fibers. Short-cut polymer fibers are normally used to protect the concrete shell in the event of a fire. Polymer binders are used to improve adhesion to the substrate and to lower the modulus of elasticity. This new test method investigates the effect of polymer binders on the bonding of fibers in concrete. It was used to determine whether polymer-containing concrete demonstrates better adhesion to the fiber, thus increasing the pull-out force.

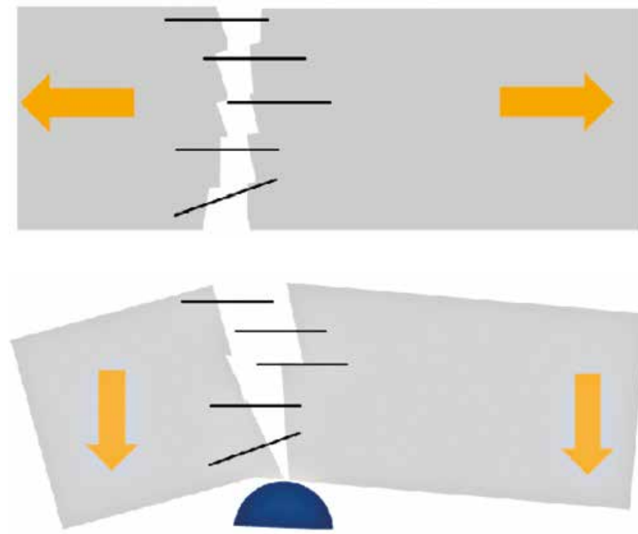

Figure 1 and 2: **Schematic crack development: fibers are distributed in the mix and can never be located in the optimum position, regardless of whether tensile or bending stress is applied.**

3. Uniaxial Testing of Fiber Pull-Out Force

The factors that influence the quality of the manufacture of the required test pieces include the nozzle, the printing technology, early strength development and the fiber material itself. Every single one of these factors can significantly influence the quality of the results. A measurement set-up on a laboratory scale could improve the quality of the data available on the fiber material's basic properties and is an objective of this work. In developing products for the application of pumped concrete, it is essential to have a test method that makes comparative results possible. Comparative means being able, with as low a standard deviation as possible, to differentiate between different products or formulations. This approach also has economic advantages, because the fabrication of large test specimens is considerably more time-consuming and cost-intensive than a reduction of the test to laboratory scale.

One of the challenges encountered in developing the test method was finding a suitable mold for making the test piece. So-called "dog bone" test pieces are well-known, but a drawback associated with them is that they have to be mounted with a high contact pressure, which means that damage in the clamping-jaw region cannot be ruled out. Based on experience with other applications, we furthermore knew that the modified area – a fiber in this case – is reinforced and that the risk of the fracture occurring outside the fiber-reinforced zone was high.

Due to the material properties and the forces that were expected to arise, reduction of the necessary variables to a simple test method based on EN 14891 was an obvious choice. The aim for developing the test method itself was to use as few fibers as possible initially, ideally only one. Since we were working with macro-fibers (length, L = 30 - 60 mm), we were able to position these centrally within the test piece, making a uniaxial tensile test possible (x axis from X-0.5 to X+0.5, whereby, along the x axis, ±0 represents the fiber center X0 or 0.5 x L).

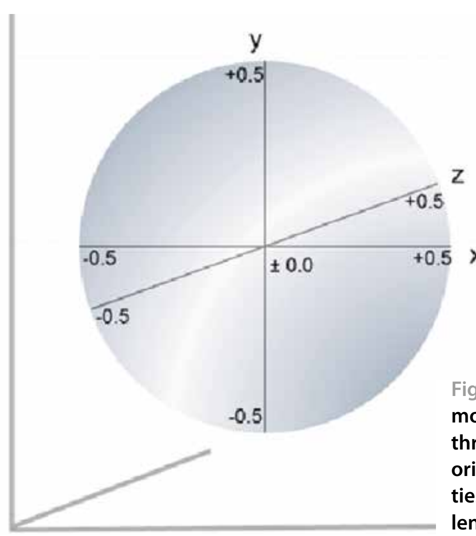

Figure 3: **Spherical model of the three-dimensional orientation possibilities for a fiber of length Lges.**

Since the anchorage of the fiber and not the mechanical strength of the concrete material was to be tested, the test piece was split at X0 during preparation. A 10-mm-thick PE foam pad was used for the splitting. This PE foam pad served as a divider between the two test-piece halves to be poured and also made it possible to position the fiber exactly in the middle. Based on EN 14891, the test piece had the following dimensions: width of 160 mm, height of 40 mm and thickness of 12 mm (15 mm at the ends). The fiber was located in the center at a height of 20 mm and depth of 6 mm in each case. The mounted length of the fiber half in the test piece is reduced by 5 mm per test-piece half due to the foam. One mold was able to accommodate 6 test pieces, which could thus be produced in a single batch at the same time. This has a positive effect both on the statistical evaluation and on error prevention.

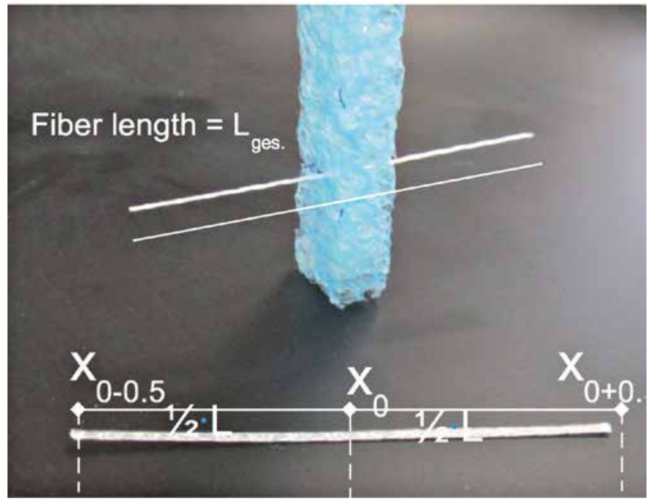

Figure 4: **Depiction of the PE foam pad with built-in fiber, prepared for use in the test piece in the mold (A) and description of splitting into L_{ges} = 2 x ½ L.**

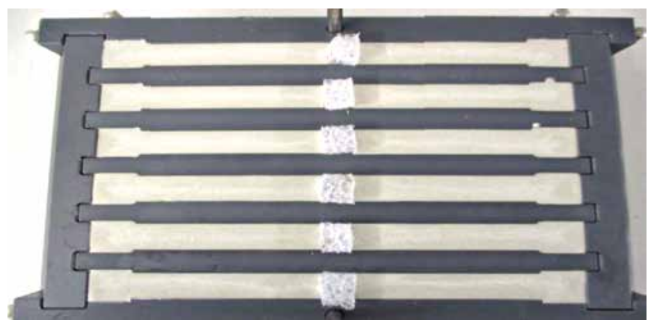

Figure 5a **on the left: Central splitting of the test piece with the PE foam divider.** Figure 5b **on the right: Mold A (6a) filled with fine printing concrete.**

The test piece described in EN 14891 has a T-shaped widening at the ends that allows the clamping jaws of the tensile tester to be fitted with minimum contact pressure. The subsequently conducted tensile test was performed at a test rate of 5 mm/min, the force was measured in Newtons.

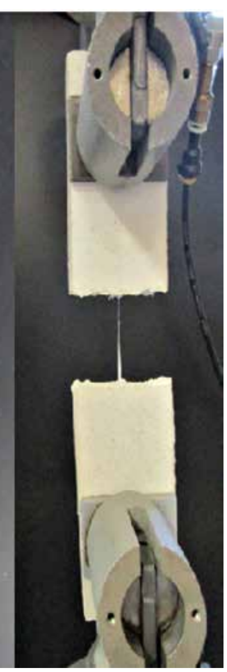

Figure 6 **on the left: Test piece after stripping; the fiber is embedded in the center of the test piece and stabilized by polyethylene foam.**

Figure 7 **on the right: Fiber pulled out of the test-piece halves, near the end of the measurement.**

4. RESULTS

4.1 Test Mixture

To simplify the testing conditions, no coarse aggregates were used. The compressive strength was measured on identical test pieces, which were also used in the tensile tests. The dimensions were: width of 40 mm, height of 40 mm and depth of 12 mm. This procedure reflected the strength generated under the testing conditions. The mixture was prepared with the addition of water in the Toni mixer. The fine concrete mixture was premixed dry and all water-based additives such as the polymer binder and any other auxiliary materials used were added to the water and then poured into the prepared mold (A) and stored at 23 °C and 50% relative humidity until the test (1 day in the mold (A) and then stripped).

TABLE 2: COMPOSITION OF THE FINE CONCRETE MIXTURES

Formulation for the Fiber Pull-Out Test	Quantity	Without Polymer	With Polymer Binder
Portland cement: Milke CEM 42.5 N	g	400	400
Quartz sand: H 33 (grain size 0 - 0.5 mm)	g	1,000	1,000
Carbonate filler: Omyacarb 5 GU (5 µm / D50%)	g	775	775
Thickener: Kelco-Crete DGF	g	0.1	0.1
Polymer binder: VAE (solids content: 50%) 10% of cement	g	0	40
Plasticizer: Melflux 2651 F (BASF)	g	4	4
Total	**g**	**2,179.1**	**2,219.1**
Water/cement ratio (w/c, water from polymer taken into account)		0.775	0.775
Compressive strength on 12 mm x 40 mm x 40 mm	N/mm^2	19.28 ± 2.71	19.51 ± 2.81

4.2 Synthetic Fiber

The reference value of the single fiber (tested in the same test equipment) was found to be 275.72 ± 0.08 N; this is the maximum force to be achieved in the test.

TABLE 3: MEASURED VALUES

Fiber Type		BarChip 56	Polymer	Polymer
Modification			Without polymer	With polymer
F_{max} (force in Newtons)	F	N	166.83	210.03
F_{max} (path at F_{max})	W	mm (m)	2.8 (0.0028)	3.3 (0.0033)
Standard deviation (Newtons)	s	N	22.98	21.32
Number of test pieces	n		6	6
Initial energy (force x path: F x W x Fk)				
Fk= area correction factor (0.6)	J	J	0.280274	0.415859
Improvement (without polymer = 1)			1	1.48

5. Discussion

The tests show that there was very strong interaction between the polymer fibers and the VAE polymer used. It was possible to increase the relative pull-out force from 1 for the reference concrete to 1.48 (+50%) for the polymer concrete. The polymer binder has a high affinity for the fiber material, thereby enabling the production of a composite material that clearly surpasses the mechanical anchorage to, or embedding in, the concrete. If composites are generated by adding 10% polymer binder, the system can also be considered to be more robust. Systems that are more robust are user friendly and facilitate better structures. Although the fine concrete formulation used does not claim to represent a printed concrete, it does, in a direct comparison, show what can be expected from a weak printed concrete.

The use of polymer contents of less than 10% had a significant influence on the pull-out energy for the synthetic fibers; a considerable increase was achieved both at peak height and on the path to reaching Fmax, which means that the test piece takes up more energy.

6. Outlook

Unlike the point loading of a panel test, for instance, determination of the pull-out energy of an individual fiber allows for a conclusion to be drawn about planar loading, because the total energy content of a given concrete compound can be specified. The three-dimensional orientation of the fibers is also known, as the pumping process orients the fibers in the direction of flow, and the potential total energy of a printed area can be calculated.

7. References

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EN 14488-7 (2005): "Testing sprayed concrete. Fibre content of fibre reinforced concrete"

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