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Klaus Bonin
Wacker Chemie, Germany, klaus.bonin@wacker.com

Christina Neumaier
Wacker Chemie, Germany

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IMPACT OF POLYMER BINDERS ON THE PULL-OUT FORCE OF MACRO-SYNTHETIC FIBERS IN SPRAYED CONCRETE

K. Bonin[1] and C. Neumaier[2]

[1] Wacker Chemie AG, Johannes Hess Strasse 24, 84489 Burghausen, Germany; PH: +49-8677-83-8265; Email: klaus.bonin@wacker.com
[2] Wacker Chemie AG, Johannes Hess Strasse 24, 84489 Burghausen, Germany; PH: +49-8677-83-6274; Email: christina.neumaier@wacker.com

ABSTRACT

Macro-fibers have been used in sprayed 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, made of steel or plastic. As is usually the case with standard concrete applications, the fibers are added to the sprayed concrete as it is mixed. This can be either wet or dry concrete (fiber-reinforced concrete or FRC). FRC's functional principle is to mechanically anchor the steel or polymer fibers in the dense matrix of the binder or concrete. The fibers' shape – for steel fibers, the manner in which they are bent, and for synthetic fibers, a modeled surface structure – aims to achieve high pull-out resistance via mechanical anchorage.

MACRO FIBERS

Based on the typical material properties, suppliers of macro-fiber technologies (whether steel- or plastic-based) develop the best geometry to achieve an optimum composite structure (see figure 1).

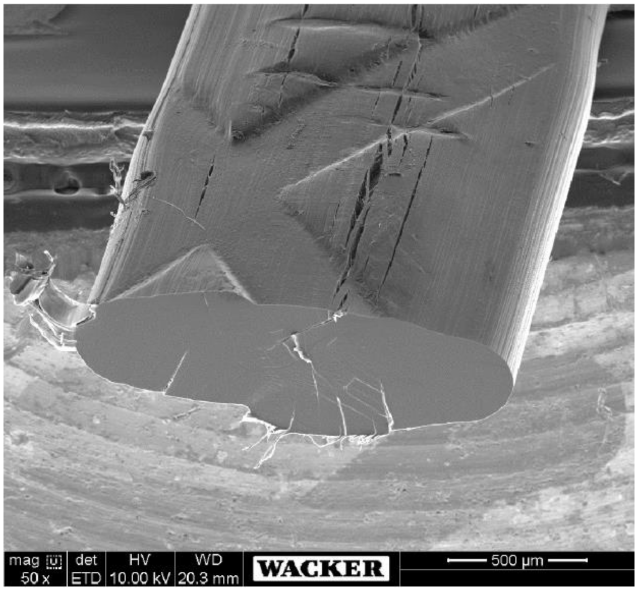

Figure 1: Cross-section and surface of a polypropylene fiber, enlarged, SEM; 60x used fiber (BarChip™ 65).

Steel fibers are differentiated according to their geometry and manufacturing process. The test used a standard fiber for sprayed concrete from Baekaert.

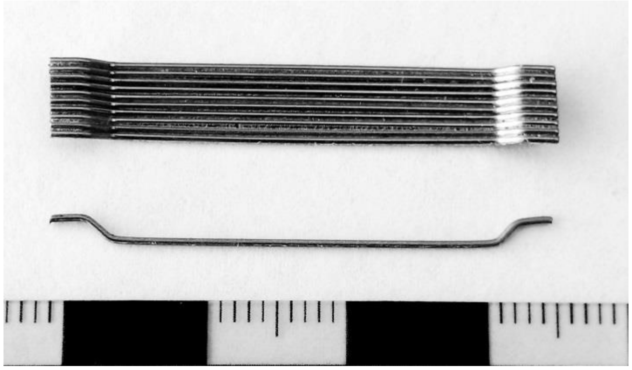

Figure 2: Top – steel fiber bundle, water-soluble bonding. Bottom – single fiber, 36-mm steel fiber, both ends bent twice (1mm scale).

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.

Sprayed concrete application primarily differs from poured concrete in its composition, especially with regard to the maximum grain size. In sprayed concrete, the diameter is usually around 4 - 8 mm, while for standard concrete, it's 32 mm and bigger. In practice, either an accelerator is added to the sprayed concrete, or the formulation has already been accelerated. This is the typical procedure for dry sprayed concrete; special binders are used here, too.

Acceleration has technical advantages. It guarantees rapid strength development, which can occur after only a few seconds. However, there are also disadvantages for the fibers used. A significant drawback is the rebound behavior, i.e. fibers adhere less well to the supposedly fresh concrete, bounce back like a spring and fall to the ground – and are thus no longer available to the concrete as reinforcement in the planned amount. The use of polymer binder can lessen rebound, which should also have a positive influence on the rebound reduction of the fibers.

Fiber dosage in the sprayed concrete varies considerably, depending on the material. The following dosage can be taken as a guide value: 5 kg/m³ for synthetic fibers and 25 kg/m³ for steel fibers.

Table 1: Fiber Types

Fiber Type	*Fiber Weight in g*	*Typical Dosage kg/m³ (Manufacturer Specifications)*	*Number of Fibers /m³*
Polymer (BarChip™ 56)	0.0274	5	182,482
Steel (Baekaert)	0.0685	25	364,964

The resulting difference in dosage is due to the density of the fiber on the one hand and the fiber's specific force absorption on the other, which is measured by panel test. Today, round or square concrete slabs are used, which originate from standards or approval regulations. A common test for sprayed concrete is the round panel test as per ASTM C1550-12a. The test involves the fabrication of a round test piece that has a diameter of 800 ± 5 mm at a thickness of 75 ± 2 mm, and subsequent measurement of the deformation in a three-point bending test. EN 14488-5 describes a square test piece, which has a side length of 600 mm and is 100 mm high. The arrangement of the support points in the ASTM test, or a circumferential support ring – which is also square – in the case of EN 14488-5, create different fracture patterns. The central loading on the concrete slab ideally creates equally distributed cracks that widen with progressing measurement and eventually lead to the failure or fracture of the test piece. From the measured force, with a given path, the area yields the amount of energy that is needed to deform the test piece. The aim of using fibers in concrete is to obtain a high energy with the given material input and thus improve the structure's stability and simplify the construction method, by being able to do without steel mesh reinforcement, for example.

If you look at an individual crack in the slab test, you will identify two kinds of crack widening that are slightly tapered in two dimensions. First, in the plane, from the slab edge to the slab center, and then in the slab depth, opposite to the acting force, the compression load. If you reduce the developing crack to a single fiber that is oriented at 90° to the crack, you have a uniaxial pull-out test. If the crack in the test piece develops at exactly half of the fiber's length, then this fiber can also be described as the ideal fiber. It needs to be taken into account that, in practice, the crack will develop at an angle of 0°- 90° to the fiber and will not always occur in the middle of the fiber. Another important factor is how far the fiber is anchored in the concrete, which is determined in tensile tests. The geometry and the fiber material properties themselves influence the result as well.

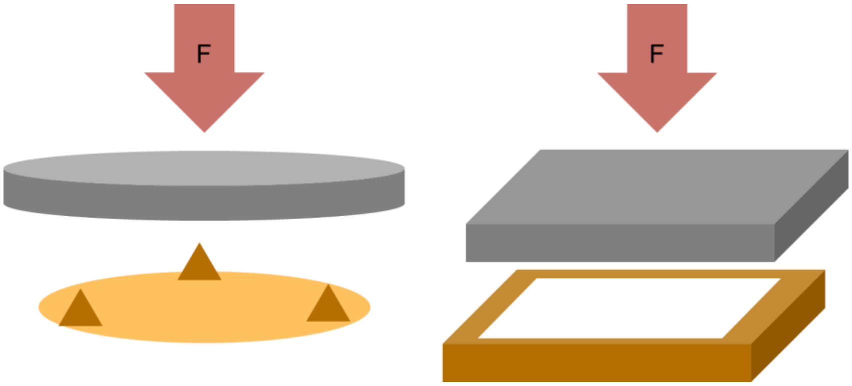

Figure 3: Schematic representation of a panel test. Left round panel test as per ASTM C1550. Right, square panel acc. to EN 14488-5.

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. VAE 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.

UNIAXIAL TESTING OF FIBER PULL-OUT FORCE

The factors that influence the quality of the manufacture of the required test pieces include the nozzleman, the spraying 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 sprayed 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 these panels 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 X_0 or 0.5 x L).

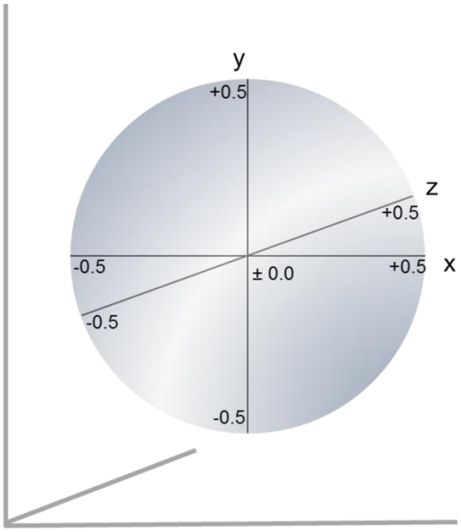

Figure 4: Spherical model of the three-dimensional orientation possibilities for a fiber of length L_{ges}.

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 X_0 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.

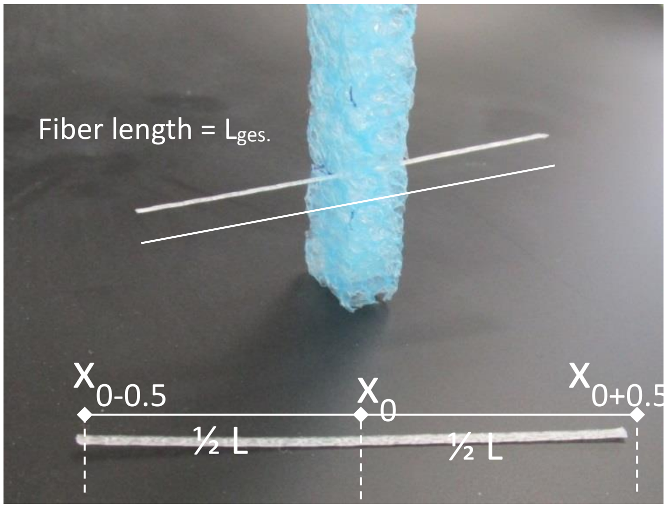

Figure 5: Depiction of the PE foam pad with built-in fiber, prepared for use in the test piece in the mold (A) and description of splitting into L_{ges}. = 2 x ½ L.

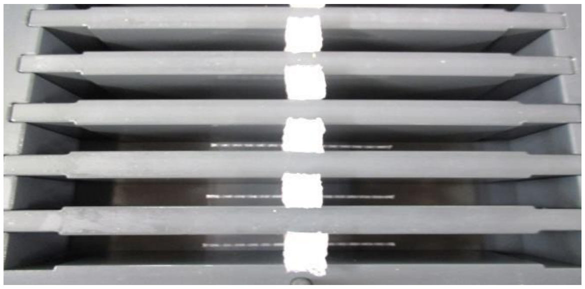
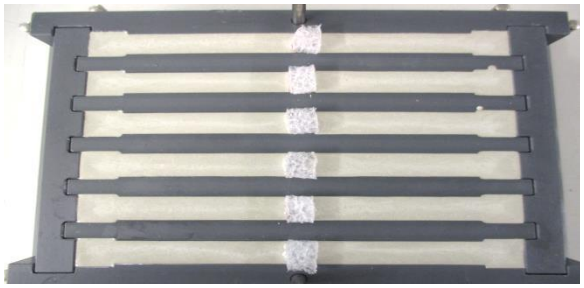

Figure 6a, on the left: Central splitting of the test piece with the PE foam divider, showing the positioning of the fiber.
Figure 6b, on the right: Mold (A) filled with fine concrete.

TESTING PROCEDURE

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 load cell had 10kN, the force was measured in N = Newton.

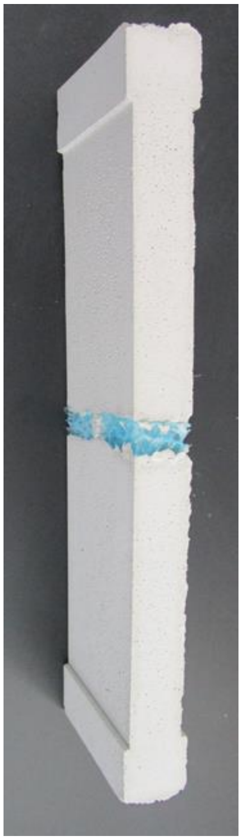
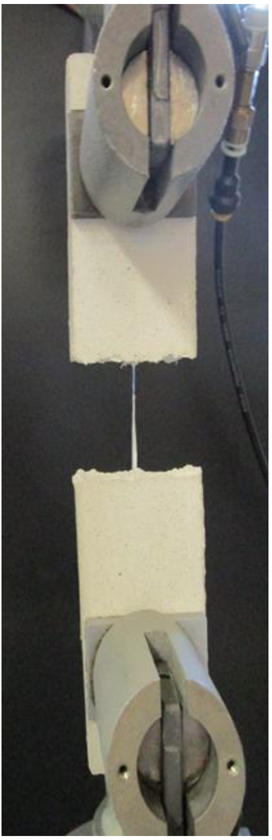

Figure 7a, on the left: Test piece after stripping; the fiber is embedded in the center of the test piece and stabilized by polyethylene foam.
Figure 7b, on the right: Fiber pulled out of the test-piece halves, near the end of the measurement.

MIX DESIGN AND TEST RESULTS

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 ETONIS®*	*With ETONIS® 150*
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 / D_{50}%)	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/mm²	19.28 ± 2.71	19.51 ± 2.81

Table 3: Synthetic Fiber Measured Values

Fiber Type BarChip™ 56			
Modification		*Without polymer*	*With polymer*
Pull out force F_{max}	N	166.83	210.03
Elongation at F_{max}: Stretch s	mm (m)	2.8 (0.0028)	3.3 (0.0033)
Standard deviation (newton)	N	22.98	21.32
Number of test pieces		6	6
Initial energy W_i $W_i = F \times s$	J	0.280274	0.415859
Improvement (without polymer = 1) $W_{i\ polymer} / W_{i\ reference}$		1	1.48

STEEL FIBER

The pull-out curve of the standard fiber used was fundamentally different to that of the synthetic fiber, because the fibers behave differently in the pull-out channel. While the steel-fiber ends are straightened in the smooth channel and then slide out with very little resistance, the synthetic fiber was stretched slightly and could thus be pulled out through an uneven channel. The pull-out curve shows a certain symmetry in the individual peaks, which correlates to the spacing of the embossed structure. Since the pull-out energy of a steel fiber without hooked ends is equivalent to only 10% of the initial energy of the bent fiber, the fiber length can be disregarded and only the bent ends materially affect the measurement result and thus energy.

DISCUSSION

The tests show that there was very strong interaction between the polymer fibers and the VAE polymer used (Vinylacetate Ethylene copolymer, TG -7°C). 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 sprayed concrete, it does, in a direct comparison, show what can be expected from a weak sprayed concrete.
The use of polymer contents of less than 10% had no significant influence on the pull-out energy of the steel fiber. For the synthetic fibers, a considerable increase was achieved both at peak height and on the path to reaching F_{max}, which means that the test piece takes up more energy.

OUTLOOK

Unlike the point loading of the panel test, 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. If the three-dimensional orientation of the fibers is also known, the volume can be used to calculate the potential total energy of an area, too.

REFERENCES

Dr. Gerhard Pittino, Dr. Georg Geier, Laura Fritz, Dr. Markus Hadwiger, Joerdis Rosc, Dr. Thomas Pabel, (2011) “Computertomographic Investigation of Steel Fibre Reinforced Sprayed Concrete Using Multi-Dimensional Transfer Functions,” Beton- und Stahlbetonbau, Volume 106, Issue 6, Pages 364–370.
EN 14488-7 (2005): “Testing sprayed concrete. Fibre content of fibre reinforced concrete”
ASTM C1550, “Standard Test Method for Flexural Toughness of Fiber Reinforced Concrete (Using Centrally Loaded Round Panel)”
EN 14891(2017): “Liquid applied water impermeable products for use beneath ceramic tiling
bonded with adhesives”
Marc Vandeewalle, (2011) “Sprayed Concrete Reinforcement: Mesh-Steel/Polymer Fibers,” Training Cource WTC 2011