Despite the relatively weak yarn-SHCC bond, the crack pattern at peak load in M-PE-T is considerably finer and denser compared to the plain high-strength SHCC. This is demonstrated by the DIC images in Figures 4b and 5b. Table 3 summarizes the values of average crack spacing and width at peak load. The average crack spacing dropped from 10.1 mm (0.398 in) without textile to 5.2 mm (0.205 in) with textile reinforcement. Moreover, the average crack width reduced from 85.8 µm (0.00338 in) in M-PE to 48.5 µm (0.00191 in) in M-PE-T; see Table 3.

Note that the post-peak load-bearing capacity of M-PE-T is structurally irrelevant, this being the reason why it was not analyzed in the current work. A proper yarn-SHCC bond can ensure considerably superior synergetic action between SHCC and textile, leading to higher tensile strength, pre-peak deformability and crack control, as demonstrated by M-PE-TE. With the additional coating of epoxy resin and sand on the TE textile, the bond strength between the yarns and SHCC increased substantially. This led to a completely different behavior of the corresponding composites compared to M-PE-T; see Figure 6a.

Moreover, as opposed to the as-received textile, the pullout behavior of the yarns coated with epoxy resin and sand is expected not only to exhibit a considerably stronger adhesion but also a slip-hardening pattern due to the enhanced mechanical anchorage. Thus, the bond strength between yarn and SHCC does not decrease with the ongoing multiple cracking in the surrounding matrix. One positive effect of this is a further increase in stress transfer from the textile to the matrix with increasing deformation and a more pronounced multiple cracking. The average crack spacing in M-PE-TE is 3.9 mm (0.154 in) only, while the average crack width is 44.9 µm (0.00177 in), which is almost two times lower compared to M-PE, and 7% lower compared to M-PE-T; see Table 3.

M-PE-TE yielded an average tensile strength of 26.7 MPa, which is 50 % higher compared to M-PE-T. If considered with respect to the cross-sectional area of the carbon yarns, the composite tensile strength of 26.7 MPa would correspond to 3560 MPa (516335 psi) in the textile, which is 109 % higher than the nominal yarn strength given by the producers. Since it was shown in previous studies that the additional coating does not affect the mechanical properties of the carbon yarns [7], the considerable enhancement in the composite load bearing capacity beyond that of the textile yarns is probably caused by three main superimposing effects: (i) higher crack-bridging contribution of the short fibers; (ii) higher residual anchorage strength of the yarns upon failure; (iii) more uniformly distributed and reduced effective tensile stresses in the yarns. All three mechanisms result from the improved bond strength, enhanced stress transmission to the matrix, and from the reduced crack spacing and crack width.

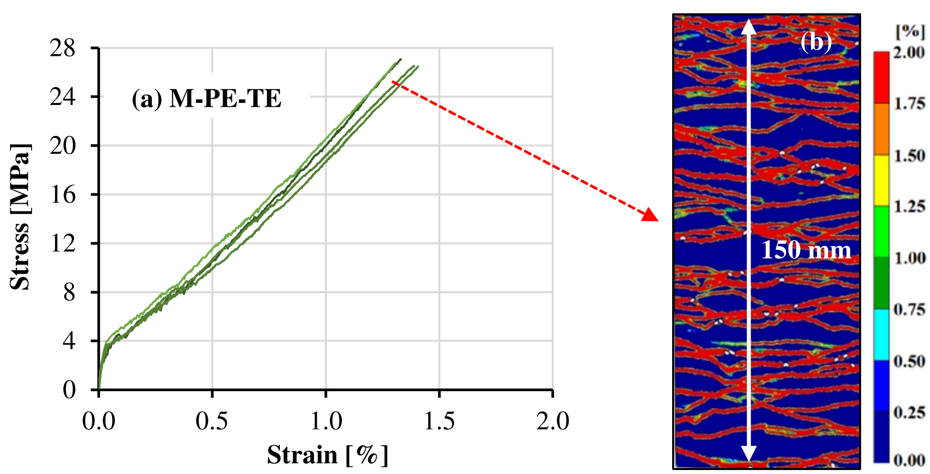

Fig. 6—(a) Tensile stress-strain curves of M-PE-TE specimens and (b) DIC evaluated images showing the crack pattern in a specimen at peak load

The average strain at peak load of M-PE-TE is 1.4 %, which is 55 % compared to M-PE-T; see Table 2. Furthermore, one important difference in comparison to M-PE-T consists in the simultaneous failure localization in the yarns and

SHCC. This effect is also related to the strong yarn-SHCC bond, which does not allow for a sufficient delamination of the failing yarns from the surrounding SHCC, in this way inducing large localized strains and causing crack localization in SHCC. Nevertheless, M-PE-TE yielded a work-to-fracture almost two times higher than M-PE-T, which is an essential parameter with respect to the protective performance of such composites against dynamic actions, such as impact or blast.

Table 2—Summarized results of uniaxial tension tests on high-strength SHCC with and without textile reinforcement. Standard deviations are given in parentheses and values in imperial units are given in the second row

Composite	Tensile strength [MPa] psi	Strain at peak load [%]	Work-to-fracture up to peak load [kJ/m^3] kJ/ft^3
M-PE	6.8 (0.6) 986	1.3 (0.6)	71.6 (36.5) 2.02
M-PE-T	17.5 (1.1) 2538	0.9 (0.0)	86.2 (8.7) 2.19
M-PE-TE	26.7 (0.3) 3872	1.4 (0.0)	191.4 (5.1) 58.33

Table 3—Average crack spacing and crack width of SHCC and hybrid fiber reinforced composites at peak load prior to failure localization. Standard deviations are given in parentheses and the values in imperial units are given in the second row

Composite	Average crack width [µm] inches	Average crack spacing [mm] inches
M-PE	85.8 (7.5) 0.00338	10.1 (1.1) 0.398
M-PE-T	48.5 (22.4) 0.00191	5.2 (1.1) 0.205
M-PE-TE	44.9 (3.3) 0.00177	3.9 (0.2) 0.154

CONCLUSIONS AND OUTLOOK

A comparative study on the tensile performance of exemplary hybrid fiber reinforced composites was performed by combining high-strength strain-hardening cement-based composites (SHCC) with carbon textile reinforcement. For analyzing the effect of the yarn-SHCC bond strength on the tensile behavior of the composites, the as-received textile was additionally coated with epoxy resin and sand, which enhanced the bond strength of the respective yarns.

It was shown that the bond strength between yarn and SHCC is an essential material parameter for a synergetic composite action. It was shown that the crack bridging effect of the short fiber reinforcement can be effective in increasing the ultimate load bearing capacity of the composites, especially if the bond strength between yarn and SHCC is adjusted to allow a proper crack control and to limit the crack width.

The apparent deformational compatibility between SHCC and textile reinforcement seems to be of secondary importance. This is because the continuous reinforcement diminishes the negative influence of structural and size effects on the robustness of SHCC, while a properly designed interaction between yarn and SHCC can promote considerably more pronounced multiple cracking and ensure better crack control compared to plain SHCC.

The carbon textile presented in the paper at hand had a high Young’s modulus and its strain capacity was similar to that of the SHCC involved in the study. In order to analyze the validity of the above-enumerated factors with regard to textiles with lower Young's modulus and higher elongation capacity, high-performance polymer textiles will be studied in future works in similar material and load configurations.

ACKNOWLEDGMENTS

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Development and design of smart textile reinforcement for concrete pipes

Goezdem Dittel, Kira Heins, Thomas Gries

Synopsis: There is a great demand in the world for low-cost and functional pipeline systems due to the renovation requirements of pipes in use and the continuous development of new settlements. Previously used pipeline systems made of steel reinforced concrete are economical and sufficiently resistant. However, due to the corrodibility of steel reinforcement and to enable sufficient crack reduction, large wall thicknesses and thus heavy constructions are required. Textile reinforced concrete (TRC) eliminates these disadvantages by enabling the production of light and thin-walled structures.

The aim of this research is the development of a concept for the realization of smart pipes made of sensory TRC by using the advantages of lightweight, thin-walled structures, focusing on the production process. Based on different warp knitted textile variations with different coating concentrations, preliminary tests were carried out using the four-point bending test. As a result of the preliminary tests, the textile variation of counterlaid tricot with a maximum coating concentration was selected as a suitable reinforcing material for the concept development. Concepts for the production of smart TRC pipes are developed accordingly. As a result, a casting mold and process were created which allowed a production with reduced diameter and depth of pores and concentric positioning of the reinforcement structure.

Keywords: leakage sensor, sensory carbon fiber, strain sensor, structural health monitoring, TRC water pipe

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INTRODUCTION

There is a great demand in the world for low-cost and functional pipeline systems. On one hand it is based on the need to renovate several pipes in use and on the other hand, the continuous development of new settlements requires a connection to sewage and fresh water systems. As a result, the question of reducing the consumption of resources and the construction of effective, safe lightweight structures arises. Previously used pipeline systems made of steel reinforced concrete are economical and sufficiently resistant. To counteract corrosion of the reinforcement and enable sufficient crack reduction and strength, large wall thicknesses and thus very heavy constructions are required. The application possibilities are limited by the size and weight of the structures [1]. Textile reinforced concrete (TRC) eliminates these disadvantages. The new innovative building material enables the production of thin-walled and light structures. These factors lead to a reduction of material consumption compared to steel reinforced concrete and reduce transport costs and weights. For some time now, research and industry have also shown great interest in the integration of sensor functions within the components [2]. These intelligent structures promise financial and operational savings in the maintenance and repair of components. In addition, production is simplified by combining the manufacturing of the reinforcing material and sensors in a single process. An additional sensor system is not necessary [3; 4; 5; 6; 7].

STATE OF THE ART

Textile reinforced concrete (TRC) is a composite material consisting of a continuous textile grid structure made of high-performance filament yarns embedded in a matrix of fine-grained concrete. The concrete carries the compressive loads of the structural element, ensures the protection of the reinforcement against environmental influences, secures the fibers in their desired position and transmits tensile forces to the textile reinforcement [8].

Textile reinforcement structures

The reinforcement in the composite is used to absorb the occurring tensile and bending tensile loads, to increase the bending strength, a higher corrosion resistance and crack bridging. It ensures usability and load-bearing capacity [1; 8; 9; 10]. Frequently used reinforcing materials in the concrete matrix are alkali resistant (AR)-glass and carbon [2; 10]. Grid structures are usually used as reinforcing textiles. These have an opening, adjustable to the application in the production process, which allows penetration with the matrix. High mechanical properties and easy handling must be guaranteed. The advantages of using continuous textile reinforcement are the orientation of the reinforcement rovings in all required spatial directions, the long reinforcement paths and the drapeability [10]. The efficiency of the load absorption depends on the undulation and orientation of the rovings. For this reason, displacement during manufacture must be prevented [10; 11]. A coating is used for two reasons: firstly, to stabilize the semi-finished textile product during processing and handling and secondly to improve the bond [9; 1; 10; 12]. The coating achieves a uniform stress condition across the yarn cross-section and increases the maximum tensile force [4]. A further advantage of coating utilization is the additional protection of the textile reinforcement against the alkaline environment.

Applications, advantages and disadvantages of TRC
Resulting from its outstanding mechanical properties and its versatility, TRC has gained importance in many applications in recent years and opens up new design potentials [8]. Due to its light weight and high strength, TRC is frequently used as facade panels, roof elements, post-strengthening bridges and special construction parts such as prefabricated garages and in lightweight construction. Furthermore, the possibility to realize three-dimensional (3D) architectural structures emerges [8; 9; 10; 13]. The light-weight also proves to be advantageous during transport, handling and assembly of the elements [1; 4; 9; 10; 13]. A major disadvantage of TRC is the high cost of the high-performance materials used and the high manual effort involved in manufacturing the components [9; 14]. At this stage, the research activities are aimed to obtain a general building approval, to reduce the price by automating the manufacturing process to serial production and to recycle obsolete concrete structures [14].

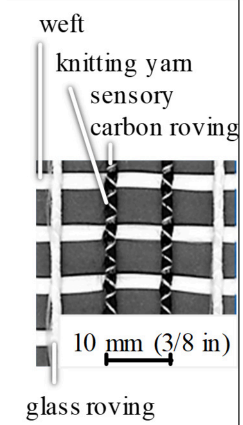
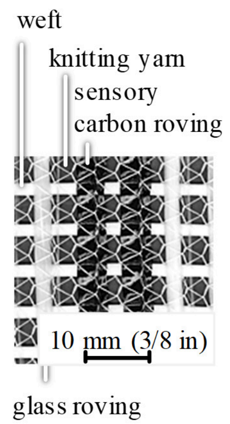
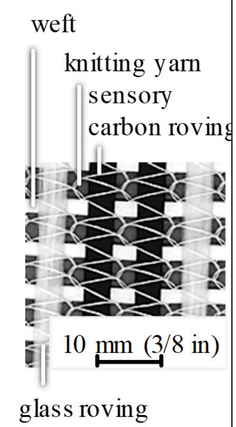
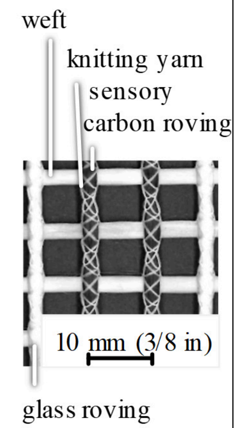
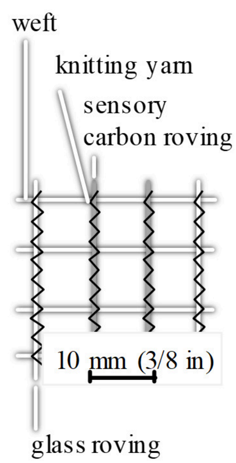
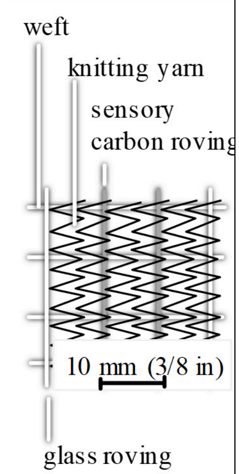
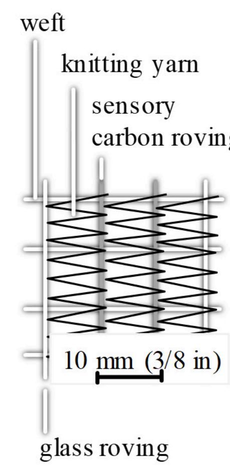
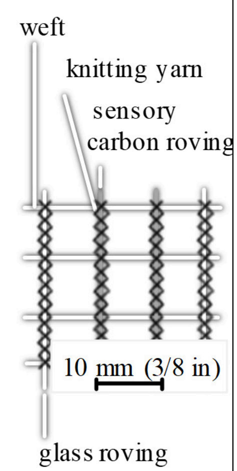
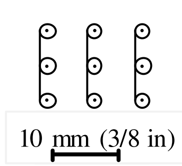
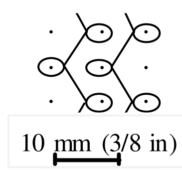
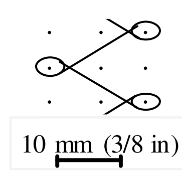
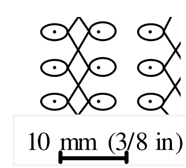
Integration of sensory functions in the textile reinforcement
Due to their electro-structural properties, carbon fibers integrated into the reinforcement can take on sensoring functions in addition to load absorption. This saves costs and effort since no conventional sensors and maintenance procedures are required. The elongation of the carbon roving leads to a reversible change in the electrical resistance. On the other hand, damage leads to an irreversible change. An increase in electrical resistance can be observed under tensile stress [15; 16]. Through continuous monitoring of the electrical resistance, cracking as well as infiltration of water can be detected [17; 18]. Previous investigations regarding the behavior of sensor fibers in case of water penetrating into the textile concrete structures were carried out. It was proven that the conductivity of the sensor system changed. Different reactions were determined depending on the width of the crack opening or the purity of the infiltrating water [19].

PRELIMINARY TESTS

Since textiles exhibit a wide range of properties, preliminary four-point-bending tests are required to select a textile construction suitable for concrete reinforcement. Bending tests are conducted due to the expected load of the application. The pressure of the surrounding soil on the apex of the pipe corresponds approximately to the load in a bending test. Due to the straight fiber orientation and the adjustable grid opening during production, warp knitted fabrics are an excellent choice. AR-glass is used as the fiber material due to its comparatively low price and sufficient mechanical and chemical properties. Carbon rovings are integrated into the biaxial warp knitted AR-glass fabric as sensor fibers. To determine the effects of the textile and coating variations on the sensory characteristics, the four-point-bending tests are carried out under a continuous monitoring of the electrical resistance of the sensory carbon rovings. In this section the production of the reinforcement textile and the execution of the tests are described.

Method of preliminary four-point-bending tests
Production of the reinforcing textile – The reinforcement textiles are manufactured at Institut fuer Textiltechnik (ITA) of RWTH Aachen University. AR-glass rovings with a titer of 2400 tex are used for the production of warp knitted fabrics with different stitching patterns.

Table 1 – Representation of the tested textile configurations

	Pillar	Tricot	Plain	Counterlaid Tricot
Photograph				
Sketch				
Path of the knitting yarn				

The distance between the center lines of two adjacent rovings is defined at 8 mm (3/10 in.). In the warp direction, two adjacent AR-glass rovings are replaced by sensory carbon rovings with a fineness of 1600 tex for 24000 individual filaments. As knitting thread a PES 167f48 is used. Fabrics are produced with a pillar binding, a plain binding, a conventional and a counterlaid tricot binding.
Table 1 shows the textile configurations in form of a photograph and a scheme including the knitting thread course. The fabrics produced are then coated with styrene-butadiene rubber (SBR) in concentrations of 10 % and 50 %. Some of the fabrics are left uncoated. SBR is chosen instead of an epoxy resin, as the latter is very brittle and fragile in the dried state and a coated textile cannot be cylindrically deformed well.

Production of specimens for the four-point bending tests - According to DIN EN 1170 - 5 [20], bending specimens with a length of 340 mm (13 2/5 in.) and a width of 100 mm (4 in.) are produced. The height is 15 mm (3/5 in.). The textile is 1/3 away from the lower surface of the specimen and 2/3 away from the upper surface. The dimensions of the sample and the textile layer are shown in Figure 1.

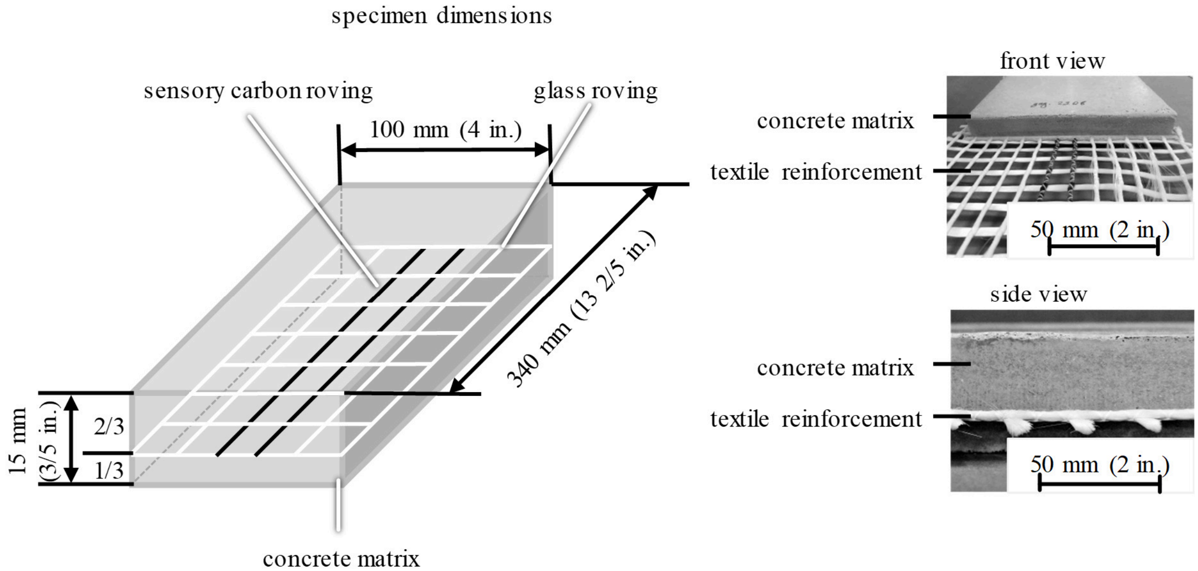


Figure 1 – Specimen dimensions for the four-point-bending tests

<u>Four-point-bending test</u> – The mechanical four-point-bending test is conducted according to DIN EN 1170 - 5 [20] (see Figure 2 - left). Before starting the test, a preload F_{Pre} of 5 N (1125 lb.) is applied to compensate waviness and thickness deviations between the specimens. The measurement is carried out displacement controlled at a travel speed of 1 mm/min (1/25 in./min). The force is measured continuously. The measurement is performed until a force drop of 75 % of the maximum force is observed, or, due to the specifics of the measuring equipment, up to a travel distance of 50 mm (2 in.). During the mechanical tests, both ends of a carbon roving are connected to a voltmeter. A continuous direct current of 5 mA is introduced into the roving. The resistance can thus be determined indirectly from the voltage over time. Figure 2 (right) shows a schematic representation of the circuit diagram used for these electrical measurements.

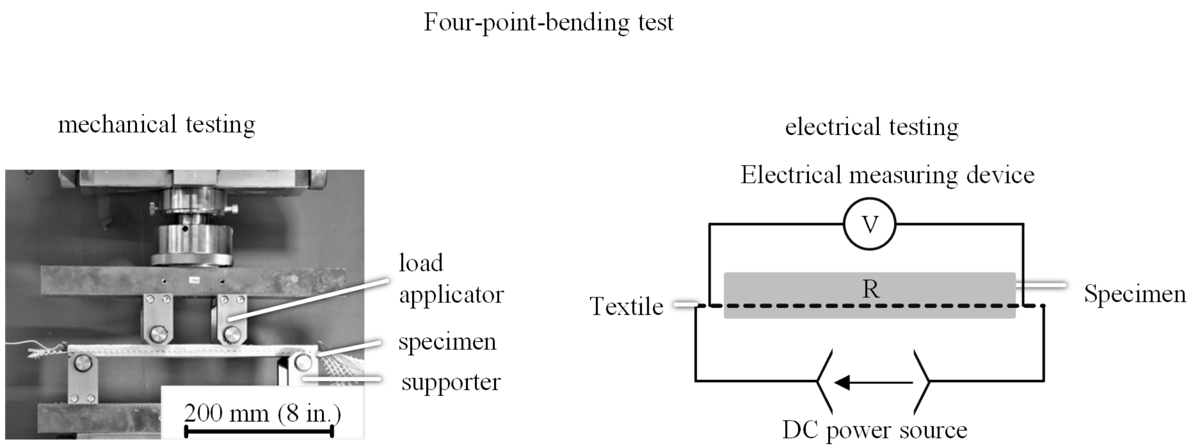


Figure 2 – Set-up of the four-point bending test (left) and circuit diagram for the electrical measurements (right)

Results of the preliminary tests

<u>Mechanical results</u> – During the four-point bending tests, depending on the textile configuration and coating ratio, large deviations regarding the maximum bending forces are determined. The highest bearable force F_{MOR} is measured for counterlaid tricot and a coating of SBR in a 50 % concentration. The coating leads to an increase in the maximum bearable force by creating a firm bond between the individual filaments in comparison to uncoated fabrics. As a result, the load-bearing cross-section is increased and the force transmission between the individual filaments is no longer achieved by friction. For counterlaid tricot, the load-bearing capacity is almost tripled compared to uncoated textiles. The higher significant improvement compared to a coating with 10 % concentrated SBR is resulting from the more uniform and pronounced bond in the roving and composite. In addition to the coating, the type of textile binding

also influences the mechanical properties of the composite. First, the mechanical properties of textiles with oval shaped rovings such as tricot and plain, exceed those of round-shaped rovings due to the higher interface surface with the concrete matrix. Furthermore, the textile architecture influences the effectiveness of the coating process. Due to the course of the knitting threads, the pillar and counterlaid tricot possess greater grid openings than a conventional tricot or plain. Therefore, the coating and matrix material penetrate the textile better and embed the roving, through which a firm bonding between matrix and reinforcement can be realized. In comparison to the oval textile bindings, the compact circular cross-sectional area of pillar binding prevents a deep penetration of each individual roving with either coating or matrix materials and hence leads to lower load-bearing capacity in coated condition. The effectiveness of the coating is higher for the binding types pillar and the counterlaid tricot. The reason for that is the number of inner filaments that are activated. Due to the oval roving shape the conventional tricot and plain already show a large contact surface with the concrete matrix in the uncoated state with a comparatively low number of inner filaments. Counterlaid tricot and pillar, on the other hand, show a smaller contact area leading to a high number of inner filaments. As the coating activates the inner filaments by generating an adhesive load transfer, its effect is higher for the latter textile configurations. The higher the concentration of SBR in the coating, the higher is the post cracking deformation. The percentage increase of the deformation by the coating varies depending on the textile configuration. The results are summarized in Figure 3. A more detailed description of the observed load reaction can be found in the associated paper [21].

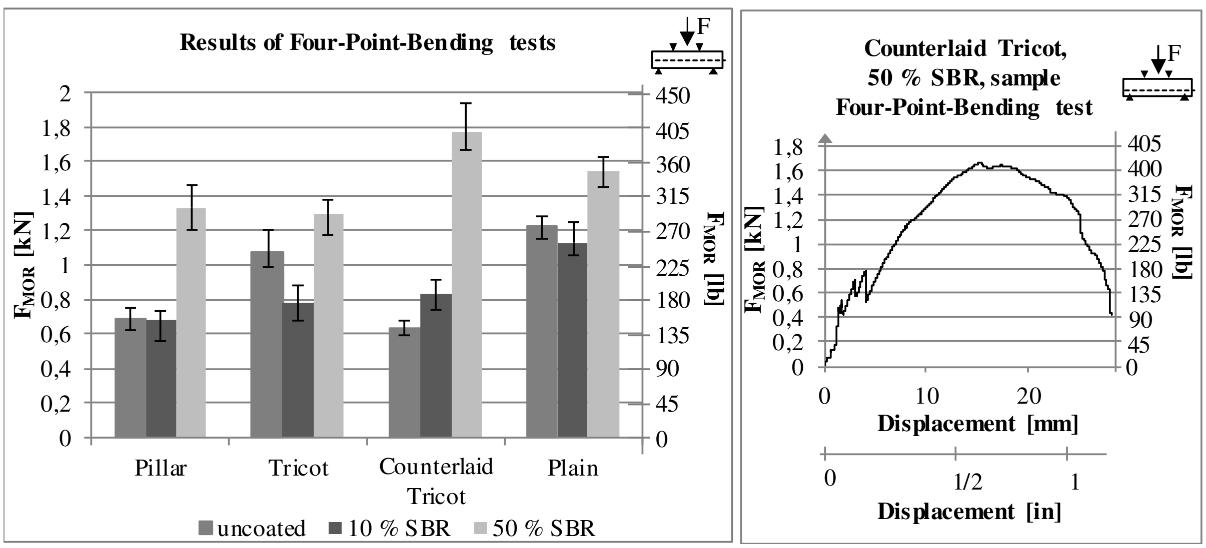


Figure 3 – Mechanical results of the four-point-bending tests and the representative load response for counterlaid tricot, 50 % SBR coating

Electrical results – The monitoring of the electrical resistance during the mechanical loading of the four-point-bending test shows that the coating of the textile with SBR led to an increased overall electrical resistance. The higher the concentration of SBR in the coating, the greater the electrical resistance. The reason for this is the contacting of the sensory fibers, which occurs through the coating. The changes of the electrical resistance under load follow the elongation of the rovings and the reduction of the diameter of the filaments. Furthermore, it should be noted that the measurement setup used had to cover a large range of electrical resistance and therefore many changes in the micro-ohm range could not be detected. This problem can be solved by using a Wheatstone bridge for subsequent testing. It increases the sensitivity of the measurements by several orders of magnitude.

DEVELOPMENT OF THE CASTING MOLD AND PRODUCTION CONCEPT

Steel reinforced concrete pipes have been used for several decades. While the main principle of production can be conveyed to TRC-pipes, special features of the reinforcing material require the development of adapted casting molds and processes. A pipe is defined as a hollow, prefabricated component that has a uniform internal cross-sectional shape over its entire length. The only exceptions are connection profiles [22].