Prospects for the Use of Textile-Reinforced Concrete in Buildings and Structures Maintenance

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Abstract: This paper discusses the state of the art in research on the use of textile-reinforced concretes in structural maintenance. Textile-reinforced concretes can be used in structural maintenance for various purposes, including the sealing and protection of the existing building structures, as well as for the strengthening of structures. The first-mentioned aspects are explained in this paper on the basis of example applications. A special focus is placed on the maintenance of heritage-protected structures. The development, characterization, and testing of a textile-reinforced concrete system for a heritage-protected structure are presented. Examples of the application of textile-reinforced concrete for strengthening highway pavements and masonry are also given. In particular, the possibility of adapting the textile-reinforced concrete repair material to the needs of the individual building is one advantage of this composite material.

Keywords: textile-reinforced concrete; repair mortar; textiles; fibers; maintenance

1. Introduction

In order to preserve our numerous reinforced concrete monuments, repair methods are required that, on the one hand, preserve the substance and appearance of the edifice as far as possible and, on the other hand, ensure the durability of the structure, including the completion of repairs. Solutions in terms of approaches, procedures, and materials must be developed for the specific object to be repaired. Another important area in the field is the repair and rehabilitation of roads, which contributes to the maintenance and development of logistics capacity. Furthermore, the repair and strengthening of masonry structure elements prevents accidents and ensures the safe operation of buildings and structures in the future.

Textile-reinforced concretes or cement-based mortars allow different approaches to the repair of reinforced concrete monuments: strengthening of the existing supporting structures [1,2], sealing and protection [3–7], and highway [8,9] and masonry [10–13] strengthening. This article will present a modern composite material—textile-reinforced concrete (TRC). Based on this, the diverse use of textile-reinforced concretes for sealing, strengthening, or protecting existing reinforced concrete structures is presented. Finally, the technique of object-specific reinforced concrete repair with carbon textile-reinforced, structurally dense, compatible repair mortars is explained.

2. The Composite Material Textile-Reinforced Concrete (TRC)

In TRC, technical textiles are used as reinforcement to carry the tensile forces. This eliminates the need for steel reinforcement in the concrete. As can be seen in Figure 1, the technical textiles are much more closely meshed, thinner, and more flexible than conventional steel reinforcement mats. As the concrete cover can be reduced to a minimum required for the bond due to the elimination of steel reinforcement and the durability of the technical textiles, this composite material enables significantly lower component thicknesses compared to steel-reinforced concrete. These two facts, comprising the mesh...
size of the textile and the thin-walled components, require an adjustment to the concrete composition, in particular the reduction of the maximum aggregate grain size.

![Image of a textile with cross-section](image.png)

**Figure 1.** Carbon textile with a mesh size of 12.7 mm × 16 mm (© Markus Beßling).

The technical textiles consist of “endless” long fibers that are combined into bundles, which are known as rovings. A roving contains up to 48,000 fibers (48 K carbon roving). The fiber material consists of alkali-resistant glass, basalt, or carbon. While glass and basalt fibers consist of mineral components, carbon fibers are based on oil. Compared to glass and basalt fibers, carbon fibers have significantly higher stiffness (about 220 GPa) and tensile strength (about 3000 MPa). The diameters of the fibers vary between 5 and 20 µm, depending on the material.

Technical textiles are produced by laying down the rovings in different directions and connecting the roving junction points with a knitted thread. Such textiles, in which the rovings are laid on top of each other, are called non-crimped fabrics. To improve the processability of the technical textiles and to increase the load-bearing capacity, the technical textiles are impregnated with a polymer after manufacturing. Epoxy resins, styrene butadienes, acrylates, and polystyrene are used as polymers. The polymers vary in their stiffness and, thus, cause differences in the load-bearing capacity and stiffness of the impregnated textiles [14]. In the data sheets of the suppliers of technical textiles, mechanical characteristic values are given for characterization and dimensioning. In the case of glass and basalt fibers, the impregnation takes on a third task in addition to processability and increasing the load-bearing capacity: resistance in alkaline media, such as concrete, is increased.

As an alternative to polymeric impregnation, mineral impregnation is also possible and is particularly useful in fine crack distribution repair [15]. As yet, however, these mineral impregnations are only feasible at the roving level and not in the created textile.

According to the static requirements of the structure to be repaired, the geometry of the technical textile can be adapted in consultation with the manufacturers, if necessary. A higher fiber cross-sectional area in the direction of the load provides a higher load-bearing capacity. As an example, a load-bearing capacity of 475 kN/m can be realized with a fiber cross-sectional area of 141 mm² [16]. Figure 1 shows the carbon textile required for this application.

The fine-grained concrete has a maximum grain size of between 1 and 8 mm, depending on the mesh size of the textile. Depending on the application, it is known as either fine-grained concrete or cementitious mortar. The composition can be adapted to the specifics of the application [7]. Whereas in precast concrete production, the fine concrete is poured into a formwork, in repair work, the application of the TRC system takes place in layers. The number of textile layers depends on the required degree of reinforcement. Figure 2 shows the layer-by-layer structure of a textile concrete repair layer.
Figure 2. Sealing (layer by layer) the roof of Mariendom Neviges with TRC (© Jeanette Orlowsky): (a) part of repair layer with TRC; (b) general view of the repaired surface.

Due to the wide range of technical textiles and the possibility of making object-specific material adjustments, the composite material TRC does not have a fixed variety of properties with which to calculate specifics. In many cases, the mechanical and physical properties must be determined for the specific textile and concrete in question, as well as for the composite material. Furthermore, there are currently no standards for TRC. There are general approvals, approvals in individual cases for TRC applications, codes of practice, and information sheets (see, e.g., [4,17]). A comprehensive test technique for characterizing TRC has been developed at several German universities and engineering models have since been elaborated [2,3,7,10,18,19].

3. Bond Behavior of Textiles in a Concrete Matrix

Compared to steel-reinforced concrete, TRC generally has a finer crack pattern due to the small-scale reinforcement structure created by the technical textiles. A larger number of cracks with narrow crack widths can enable a repair layer that is impermeable to liquids, even in the cracked state. This will be discussed further, below.

To ensure the stated fine-crack pattern, the bond behavior between the fine-grained concrete and the textiles must be very closely studied. In the last few decades, much research has been conducted to elucidate the bond properties. The impregnation material is the main influence on the bond properties [20,21], along with the tensile strength of the yarn [14]. It is important to emphasize that the textile yarn is covered with a thin layer of impregnation material, which, in turn, makes it impossible for the cement matrix to penetrate inside the textile reinforcement [22–24]. This contributes to the equalization of tensile stresses across the entire yarn cross-section. The bonding forces between the concrete and the yarn are transferred through the contact zone of the treated yarn surface. At first, the adhesion strength is unbroken, and the bond remains rigid. As the load increases, the adhesive bond between the concrete matrix and the yarn is broken and the bonding forces are transmitted through frictional forces. In turn, the friction forces are greatly influenced by the geometric characteristics of the yarn, the yield strength of the material, and the type of surface treatment. Depending on the cross-sectional shape of the fiber strand and its variation along the length, the bond forces are transformed into forces vertical to the fiber strand (Figure 3b, $T_{e,p}$) that are transferred to the concrete [25]. If the stresses exceed these vertical forces giving tensile strength to the concrete, a crack that is parallel (splitting) or vertical to the textile layer occurs (Figure 3a). In a previous paper [18], the splitting tendency of different textiles and the resistance against the splitting crack were calculated using a simplified mechanical model (see Figure 3b).
The resistance against a splitting crack depends on the tensile strength of the concrete and the width of the concrete area (defined by the mesh width of the textile) which counteracts each single fiber strand. Thus, the question arises as to what influence the concrete strength has on the bond forces (acting forces) between the fiber strand and the concrete [18]. It can be concluded that the bond forces increase with rising concrete strength (e.g., bending tensile strength) in general (Figure 4a). This phenomenon is independent of the geometrical properties and the impregnation material of the fiber strand. Calculating the resistance of the concrete against a crack, the usable concrete area is of interest. The question, “Is the full width between the fiber strands usable for the calculation, or must the width be reduced, due to an uneven stress distribution?” needs to be answered. The results in Figure 4b show that with an increasing free mesh width, \( e_{0,li} \) (\( e_0 \) represents the fiber strand width, see Figure 3b), the usable concrete width has to be reduced and tends toward a limit value. The behavior can be explained by a crack that starts directly beside the fiber strand and grows out to the sides. The model presented in [18] describes this behavior, simplified by a constant stress block, which is calculated using the reduction factor, \( \gamma \) (see Figure 4b).

**Figure 3.** Splitting of a TRC specimen due to the pulling out of a single fiber strand: (a) cracked specimen [18]; (b) mechanical model to describe the acting (\( T_{E,P} \)) and resisting (\( T_{R,P} \)) forces in the TRC.

**Figure 4.** (a) The correlation between the flexural tensile strength of fine-grained concrete on the maximum bond flow; (b) the influence of the concrete width per fiber strand (\( e_{0,li} \))/mesh width of the textile on the resistance against a splitting crack (\( T_{R,P} \)), calculated via a reduced concrete width (\( b_{usable} \)) [18].
4. Protection of Steel-Reinforced Concrete Structures with TRC

In addition to the strengthening of existing load-bearing structures with TRC, there is great potential in terms of the repair of steel-reinforced concrete components in which unplanned cracks or cracks with unacceptably large crack widths have occurred. In waterproof structures, tanks, and water and tunnel structures, the tightness of seals and, consequently, their serviceability are endangered due to cracks. To ensure durability, crack widths are limited for service conditions in steel-reinforced concrete constructions. Common methods of repairing cracks involve filling them with crack fillers or coating them with crack-bridging surface protection systems [26]. Unfortunately, practical experience often shows that these repair methods quickly reach their limits.

At the RWTH Aachen University, research is being conducted together with the Federal Institute for Hydraulic Engineering on textile-reinforced sprayed mortar layers for the repair of hydraulic structures [3,4]. The aim is to use textile-reinforced sprayed mortar on old concrete surfaces, to distribute crack movements in the old concrete into many fine cracks in the textile concrete. The cracks should then remain so fine that the TRC is impervious to the effects of water. It was shown that textile-reinforced concrete can be produced in the classic dry-spray process and that crack movements in the substrate can be distributed in very fine crack widths of around 0.1 mm in the textile-reinforced concrete. However, reproducible proof has so far only been achieved in uniaxial tensile tests, with a material combination of epoxy resin-impregnated carbon textiles sprinkled with sand and dry spray mortar on small-format composite bodies [3]. The system focuses on hydraulic structures with low-strength old concrete types with or without minimal steel reinforcement [3]. As part of an ongoing Ph.D., Mr. Lenting shows that mineral-impregnated carbon fibers also meet the requirements explained above [15].

The approach chosen in another study [4] is not only suitable for hydraulic structures but also for the repair of reinforced concrete structures with a required impermeability to water, as shown in [5]. The Mariendom in Neigves is a reinforced concrete church, built by the architect Gottfried Böhm in 1965–1968. Over the decades, water entered the building through cracks in the steel-reinforced concrete roof. A surface protection system could not bridge the crack movements and a covering would have spoiled the appearance of the building. Therefore, the roof was sealed with textile concrete. The proven material combination of epoxy resin-impregnated, sanded carbon textiles and dry spray mortar was used. Figure 2 shows the damage and the repair work.

In addition to protecting steel-reinforced concrete structures with TRC, the steel reinforcement can also be protected against corrosion, with carbon textiles embedded in mineral mortar. For example, carbon textiles can be used instead of titanium anodes for cathodic corrosion protection (CCP). The performance of the system is significantly influenced by the coating of the textiles [27]. As part of a ZIM research project, the TU Dortmund University, together with partners from the University of Applied Sciences, Münster, Massenberg GmbH, InstaKorr GmbH, and Mitsubishi Chemical Advanced Materials GmbH (carboNXT) are currently investigating the extent to which conductive carbon mortars, made from recycled carbon fibers, can act as a chloride barrier. The chloride barrier on steel-reinforced concrete structures is achieved via a full-surface anode of homogeneously distributed carbon fibers in the repair mortar [6].

5. Monument-Specific Steel-Reinforced Concrete Repair with Textile-Reinforced Concrete

As part of the DFG priority program, SPP 2255 “Cultural Heritage Construction”, the TU Dortmund University (Department of Building Materials) is working together with the Institut für Steinkonserierung e.V. (Institute for Stone Conservation), the Rhein–Main University of Applied Sciences (Department of Architecture and Civil Engineering), and the University of Kassel (Department of Construction Materials and Chemistry) on the conservation of steel-reinforced concrete structures of the ultra-modern era [28]. For this purpose, restoration methods that are appropriate for listed buildings and that preserve...
their fabric are developed for specific applications, using the latest concrete technology approaches. For the broadcasting tower of the Europe 1 broadcasting center in Saarland, for example, a structurally dense, compatible repair mortar, reinforced with carbon textiles, was developed to protect the existing steel reinforcement from further corrosion, on the one hand, and to replace the cross-sectional losses of the reinforcement on the other. Figure 5 shows the transmission tower and a typical damage pattern.

![Europe 1 broadcasting center tower: (a) general view (© Franziska Braun); (b) a typical damage pattern (© Melanie Groh).](image)

Figure 5. Europe 1 broadcasting center tower: (a) general view (© Franziska Braun); (b) a typical damage pattern (© Melanie Groh).

Often, in vertical structural elements, the problem areas of strengthening are the corner parts. Textile-reinforced concrete with curved strands can be used for this type of repair work [7,29–31], to hold the forces in this area of the structure. In turn, the bend in the strand is the main weak point of a corner repair system and requires special attention during repair operations.

Figure 6a shows a concrete specimen used to investigate the load-bearing capacity of the strands in a 90° angle joint, which was achieved by bending the preheated strands along the “sharp” edge. The tests were carried out using the central tension method. It is important to emphasize that all strands were fractured due to the loss of load-bearing capacity in the textile—a pure textile fracture, since, during the concreting of the samples, spacers were used that excluded any contact of the concrete matrix with the textile material above a 90° angle. It was found that in the range of bend radii from 0 to 20 mmm the ultimate tensile strength is only 16 to 23% of the tensile strength of the straight strand, which finding should be considered during the design of the repair system.
Often, in vertical structural elements, the problem area of strengthening are the corner parts. Textile reinforced concrete can be the overlapping area of the technical textiles. Therefore, it is important to determine the optimal overlap length of the technical textiles with regard to the maximum utilization of materials, while maintaining the load-bearing capacity.

Central tensile tests were carried out on double-layer TRC specimens with an overlap of 10, 15, and 20 cm. The results were compared with a reference specimen without overlap. The specimen after the test is shown in Figure 6b. As can be seen from the figure, major failures can occur as a result of textile strands breaking (the loss of the load-bearing capacity of the textile) or their detachment from the concrete matrix (insufficient adhesion of the textile to the concrete matrix). The results show that the optimal overlap length for this composite material is in the range of 11 to 16 cm.

Figure 7 shows a trial repair, on a scale of 1:1, of a pillar section replica of the transmission tower in the laboratory of the Materials Department of Civil Engineering.
The application of a structurally dense, building-compatible repair mortar, reinforced with carbon textiles over the entire surface, would, as in the case of the roof of the Mariendom in Neviges, cover the actual substance. This approach contrasts with the preservation approach of only supplementing the fabric to the minimum level necessary (see the damage pattern, Figure 5), repairing locally with mortar, in order to preserve the authenticity to a great extent. However, if one considers the period of use of the structure over decades, the monument preservation approach described causes significantly higher losses of the actual substance, since the damage process, the carbonation of the concrete, and the associated corrosion of the reinforcing steel are not prevented by local repair measures. With the “TRC approach” described in this paper, on the other hand, the carbonated concrete can be preserved, and the damage process is prevented in the long term by means of the reinforced, structurally dense, surface-repair layer. A wide-ranging discussion about the two solution approaches, considering the building history coordinate system in which the respective steel-reinforced concrete structures are located, is the basis for finding an object-specific solution.

6. Repair and Rehabilitation of Road Pavements

It is well known that a road pavement works as a slab on an elastic base and, hence, the main strength characteristic of this structure is its flexural strength. In addition to dynamic loads from vehicles, pavements are subject to additional negative effects from the environment, namely, freezing and thawing. Separately, it should be noted that pavements also absorb braking loads; therefore, they are subject to abrasion. The additional annual increase in freight and transport traffic exceeds the original design loads, leading to the premature failure of pavements before their service life has expired.

Since TRC has good tensile strength and increased flexural tensile strength, this composite material can be used for the repair and rehabilitation of road pavements. A prefabricated rollable pavement textile-reinforced concrete system has been developed at RWTH Aachen University to repair damaged road surfaces after winter cracking [8]. It was found experimentally that the 10-millimeter-thick textile-reinforced concrete had a flexural strength of 12 MPa at 28 days of age, which significantly exceeded the strength requirements for highways. This strength indicator is an undeniable advantage in terms of the rational use of materials.

Ruhr University Bochum developed TRC [9] using carbon fibers for the concrete overlays, which allows the repair of pavements with an infinitely long slab without the need for cutting expansion joints in the repair material. The thickness of concrete overlays ranged from 30 to 70 mm and the overlays were reinforced with 1 to 3 layers of carbon fiber mesh. Samples were loaded in a 4-point pattern flexural test, with a load rate of 1 mm/min. The results showed the effectiveness of this method since no reflected cracks were observed in the repair TRC in the area of the old pavement joint. There was not a single failure in the area of the contact zone comprising “old pavement—repair material”, which indicates high adhesive strength when using this method.

It is important to emphasize that TRC can be a more effective material for thin-layer repairs of rigid pavements (with a partial-depth repair up to 3 cm deep) compared to coarse-grained fiber concrete [32].

To increase the durability of textile-reinforced repair concrete and to extend the service life of the pavement, special attention should be paid to the selection of the concrete matrix composition [33]. Poor-quality concrete can lead to the premature failure of bonds between the textile reinforcement, which will lead to a deterioration in the physical and mechanical properties of the composite and a decrease in its durability. For example, the authors of [34] emphasize the importance of considering the amount of entrained air and the coefficient of modifier efficiency when designing concrete mixture composition. In addition, for any repair material, adhesive strength and shrinkage are important characteristics that largely determine its quality.
7. Reinforcing Masonry Using Textile-Reinforced Concrete

During the operation of buildings and structures, masonry components can be subjected to considerable damage as a result of increased loads, changes in the intended use of the building or structure, changes in its design scheme, and material degradation. Other causes of masonry damage may include: the violation of the technology of preparation and application of masonry mortar; the influence of natural factors, namely, the freeze–thaw process, over-moistening, the weathering of masonry mortar, or the impact of mold fungi. The appearance of cracks in existing masonry columns, walls, and partitions significantly affects the serviceability of the structure as a whole. The main repair methods for such structures are section build-up using reinforced concrete, crack injection using non-shrinkage mortars, or reinforcement with steel casings. It is important to note that these techniques are quite labor-intensive and require the use of a considerable amount of repair materials, namely, steel and concrete.

Researchers [10] have applied TRC using glass textile meshes to reinforce the damaged brick columns by means of a build-up method with a maximum thickness of 8 mm. The results obtained show a high level of efficiency, namely, an increase in the bearing capacity by 1.7–2 times. It is noted that special attention should be paid to the corners of the repaired structure (Figure 6a).

The authors of [11] used fast-hardening fine-grained concrete with a compressive strength at the age of 1 day of 27 MPa and a design strength of 45 MPa at the age of 28 days as the main matrix, with glass fiber meshes as the textile reinforcement. This approach was explained by the accelerated commissioning of the buildings under repair by achieving the design characteristics in the shortest possible time. Two types of single-sided reinforcement were used: the first type was the build-up of a 20-millimeter textile-reinforced concrete monolithic layer, concreted on site; the second type was the use of 20-millimeter textile-reinforced concrete precast slabs, which were recessed into the applied quick-curing concrete. Both methods were effective and increased the compressive strength of the studied masonry by 24% and 30%, respectively.

Other researchers [12] pointed out the need to retrofit brick walls against seismic effects. TRC with carbon, basalt, and glass fibers has been used as a reinforcing material. Flexural strength tests carried out on the reinforced masonry show the positive effects of this technique. Special attention should be paid to the data obtained from the experiment detailed in [13], in which a three-story reinforced concrete frame with masonry partition walls was constructed. The brickwork was reinforced with TRC on the exterior side; then, the structure was subjected to seismic forces. The reinforced sample, which simulated a real three-story building, absorbed a 22% greater seismic load compared to the unreinforced structure. By locally redistributing the load, TRC contributes to maintaining structural integrity, even in the presence of cracks. In conclusion, all authors [10–13] note the need to increase the adhesion strength of TRC to the existing masonry, because once the repair material peels off, its effectiveness decreases dramatically, despite its high physical and mechanical characteristics.

8. Conclusions

This article illustrates that different goals can be achieved with the use of TRC in building and structure restoration. The flat application of TRC on steel-reinforced concrete structures can function as a crack-bridging mineral seal if the design is appropriate. The polarization of the carbon reinforcement in relation to the steel reinforcement in the concrete can provide cathodic corrosion protection or a chloride barrier. In addition, retrofitting the reinforced concrete support structure with textile concrete is possible. TRC is also an effective material for repair work on highways. Furthermore, this composite material is widely used in masonry reinforcement.

The methods presented here are already being implemented in practice and, in some cases, codes of practice or approvals are already available. In any case, there is routine in the experimental characterization of textile concrete, as well as the development of object-
specific solutions. TRC, with its wide range of applications and the possibility of object-specific material adjustments, offers notable solution options, especially for reinforced concrete components that are listed as part of historical monuments.

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