textiles

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Review

Current and Future Trends in Textiles for Concrete Construction Applications

Martin Scheurer [1,*], Danny Friese [2], Paul Penzel [2], Gözdem Dittel [1], Shantanu Bhat [1], Vanessa Overhage [1], Lars Hahn [2], Kira Heins [1], Chokri Cherif [2] and Thomas Gries [1]

[1] Institut für Textiltechnik, RWTH Aachen University, 52074 Aachen, Germany; goezdem.dittel@ita.rwth-aachen.de (G.D.); shantanu.bhat@ita.rwth-aachen.de (S.B.); vanessa.overhage@ita.rwth-aachen.de (V.O.); kira.heins@ita.rwth-aachen.de (K.H.)

[2] Institute of Textile Machinery and High Performance Material Technology, TUD Dresden University of Technology, 01062 Dresden, Germany; danny.friese@tu-dresden.de (D.F.); paul.penzel@tu-dresden.de (P.P.); lars.hahn@tu-dresden.de (L.H.)

* Correspondence: martin.scheurer@ita.rwth-aachen.de

Abstract: Textile-reinforced concrete (TRC) is a composite material consisting of a concrete matrix with a high-performance reinforcement made of technical textiles. TRC offers unique mechanical properties for the construction industry, enabling the construction of lightweight, material-minimized structures with high load-bearing potential. In addition, compared with traditional concrete design, TRC offers unique possibilities to realize free-form, double-curved structures. After more than 20 years of research, TRC is increasingly entering the market, with several demonstrator elements and buildings completed and initial commercialization successfully finished. Nevertheless, research into this highly topical area is still ongoing. In this paper, the authors give an overview of the current and future trends in the research and application of textiles in concrete construction applications. These trends include topics such as maximizing the textile utilization rate by improving the mechanical load-bearing performance (e.g., by adapting bond behavior), increasing design freedom by utilizing novel manufacturing methods (e.g., based on robotics), adding further value to textile reinforcements by the integration of additional functions in smart textile solutions (e.g., in textile sensors), and research into increasing the sustainability of TRC (e.g., using recycled fibers).

Keywords: textile-reinforced concrete; buildtech; composites

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1. Introduction

The construction industry is a very important part of the global economy, making up about 13% of global gross domestic product and employing about 7% of the global working population [1]. At the same time, the construction sector is responsible for about 33% of global energy consumption, about 40% of global raw material consumption, and about 40% of global solid waste generation [2–4]. Therefore, any initiative to reduce global greenhouse gas emissions will have to take the construction sector into account [2].

Megatrends such as increasing global population, increasing urbanization, and increasing amount of used living space per resident lead to a further projected increase in materials and energy used in the construction industry [5]. Continuing construction business as usual may more than double global raw material extraction until 2050 [6,7].

These facts and figures demonstrate the importance of a paradigm shift in the construction industry. While more construction for the increasing global population is inevitable, sustainability concerns need to be addressed swiftly and comprehensibly. Regulators in several countries are planning to or have already introduced measures to limit resource and energy usage in the construction industry [8].

One of the main drivers of greenhouse gas emissions and energy use in the construction industry is the production of ordinary cement, which itself is responsible for about 8%

of global greenhouse gas emissions [9]. Cement is a component of concrete (the other components being water and aggregates, such as sand or gravel). Concrete is the second most used material in the world, only surpassed by water [10]. Concrete has a high compressive strength but low tensile strength. If tensile or bending loads are present, concrete is commonly reinforced, often using steel bars or grids, which carry the tensile load [11]. However, since the steel reinforcement corrodes when in contact with air, a minimum concrete cover is required to protect the steel reinforcement from corrosion [12]. This minimum concrete cover is often thicker than required by the present loads, leading to increased and mechanically redundant material usage [13].

Novel materials with lower energy and material usage as well as lower greenhouse gas emissions are one possibility to reduce the impact of the construction industry. One possible novel material combination, which has been researched since the late 1990s, is textile-reinforced concrete (TRC). In TRC, the steel reinforcement is substituted by a reinforcement made of technical textiles [13]. These textiles are usually made of high-performance materials such as glass or carbon fibers, which do not corrode when in contact with air and therefore enable the reduction in the concrete cover to a minimum [14]. Thereby, TRC enables the construction of lightweight, thin-walled concrete elements, such as bridges [15], precast elements [16–18], and facades [19–21]. Another application of TRC is in the retrofitting of existing concrete structures [22,23]. Another example of the use of TRC is the building "CUBE" in Dresden, Germany, which is the first building constructed entirely from TRC [24].

While TRC is used in more and more industrial applications, as shown above, it is still a highly topical research area. Due to the complex nature of this composite material, research from multiple disciplines, e.g., textile engineering, manufacturing, civil engineering, architecture, etc., is ongoing. Within this paper, the authors aim to provide an overview of currently ongoing research in the area of TRC from the textile and material engineering side. To that end, this paper is split into six chapters, each presenting a highly topical research field in TRC. First, research into improving the mechanical performance of TRC by improving the bond between textile reinforcement and concrete matrix is presented in Section 2. Second, research into increasing the drapability of reinforcement textiles to allow for the production of shaped reinforcements is presented in Section 3. In Section 4, novel manufacturing methods for and with reinforcement textiles are presented, which allow for an increased freedom in design of TRC elements and buildings. In Section 5, research into integration of additional functions for added value of the textile reinforcements is presented. Ongoing research into the ecologic impact of TRC and improvements to the sustainability of TRC are presented in Section 6. Finally, Section 7 gives a short summary and outlook for the presented research.

2. Improving the Mechanical Performance of TRC

The bond between the textile reinforcement and the concrete matrix is a key factor influencing the macroscopic mechanical behavior of the TRC composite [25–27]. In traditional steel-reinforced concrete (SRC), the load is induced into the isotropic, solid steel reinforcement via mechanical interlocking achieved by surface profiling [28]. Since the textile reinforcement does not consist of a singular, solid material but of hundreds to tens of thousands of individual, anisotropic filaments, load induction in TRC differs greatly from that in SRC [29]. Since the individual filaments have diameters below 30 µm, the concrete matrix with aggregate sizes that are at least an order of magnitude larger cannot penetrate into the space in between the individual filaments of the roving. Therefore, only the outermost filaments are in direct contact with the concrete and any load is only directly induced into these filaments. The inner filaments of the roving are only loaded by friction, leading to low utilization of these filaments and to early pull-out failure of the TRC bond. To improve the bond, textiles are usually impregnated with a polymeric material, which transfers the load into the inner filaments of the roving. This greatly improves the utilization of the rovings, leading to higher bond performance and therefore to better mechanical properties of the TRC composite [14]. This bond behavior of TRC is illustrated in Figure 1 below. Common polymers for the impregnation of TRC are epoxy resins as well as styrene–butadiene–rubber and acrylates [14,30].

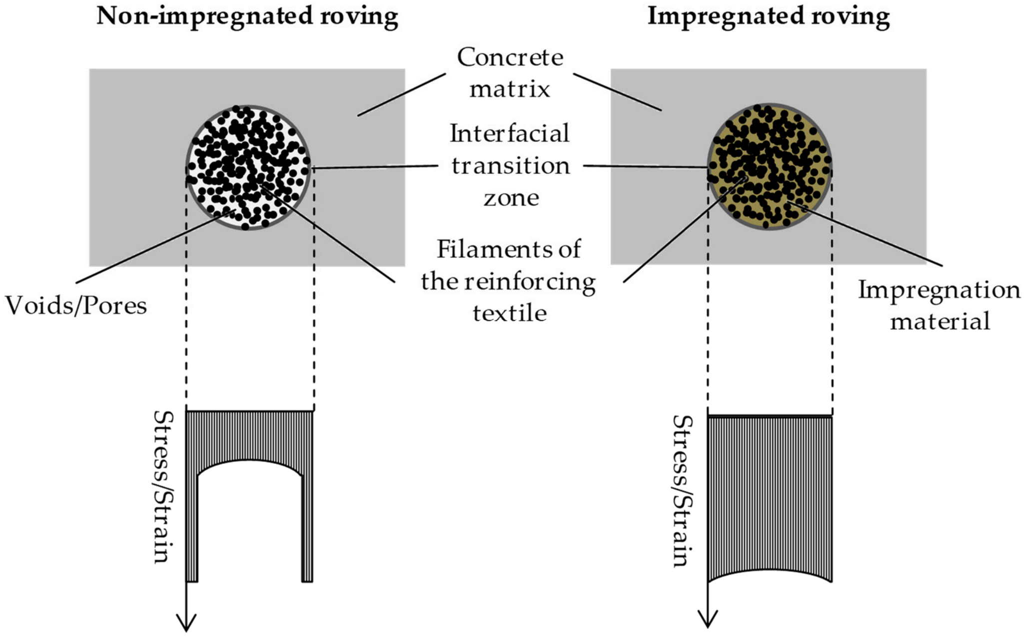


Figure 1. Schematic illustration of the bond of nonimpregnated and impregnated rovings in concrete, based on [14,31].

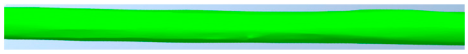
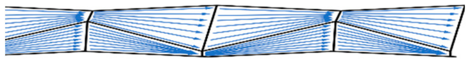
Due to the high material costs of textile reinforcements compared with steel reinforcements, especially if carbon fibers are used, maximizing the utilization of the reinforcement material is key to the economic viability of TRC. Therefore, improving bond strength and mechanical performance is a key area of research in TRC. Various different approaches to improve the bond strength exist and are illustrated and explained below.

2.1. Surface Profiling of Textile Reinforcements

A promising approach for improving the mechanical performance of TRC by creating a dominant shear bond is the profiling of the reinforcement structure. For rigid fiber-reinforced plastic (FRP) rebars with large cross-sections, additive and subtractive profiling methods are established, such as additive wrapping of an additional helix structure, the application of anchoring structures such as plastic ribs, or the subtractive milling of a rib-like structure [32–34]. Decisive for the effectiveness of the form fit is its durability, as well as the (composite) strength between roving and cover/anchoring [35,36]. In particular, when transmitting high bond forces, the material connection usually fails, which results in the pull-out of the roving [33,35,36]. Another disadvantage is the additional process and material usage required by the application. Moreover, such additive or subtractive methods are unsuitable for thin roving structures made of multifilament yarns (e.g., 48K filaments or 3200 tex carbon fiber) for grid-like reinforcements produced with the highly productive multiaxial warp knitting technique.

Novel technologies for the reproducible and continuous production of bond-optimized profiled rovings for concrete applications were developed at the Institute of Textile Machinery and High-Performance Material Technology (ITM) of the TU Dresden on the basis of braiding and shaping technology (see Table 1). The 3200 tex carbon fiber type Teijin Tenax-E STS 40 F13 48K (Teijin Carbon Europe GmbH, Wuppertal, Germany) and a polymer impregnation TECOSIT CC 1000 (CHT Germany GmbH, Tübingen, Germany) with a resulting mass content of about 22% were used for the production of the novel rovings.

Table 1. Comparison of unprofiled and profiled reinforcement yarns (3200 tex carbon fiber with polymer impregnation Tecosit CC 1000 at approx. 22% mass content) [37].

Yarn Type	Illustration	Scheme
Unprofiled roving		
Profiled roving		
Braided roving		
	20 mm	

The novel profiled rovings are able to transmit significantly higher bond forces in concrete, with up to 500% higher bond strength compared with unprofiled rovings (100 N/mm compared with 20 N/mm). Yet they maintain high tensile properties and minimal structural elongation [38–40]. The significant improvement of the mechanical properties is realized through a dominant form-fitting effect between the reinforcement roving and the surrounding concrete matrix, on the basis of a stiff and symmetrical roving surface profile in order to enable a constant and high bond force transmission. A major prerequisite for the use of textile reinforcements in concrete is a minimal structural elongation, so that an initial force transmission between reinforcement and concrete is possible and the composite crack widths (durability) and deflection (functionality) under load are minimized when the concrete matrix fails at approx. 0.2% strain [41,42].

In order to produce braided roving with a defined surface profile and minimal structural elongation, the braiding technology was further developed to enable low undulation and prestabilization of the braided roving structure (made of 4 × 800 tex carbon fibers) during the braiding process, while still ensuring further textile processing. In particular, the braiding technology was extended by an inline impregnation and consolidation process with defined pre-extension of the braided roving, resulting in an outstretched and prestabilized roving structure with enough flexibility to be winded on common 84 mm spools.

Rovings with a defined and patented tetrahedral profile [43] are created by shaping the polymer-impregnated multifilament yarn (3200 tex carbon fiber) inbetween interlocking profile tools. The profile geometry is permanently stabilized through the consolidation of the roving by infrared radiation (IR) during the shaping process. This technique enables the production of profiled rovings with different profile characteristics and defined bond behavior in dependence on the profile parameters, such as profile depth, length, period, etc. [38,39]. In contrast to additive or subtractive methods, the shaping of impregnated rovings allows a rearrangement of the single filaments without an interruption of the filament course, resulting in a uniform filament arrangement along the longitudinal yarn axis and a therefore high utilization of the tensile properties.

The novel profiled rovings are characterized by up to 500% higher bond properties (100 N/mm bond strength) compared with carbon rovings without profile (20 N/mm bond strength) and the highest tensile properties without any noticeable structural elongation (see Figure 2). Additionally, the profiled rovings show a very high bond stiffness and full anchoring at a bond length of only 50 mm, which is of particular interest for an initial force transmission and high material efficiency [37].

For the production of grid-like reinforcement structures made of profiled rovings, the multiaxial warp knitting technology can be used. Due to the increased rigidity of the profiled rovings, minor modular modifications of the yarn feeding, weft yarn insertion, knitting process, impregnation, and winding are required. The weft thread laying process in particular has to be modified. For the laying of the prestabilized braided rovings, a newly developed weft thread guide with increased radii and openings is used. The tetrahedral profiled rovings with increased rigidity need a rod placement system, because they cannot be processed using the conventional weft laying process. Hereby, precut rods are inserted individually by the rod placement system into a continuous transport chain. For secure and precise transport of the rods, modified fixing elements are used. For the gentle and endless thread feeding in warp direction, strong thread guides with increased openings are used. Narrow radii are avoided, and the textile is winded on coils with big diameters (ca. 80 cm). During textile processing, the prestabilized braided rovings are impregnated and consolidated after the warp knitting process. The rigid profiled rovings do not require any further impregnation [37].

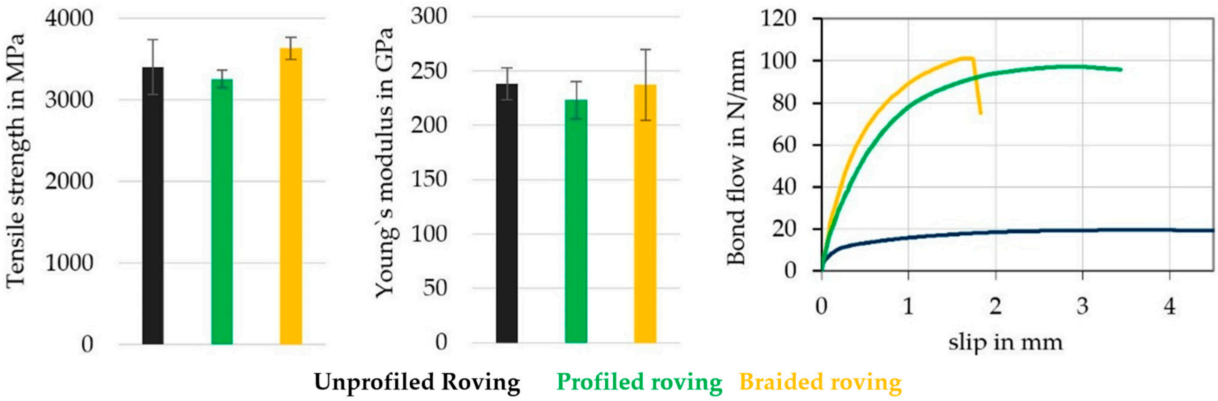


Figure 2. Tensile properties and bond flow–slip relationship (in concrete) of unprofiled and profiled rovings (3200 tex carbon fiber with polymer impregnation) [37].

2.2. *Preimpregnated Textile Reinforcement Cured in Concrete*

Textiles impregnated with reaction resins that are not fully cured are commonly referred to as prepregs. Such prepregs are often used in the aerospace industry, since they allow for high fiber volume content of up to 60%, high mechanical performance, and high component quality [44]. Prepregs are usually impregnated with thermoset resins at one location and stored and transported frozen until they are processed into the final component at another location [44]. This approach can be directly adapted to TRC, placing preimpregnated but uncured prepregs within the concrete matrix and only curing them after the concreting process is completed [45,46]. The uncured state of the impregnation enables an intermingling of polymer impregnation and concrete matrix in the interfacial transition zone, as illustrated in Figure 3 below.

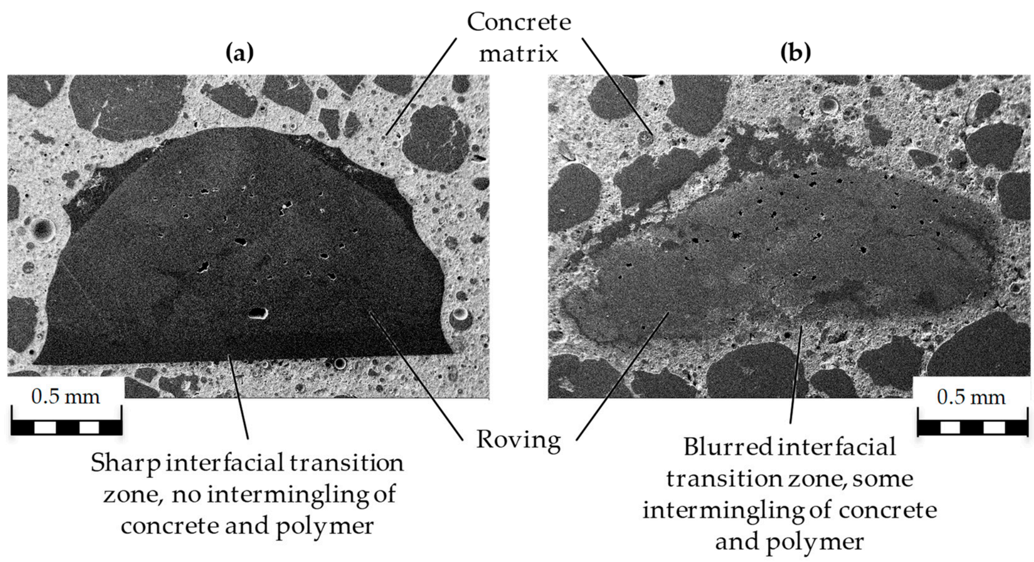


Figure 3. Microscopy images of rovings placed within the concrete matrix: (**a**) Roving cured prior to insertion into concrete. (**b**) Roving cured within the concrete matrix.

While initial results show that prepregs enable similar pull-out forces in concrete as cured epoxy resin-impregnated textiles [45], further analysis indicates that improvements in mechanical performance are highly dependent on the specific impregnation material used for preimpregnation [47]. For various materials, the alkaline and wet environment of the concrete matrix inhibits the curing reaction, leading to lower mechanical performance compared with traditionally cured specimens [47].

Further research into this novel approach is necessary to realize the potential gains in bond performance. The main avenues of research are in the selection of suitable preimpregnation materials and in controlling the curing process within the concrete matrix, for example, by heating the carbon fibers of the prepreg [48].

2.3. Textile Reinforcements Based on Spread Rovings

As explained above and shown in Figure 1, in nonimpregnated textiles, only the outermost filaments of a roving are in direct contact with the concrete matrix, and therefore, the load is only induced directly into these filaments. The amount of filaments in direct contact with concrete depends on various factors, for example, the diameter of the filaments and the minimal aggregate size of the concrete mixture [49]. A promising approach to increase the amount of filaments in direct contact with the concrete matrix is by changing the shape of the roving. As illustrated in Figure 4, by increasing the eccentricity of the roving cross section, more filaments are in direct contact with the concrete matrix.

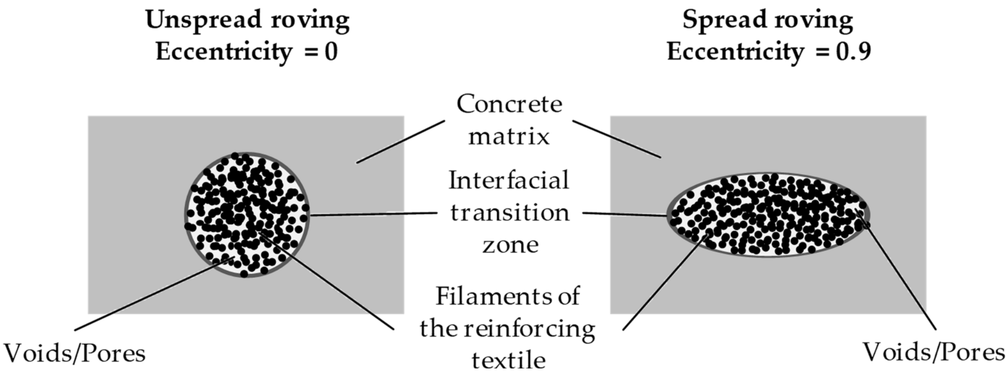


Figure 4. Illustration of the principle of spread rovings to increase the amount of filaments in direct contact with the concrete matrix.

Several approaches for spreading the rovings in TRC to increase the eccentricity of the roving cross-section have been researched. Janetzko et al. used air jet texturing to open alkaline resistant glass rovings, which were then processed into 2D noncrimp fabrics, more than tripling maximum pull-out stresses (from about 300 N/mm^2 to more than 1000 N/mm^2) and increasing the maximum load bearing of TRC elements by about 40% (from 420 N/mm^2 to 570 N/mm^2) [50]. Perry et al. as well as Quadflieg et al. used variations in the stitch pattern during the production of biaxial noncrimp fabrics to influence the shape of the rovings [51,52]. Both reported higher mechanical performance of more eccentric rovings shapes for nonimpregnated textiles [51,52]. Taking the approach of increasing the eccentricity of the roving to its extreme, tapes enable the spreading of the rovings until nearly all filaments are aligned in parallel. Initial research into this approach shows that load bearing, measured in flexural TRC tests, can be increased by up to 125% (from 8.67 MPa to 19.52 MPa) compared with unspread reference rovings [53].

Tapes offer a promising alternative as local reinforcement in concrete elements with high loads and as reinforcement in novel manufacturing methods, such as concrete extrusion or additive manufacturing of concrete. However, only initial research has been performed, and a complete characterization and modeling of tape reinforcement as well as processing methods for tape-reinforced concrete are still lacking and subject to further research and development.

2.4. Mineral-Impregnated Textile Reinforcements

As discussed above, the main purpose of the impregnation material is to penetrate in between the closely packed filaments of the reinforcement textile to fill voids/pores and to facilitate the load induction into all filaments of the reinforcement. Due to their processing properties, especially comparatively low viscosity and particle size, polymers are very well suited for this purpose. However, the use of polymers in mineral matrices such as concrete leads to several challenges: degradation due to the alkaline matrix must be avoided, recycling/disposal can be difficult since the addition of polymers changes the classification of waste materials, and polymers degrade at higher temperatures, for example, during a fire, leading to safety issues in construction applications. One possibility to avoid these challenges is to omit the polymer impregnation and replace it by an impregnation with a mineral material. The use of mineral impregnation materials is in idea and application very similar to the conventional polymer coatings. Figure 5 illustrates this similarity.

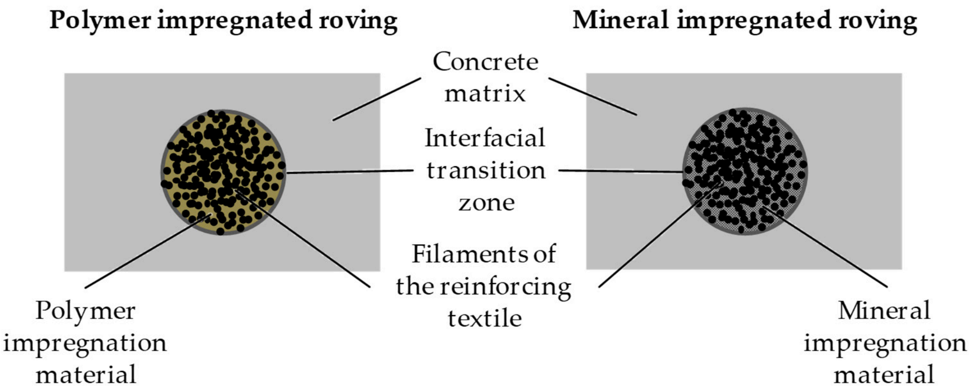


Figure 5. Illustration of the similarity of polymer- and mineral-impregnated rovings as reinforcement for concrete.

One important factor for the mineral impregnation of textile reinforcements for concrete is the size of the particles of the impregnation material. Since carbon fibers have a filament diameter of about 7 µm and AR-glass fibers have a filament diameter of about 20 µm, the particles of the mineral impregnation need to be sufficiently fine to penetrate the spaces in between the filaments. Cohen and Peled analyzed two silica fumes with particle sizes of 200 nm and 50 nm, respectively, and used these to impregnate an AR-glass textile, reporting the highest mechanical performance using the 200 nm silica fume, since the smaller particles agglomerated quickly during the impregnation process [54]. Dvorkin and Peled used similar silica filler for carbon fiber textiles, reporting increases in mechanical performance compared with nonimpregnated textiles [55]. Nadiv et al. analyzed alumosilicate and silica fillers and achieved similar results [56,57]. Signorini et al. used the sol–gel method to coat AR-glass and carbon fabrics with silica particles and reported significant improvements in mechanical performance compared with uncoated fabrics [58]. Schneider et al. combined the mineral impregnation with a plasma treatment of the carbon fiber to further improve the bond strength, reporting increased pull-out strength for all types of plasma treatment [59].

The suspected advantage of mineral impregnation materials compared with polymer impregnation materials at high temperatures has also been subject to study. Schneider et al. compared mineral-impregnated carbon fiber reinforcement with polymer-impregnated carbon fiber reinforcement, showing higher mechanical performance measured in pull-out stresses for mineral impregnation at the elevated temperatures of 100 °C and 200 °C [60]. Similarly, Silva et al. report the sufficient bond of mineral-impregnated carbon fibers at temperatures up to 300 °C [61].

The advantages of mineral-based impregnation materials have been demonstrated in several research projects, a few of which are outlined above. However, the processing of the mineral impregnation to prevent agglomeration of the small particles is more complex than the processing of polymers, and the final processing of the impregnation step (getting the material into the fibers) is very complex due to the higher viscosity of the mineral impregnation. Therefore, research and development into this promising class of impregnation material is still ongoing.

3. Improving Drapability of Reinforcement Textiles

Three-dimensional reinforcement cages are required for the realization of three-dimensional building components in both structural and architectural areas. With conventional steel reinforcement, these can be realized comparatively easily by cold or hot forming of the reinforcement, for example, on presses or automatic bending machines [62,63]. The same need also exists for the production of textile-reinforced concrete elements. Here, the drapability of the textile plays an important role in the realization of these three-dimensional reinforcement components [64]. Drapability describes the possibility to transform planar two-dimensional textiles into three-dimensional geometries [65].

Unimpregnated textile reinforcement systems usually have high drapability. It is influenced by the textile architecture, i.e., the type of binding in the stitch thread, its tension, and the compactness of the rovings [66]. The currently used reinforcements require, as described above, the use of an impregnation in order to improve the efficiency of the load transfer in the interior and thus the mechanical performance of the composite material. The currently used impregnation materials such as epoxy resins or aqueous polymer dispersions lead to higher mechanical properties but limit the drapability of the reinforcements due to their chemical cross-linking behavior. As a rule, this produces reinforcements which, in the form of stiff plates or large rolls, are not able to map three-dimensional structures at all or only in large radii of curvature. Since impregnation with regard to mechanical performance cannot be dispensed with, approaches are currently being investigated to increase the drapability of the reinforcements through the development of new material systems and processes without compromising strength [64,67]. Three of these research approaches are briefly described below.

3.1. Adapting the Textile Structure of the Reinforcement Textile

In the future, TRC could be increasingly used in the form of double-curved concrete elements with the aim of producing filigree yet load-bearing concrete shell structures. To assess whether a textile is suitable as a reinforcement structure in double-curved textile concrete elements, numerous properties need to be investigated and evaluated. The most important of these include good handling properties, bending stiffness tailored to the application, sufficiently pronounced mesh openings, and defect-free drapability. In the course of research work carried out at ITA, biaxially reinforced knitted fabrics (basic elements shown in Figure 6) with five different binding types (pillar open, pillar closed, tricot counterlaid, tricot closed, and plain) were investigated to evaluate the aforementioned properties. The aim of the drape test is to measure and evaluate the drape behavior of textiles with regard to the deformation mechanisms and drape effects. Draping effects (see Figure 6) that occur within the textile surface result mainly from the unavoidable fiber displacements during draping [68]. Undulations, loops, gaps, and folds are the common drape effects which were evaluated.

The draping tests were conducted on a robot-controlled draping test apparatus developed at ITA and evaluated with the aid of an optical measuring system. In addition, the geometric relationship between surface curvature of the double-curved elements and the shear angle of different textiles was used to classify the influence of the stitch type on the drapability. The type of binding significantly influences the magnitude and distribution of local shear angles. The formation of drape defects is influenced by the knitted yarn characteristic of a binding type and the associated restricted freedom of movement of the rovings. At almost 40°, the open pillar binding exhibited the highest shear angle formation and thus the smallest lattice openings. The tricot closed and plain binding types showed pronounced wrinkling and are thus unsuitable as textile reinforcement in components with similar geometry. An almost faultless drapability on a hemispherical drape form could be achieved in the specimens with the pillar and tricot binding types in opposite directions. In the table below, the requirements for textile reinforcement are listed, based on which the suitability of textiles as reinforcement structures is evaluated (see Table 2). These categories are selected from the perspective of a precast factory and the quality standards to be fulfilled for the TRC panels [69].

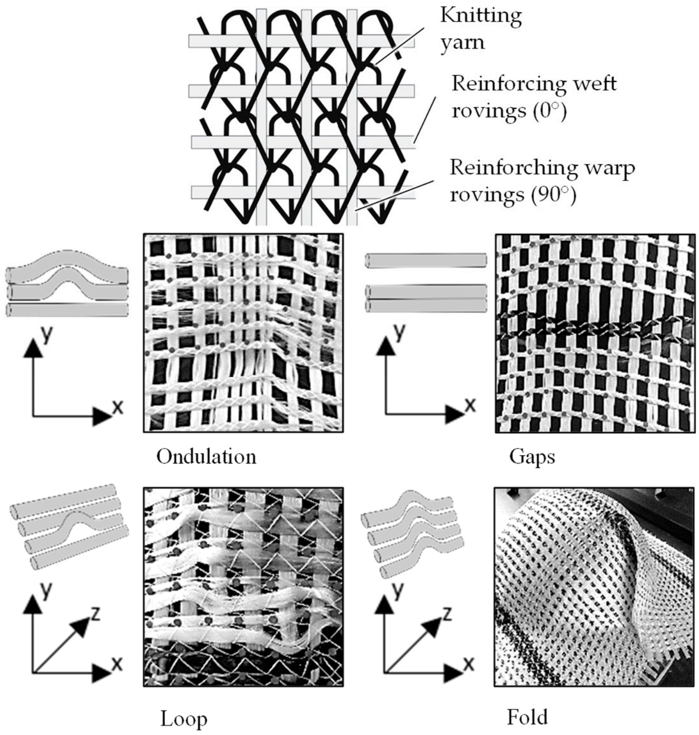


Figure 6. Drape effects occurring in open-meshed textile reinforcements.

Table 2. Ratings of different textile stitch patterns in regard to drapability (PO—illar open, PC—Pillar closed, TG- Tricot counterlaid, TC—Tricot closed, P—Plain).

	PO	**PC**	**TG**	**TC**	**P**
Handling	◕	◕	◕	◔	◔
Shape deviation	◕	◕	◕	●	●
Mesh opening	◕	●	◕	◔	◕
Drape quality	◕	◕	◕	○	○
Fulfillment (%)	75	**88**	75	38	50
○ Unsuitable	◕ Rather suitable				
◔ Rather unsuitable	● Suitable				

An optical evaluation is undertaken to determine the correlations between shear angle and drape defects. Figure 7 shows the frequencies of the occurring draping errors for the five specimens for each binding type.

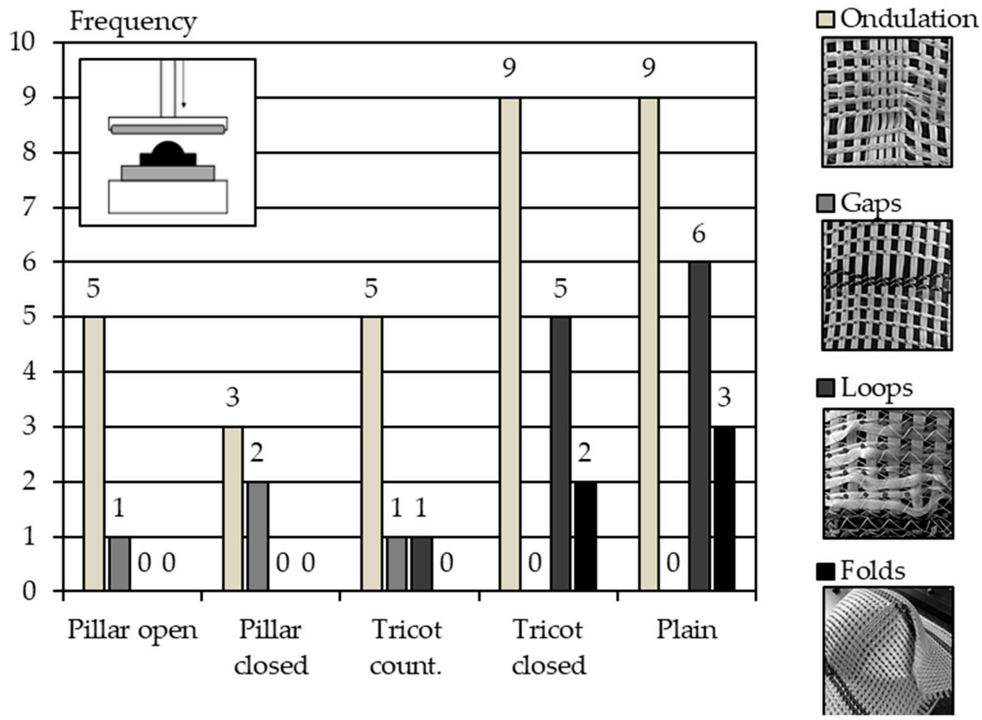


Figure 7. Overview of optical evaluation of drape.

The following statements can be drawn from the optical evaluation [70]:

- The binding type significantly influences the formation of the various draping effects.
- The tricot closed and plain binding types show more or less pronounced wrinkling, which reduces the drape quality.
- Cross-connections of the rovings in the tricot closed and plain binding types prevent roving displacement parallel to the warp direction.
- Both pillar binding types can be draped almost faultlessly.

With regard to the future research prospects, numerous questions remain open. There are other influencing textile parameters whose effects on drapability of textiles must be investigated in future work. The most prominent of these are the fineness of the roving, the draw-in, and the mesh opening size. Furthermore, the warp knitting yarn tensions of the individual binding types, which differ due to the different addition speed of the warp knitting yarn during the manufacturing process, must be investigated in more detail. The knitted yarn tension represents a significant influencing factor on the shear angle distribution. Textile orientation and test direction could also provide significant differences in terms of drape results. The decision of the direction in which to drape the textiles is likely to have a more or less pronounced influence on drapability due to the different bending stiffnesses of the top and bottom sides.

Alongside the drape errors, which have a significant influence on the mechanical properties of the component, the influence of a stronger shear angle formation on the force flow in the concrete part must also be taken into account in future investigations. Only in this way can isotropic and anisotropic shear distributions be evaluated in terms of their influence on the load-bearing behavior.

In the production of double-curved components, alternative manufacturing options must be investigated due to the limited application possibilities of the laminating process. On the one hand, the casting process with coated textiles and, on the other hand, the manufacture of such components using adaptive formwork with both coated and uncoated textiles come into question.

3.2. Thermoset Preimpregnated Textile Reinforcements

The use of thermoset preimpregnated but not fully cured textiles as a semifinished material is common in fiber-reinforced polymer composites, e.g., for the aerospace or automotive industry [71]. The main advantage of the use of this so-called prepreg approach is that the preparation of the preimpregnated textile can be carried out by a specialized manufacturer, while the final shaping and curing of the desired component can be performed at the final production plant. The common process steps in prepregs are outlined in Figure 8 below.

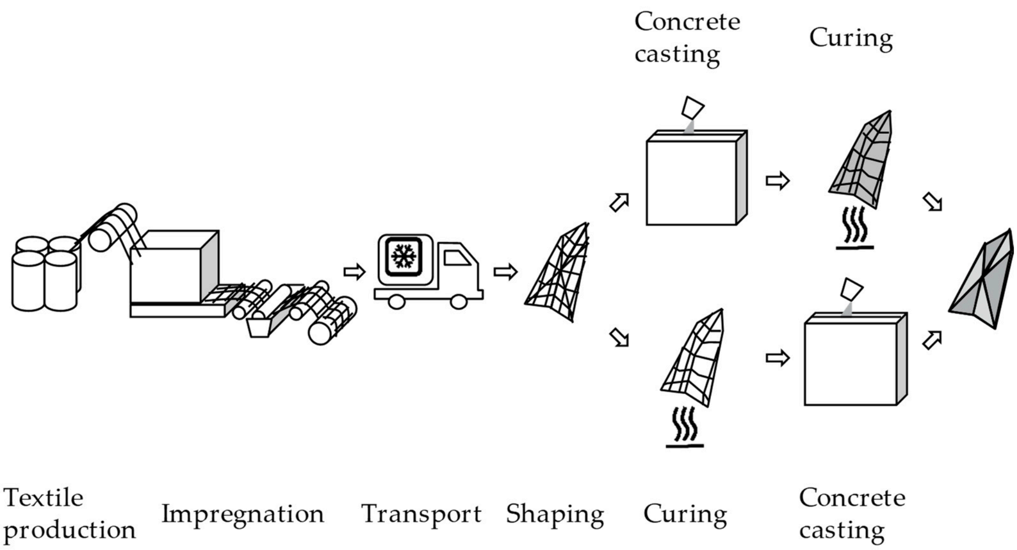


Figure 8. Schematic of the production chain for prepreg-reinforced concrete elements.

This approach can be transferred to the construction industry, enabling greater flexibility in design and manufacturing. As described above, currently, impregnated textiles for the reinforcement of concrete are delivered in a fully cured state, drastically limiting the shapeability of the textiles. Therefore, complex shapes (e.g., double-curved designs or reinforcement cages) need to be prepared prior to the delivery of the textile reinforcement to the construction site or plant, drastically increasing transport volume and costs and limiting design freedom. With the prepreg approach, suitable prepregs could be delivered to the construction site on rolls, minimizing transport volume and costs. After delivery, the reinforcement textiles could then be shaped and finally cured according to the project requirements. Two types of curing at the construction site are possible: In the first approach, the reinforcement is shaped at the construction site, then cured, and afterwards placed within the concrete matrix. In the second approach, the process steps are run in parallel, and the reinforcement is placed within the fresh concrete matrix and cured within the concrete during the hydration of the concrete matrix.

In theory, the common curing methods for fiber-reinforced polymer composite prepregs using autoclaves or ovens can be transferred to the use in the construction industry. However, this approach is not very economical or ecological, since it would require large ovens at the construction site or plant to heat the reinforcing cages. If the curing is performed within the concrete matrix, this approach would also require the heating of the whole concrete element, requiring a lot of energy and possibly influencing the concrete hydration reaction [72,73]. Therefore, alternative curing methods that enable a comparatively easy curing of large-scale elements on site, preferably by only heating the reinforcement within the concrete matrix, are needed. Several approaches are currently being investigated, such as Joule heating or inductive heating of a carbon fiber reinforcement [74], UV curing of glass fiber reinforcements, and other methods. However, all these approaches are currently being researched at a basic level and require further research and investigation from different disciplines, e.g., textile engineering, process engineering, civil engineering, etc.

3.3. Thermoplastic-Impregnated Textile Reinforcements

The aim of this approach is to exploit the thermal softening properties of thermoplastic polymers to realize a universally applicable textile reinforcement for the implementation of individually shaped concrete components. For this purpose, a thermoplastic impregnation, for example, based on polystyrene or polyacrylate, is applied to the textile. The impregnation is carried out in an immersion bath process, which can be connected directly inline to the textile production or carried out separately. The textile is immersed in a bath of impregnation. The excess material is then squeezed off before the solvent is evaporated, and the impregnation is then consolidated at an elevated temperature. Heins et al. showed that these thermoplastic impregnation materials in the reinforcement system are in no way inferior to the mechanical performance of the epoxy resin impregnation customary on the market and even exceed that of SBR [75].

The textile reinforcement is delivered to the precast concrete plant in the form of plates or on rolls. Here, the reinforcement can be shaped according to the product and requirements. In terms of shaping, a distinction must be made between single- and multiple-curved structures, closed structures in the style of winding, and global double-curved structures. For the first two applications, universal shaping tools can be used. The bending is implemented in such a way that the workpiece is first fed to the shaping unit. There, a heating system heats the bending zone to temperatures above the glass transition temperature. This softens the polymer so that the polymer chains become mobile. During the bending process, the impregnation does not resist the movement and flows with it. After the bending is completed, the reinforcement solidifies in the new shape. In this way, there is still a complete adhesive bond in the bend. The shaping can be repeated as often as desired with suitable process settings (temperature and dwell time). To simplify the special case of winding structures, the winding can be carried out on a core instead of a successive execution of the bends. A schematic representation of the production chain for TRC elements with thermoplastic impregnation materials is given in Figure 9 below.

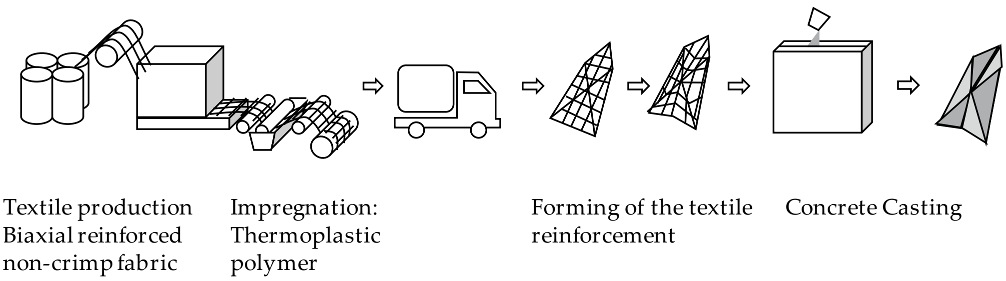


Figure 9. Schematic of the production chain for concrete elements with thermoplastic-impregnated hot formable textile reinforcements.

Based on the current state of research into the mechanical performance of thermoplastic-impregnated textile reinforcement, the following research and development tasks are to be fulfilled: the development of an automated and standardized shaping tool, including a system of process and quality control; research into composite behavior, especially with regard to durability and behavior under elevated temperature; and investigation of the socioecological effect of the reinforcement.

4. Novel Manufacturing Methods

The combination of new materials and novel manufacturing processes can be the key to new environmental designs and resource-saving types of construction [74,76,77]. The potential of textile-reinforced concrete is demonstrated by its ability to produce geometrically demanding, branched, and complex topologies [74]. For three-dimensional (and internally branching) textile reinforcements, conventional textile manufacturing processes do not offer the variability of the machine technology to produce these textile structures without costly machine and process modifications, reworking, and significant material waste [31]. Traditional textile reinforcement manufacturing techniques, such as multi-axial warp knitting technology, which is capable of producing grid-like reinforcements with high productivity, reach their limits in terms of manufacturing geometry. Additional process steps (e.g., cutting and stacking) are necessary to obtain the final near-net-shape geometry. New technological and conceptual approaches, for example, using industrial robots, adaptive molds, additive manufacturing processes, or tailored fiber placement technology, are powerful tools to implement new, material-minimized design principles in the construction industry in order to produce textile reinforcement structures free of cuts for concrete applications (e.g., TRC components) [76,78].

4.1. Robot-Based Manufacturing Methods for Reinforcement Textiles

Robot-supported manufacturing technologies enable the production of resource-saving and cost-efficient but also freely formable and arbitrarily designable textile reinforcement structures for concrete constructions. These promising technologies are based on industrial six-axis robots, which are highly versatile machines that can be programmed to perform various tasks in manufacturing and other industries. They are capable of precise and repetitive movements, making them ideal for tasks that require speed, accuracy, and consistency. Industrial robots can also operate without fatigue and in hazardous environments or perform tasks that are too dangerous for humans. A six-axis industrial robot has six degrees of freedom, allowing the robot to perform translational (X, Y, Z) and rotational (A, B, C) movements. This allows the robot to work in three dimensions and move its tools to any position within its reach, enabling the on-demand creation of free-form textile reinforcement structures. Six-axis robots are widely used in the automotive, electronics, and aerospace industries due to their beneficial properties such as productivity, increases in quality from high-precision and high-repetition accuracy, variable adaptability, and reduced labor costs by replacing humans with robots. Thanks to their highly variable movement capabilities, they are also able to manipulate yarn-guiding tools in order to deposit the yarn, for instance, on a yarn fixation rack, on winding cores, or simply free in space. For this purpose, carbon fiber heavy tows (CFHT) Tenax-E STS 40 E23 48K (Teijin Carbon Europe GmbH, Wuppertal, Germany) with a fineness of about 3200 tex are often used to efficiently manufacture the nonmetallic reinforcement structures [79].

To pave the way for novel resource-saving and cost-efficient textile reinforcement structures, researchers have developed distinctive robot-based machine technologies. Several robotic yarn deposition technologies already exist or are currently being developed for the production of textile reinforcement structures for the construction industry or fiber-reinforced plastics for the composites market. All robotic manufacturing technologies consist of several functional modules, namely the manipulating robot, the yarn deposition tool—which performs the function of storing, guiding, and impregnating the yarn—and the workpiece carrier, which is used to temporarily fix the reinforcement structure. However, they all differ in their mode of operation. There are robotic manufacturing processes that have been developed to meet the needs of the construction industry (focusing on the reinforcement of concrete components) and those that have emerged from other industries (e.g., architecture or automotive). Basically, there are different ways to produce textile reinforcement structures—either by manipulating the yarn placement tool, where the workpiece carrier is fixed, or by moving the workpiece carrier while the yarn placement tool stands still, as in the winding, using a winding core [80,81]. Figure 10a,b show the two basic process principles of robotic yarn deposition technologies, where a single robot moves either the tool or the workpiece carrier. Collaboratively used robot systems consist of various six-axis robots and, in some cases, of additional unmanned aerial vehicles (UAVs) and climbing robots, as in the translational cross-winding technique or the filament-winding technique by means of UAVs [82,83]. They are also being used to produce large-scale shell elements with membranous outer appearance exclusively using both preimpregnated and freshly impregnated rovings [83,84].

4.1.1. Process Principle A

The technological design by von Zuben et al. is shown in Figure 10a using freshly impregnated carbon fiber heavy tows ((CFHTs), used here is a roving Tenax-E STS 40 E23 48K from Teijin company, and the matrix is Biresin CR84/CH120-6 from SIKA company)—the yarn spool and the impregnation unit are both manipulated by the robot—for the production of planar and lattice-like reinforcement structures [15]. Here, yarn impregnation is only performed immediately prior to yarn deposition. The operation consists of the robot manipulating the yarn deposition tool. The workpiece carrier is fixed. Von Zuben et al. focus on the use of conventional epoxy resin as an impregnation agent; so, the plant technology is also designed for this two-component resin system [85]. This manufacturing principle can already be used to produce planar 2D reinforcement structures with cut-free geometries.

4.1.2. Process Principle B

Another technological approach, shown in Figure 10b, is the winding technique using a winding core. The workpiece carrier is manipulated by the robot arm, while the yarn tool is stationary on the floor [86]. An impregnation bath with a yarn eye for precise deposition can be used as the yarn tool. Michel et al. used a mineral impregnation of the carbon fibers. Due to the homogeneity of the mineral material, a high bond to the concrete is achieved, and the roving can be processed flexibly within a process window of four hours after impregnation [60]. Alternatively, preimpregnated CFHTs can be used to produce extremely lightweight reinforcement structures with graded fiber distribution, such as a reinforcing cage for a balcony [81].

4.1.3. Process Principle C

The 3D coreless filament winding technology with two cooperating robots by Minsch et al., shown in Figure 10c, is another production technology being developed [87]. The 3D coreless filament winding uses a translational cross-winding technique to produce truss-like structures. The yarn impregnation process is conducted off the robotic manipulation on a fixed impregnation unit. The freshly impregnated carbon fiber yarn is delivered directly afterwards to the filament winding tube. The yarn is a Toray T620SC-24000-50C roving (CFHT) in combination with epoxy resin Hexion MGS LR385 and hardener LH 386. The robot simply manipulates the freely fed yarn using a yarn guide tube, as the impregnation tool is stationary on the floor and the yarn is therefore impregnated outside the robot handling process. This technology was originally developed in response to the challenge of providing lightweight materials for energy-reduced manufacturing processes in the automotive industry.

4.1.4. Process Principle D

A fourth robot-assisted technology for direct yarn deposition is shown in Figure 10d with the collaboratively working multirobot system by Knippers et al. [88,89]. This robotic system uses robotic systems consisting of six-axis robots, UAVs, and optionally, climbing robots [83,90]. The workpiece carrier is fixed, and the individual robots manipulate the preimpregnated yarn. The yarn impregnation tool is also stationary. In a different application, where the textile topology is more complex or the deposition process requires additional degrees of freedom, Knippers et al. use a rotating, single-axis workpiece carrier to provide additional uniaxial motion [91].

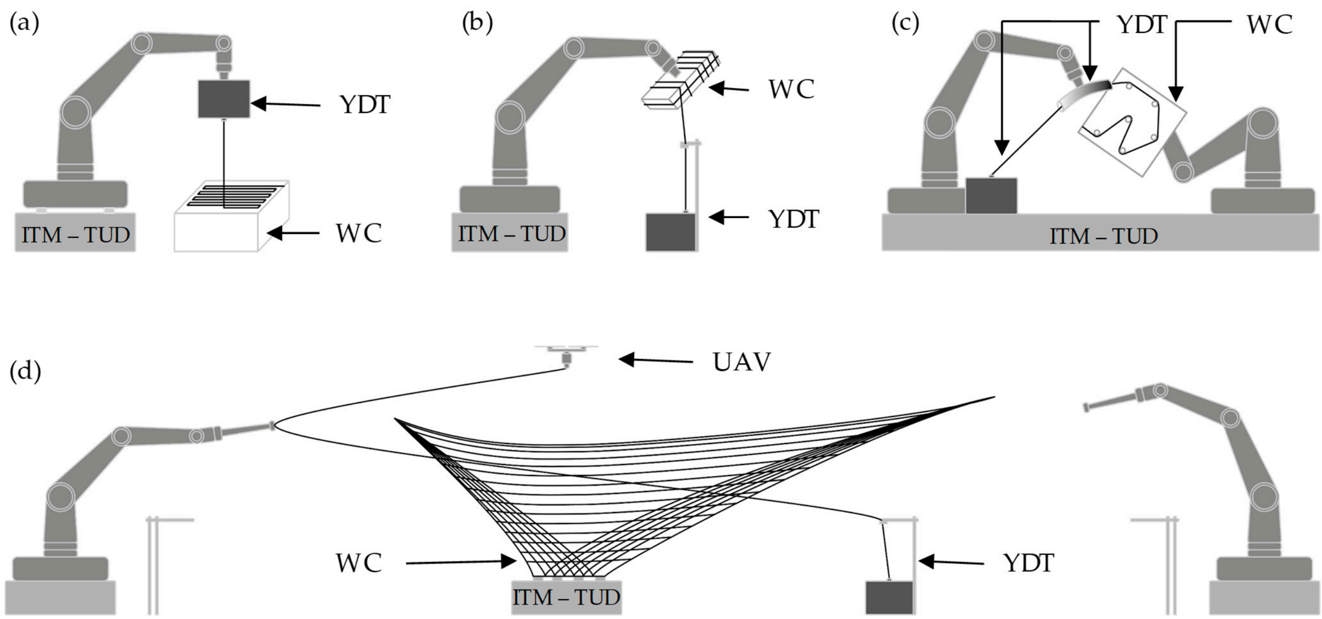


Figure 10. Robot-assisted yarn deposition principles: (**a**)—process principle A; (**b**)—process principle B; (**c**)—process principle C; (**d**)—process principle D; WC = workpiece carrier, YDT = yarn deposition tool, UAV = unmanned aerial vehicle [80,81,83,87,89,92,93].

The ability to produce planar and grid-like two-dimensional textile reinforcements, as well as complex hierarchical and internally branched three-dimensional textile reinforcement structures, is the main advantage of the presented robotic manufacturing technologies [76,85,88]. Thus, one-dimensional structures as reinforcement bars (rebars), simple two-dimensional structures as grid-like reinforcement mats, and even more sophisticated three-dimensional textile reinforcement structures with spatial branchings and load-adapted fiber orientations such as reinforcement cages or bionic reinforcement topologies for pillars can be provided by these robot-based manufacturing technologies [14].

4.1.5. Future Process Principle E

A technological outlook is represented by the novel robotic manufacturing process with a robotic yarn impregnation and an intelligent yarn fixation module in Figure 11, which will be implemented in the near future. The yarn impregnation module consists of several submodules, which are mounted at different points of the robot. The impregnation material storage and their feed pumps are designed as a kind of backpack solution. They are mounted on the main axis (axis 1). The yarn spool, the piston rod cylinder for regulating the yarn tension, and the mixing chamber are mounted on the robot's swivel arm. Here, various impregnation agents as two-component polymer systems and aqueous water dispersions are supposed to be homogenized. In the future, it should also be possible to process photopolymers with this impregnation module. The yarn fixation module, controlled by the higher-level programmable logic controller, is located within reach of the robot arm. The controller of the yarn fixation module interacts with the robot controller via a PROFIBUS interface. This allows the recipe sequence of the fixation module to be matched to the generated winding paths. The 3D yarn fixation module is integrated into a robotic system that consists of a protective robot cell and the industrial robot with the yarn impregnation tool attached to it. The geometrical dimensions of the yarn fixation module allow the realization of proper textile reinforcement structures for the construction industry. To ensure geometric accessibility of the yarn fixation module by the robot-guided yarn tool without collision, the individually controllable support rods can only be extended when necessary for the yarn placement process. In this way, the fixation module provides supporting points in space corresponding to the required fixation points, without obstructing the placement paths by machine parts. Supporting points, and therefore even rods, can be ignored if they are not required for the fixation of the yarns (3200 tex carbon fiber heavy tow).

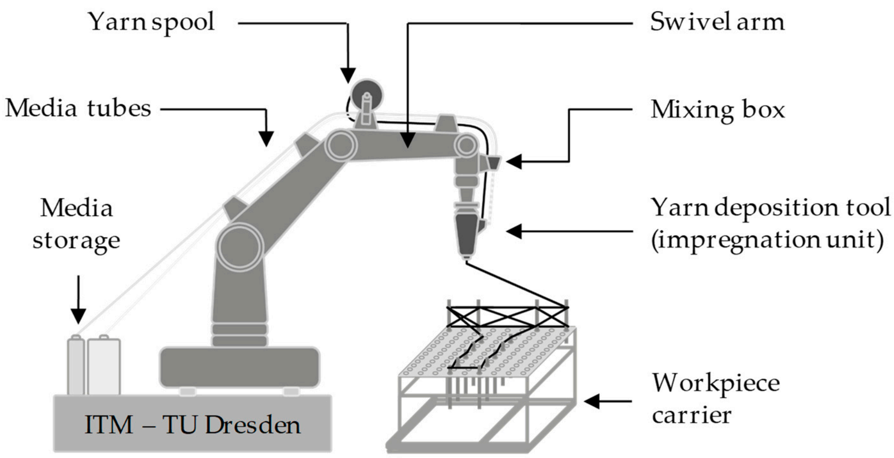


Figure 11. Developed robot-assisted manufacturing technology (principle E) with functional modules working hand in hand in order to produce complex, bionic 3D textile reinforcement structures [76].

4.2. Production of Shaped TRC Elements Based on Adpative Molds

Adaptive formwork systems are suitable for the economical production of free-form concrete parts. They are based on multipoint tooling technology or pin-type tools. The basic principle is that a large number of pins or props are variably adjusted in height. This stepped representation of the desired geometry is smoothed with an elastic layer. A formwork of rubber or other elastic material is placed on the elastic layer, which is later filled with concrete and demolded. After completion, the same conformable form can be redesigned for a differently shaped panel [94].

Since textiles are thinner and more flexible than steel rebars, TRC elements can adopt curved shapes more easily, as well as achieve tighter or sharper curves (smaller curvature radii) compared with what is allowed by steel reinforcement. Reduced concrete cover and light weight makes TRC a more suitable option for adaptive molds, because their reduced thickness makes it easier to obtain curved shapes (thicker elements are harder to curve). Additionally, TRC reinforcement grids can be fabricated more efficiently than steel-reinforced reinforcement grids [94].

Preliminary studies are currently being conducted at ITA to investigate concrete penetration and positioning of the textiles in the free-form TRC panels prefabricated with adaptive molds. Figure 12 illustrates the casting of TRC panels on an adaptive mold. The coated and uncoated textiles with different textile architecture and materials are tested for their suitability with adaptive molds. The demonstrator TRC panels fabricated with an adaptive mold at ITA are depicted in Figure 12. An alternative way to use the adaptive mold is to apply concrete after deforming the mold into the desired shape. This is possible through the use of shotcrete (this method is already used with CNC-milled molds) and through the use of robotic techniques for placing textiles, such as automatic fiber placement and automatic tape placement, which are widely used in the composites industry. Commercially, adaptive formwork is already available from Adapa AS, Aalborg, Denmark. Computer-aided control means that the production of multicurved components requires less effort than with conventional formwork systems [95].

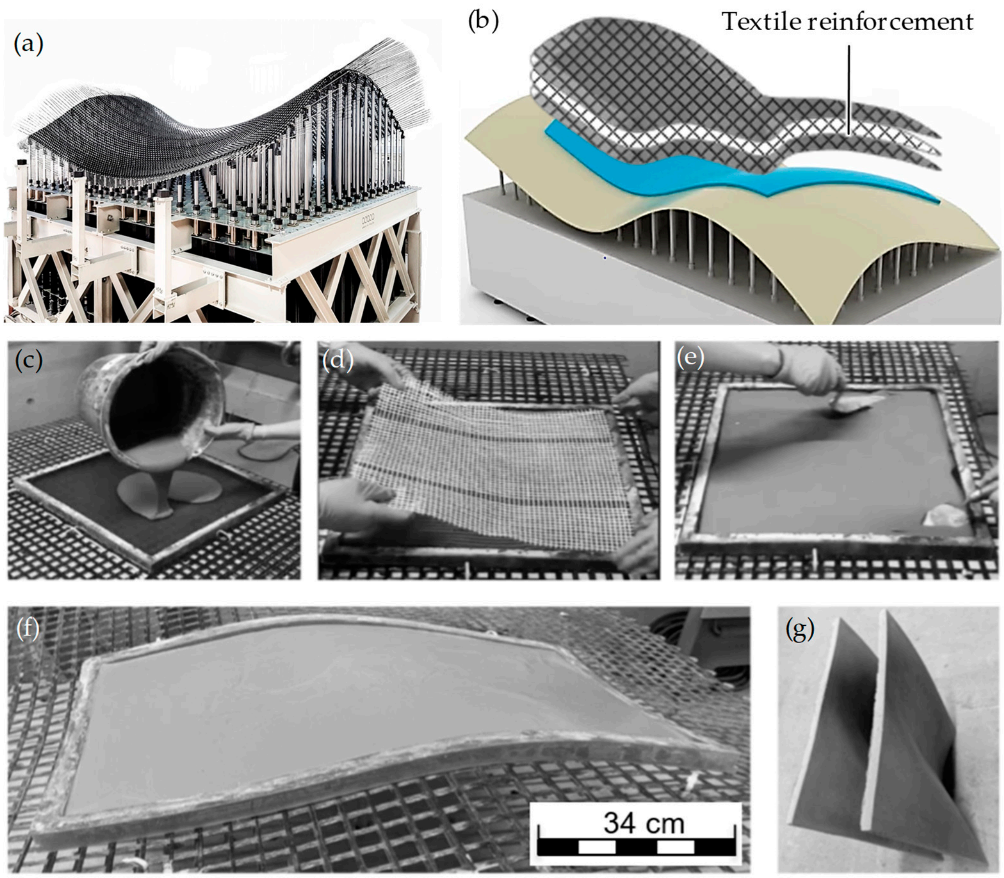


Figure 12. Precasting of TRC with adaptive mold at ITA: (**a**) industry-scale adaptive mold form ADAPA AS; (**b**) schematic; (**c**) filling silicon mold with first layer of concrete in flat position; (**d**) placement of textile reinforcement; (**e**) pouring second layer of concrete; (**f**) deforming on the adaptive mold; (**g**) precast TRC panels.

A great deal of research is still needed to improve the understanding of these new materials and to find suitable applications. The greatest challenge is the series production of such TRC double-curved or free-form structures in a precast plant and their transfer to the construction market. To achieve this, the benefits of the advances made in the above projects must be combined in a single process chain, with the involvement of architects closely associated with the builders and investors. The following research questions are proposed to be addressed in the future:

- Definition of design potentials and aesthetic trends in construction for TRC elements.
- Classification of building components with regard to form specifications and derivation of ideal textile architectures for the classified component groups.
- Fabrication of component-specific textile reinforcements.
- Shaping of TRC in the fresh state.
- In situ integration of insulating materials on the TRC panels in the precast plant.
- Integration of anchoring elements into the textile reinforcement.
- Design of a process chain for series production of functionally integrated curved TRC panels.
- Preparation of the implementation of a complete process chain for the form-flexible production of TRC components.

4.3. Textile Reinforcement for Additive Manufacturing of Concrete

Additive manufacturing methods have made great advancements in various industries in recent years, including the construction industry. Especially, digital fabrication with concrete (often called 3D concrete printing (3DCP)) has received a lot of interest in academia and industry alike, promising faster and safer fabrication of concrete elements and even whole buildings. While large advances have been made, many research challenges for 3DCP remain. Chief among them is the integration of reinforcement structures into the manufacturing process, since reinforcements are mandatory for nearly all structural applications. Various approaches to integrate reinforcements into 3DCP have been developed, researched, and classified, as presented by Mechtcherine et al. [96]. While most of the current approaches use steel-based reinforcements, as is common in the construction industry (e.g., [97–99]), some research into the usage of textile solutions has been performed.

The simplest solution for the integration of textile reinforcements into 3DCP is the integration of randomly oriented short fibers into the printed concrete, as preformed, for example, by [100,101]. However, the strength increase that can be reached by this approach is limited. Another possibility is the integration of rovings or yarns into the printed concrete layers, as, for example, researched by [102]. This approach offers improved bending strength of the layers but does not improve the interlayer connection or strength. To improve this interlayer strength, the integration of (at least) two-dimensional textiles is necessary. These two-dimensional textiles are often grid-like structures (e.g., biaxial noncrimp fabrics as used in conventional TRC) and can be applied at various steps of the digital concrete production process. They can be applied as an initial reinforcement cage onto which the concrete is added (e.g., [103,104]), placed during the digital concrete production (e.g., [105]), or added as an additional reinforcement layer after digital concrete production is concluded (e.g., [106,107]).

Two approaches for the integration of multidimensional textile reinforcements into 3DCP are presented in Figure 13 below. In both approaches, the textile is fixed in place prior to the additive concrete manufacturing process, and the concrete is added to the textile [108]. Differing from the approaches described above, the concrete can penetrate through the textile and encloses the textile within the concrete matrix. Initial trials into the approach presented in Figure 13a showed the same performance for TRC specimens produced by using 3DCP and using traditional TRC casting methods [109,110]. For the approach presented in Figure 13b, initial trials show that adhesion between a spacer fabric made from AR-glass and a printed concrete matrix is sufficient [111–113].

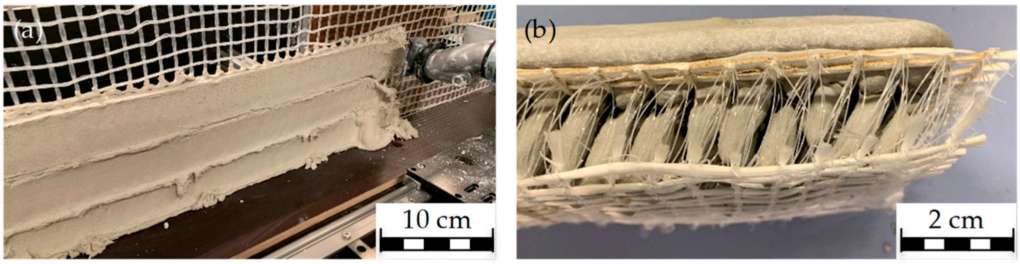


Figure 13. Two approaches for the textile reinforcement of 3D concrete printing: (**a**) printing though a two-dimensional, grid like textile; (**b**) specimen made by printing onto a three-dimensional spacer fabric.

3DCP is a highly topical research area offering interesting and relevant solutions to many of the challenges the construction industry faces today, especially regarding workplace safety and loss of workforce. Since the integration of a reinforcement is a key challenge for the widespread application of 3DCP, solutions to this challenge are highly relevant. Textile reinforcements are uniquely suited for the integration into 3DCP, since they offer high-performance reinforcement that only needs minimal concrete cover, while being lightweight and easy to handle. However, research into the integration of textile reinforcements in 3DCP is only beginning, and many promising research approaches (integration method, type of textile, etc.) and challenging questions (regarding material, processing, performance, etc.) remain.

4.4. Load-Path-Oriented Textile Reinforcement Using Tailored Fiber Placement

The technological developments in fiber-reinforced plastics (FRP) manufacturing offer great potential to be transferred to the processing of textile-reinforced concrete. The development of FRP opens up the potential for high strength, stiffness, and light weight of structural components. To achieve full performance, the anisotropic fibers need to be oriented to match the load being applied. In most cases, however, layered structures of unidirectional (UD) yarns, known as multiaxial laminates, are used for composite fabrication. This is mainly due to the availability of semifinished textile products (e.g., woven and nonwoven) and well-established numerical methods for the design of multiaxial laminates [114]. However, this leads to a significantly reduced component performance. Tailored fiber placement (TFP) is a new automated textile process for the production of reinforcing structures. TFP is an embroidery-based, tow-steering process that enables complete control over fiber placement and directionality in a composite preform. During the process, a reinforcing roving is stitched to a base material using numerical control. The results are highly engineered composite structures that take full advantage of the anisotropic nature of fiber reinforcement. This process allows the consistent transfer of calculated locally optimum fiber quantities and orientations into fiber preforms. TFP has become well-established in the automotive or aerospace industries, but it still is not a common solution for the construction industry. However, recently, there has been an increased used of this technology in the building and architecture sector, and some examples of experimental or academic nature are presented below.

In the case of concrete precast panels, the TFP machine lays the rovings on top of a substrate that can be permeable (i.e., an open fabric with gaps through which fresh concrete can flow and thus embed the fibers properly) or removable (i.e., a closed fabric that must be removed to allow concrete to fully embed the carbon fibers). An example of load-path-oriented advanced textile reinforcements is shown in Figure 14. To increase the productivity of TFP, a new process called Tailored Fiber Placement high-Volume TFP (hV) was developed by Hightex Verstärkungsstrukturen GmbH, Klipphausen, Germany, allowing placement of up to 2000 g/h of 50K rovings.

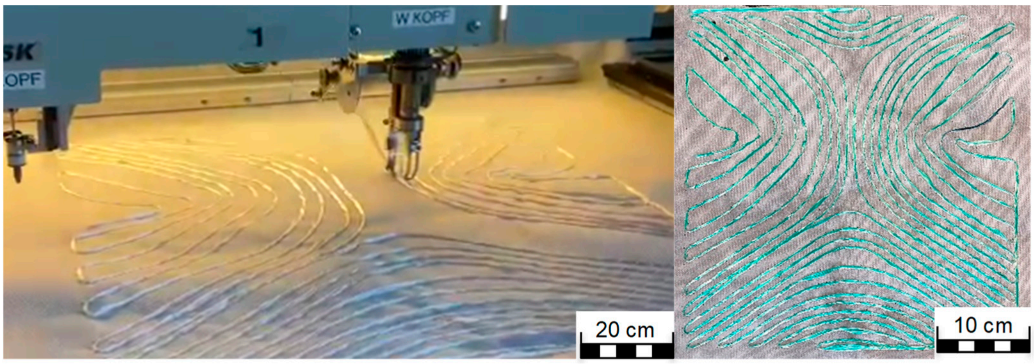


Figure 14. Load-path-oriented advanced textile reinforcement for freeform concrete panels using tailored fiber placement (TFP).

Finally, one of the main limitations of TFP elements is their characteristic flat (2D) fabrication state, which remains in their final shape. In order to eliminate this constraint and produce freeform elements, research has been conducted at the ICD and ITKE institutes of the University of Stuttgart, in which "technical" carbon fibers or "natural" flax fibers (embedded on oil-based or bio-based epoxy resins) are used to produce nonconcrete structures with 3D or "2.5 D" geometries. Examples of this are the "Tailoring Self-Formation" [115], "FlexFlax Stool" [116], and "Biomimetic NFRP Stools" [117] projects. In most of these projects, the density and direction of the rovings is adjusted to the naturally occurring load paths (in order to achieve structural efficiency or to help generate the desired final shape of the element (due to localized stiffness variations)) [115].

The development of novel load-path-oriented structures is linked to issues of manufacturability, product-related sustainability assessment, and further development of the composite material itself. New and innovative design strategies enable a completely different design methodology, reduce resource and energy consumption, and at the same time ensure high serviceability, load-bearing safety, and durability. Further research on the aforementioned aspects needs to be performed for the tailored fiber placement technology, thereby establishing TFP as a novel manufacturing technique for textile reinforcements used in building panels.

5. Integration of Additional Functions in Reinforcement Textiles

Ensuring an added value by providing additional functions to the TRC systems, such as sensory properties for structural health monitoring (SHM) or energy harvesting, is a highly topical research area. The findings on two important examples, strain and leakage sensing as well as energy harvesting, are summarized below.

5.1. Structural Health Monitoring

Despite the advantages, TRC structures still exhibit certain unfavorable characteristics, including a susceptibility to cracking [118]. Particularly, in the case of TRC structures such as bridges or pipes, regular condition monitoring and timely implementation of countermeasures to mitigate the risk of significant damages pose challenges [119]. Therefore, the implementation of an SHM system becomes necessary to assess the structural condition, estimate the remaining service life, and detect potential structural failures at an early stage [120].

An SHM system can be realized through the use of either external or internal devices. However, in both cases, monitoring requires integrating an additional sensory system with the primary structure, which entails extra costs, considerations of physical compatibility, installation requirements, and time investment. Furthermore, the use of internal devices may potentially compromise the load-carrying capacity of the structures [118]. To address this issue, in TRC structures, the sensory system can be integrated directly into the main structure. Ongoing research focuses on incorporating electrically conductive carbon rovings into TRC structures, serving both as reinforcement elements and as sensors for strain or leakage measurement [118,121–124].

Strain sensing by using carbon rovings: The load-carrying capacity of TRC structures is significantly influenced by the bonding mechanism between the concrete matrix and the roving, as well as the transfer of stress between the filaments [125]. When the filaments are bundled together, they form only microscopic gaps between them. Due to these narrow gaps, the concrete matrix cannot penetrate, resulting in only the outer filaments on the surface of each roving interacting with the matrix and bearing the load through shear stress adhesion (see Section 2 above). The absence of tension in the inner filaments limits the load factor to approximately 30–35% [126,127]. As the tensile stress increases and the structure begins to crack, the outer filaments, experiencing the greatest stress, may also break [51,125]. When a microcrack progresses into a macrocrack, some of the inner filaments also break, along with all the outer filaments, causing the remaining filaments to shift. This degradation of the structure significantly reduces its load-carrying capacity and leads to structural damage [51,118,125].

The sensory capabilities of carbon rovings have been investigated to detect this behavior and characterize the structural condition of the component [122,123,125,128]. The system relies on continuously measuring the electrical properties of a carbon roving, which are correlated with strain. Any deformation in the structure affects the reinforcement and causes the rovings to either lengthen or shorten, resulting in changes in their electrical properties. For example, when a structure is subjected to tensile stress, the roving elongates and its cross-sectional area decreases, leading to an increase in electrical resistance [124,128]. It is important to distinguish between strain sensing and damage sensing. The change in electrical resistance observed in strain sensing is predominantly reversible, while damage causes irreversible changes [125].

Numerous investigations have been conducted in the literature regarding the utilization of carbon rovings for strain sensing purposes. In most cases, AR-glass-based biaxial warp-knitted reinforcing textiles with integrated carbon rovings in warp direction, embedded in concrete matrix, have been used for the investigations. The self-sensing potential under cyclic loading [123] and under monotonic loading [124], sensitivity of electrical resistance [128], the correlation between electrical changes with micro- and macrostructural effects [122], the relationship between the electrical response and the structural behavior to sense damage under cyclic mechanical load [125], elasticity of carbon rovings embedded in concrete [129], characterization of material properties of textile reinforcement equipped with carbon rovings [130], and the effects of coating on the self-sensing capabilities under cyclic mechanical loading [126] have been investigated in different studies by using direct current (DC) circuit. Recent research proposes using alternating current (AC) circuits to characterize the electrical properties of carbon rovings due to mechanical strain and cracking at various structural states. The reason is that a carbon roving in a TRC structure is characterized by not only electrical resistance but also other electrical quantities that can only be characterized using AC circuits. These are affected by the geometrical properties of the roving, by textile coating, and by the concrete matrix [131,132].

Leakage sensing by using carbon rovings: The general concept for leakage sensing with carbon rovings revolves around the utilization of electrical changes in a pair of adjacent carbon rovings positioned parallel to each other in the warp direction. The purpose is to ensure that the carbon rovings align vertically with the cracks that form under mechanical loading. This arrangement enables, for example, water entering through the cracks to create a short circuit by connecting the carbon rovings, thereby altering the electrical properties of the system. To prevent the connection of carbon rovings, except in the case of water infiltration, isolator rovings such as AR-glass are employed in the weft direction [119,121,133]. To gain a comprehensive understanding of the electrical system, proper characterization is necessary. Also, in the framework of leakage sensing, both DC and AC circuits have been investigated in the literature for the characterization of such systems. It has been observed that the wetting of a single carbon roving does not impact its electrical resistance but affects other electrical quantities that can only be characterized using AC circuits [119].

In an AC circuit, the conductive carbon rovings adjacent to each other are separated by the concrete matrix, which possesses high electrical resistance in a dry state. However, when water leaks occur, the concrete becomes moist, resulting in the electrical connection between the carbon rovings. This connection triggers an electrical response and modifies the previous electrical parameters. Consequently, the conductivity of the medium increases while the capacitance decreases. Beyond this point, a new conductor influences the electrical behavior, leading to a short-circuit response [133].

In the literature, different leakage principles and effects of fiber type are investigated by using DC, and it is observed that water penetration through the concrete into the roving can be reflected by the resistance change in the carbon rovings [124]. The determination of the magnitude of leakage to examine the sensitivity of carbon-based TRC systems is studied by using DC and AC circuits [121]. The electrical mechanism in terms of AC circuit is characterized [119], and the water infiltration in cracked zones [134] and the effect of binding types and coating on the electrical response are investigated by using AC circuit [133].

5.2. Energy Harvesting

The integration of a solar absorber or an organic photovoltaic (OPV) film for energy harvesting via the building envelope has been investigated in the past. The ecological quality of a TRC roof element with an integrated solar absorber can be rated higher compared with a conventional roof system. In July 2013, temperatures of up to 60 °C could be reached in the installed solar storage tank. Nevertheless, the efficiency of the system is lower than that of conventional solar absorber systems due to thermal losses caused by wind [135].

By developing a solar TRC element, the design possibilities have been realized with the material combination "OPV film and TRC". The OPV film is integrated evenly and seamlessly into the TRC surface, so that both components form a unit in terms of design [135]. In addition to the integration of a solar absorber or an OPV film for energy generation via the building envelope, the use of the carbon-based textile reinforcement as a heating system for the realization of an ice-free façade or roofs offers itself as another function for integration into textile concrete elements [135].

The functionalization offers a huge potential in the field of further development of textile concrete elements, which will be used in the future in the course of further research projects for the development of multifunctional textile concrete systems [135].

6. Increasing the Sustainability of TRC

As mentioned in the introduction, the building and construction sector is the most resource-intensive sector. Concrete is currently by far the most widely used building material in the world [10]. Concrete requires a huge amount of resources, with a demand of 30 billion tons per year [136]. The key components of concrete are water, cement, and aggregate, e.g., in the form of gravel and sand. All these materials are nonreplicable resources. Sand, for example, is currently the most important trading raw material worldwide and competes in its use with a wide variety of industries. Furthermore, cement production, which is responsible for around 8% of global CO_2 emissions, also has a high potential to damage the environment [137]. In total, the building sector, including the maintenance of buildings, alongside the manufacturing, transportation, and processing of construction materials, is responsible for 38% of the world's CO_2 emissions [2]. Reducing greenhouse gas emissions is an essential requirement for achieving the goal of the Intergovernmental Panel on Climate Change to limit global warming to a maximum of 1.5 °C [138]. The construction industry can make a significant contribution to achieving this goal due to its high share of global greenhouse gas emissions.

Furthermore, construction and demolition waste is about more than 25% of the total generated waste around the world [139]. The EU waste policy aims to enhance waste management, promote innovation in separate waste collection and recycling, restrict the use of landfilling, and develop encouragement to change consumer behavior. Its goal is to lessen the quantity of waste induced and the toxic substances it possesses [140]. Several aspects of how this goal can be achieved at the level of building components exist. These include reducing resource consumption, extending service life, and using recycled materials.

One approach to achieve the goals of the EU waste policy is to use recycled carbon fiber (rCFs) as an alternative reinforcement material for concrete. In addition to the existing advantages as reinforcement material, CFs have some disadvantages, such as high costs, energy-intensive production processes, and challenges related to end-of-life handling [141]. In particular, the end-of-life treatment of CF is highly problematic, as the fiber length of rCF is shortened, which significantly limits further applications. Therefore, the use of rCF in the construction industry can take place as short-fiber reinforcement or after the production of textile semifinished products made of rCF from textile reinforcement [142]. Compared with already existing short-fiber reinforcements made of steel fibers, AR-glass fibers, CF or PVA fibers [14], there are advantages and disadvantages of rCF in fiber-reinforced concrete [142]. The corrosion resistance of carbon fibers is an advantage in rCF short-fiber-reinforced concrete. In addition, the fibers have high tensile strengths and a lower price compared with virgin CF. A disadvantage is the low density of rCF, because the fibers float to the top of the concrete. In addition, the small fiber diameter results in difficult workability compared with the distribution of macrofibers, and the low elongation at break causes brittle failure [142]. According to [142], the recommended fiber volume content for rCF is 0.5–1.5%. With this, an increase in the flexural tensile strength of 11–40% (up to 10.7 N/mm^2) can be achieved compared with steel- and AR-glass-fiber-reinforced concrete. Depending on the application, the primary energy requirement is up to 54% lower with rCF short-fiber reinforcement [142].

Until now, recycled carbon fibers have been used in the construction industry mainly as fillers or as substitutes for less efficient fiber materials [138]. Neither of these applications can be regarded as efficient, value-preserving recycling due to the lower requirements. Value-preserving recycling means utilizing the mechanical properties of the recycled carbon fibers as fully as possible. Therefore, in addition to the reuse of the recycled carbon fibers as individual short fibers, there is also interest in the further processing of recycled carbon fibers into textiles. The use of recycled carbon fibers as textiles has the advantage that the carbon fibers can be positioned where they have the greatest benefit in terms of mechanical properties.

One possibility to use rCF as textiles is in nonwoven reinforcements. However, with nonwoven reinforcement, the reinforcing layer might act as a two-dimensional separating layer in the concrete (see Figure 15a) [142]. Therefore, high strength values are only possible with a low volume content, as the nonwovens otherwise act as a two-dimensional separating layer in the concrete [142]. Further developments in the production of nonwovens with high rCF contents are required, and other processing methods for the insertion of nonwovens are being investigated. One possible method is the insertion of nonwovens in the form of stripes as reinforcement in concrete, so that the nonwovens do not act as a separating layer (see Figure 15b). In this case, a nonwoven with an rCF content of 96% and 4% of PET Binder thread was used.

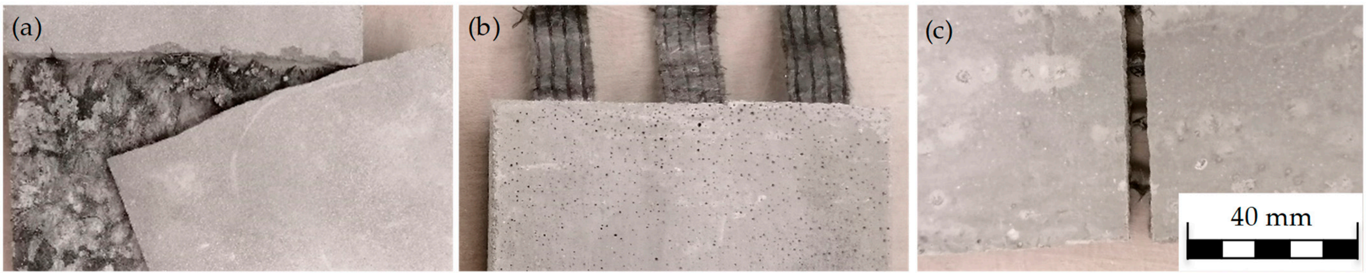


Figure 15. Variations in using rCF as textile reinforcement in concrete: (**a**) rCF nonwoven reinforcement occurs as a separating layer; (**b**) nonwonven reinforcement inserted in stripes; and (**c**) rCF hybrid yarn reinforcement.

For the production of a textile with a grid structure as is commonly used with virgin CF, it is necessary to produce yarns from rCF (see Figure 15c). Therefore, hybrid yarns from rCF in combination with PA6 fiber material are produced, because yarns cannot yet be produced from rCF alone. So far, these staple fiber yarns were produced as friction-spun yarn and as wrap yarn, both with an rCF content of 52.5% and 47.5% of PA6 fibers. Further investigation is needed to produce yarns with higher rCF content in the future, as better mechanical properties are expected. Fabric production as reinforcement is conceivable from these hybrid yarns. In addition, compared with virgin CF production, rCFs that are produced using pyrolysis can be a good alternative considering the great amount of reduced GWP [143].

In the terms of the Circular Economy, it is important to consider component manufacture, including material extraction and production, as well as to include the end-of-life phase. This includes the possibilities of recycling and the use of recycled material instead of new materials. Kimm et al. have investigated the separability of textile concrete [144,145]. They have shown that it is possible to separate coated textiles from concrete. The material, construction, and crushing method have a significant influence on separability. A suitable coating has a positive influence on separability. The highest recovery rates were achieved with an epoxy coating. A larger roving cross-section also has a positive effect on recycling.

Carbon and AR-glass reinforcements were best separated with the hammer mill, with a textile recovery rate of >90% and a remaining organic fiber content in the minerals of <0.2% [142]. As mentioned above, the recycling of short fibers in fiber concrete is possible, but currently, no immediate reuse of the textile structure is possible due to the resulting strength losses. The mineral content of the recycled TRC can be used as recycled concrete aggregates in concrete, road, and path construction. A crushing of TRC with the use of rCF-yarn-reinforced concrete is considered in [143]. Similar to the separation of TRC, a separation is only possible if the yarn material is coated, compared with unimpregnated rCF yarns.

7. Summary and Outlook

The construction sector is one of the most important industries, both economically and in terms of its impact on the environment and human well-being. Therefore, it is of utmost importance to face the many contradictory challenges of the construction industry: New buildings need to be built fast but should use less resources and emit less greenhouse gases. New buildings need to be built using a decreasing workforce, and safety concerns during construction need to be taken into account.

As shown in this paper, for many of the challenges of the construction industry, textiles can be adapted and tailored to offer uniquely fitting solutions. Textile-reinforced concrete, for example, enables the construction of thin-walled concrete elements with high mechanical performance, enabling resource savings and allowing for the efficient automated production of concrete elements. TRC can also be used for the retrofitting of existing concrete structures, which of course is more efficient than demolishing and rebuilding an entire structure. TRC also enables novel concrete designs that are impossible with traditional steel-reinforced concrete, since textiles can be shaped freely, allowing for novel architectural trends. Textiles are also particularly suited to automated production processes, enabling a much-needed increase in productivity in the construction sector, leading to the development of new, high-skilled job profiles. The integration of sensors and other functions into textiles for TRC provides value to the textiles in addition to their use as reinforcement. It also improves the usability of TRC products, either by providing additional functions or by increasing longevity, since the status can be continuously monitored, as well as enabling targeted retrofitting. While many of these functions of TRC have been demonstrated in first research projects and commercial pilot projects, a comprehensive market introduction of the technology is still ongoing. In addition to the many research approaches shown in this paper, topics such as the integration of natural fibers and recycled carbon fibers into TRC and the development of ductile textile reinforcement are highly topical areas of research.

To realize the full potential of textile materials in the construction sector, especially in conjunction with concrete, wide-ranging research and development in collaboration with various disciplines is necessary. The construction industry is a complex industry with many actors and even more stakeholders, all of which need to benefit from any potential solution. Therefore, the close collaboration of engineers from various disciplines (civil, textile, processing, mechanical, etc.), architects, and planners, as well as customers, political actors, and more is the key to make fiber-based materials the construction materials of the future.

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