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RILEM TC REPORT

Article of RILEM TC 292-MCC: bond behaviour of textile-reinforced concrete—a review

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Abstract Textile-reinforced concrete (TRC) has gained a lot of attraction in recent years. Adequate bond between the phases in this system allows to transfer high loadings, thus enabling high performance. The terminus textile reinforcement, however, comprises many different types of fabrics, which differ in their chemical composition, geometry, surface properties etc., and thus exhibit substantially different bond properties. In the course of RILEM's Technical Committee 292 work on TRC it was found that a comprehensive understanding of the complex interactions between individual parameters is still lacking. This is amplified by the fact that different types of textile reinforcement are preferably used in different regions of the world. This paper therefore attempts to compile findings from literature on the bond in TRC. The database used was created in the course of the TC work. Additional papers of relevance were identified by scanning scientific web databases. The different influencing parameters are given in this paper in a hierarchical order, starting from the level of the individual constituents (filament and matrix) to impregnated fabrics and the influence of textile manufacturing and architecture on the bond. Finally, by mapping all the cited literature used in this paper based on grouped keywords the complex intercorrelations are visualised.

This article has been prepared by members of WG 1 – Materials and Material Systems within RILEM TC 292-MCC. The article has been reviewed and approved by all members of the TC 292-MCC.
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1 Introduction

Today's technological advancements are driven by the urge for a reduced ecological impact. Textile Reinforced Concrete (TRC) has a huge potential to reduce the carbon footprint of concrete structures. The textile reinforcement is usually made of high-performance fibres such as glass, basalt or carbon and are characterised by a superior strength whilst providing excellent durability. At the structural scale, TRCs therefore offer a slender and lightweight alternative to traditional building systems, which can reduce the amount of raw material used by up to 85% [1–4].

In TRCs a textile mesh is embedded within the concrete to serve as a reinforcement. These textiles are usually made from continuous yarns that contain numerous filaments (rovings) using textile fabrication methods such as warp knitting or leno weaving. Following the same principles as in steel-reinforced concrete, once the cracking load of the concrete is reached the tensile forces are taken by the textile. The load is transferred by bond stresses at the interface between the reinforcement and the concrete. The bond properties of TRC are therefore crucial for the functionality of the building component, as it affects the structural integrity as well as the serviceability of the system.

In general, the same bonding mechanisms as in steel reinforced concrete, namely adhesion, friction and mechanical interlock can also occur in TRC, albeit at a scale that is an order of magnitude or two smaller than for conventional reinforcement. Furthermore, the magnitude of each contribution differs significantly due to multiple parameters such as fibre volume ratio, yarn type and geometry, surface roughness, impregnation composition, as well as fiber treatment, binder additives and textile architecture. In the case of natural fibres, poor bonding with the binder may exist due to fiber swelling under wet conditions of the fresh concrete and subsequent shrinkage upon drying [5–7]. And since no standardisation of textiles has yet been established, a broad variety of bond performance of TRC has been observed and reported.

Figure 1 qualitatively displays the bond pull-out behaviour of three different textiles from a concrete sample. Analogies to the classification of the tensile response of fibre-reinforced concrete (strain hardening/strain softening) can be found [8]. Type (a) shows a peak bond strength at small slip values that can be traced back to the adhesive bond, followed by a lower, constant friction component once the peak bond strength was surpassed (bond-softening behaviour; e.g. in the case of dry textiles or soft impregnation material [9–11]). In type (b) the friction component exceeds the peak bond-strength due to adhesion, leading to an increased bond performance at higher slip values (bond hardening; e.g. due to additional sand-coating [12, 13]). The highest performance is observed when mechanical interlock is achieved between the textile and the concrete (type (c); e.g.

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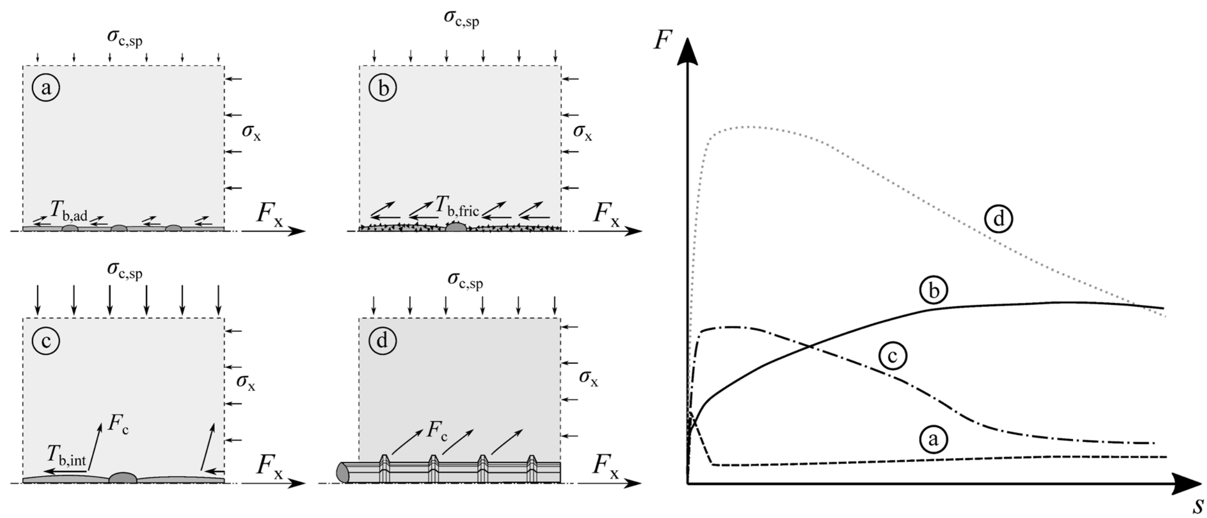

Fig. 1 Qualitative comparison of bond stress-slip relationship obtained from pull-out tests on **a** textile with bond-softening behaviour (e.g. [9–11]), **b** textile with bond hardening behaviour (e.g. [12, 13]) and **c** textile with mechanical interlock as decisive bond mechanism (e.g. [14–16]). The bond stress-slip relationship of deformed bars during pull-out is depicted for comparison **d** (Figure taken and adapted from [18], licensed under CC BY 4.0)

for textiles with irregular cross-sections impregnated with a stiff material [14–16]). This is accompanied by a very high bond stiffness and stress concentrations in the concrete which may eventually lead to a concrete splitting failure [17]. To illustrate the similarity of the bond performance of textiles type c with a steel-rebar (that remains elastic during pull-out, type d) its pull-out response is also depicted.

The differences in bond behaviour must also be seen against the background that TRC is still a novel material under development. While in the past dry textiles (non-impregnated) have been investigated [19–23], the current practice focuses on partial or full impregnation of the fabrics with typically a polymeric matrix. The impregnation improves the strength and stiffness of the textiles, as evidenced by the measurement of the tensile and bending response of TRC specimens (e.g. [24, 25]). This is because the inner bonding of the fibres makes the tension more uniformly distributed across the filaments and prevents local stress peaks. The impregnation, however, has a significant influence on the bond properties. While for the dry textiles, the bond is decisively influenced by the cementitious matrix that partly penetrates into the yarn, a closed surface is formed by the polymeric matrix in impregnated textiles. Driven by economic factors there is also a noticeable trend towards using yarns with a higher yarn count, since more fibres are handled and processed simultaneously [26]. This makes the bond behaviour of TRC even more complex as the ratio of bonded to cross-sectional area of the yarns decreases with larger sizes, thus playing a decisive role in the bond performance of textiles. A sound understanding of all the governing factors on the bond behaviour of TRC would allow to tailor the textiles for optimal performance.

A wide range of investigations have therefore addressed the bond properties of different types of textiles [9, 10, 15, 21–23, 27–43]. This paper aims to compile these findings and to reveal the complex interactions between individual parameters that contribute to the bond performance in TRC. The focus is on the short-time performance of the general bonding principles only, thus no time-dependent behaviour e.g. durability aspects, impact or fatigue are considered. The paper also classifies and reviews different test setups and evaluates the advantages and shortcomings of experimental setups for determination of the bond behaviour of TRC.

2 Methodology

The paper evolved from the working group (WG) 1 of RILEM Technical Committee (TC) 292-MCC: Mechanical Characterization and Structural Design of Textile Reinforced Concrete. A general state-of-the-art report document could not fully capture the depth of topics dealing with the complex bond behaviour of TRC in detail, but the literature database that was created in the course of the TC work served as a basis also for this paper. The database was compiled by the TC-experts from the relevant topics. Additional papers of relevance were identified by conducting a keyword search in SCOPUS, using the following key:

(TITLE-ABS-KEY (textile OR trc OR fabric) AND TITLE-ABS-KEY (bond OR bonding) AND TITLE-ABS-KEY (concrete OR "cementitious matrix").

Papers related to the strengthening of existing structures, e.g. adhesive bonding of laminates or interfacial bond between TRC and substrate were excluded from the list. A total number of 267 journal articles were considered (as of April 2023). It is noticeable that the number of publications per year is still sharply increasing (see Fig. 2), underpinning the fact that this is a highly relevant research topic.

Papers that fell out of the defined scope after an initial screening were removed from the database. After describing the test methods, the structure of the paper follows a hierarchical order to address the influence on the bond behaviour due to (a) individual constituents, filaments and (cementitious) matrix, (b) impregnation materials and (c) textile architecture and manufacturing process (see Fig. 3). The author keywords of the referred literature sources are then extracted from SCOPUS database and cleaned of ambiguities, e.g. due to singular and plural mentions, to ultimately visualise in Sect. 6 the cross links between individual influencing parameters. This was done by mapping the grouped keywords with the program VOSviewer.

Many different terms are used synonymously in the literature for the various aspects of textile reinforcement, which often has been the source of confusion. In this paper, unidirectional endless fibres are called

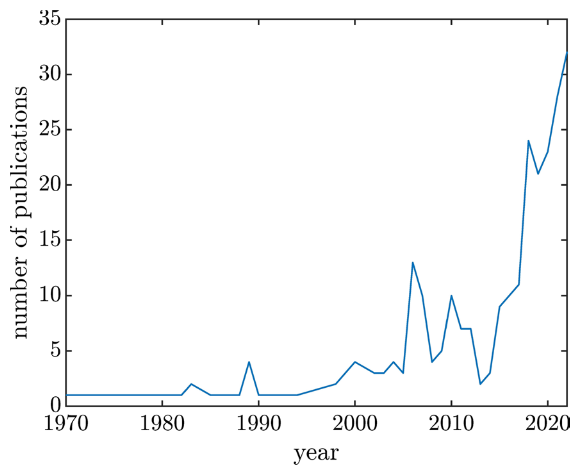

Fig. 2 Articles on the bond behaviour of TRC that were published in the years between 1970 and 2022 (data extracted from SCOPUS)

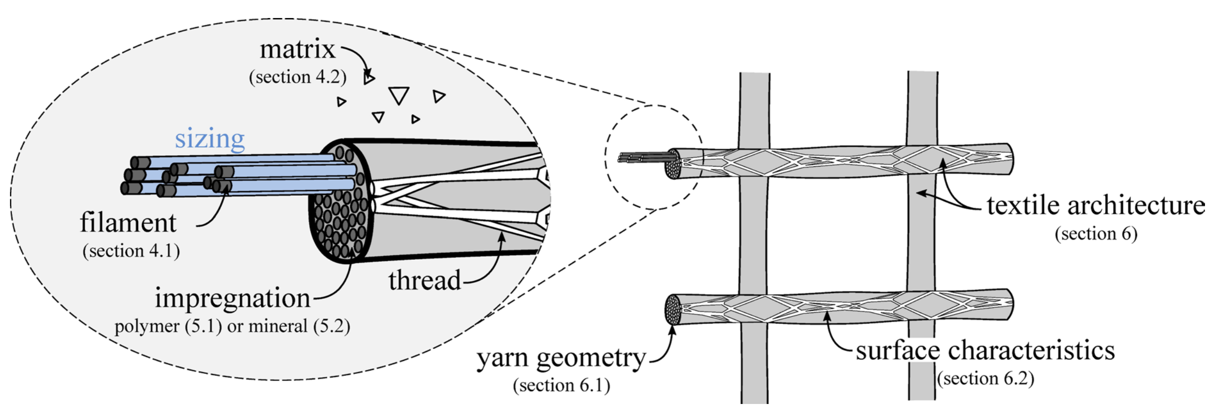

Fig. 3 Potential influencing parameters on the bond behaviour of textile reinforcement: level of yarn (left) and level of textile (right)

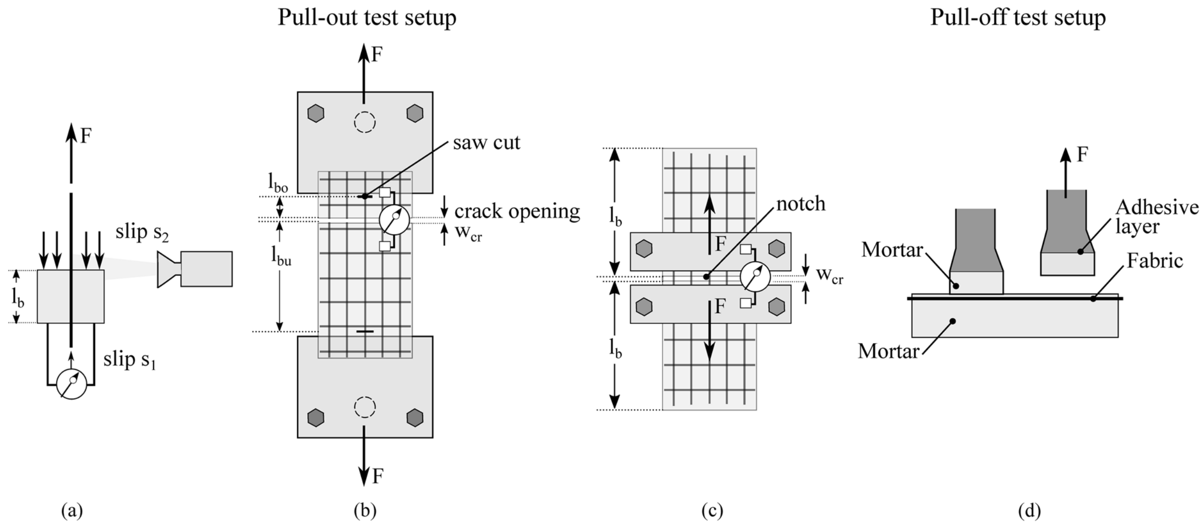

Fig. 4 Different setups for testing the bond behaviour of TRC: **a** yarn pull-out test (YPO) **b** single-sided pull-out test (SSPO) **c** double-sided pull-out test (DSPO) and **d** pull-off test; (Figure taken and adapted from [18], licensed under CC BY 4.0)

filaments. For multifilament bundles, the term yarn is used. Roving, which is also often used in literature, describes untwisted multifilament yarns. Although this type of yarn is most commonly used, textiles can also be made from other yarn types. Moreover, yarns can consist of more than just one roving. Other terms like fibre strands and multifilament bundles are more generic and therefore avoided in this paper. For the matrix that is used to fill the interstices, impregnation is considered to be the most precise term. Coating is often used synonymously in literature but is only correct for near-surface impregnation. Finally, the thin coating of the filaments is the sizing.

3 Testing methods

Various test methods were developed to measure the bond behaviour of textile reinforcement embedded in a cementitious matrix (see Fig. 4). Pull-out tests on single yarns as depicted in Fig. 4a, are similar to the RILEM test for RC, and allow the slip to be measured at both ends of the test specimen. The specimen dimensions are chosen to avoid cracking of the concrete. Several research groups test TRC-stripes for ease of handling while allowing for a thin concrete cover; i.e. the single-sided pull-out test (SSPO) as shown in Fig. 4b. The double-sided pull-out test (DSPO; Fig. 4c) was developed for testing the textile anchorage behaviour in which the bonding length can easily be varied. While the basic procedure for each of the pull-out tests in Fig. 4a-c is the same, the experimental setup differs significantly in the reported literature. Thus, there is a need to standardise those test setups to ensure comparability and reproducibility of results. First attempt in this direction has been made for the SSPO in the recently published German Guideline for concrete structures with non-metallic reinforcement [44].

The adhesion (chemical) bond strength between textile and cement matrix can be measured by pull-off test according to ASTM D7234 [45]. In this technique, a normal force applied on a TRC sample leads to complete separation between the matrix and the textile (see Fig. 4d). The adhesion bond strength is obtained from maximum force divided by the detached cross section [45].

3.1 The pull-out test

Testing and modelling of the textile-to-mortar bond behaviour in cementitious matrices have been studied for decades, see e.g. [19, 20, 32, 46–53]. Besides the categorisation given in Fig. 4 and followed throughout Sect. 3.1.1 – 3.1.3, these tests are commonly referred to in the literature as push-push, pull-push or pull-pull test, according to the boundary conditions of the supports [54].

3.1.1 Yarn pull-out test (YPO)

The most common method used for characterization of the bond of textiles embedded in a matrix is the Yarn pull-out tests [55–57]. Their main output is force-slip curves which, by means of analytical or numerical models [12, 13, 58], can be used to extract bond-slip laws. The main challenge in this process is to ensure the uniqueness of the solution to the bond-slip laws. This requires accurate measurement of the slip (at both loaded and free ends of the sample). Due to the complexity of measuring the strain distribution along the embedded length, a stress/strain distribution is usually assumed. To minimize the effect of contact compression force occurring at the support, a tube can be inserted in the concrete located at the loaded part of the yarn [13]. This procedure is consistent with the standard RILEM bond test for bond-strength of ordinary RC [59], leads to a less disturbed bonded area, and determines a more realistic bond behaviour. However, due to the large thickness of the specimens, which in most cases do not reflect the thickness of real TRC-specimens, splitting failure is most likely suppressed, and the force-slip relationship obtained from these tests is typically an upper limit of the bond strength.

3.1.2 Single-sided pull-out test (SSPO)

The geometrical details of the specimens are shown in Fig. 4b. By saw cuts on each side the outer yarns are separated, so that only the middle yarn connects the two parts of the specimen. The lower part exhibits a long bonding length ($L_{E,u}$) while the upper part has a defined bonding length of one weft yarn distance ($L_{E,o}$). While $L_{E,u}$ leads to a full anchorage of the yarn and no movement of the yarn is suspected, the upper part is pulled out. The process requires careful inspection since the specimens that are damaged by the cutting need to be sorted out. Metal rings can be used as guides in the formwork before the matrix is added to help with the sample installation in the testing frame. The testing procedure involves a fixing of the lower part of the specimens with clamps while the load is applied to the upper part through a bolted connection. Other specimen installation methods are by clamping the upper part between two steel plates using hydraulic jacks or prestressed screws. Both loading procedures apply the force gimballed and axial to the yarn. Researchers have also introduced variations of this test setup where the specimen is narrowed in the bonded area so that the remaining cross-sections equals the concrete area that can be attributed to one yarn [14, 16, 35]. This unique approach allows to measure the bond performance of textiles under explicit consideration of a potential splitting failure. The crack opening in all cases is typically measured by Linear Variable Differential Transformer (LVDT).

3.1.3 Double sided pull-out test (DSPO)

The double-sided pull-out (DSPO) test was initially developed for measuring the required anchorage length of flexible textiles such as SBR impregnated carbon fabric and dry fabrics [60–63]. It resembles the conditions of a reinforcement bridging a crack (multiple yarns and small concrete cover). The specimen in the DSPO test consists of a rectangular TRC plate with a horizontal notch on both faces that defines the position of the first and only desired crack, as shown in Fig. 4c. The notch-depth is related to the reinforcement layout in the cross-sectional area. In an alternative configuration for the DSPO test a doubly symmetrical narrowed prism with a 1-mm notch in the midspan is created. In either case the top and bottom halves of the specimen are pulled apart by steel plates that are either glued to the specimen or clamped in place using screws or hydraulic pressure. Test results with stiffer textiles such as epoxy-impregnated carbon fabric might be affected by the clamping pressures. Furthermore, this type of reinforcement usually achieves a higher bond with concrete matrix that may lead to longitudinal cracks. High clamping pressures suppress this cracking mechanism, reduce the necessary anchorage length, and influence the bond characteristics [64].

3.2 Pull-Off test

A Pull-off test is used to study the adhesion (chemical bond strength) between textile fabric and cementitious matrix. In this test method, a stamp is glued to the top surface of a protruding matrix cylinder that was attached to a textile embedded in a cement matrix (see Fig. 4d). After curing, the stamp is pulled-off the matrix cylinder until clear failure in the vicinity of the fabric–matrix interface is obtained [45, 65]. The force at this point divided by the detached cross section is defined as the bond strength between the matrix and the textile fabric. This type of data reduction from loads to stresses to report the bond strength assumes that the force is uniformly distributed across the sheared section and there is no incremental debonding and crack propagation. The strength is thus reached instantaneously at the maximum load, resulting in an average nominal representation of the stress in the sample at the moment of failure. Generally, the pull-off test provides a direct and accurate measurement of chemical adhesion between textile fabric and matrix on one side, although transverse tension can occur in pull-off due to delamination, while pull-out yields an estimation of adhesive bond over the entire perimeter based on the measured debonding energy. A comparison between the chemical adhesion (measured by pull-off) and chemical debonding energy (calculated from pull-out results) showed that these two test methods are correlated to each other, exhibiting similar trends but different values [66]. The moment of chemical debonding in pull-out tests, however, is often hard to determine, especially if there is a bond-hardening behaviour.

4 Influence of individual constituents of TRC on bonding

4.1 Filaments

The influence of the fibre type on bonding is strongly dependent on whether the yarn is impregnated or not, since only in case of the latter a direct contact exists between the fibres and the (cementitious) matrix. Bond is then mostly governed by adhesion and friction between the two constituents. Analogies exist with bonding between short fibres and the matrix in fibre reinforced concrete (FRC) [67], however this is dependent of the surface contact area that is affected by the infilling of the interstitial spaces. In general, the bond increases with a dense microstructure at the vicinity of the fibres. Studies carried out on polypropylene (PP) fibres with hydrophobic characteristics found that higher porosities exist in the contact area, hence weaking the bond [68–70]. This agrees with earlier work on the bond behaviour of textiles where High Density Polyethylene (HDPE) and aramid fibres showed significantly higher bond strengths than Nylon and PP [71]. On the other hand, it was found that the bond performance increased by increasing wettability of fibres. Comparing PP, steel and carbon fibres the latter showed the best performance [72]. Williams Portal et al. [11] conducted single-sided pull-out tests with both basalt and carbon fabrics, where the bond strength was found to be of similar magnitude. Similar bond strength results were also obtained between dry carbon and alkali-resistant (AR)-Glass yarns [73]. However, while carbon fibres are resistant to alkaline environments [74], AR-Glass fibres can degrade under two mechanisms: chemical damage and physical embrittlement. The alkaline environment of the concrete over time thus degrades the fibre, a consequence of infilling of the interstitial pores between the filaments to increase the bond between the filaments. The bonding of filaments in turn decreases the flexibility of the yarn, especially in conditions where the yarn is not aligned perpendicular to a newly formed crack in the matrix. Instead of bending of the yarn at the crack and relative slipping of individual filaments against one another, the mode of failure changes to fracture of the yarn, due to an increased flexural stiffness which resists the imposed curvature during the pull-out phase [75]. These fibre fractures result in weaker strengths.

Much research has also been conducted on natural fibres [76–78], but the lack of durability in alkaline environment is noticeable here. Also, natural fibres such as malva or sisal tend to be susceptible to water absorption and desorption, which increases the porosity at the interfacial transition zone due to expansion and shrinkage, hence decreasing the bond performance [79, 80]. On the other hand, the surface roughness of natural fibres positively influences the mechanical bond-performance [81].

Other studies have been conducted at the materials and polymer science level to modify the surface of the filaments to achieve better affinity to the matrix. According to Li et.al [82] various processing methods are being investigated in this regard for carbon fibres and include (a) Oxidation, e.g. in Air, Ozone, Nitric Acid, NaOH, Acetic Acid, H_2O_2, (b) Grafting, e.g. Silane Coupling, Carbon nanotube Grafting, Graphene Oxide grafting, (c) Electrophoresis, e.g. Nano Silica and (d) Plasma, e.g. Oxygen plasma, Nitrogen plasma, Silicon oxide. These surface treatment techniques fall under the broader aspects of research to address the fiber-polymer, sizing, or fiber-cement bonding aspects. A surface modification to improve bond can also be achieved with chemical modification, such as alkaline surface treatment or plasma treatment, on fibres like PP or Polyethylene terephthalate (PET) [83, 84]. Kimm et al. [85] applied wet chemical treatment with silane on recycled glass yarns and found that it had a detrimental impact on bonding when compared to other series. This may be brought on by the fact that concrete forms a hydrophobic silicone resin layer when it crosslinks with calcium silicate hydrates and releases water.

4.2 Matrix

Bond is influenced by several micromechanical properties that control the interface fracture modes. The water to binder ratio has a decisive influence on these properties and thus the bond strength [86]. Furthermore, the influence of the concrete strength on the bond behaviour is well known from reinforced concrete: in general, the higher the concrete strength, the higher the bond stiffness and strength. In case of textile reinforcement, specific requirements arise from the fabric's mesh size and the complex and filigree geometry of the structure, which usually requires TRC matrices to be fine-grained concrete with a high strength to ensure compatibility of the two components, concrete and textile. Due to this high baseline, fewer studies on the influence of the composition of the cementitious matrix on the bond can be found in literature. Donnini et. al [87] for example used three different mortar types, designated "Mortar-15," "Mortar-30," and "Mortar-45," corresponding to mortar class strengths of 15, 30, and 45 MPa, respectively, together with dry and partially impregnated textile fabrics. In the case of dry textiles, the bond strength was decisively governed by the penetration of the fine concrete matrix into the interior of the yarn and bond strength correlated with an increasing mortar tensile strength [87]. However, even in the case of fine-grained mortar or concrete, since the cement grains are usually larger than the cavities between the individual fibres [88–90], only the outer fibres are in direct contact with the matrix [91]. The addition of silica fume to the concrete mix, can improve the bond behaviour of dry textiles by penetration of small particles in between the yarn [92].

Different mechanisms are decisive in case of impregnated textiles, but still the bond strength is correlated with the concrete strength [93, 94]. Also, it was shown that the same concrete yields higher bond strengths for textiles impregnated with epoxy resin than for dry textiles [22, 95], while some SBR-coatings cause a lack of water in the interfacial zone due to swelling effects [96], thus leading to a reduced bond performance. This suggests that epoxy resin provides a more uniform interaction with the concrete than SBR-impregnated and dry textiles, even if only a partial impregnation at the outer surface of the textile is applied [87]. If the failure, however, is governed by bond induced splitting of the concrete matrix, no increase in the bond strength was observed on both high-performance concrete (HPC) and ultra-high-performance concrete (UHPC) specimens. Due to the lower fracture energy of the UHPC mix (without any fibres), the failure was more brittle, with a smaller fracture process zone [18]. In case of fibre-reinforced UHPC studies suggest a marginal influence of the fibre-volume content v_f on the bond strength, especially for values of v_f larger 1% [97].

Peled et al. [34] studied the effect of three fabrication methods on the bond properties, namely casting, pultrusion and vacuum condition,. Results indicated that for warp-knitted and woven dry fabrics, the pultrusion process successfully improved the bonding properties by filling the interstitial filament spaces. However, pultrusion failed to significantly improve the bond strength of non-tightened yarns with a more open structure and for impregnated yarns. This is because for the former the interstices between the filaments can be filled without intensive processing and for the latter because penetration of the concrete matrix into the yarn of impregnated textiles can be ruled out.

The addition of short fibres to the matrix has gained interest in recent years [6, 86, 99–103]. Gong et al. [104] found that a highly synergetic composite action can be achieved for textile-reinforced strain-hardening cement-based composites (SHCC). The bond performance, however, is strongly dependent on the polymeric matrix used, with a significantly higher bond strength achieved for textiles with a stiffer polyacrylate impregnation. The higher bond performance in SHCC was also observed in Goliath et al. [103] and was attributed to a confining effect caused by the Polyvinyl alcohol (PVA)-fibres which were mixed to the concrete, thus mobilising higher friction when the yarn is pulled out of the concrete. Barhum et al. [86] investigated the effect of short, dispersed AR glass and carbon fibres on the bond of polymer-impregnated yarns in a cementitious matrix and also found a favourable effect for both fibres. Similar studies observed a bond enhancement when short fibres are used, which do not disperse when the concrete is mixed (integral fibres) and attributed this to a cross-linking effect [99]. When comparing the integral fibres with the dispersed ones, TRC specimens containing the latter type of fibres formed more fine cracks than the specimens with integral fibres. In a different study, increase in bond strength that led to a finer crack pattern was also observed with poly(p-phenylene-2,6-benzobisoxazole) (PBO-AS) fibres, while the addition of polyethylene (PE) fibres did not improve the bond [105]. Contrary to these findings it was found in another study, that the addition of AR-glass fibres in concrete reinforced with dry textiles did not increase bond strength [98] while PE and PP fibres even adversely impacted the bond. This underpins that the bond performance is complicated and not influenced by a single constituent but must be viewed in a holistic way by considering the whole composite. In addition, parameters such as the long-term performance have to be taken into account.

Butler et al. [62, 63] studied the effect of matrix composition and accelerated aging on the bond behaviour of dry glass textile reinforcement. They found that the matrix with high content of OPC (M3) had a better initial bond performance due to a dense microstructure formed by the C-S–H phases. In contrast, matrix with a cement blend (M1) showed a more porous microstructure at the interface, leading to a lower bond performance. When the specimens had undergone an accelerated aging, however, matrix M3 showed a decisive loss in bond performance and a brittle failure, while matrix M1 maintained good bond properties and a more ductile behaviour. This was attributed in [62] to the reduced precipitation of portlandite between the filaments with lower OPC content, as these crystals can split and thus notch the filaments when the yarn is strained.

Because the binder composition has a huge impact on the carbon footprint of concrete, it has received significance by the climate crisis and researchers have started to look also at the influence of binary, ternary and quaternary [98] blended mixes on the bond properties in TRC. It is shown that blended mixes achieve comparable bond strength and toughness to mixes with ordinary Portland cement (OPC). The use of alternative binders, such as geopolymer-based mortars, may also be a promising means to explore new types of textile reinforcement not employed previously due to the high alkalinity of the OPC binder solutions. Still, there is limited literature available on the bond behaviour of textile-reinforced geopolymer concrete. Most of the work conducted to date suggests that in the case of geopolymers, the matrix is unable to penetrate the yarn, but rather bonds only to the outer filaments [106, 107]. Other studies on alkali-activated materials suggest a significant influence of the precursor and the type of chemical activation. When using unprocessed high calcium fly-ash as precursor a relatively poor bonding capacity was achieved, while potassium-based activators promoted a better bonding compared to sodium-based ones [108].

5 Influence of Impregnation on Bonding

In addition to the fibre and matrix, an impregnation of the textile plays a major role in the bond behaviour of TRC. The impregnation serves multiple purposes such as load transfer between the filaments and the phases, covering filament surface flaws, protecting the fibres against aggressive media and consistency of the yarn as a single unit during fabrication and loading [109–111]. Additionally, the frictional coefficients and adhesion characteristics can be changed, and the surface contact angle of the fibre can be engineered to allow water wicking due to the capillary action in the textile to be controlled by the impregnation material. The textile impregnation process can be carried out online or offline. Figure. 5a illustrates the process. Typically, the dry textile is immersed in an impregnation bath and then squeezed through rollers so that the impregnation can better penetrate the yarn.

The impregnation is followed either by a heating unit (current standard) in which the impregnation is cured and can then be cut off or rolled up by a rewind unit which rolls up the uncured textile. The chosen impregnation material and manufacturing method has a decisive influence on the bond behaviour of TRC, with impregnated textiles usually exhibiting higher bond strengths than dry ones [22, 32, 73, 115–118].

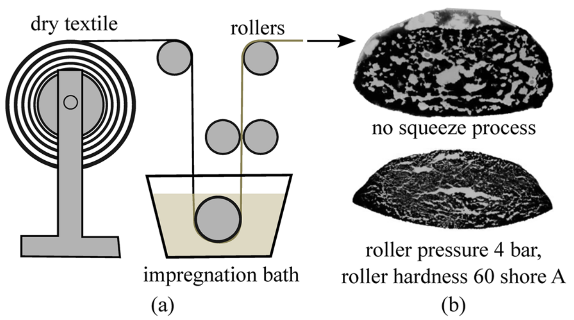

Fig. 5 Overview of the impregnation processes: **a** immersion in impregnation bath and squeezing trough rollers (in accordance with [112, 113]). **b** Yarn cross-sectional shape in dependency of roller pressure and shape (Figure taken and adapted from [114], licensed under CC BY 4.0)

Also, the used rollers and the squeeze pressure not only influences the impregnation rate, but also the geometry of the textile, see for example Fig. 5b where the cross-section of non-treated epoxy-impregnated yarns and yarns where the epoxy was squeezed with hard rollers (60 shore A) and a pressure of 4 bar into the textile [114] are displayed.

5.1 Polymer-based impregnations

The key criteria for selection of a suitable polymeric impregnation matrix are the impact on chemical and mechanical properties, temperature range and exposure time that the impregnation matrix must withstand during its application. The impregnation forms a closed surface on the fabric, which determines the bond performance, mostly independent of whether the fabric is fully or only partly impregnated. Donnini et al. [87], investigated the effects of various kinds and dosages of organic impregnations of a carbon fabric on the bonding behaviour with mortar. Direct tensile, pull-off, and shear-bond double-lap tests were conducted. By altering the degree of impregnation of the fabric during its manufacture, experiments are conducted on various combinations of textiles and mortars, namely: dry fabric (Dry), light impregnation (L), medium impregnation (M), and high impregnation (H). While the failure mode did not alter, the peak load increased by 75% in the double shear test results when the fabric exhibited a medium (M) or high impregnation grade (H). Only in the case of very light impregnation grade (L) the behaviour was quite similar to the dry fabrics.

In an industrial scale, epoxy resin or styrene-butadiene rubber are currently used as polymeric impregnation materials [112, 113]. SBR impregnated textiles are addressed as "weak" impregnation, where the bond behaviour between yarn and matrix is composed by friction and chemical bond on the surface [35], visible by a larger volume of reaction products of the hydration on the fibre surface [119, 120]. By contrast the epoxy-based impregnations show a relatively poor chemical bond between resin and cementitious matrix. The bond performance is mainly governed by friction and mechanical interlock which relies on geometric irregularities along the yarn [15]. Studies have adopted the strategy of decorating the surface of the epoxy-impregnated fabric aiming at invoking a pozzolanic reaction at the polymer-cement interface [66]. Coating the epoxy-impregnated fabric with cement powder, for example, enhanced the bonding strength by 25% over the control samples. Hybrid fillers combining epoxy and active micro-silica particle also significantly improved the bond performance of the composites [121].

5.2 Mineral impregnation

Polymeric impregnations are sensitive to moist and alkaline environments (ageing). Consequently, the composite material often fails to perform over time according to expectations. Moreover, an increase in temperature reduces the stiffness for interfilamentous and interfacial load transfer, thus decreasing mechanical performance and increasing the deformability of the yarn [122–124]. This can be linked to the glass transition temperature (Tg) of the plastic-based impregnation, which for polymer-based impregnations is comparably low at around 100 °C. Researcher have instead tried to use inorganic particle impregnations (e.g., micro and nano-silica slurries) without the use of polymeric impregnations. In one of the first studies on this topic the effect of nano- and micro-silica impregnation in comparison to dry and epoxy-impregnated textiles was investigated, with good mechanical properties observed for the micro-silica type [40]. Shrinkage issues, however, became apparent for this new impregnation type [32], initiating broader investigations in the field of mineral based impregnations.

To ensure good impregnation abilities, mineral-based suspensions require small maximum grain size of the solid raw materials and an optimised grain size distribution. A small maximum particle size enables soaking of the fine filament interspaces of carbon fibre yarns [125, 126], while a low plastic viscosity allows for rapid penetration of the filament interstices. The large surface area of the small particles, however, makes it difficult to set an optimal and consistent suspension. A particle size distribution according to the principle of closest packing provides improved rheological properties of the fresh suspension and reduces instabilities such as sedimentation and bleeding. Materials such as Portland cement clinker, granulated blast furnace slag and micro silica with different compositions are used as textile impregnation material, as can be found for example in [10, 125, 127, 128]. Alternative binders with latent hydraulic or pozzolanic substances such as granulated blast furnace slag, metakaolin or fly ash, whose reaction is caused by an alkaline activation, so called alkali-activated binders (AAB), and geopolymer binders (GP) [129], have also been used [130–136]. The resulting reaction products are also called aluminosilicate binders. Mineral-impregnated yarns can be placed in the concrete either in the fresh state or cured [137], which changes the bond strength. Both variants can be attributed to a very high chemical bond between the mineral impregnation and the surrounding concrete, as they are chemically complementary to one another and promote formation of more reaction products from cement hydration. This results in a fine distributed crack pattern with crack widths below 0.1 mm [135, 138]. Due to the small crack width, elements reinforced with mineral-impregnated textiles have self-healing capabilities. Moreover, the inorganic impregnation is less susceptible to high temperatures [126].

6 Influence of textile architecture and surface characteristics on bonding

In addition to composition, the architecture and geometry of the textile reinforcement influences their bond performance. These effects can sometimes work against the mechanical properties, for example, higher yarn fineness in dry textiles leads to higher surface area and adhesion, but a weaker tensile strength [74, 117]. Moreover, the interfacial area is impacted by the yarns flattening (in the case of textiles with tricot and plain stitches) or compactness (in the case of textiles with the pillar stitch) [139].

6.1 Textile architecture

The geometry of the textiles is influenced by the manufacturing process. In general, impregnated textiles tend to have a flat, elliptical shape because of the fabrication process [140, 141], where the impregnation material is squeezed into the voids between the filaments by means of rollers [114]. This results in a high circumference to cross-sectional area ratio, which is naturally a minimum in case of a circle [142]. The high ratio leads to a larger contact area with the cementitious matrix, thus increasing the transferable bond force [31]. The elliptical shape, however, causes a non-uniform distribution of the concrete stresses due to bond action (see Fig. 6; [43]), increasing the splitting tensile stresses and thus making the TRC-component more susceptible to splitting bond failure [143, 144].

Besides the elliptical shapes it was observed that textiles often exhibit a geometrical variation in longitudinal direction. This variation is influenced by the manufacturing process as for example in warp-knitted fabrics the knitting thread compresses the weft and warp thread by tightening around them [145]. In addition, the impregnation material is squeezed into the yarn by rollers which leads to a periodic widening and thickening of the yarn between the intersections [146]. Yarns that exhibit such a periodic geometry can achieve mechanical interlock if stiff impregnation material locks this shape in place [14, 35]. Figure. 7a-b depicts digital 3D models obtained from laser scans conducted on two different types of yarns and the results of pull-out tests on them [16]. While yarn type F (Fig. 7a) is straight in longitudinal direction, yarn type S (Fig. 7b) exhibits a pronounced periodic variation in cross-sectional dimensions. Figure. 7c indicates a clear difference in the bond stiffness and strength due to different mechanisms acting at the interface (Friction against mechanical interlock). Similar results were shown by Peled and Mobasher in comparing pull-out responses of yarns extracted from woven, knitted and bonded textiles [53].

Researchers tried to make use of the increased bond performance and created textiles with profiles

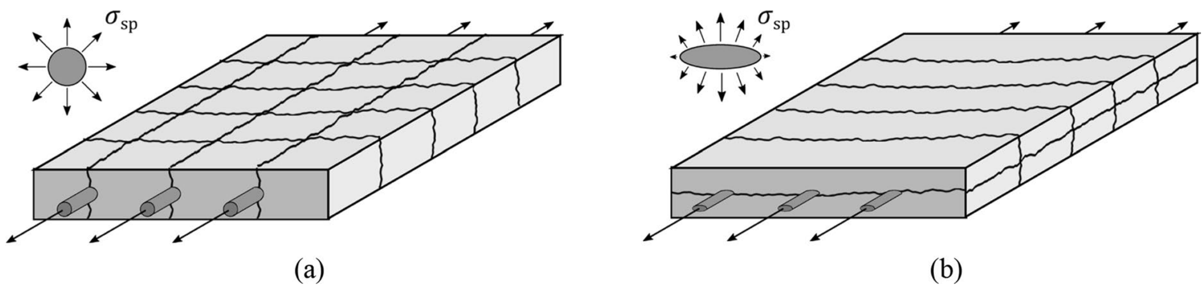

Fig. 6 Possible formation of splitting cracks in TRC depending on the cross-sectional geometry of the reinforcement: for a circular cross section **a** and an elliptical cross section **b** (Figure taken and adapted from [18], licensed under CC BY 4.0)

to achieve this mechanical interlock with reliable quality. Penzel et al. [147], studied the effect of profiles on tensile and bond behaviour and showed the bond profiled yarns to be superior to standard yarns and that bond modification is feasible by varying the profile geometry as well as the impregnation and consolidation parameters. Different profile characteristics of textiles such as dry yarn, impregnated yarns, yarns from warp-knitted textiles and tetrahedral profiled yarns were investigated in this study. The latter was able to transmit greater pull-out loads of 500% compared to unprofiled yarns and 140% compared to warp-knitted yarns (that shows slight waviness and yarn constriction), while still retaining a high tensile strength because of an effective penetration of the impregnating agent. The greatest bond strength was measured to be as high as 100 N/mm and was achieved for yarns with a distinct profile and a high solid content of the impregnation agent (50%), which was consolidated for a long time [147].

Fabrication process also attributes to the potential waviness of the textiles, which can be due to yarns not being perfectly straight or connected asymmetrically at the intersections [146]. A bond-increasing influence in the presence of a textile waviness was observed by researchers [21, 148], who showed that a mechanical anchorage is achieved for high curvatures when the yarn is pulled out of the concrete. The deviation forces that occur from the deviation of the yarn axis to the layer of reinforcement cause additional splitting tensile stresses [149, 150]. On the other hand, it was shown that prestressed textiles have higher bond strengths than textiles that are not prestressed [93]. While a potential waviness is eliminated, the Poisson's effect friction is increased between the textile fabric and the matrix. This has been shown for aramid, AR-Glass and carbon fibres [118].

Furthermore, the transverse yarns of the textile affect the bond performance. The knot resistance at the intersection of the warp and weft yarn is the subject of numerous studies [14, 35, 151]. A knitting thread solely provides little displacement resistance. However, the intersection is stiffened by impregnation, thus potentially creating a restraining force [152]. The resulting influence on the composite load-bearing behaviour is partly answered contradictorily. Bielak et al. [14], for example, assumed the knot resistance to be negligible while Ortlepp [153] observed a bond performance-increasing effect. Newer investigations indicate that the magnitude of the knot resistance is strongly dependent on the impregnation level of the textile and, more importantly, on the amount of impregnation material at the intersection. It also seems evident that the bond-increasing effect is increasing with smaller mesh width, as there are more transverse yarns present [153].

6.2 Surface characteristics

In addition to influencing the yarn geometry, a knitting thread affects the surface roughness and thus influences friction [22]. Ortlepp [153] considered this effect to be less distinct, especially for yarns with a higher yarn count, as in her experiments also the weft yarn showed similar bond properties when impregnated. In newer studies on epoxy-impregnated textiles with double-tricot binding, however, it was observed that the knitting thread creates small dips along the warp yarn, which compared to the weft yarn,

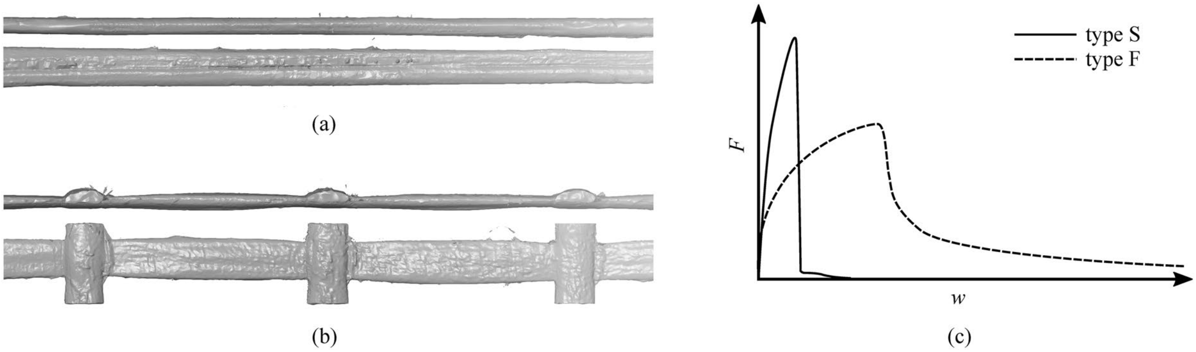

Fig. 7 Digital 3D models of different types of textile reinforcement: **a** Flat cross-sectional shape—type F, **b** Weft thread (German: Schussfaden)—type S (Figure taken and adapted from [43], licensed under CC BY 4.0). **c** Comparison of bond performance between those two yarns by means of a pull-out test (Figure reused from [16] with permission of Elsevier Ltd.)

where no such unevenness was present, significantly increased the bond performance. A negative influence on the bond strength due to thread coverage or the denser arrangement of filaments, as observed with unimpregnated textiles [154], is excluded due to the closed surface of the yarn as a result of impregnation.

It is well known that an additional sand-coating is significantly enhancing the bond performance of textile reinforcement [115]. This effect is also observable for FRP-bars [2, 85, 155–157] where sand-coating is widely implemented and can be traced back to a very good interlock of the fine quartz sand, which is applied on the yarn, with the surrounding cementitious matrix. In Donnini et al. [87] quartz sand was applied to fabrics with low (LS), medium (MS), and high (HS) degrees of impregnation. In comparison to the neat case, the peak load increases by 117% with a layer of quartz sand applied to the fabric surface (HS). The addition of sand also enhanced the pseudo-ductility and kept the strength greater after the peak load. To enhance the bond qualities of TRC, Morales Cruz et al. [158] studied the effect of a surface coating with epoxy resin and sand as a bonding agent. Sand mixed in resin and sand sprinkling methods were used in this experiment. The sand sprinkling method involves a standard coating procedure followed by the sprinkling of sand over the coated but uncured textile sample. The amount of sand sprinkled at an open mesh structure cannot be precisely controlled since the sprinkling procedure is manual [159]. However, it creates an even sand distribution and a high surface roughness, which improves the bond performance. If the sand is mixed into the resin already a higher adherence of the sand to the textile can be achieved.

Recent studies have investigated the effect on bonding when nano and micro hydrophilic particles are sprinkled on freshly impregnated textiles [50, 66]. While the method in general is the same as sand-coating and both improve bonding, the underlying effect is of different nature: the coarser and much larger sand particles increase the surface roughness while the hydrophilic particles aim at an enhancement of chemical bonding. In Alatawna et al. [50] the maximum bond strength was achieved for cement decorated epoxy-impregnated fabrics, where the pull-out strength was roughly twofold compared to a neat epoxy-impregnated fabric. This is because the cement reacted with the cementitious matrix and created a strong interlayer (see Fig. 8). On the other hand, decoration with graphene oxide (GO) particles provided the highest slippage energy, making this a suitable option for energy adsorbing systems.

7 Summary and concluding remarks

In Fig. 9 the complex interrelationships of the bond behaviour of TRC are visualised on the base of grouped author keywords from the cited literature. Four clusters are displayed in different colours: (a) Cluster green – bond properties, (b) cluster yellow – test methods, (c) cluster blue – mechanical properties and (d) cluster red – structural behaviour.

The connecting lines indicate when keywords were used in the same reference. Figure. 9 allows to draw

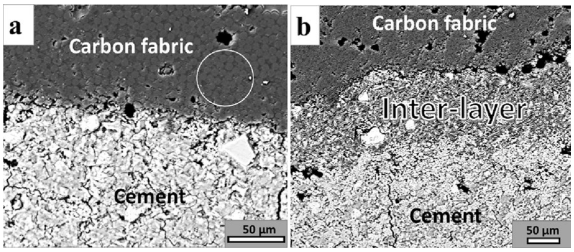

Fig. 8 SEM micrographs of the interface between epoxy impregnated carbon fabric and cement matrix: **a** neat epoxy (no coating), and **b** coated yarn with cement particles, showing an inter-layer due to chemical reaction between the coating cement particles and the cement matrix; (Figure by [66], licensed under CC BY 4.0)

conclusions on the interrelationships between individual parameters:

- Cluster green: The bond properties strongly differ whether the textile is impregnated or not. In case of dry textiles, the matrix composition has a strong influence on the chemical bonding with the fibres. Fibre surface modifications aim at improving the fibre/matrix bond. In case of impregnated fibres, the matrix is not able to penetrate the interstices of the yarn due to the closed surface. Mechanical interlock becomes a decisive bonding mechanism if geometric irregularities in longitudinal direction are preserved by the impregnation, e.g. yarn waviness or repeating thickening or widening of the yarn as a result of the fabrication process. Friction is dependent on the surface roughness and is influenced by the thread layout and textile architecture. It can be enhanced by applying a sand-coating to the textile. These aspects are not always differentiated in the literature, which makes it difficult to compare individual studies. More emphasis should be placed on fully characterizing the textiles used.
- Cluster yellow: The bond behaviour itself is determined by means of different test methods. These should be aligned with the test parameters. Yarn pull-out tests for example are well suited to determine the pull-out slip response of single yarns, whereas it cannot capture a potential splitting failure of the composite. Here pull off test or single-sided pull-out tests are more appropriate. Single-sided pull-out tests are a method to investigate the bond properties of a yarn under conditions similar to the intended application, e.g. matching cover thickness, whereas Double-sided pull-out tests allow for an easy determination of the anchorage length of textiles, considering also stochastic influences as several yarns are tested simultaneously. The results may be influenced by clamping pressure, however, for textiles impregnated with a stiff material. As in all cases the strains cannot be measured along the tested length, analytical models have to be used to derive a bond-slip law. In general, there is a wide variety in test configurations. More efforts should be made to harmonise them to a common standard.
- Cluster blue: The mechanical properties of the composite are directly affected by the bond performance of TRC. This is particularly true for non-impregnated (dry) and mineral-impregnated textiles, where a better fibre/matrix bonding increases textile utilization rate. Moreover, if the matrix better penetrates the interstices of the yarn, a telescopic failure can be avoided. Most research on the influence of bond on mechanical properties of TRC has been carried out for carbon and glass fibre, while fewer investigations can be found for basalt fibres. Other fibre types, such as natural fibres, PP or aramid fibres are seldom the focus of research due to various different reasons such as a low modulus of elasticity, lower alkali resistance or higher costs. The addition of short fibres can help to improve bond properties due to an additional crack bridging effect and cross-linking between textile and matrix. Current research topics include geopolymer matrixes, where little knowledge is still available. More general it can be stated that literature lags behind new developments, such as low carbon concretes and sustainable composites.
- Cluster red: The bond behaviour affects the structural behaviour of TRC. Higher bond strength and stiffness typically result in smaller crack distances and crack widths. High bond-stresses, however, may cause splitting cracking, thus leading to spalling of the concrete cover. This effect can be amplified by the geometry of the yarns, where in the case of an elliptical cross section, splitting tensile stresses are concentrated perpendicular to the dominant direction. With a sound understanding of the bond behaviour, the properties can be tailored according to the requirements of a structure,

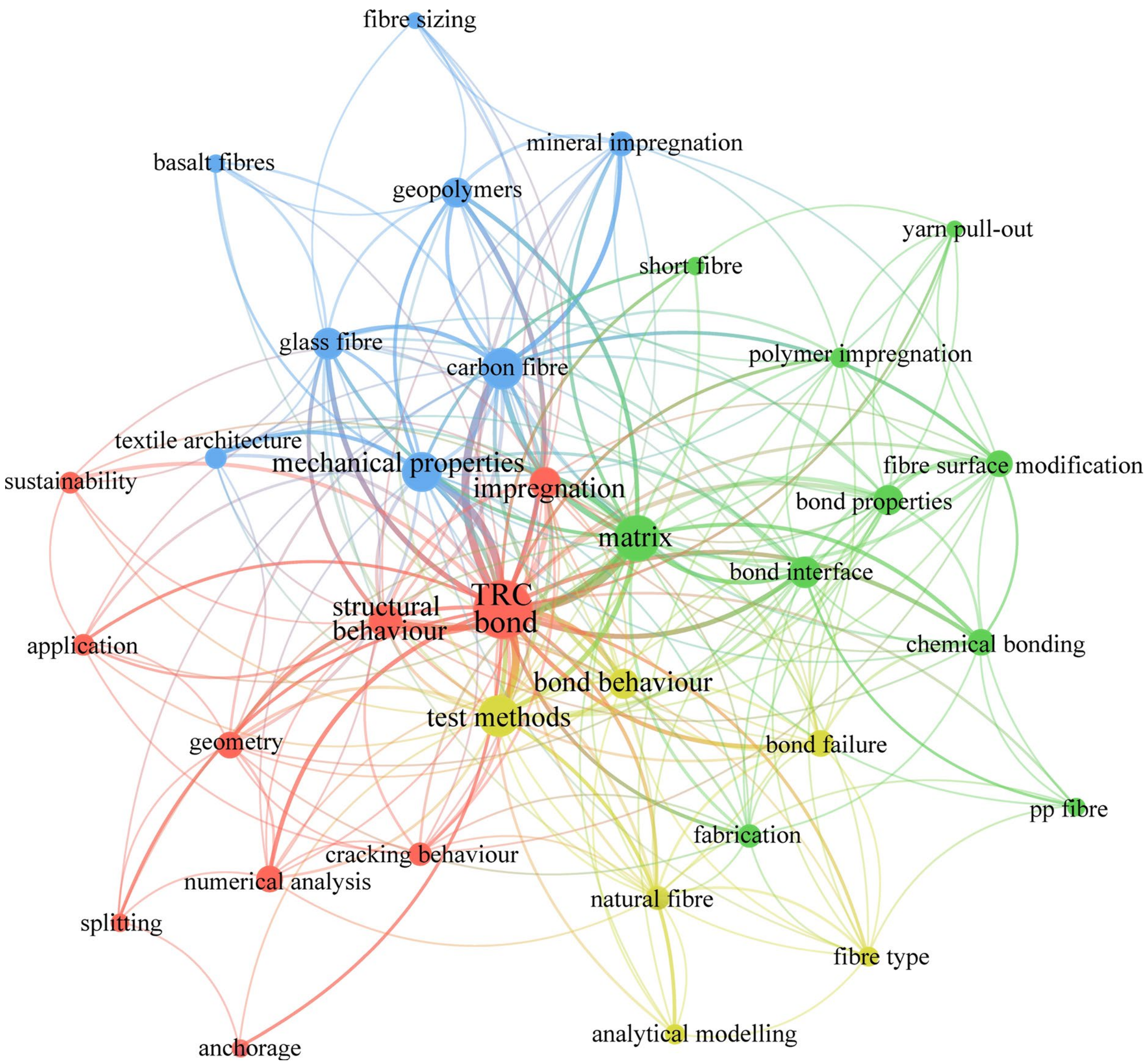

Fig. 9 Mapping of the complex interconnections of the bond behaviour of TRC on the base of grouped keywords. The visualisation was carried out with VOSviewer

hence increasing the sustainability of the application. However, little attention has been paid to this aspect in the past. Numerical analysis can help to account for the various different bond parameters that influence the structural behaviour.

In addition to the complex interrelationships in the bond behaviour of TRC, a source of confusion in the past has been the inconsistent and somewhat conflicting use of terms in the context of the bond behaviour of TRC. In the course of the RILEM TC292 WG1 work, and while preparing this manuscript, it was aimed for a unification of terms, see Fig. 3. It is expected that a clear naming of individual constituents, parameters and methods promotes a better understanding of this complex topic.

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