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Review

Textile-reinforced mortar as a potential for enhancing the frost resistance of strengthened structural members

Paraskevi D. Askouni[1,2,*]

[1] Department of Civil Engineering, University of Patras, 26504, Patras, Greece
[2] Service of Modern Monuments and Technical Works of Western Greece, Peloponnese and Southern Ionian Sea, Ministry of Culture, 26223, Patras, Greece

* **Correspondence:** Email: askounip@upatras.gr

Abstract: In this review, the potential of the textile-reinforced mortar (TRM) to act as a strengthening overlay of existing structural members and as a protective mean against frost damage of these members was investigated. The first part of the study regarded the effect of freeze-thaw cycles on the mechanical characteristics of various examined TRM systems, while the second part regarded the post-frost response of TRM-strengthened concrete or masonry members. The reduction of the tensile and flexural strength of the TRM systems due to freeze-thawing was significant. In addition, the increase of the number of freeze-thaw cycles led to the degradation of the stiffness of the textile-to-matrix and the TRM-to-substrate interface. However, when TRM was used as a strengthening overlay of concrete or masonry members, it could provide a protective barrier for the substrate against frost damage. It is highlighted that in most of the studies, the capacity of the exposed/strengthened specimens has been compared only with that of unexposed/strengthened counterparts. It is proposed that the role of TRM overlays will be better illuminated if researchers also compare the performance of exposed/strengthened specimens with that of exposed/un-strengthened ones. It is also noted that there is a need for an established standard dedicated to the assessment of the residual capacity of TRM-strengthened members after exposure to freeze-thaw cycles.

Keywords: textile-reinforced mortar; concrete; masonry; strengthening; freeze-thaw cycles; frost damage

1. Introduction

Textile-reinforced mortar (TRM) is a composite material consisting of a fibrous grid and inorganic matrix. The textile yarns can be made of various fiber types such as carbon, glass, basalt, aramide, polyphenylene benzobisoxazole (PBO), and flax [1,2]. In the common case of 2D grids, yarns are usually arranged in two orthogonal directions and may consist of dry fibers or be treated by coating or impregnation with polymers [3]. The mortars used as matrices are cement-, lime-, and gypsum-based, as well as alkali-activated [4,5]. In some design guidelines and in the relevant literature that regards the repair and strengthening of existing structures, this composite material is also referenced as fabric-reinforced cementitious mortar (FRCM) (e.g., [6,7]). In addition, some researchers use the term textile-reinforced concrete (TRC), which, however, is more accurate when this composite material is utilized for the construction of precast elements (e.g., [8]).

TRM is suitable for use as externally bonded strengthening reinforcement of concrete and masonry load-bearing members. Koutas et al. (2019) [9] reviewed scientific studies regarding the experimental investigation of TRM as a means for flexural, shear, confinement, and seismic retrofitting of concrete members. They concluded that TRM can increase the flexural and shear capacity of reinforced concrete members with typical geometries and the axial deformation capacity of confined elements. Furthermore, TRM can improve the seismic response of RC columns or joints in terms of ductility and energy dissipation, while it can also enhance the in- and out-of-plane performance of masonry-infilled RC frames. In the study by Toska et al. (2022) [10], it was also concluded that confinement and flexural strengthening of RC pre-damaged columns with TRM systems can lead to the recovery of their load-bearing capacity and lateral stiffness, respectively, when subjected to cyclic loading. In addition, in the study of Qu et al. (2024) [11], it was found that the TRM strengthening of pre-damaged masonry-infilled RC frames can restore the shear capacity and stiffness of the wall when the frame is subjected to cyclic lateral load. Kouris and Triantafillou (2018) [12] implemented state-of-the-art research in the studies regarding the effectiveness of TRM as a retrofitting technique for masonry columns, spandrel beams, and piers. They concluded that confinement of masonry columns with TRM jackets increases their ultimate load capacity as well as their ultimate strain. Additionally, they pointed out that TRM-based strengthening of masonry elements improves their in-plane or out-of-plane response in terms of strength and deformation capacity. Furthermore, in the study of Incerti et al. (2019) [13], it was pointed out that the TRM reinforcement of pre-damaged masonry walls subjected to diagonal compression partially recovered the shear strength of the walls that experienced a more ductile failure.

The service life of TRM highly depends, among other parameters, on its resistance to aggressive environments simulated by: immersion in chemical solutions (alkaline, saline, chloride, and acid); immersion in hot water for a certain period or exposure to wet-dry cycles (hygrothermal environment); and exposure to elevated/high temperatures or fire; exposure to freeze-thaw cycles [14–16]. However, there are no established standards for the evaluation of the TRM's durability. The researchers adopt various guidelines within which the simulation of the aggressive environments differentiates. It is noted that the features of these environments (e.g., the PH variation of an acidic environment [17], the immersion period in an alkaline solution [18], or the time inside a furnace [19]) are some parameters that among others affect the results of the durability tests. Focusing on the aggressive environment of freeze-thaw cycling, it is well known that porous materials such as concrete (as well as mortars) and bricks (being used as masonry units) are susceptible to frost damage and can suffer surface scaling or complete disintegration [20]. Frost damage of these materials is attributed to several mechanisms, among which the 9% volumetric expansion of water as it freezes is the dominant one [21]. The mortars used as a matrix are porous materials that render the TRM composite prone to damage caused by freeze-thaw cycling (e.g., [22]).

As has been proven in practice, the load-bearing elements of RC or masonry structures situated in areas with cold climate could suffer cracking or scaling due to frost, resulting in the deterioration of their material strength. In the scientific literature, there are experimental studies dedicated to the assessment of the freeze-thaw cycling effect on the residual capacity of various structural elements. Xu et al. (2016) [23] studied the seismic performance of frost-damaged RC columns, focusing on the effect of the number of freeze-thaw cycles (0, 100, 200, and 300) and the axial compression ratio (0.20 and 0.32). It is noted that during freeze-thaw exposure, the specimens were not submerged in water but only sprayed, and hence each number of cycles was related to different specimen's saturation degree. The maximum load corresponding to specimens subjected to 100 and 200 cycles was slightly higher than that of the reference one due to the late hydration of concrete, while the maximum load after 300 cycles was lower because of the higher amount of saturated water and hence the reduction of concrete's compressive strength due to its frost damage. It was also found that, for each number of cycles, the specimen with the higher compression ratio attained a higher maximum load. Rong et al. (2020) [24] studied the seismic behavior of frost-damaged RC shear walls, examining the parameters of: The number of freeze-thaw cycles (0, 100, 200, and 300); the concrete strength (C30, C40, and C50); and the axial load ratio (0.10, 0.20, and 0.30). It was concluded that the increase of cycles changed the flexural-shear failure mode of the walls from flexural- to shear-dominated and deteriorated their load carrying capacity. Additionally, the increase in the concrete strength or axial load ratio improved the load carrying capacity of the walls. Rong et al. (2022) [25] studied the seismic resistance of frost-damaged RC beams for various numbers of freeze-thaw cycles (0, 100, 200, and 300) and different concrete strengths (C30, C40, and C50). It was found that the increase in cycles increased the number and width of frost-induced cracks and a decrease in the load-bearing capacity. It was also pointed out that the increase in concrete strength enhanced the load-bearing capacity. Based on the aforementioned studies that are indicative of the effect of freeze-thaw cycling on various RC elements, it appears that the compressive strength deterioration of concrete is the main cause for the decrease in elements' load-bearing capacity. Regarding masonry elements, Uranjek and Bokan-Bosiljkov (2015) [26] studied the combined influence of various freeze-thaw cycles and moisture content on the performance of two types of historical brick masonry wallettes under post-frost-treatment uniaxial compression. Each wallette type was built with a different mortar. The residual mechanical properties of all wallettes subjected to 50 cycles were almost unaffected. The damages of wallettes after 150 cycles (detected in the bricks' surface and mortar joints) resulted in the stiffness reduction of the wallettes built with the mortar presenting the highest bond with the bricks. Tang et al. (2018) [27] studied the effect of both the number of freeze-thaw cycles and saturation degree on the compressive response of ancient brick masonry prisms under post-frost-treatment uniaxial loading. They concluded that the bricks' saturation degree related to the highest compressive strength and elastic modulus of all specimens (both unconditioned and conditioned) was approximately equal to 50% and was achieved after specific raining conditions and 10, 15, 20 freeze-thaw cycles. For higher saturation degrees (from 70% to 80%, corresponding to 25–35 cycles) both aforementioned prisms' mechanical characteristics decrease. Furthermore, Niu et al. (2018) [28] and Zhou et al. (2021) [29] studied the post-frost seismic performance of one-story/two-bay and one-story/one-bay RC frames, respectively, infilled with walls made of concrete bricks and cementitious mortar. It was found that load-carrying capacity, ductility, lateral stiffness, and energy dissipation capacity were decreasing while the number of freeze-thaw cycles was increasing from 0 to 120 cycles with step 40. It was highlighted that the degradation of frames' seismic response was due to the deterioration of the mechanical properties of frames' concrete and wall constituents, as well as due to the reduction of shear bond strength between brick and mortar.

I examine the potential of the TRM composite to act simultaneously as a strengthening overlay of existing structural members and as a protective means against frost damage of these members. In the first part of the study, I regard the effect of freeze-thaw cycles on the mechanical characteristics of various examined TRM systems, while in the second part, I asses the capacity of TRM-strengthened concrete or masonry members after their exposure to freeze-thawing are critically discussed.

2. Mechanical response of TRM after freeze-thaw cycling

In this section, I regard the effect of freeze-thawing on the residual mechanical characteristics of various TRM systems examined in the literature. Among the studies that examine the tensile and flexural response of TRM systems, as well as the yarn-to-matrix bond, only those regarding the effect of various numbers of freeze-thaw cycles are presented. Thereafter, the major conclusions of the studies dedicated to the topic of the post-frost TRM-to-substrate bond are discussed in more detail. It is highlighted that the TRM bond capacity when applied as external reinforcement to existing structural members is a crucial parameter for the successful exploitation of this composite material as a strengthening technique [30,31].

2.1. Tensile response

Colombo et al. (2015) [22] conducted post freeze-thaw tests of uniaxial tension employing TRM coupon-shaped specimens with rectangular cross-section made of coated alkali resistant (AR) glass fiber textile and cementitious matrix. They investigated the effect of various numbers of cycles (i.e., 0, 25, 50, 75, 100, 150, and 500 cycles simulated according to the Procedure A of ASTM C 666 recommendation [32]) on the tensile response of both un-cracked and pre-cracked specimens. It was concluded that the average tensile strength of the un-cracked specimens decreased as the number of cycles increased, while the strength reduction was significant for 500 cycles (equal to 21%). In the case of the pre-cracked specimens, the strength reduction was prevented by the textile-to-matrix bond recovery that was assumed to take place due to the self-healing and late hydration of the matrix. Machovec and Reiterman (2018) [33] also implemented post-freeze-thaw uniaxial tensile tests using TRM dog-bone shaped specimens made of coated E-glass fiber textile and cementitious matrix. Specimens reinforced with one or two layers of textiles with various square weights (representing different fiber volume ratios of the composite) were subjected to 0, 50, 100, and 150 cycles. It is noted that the tensile response of both the unconditioned and the conditioned specimens was not characterized by strain-hardening, and the first crack stress was the maximum stress attained during testing. It was found that the average first crack stress decreased as the cycles increased from 0 to 100, while it was not further affected by the cycles' increase from 100 to 150 (corresponding percentage reductions were comparable). In addition, the authors concluded that the resistance to freeze-thaw cycles increased as the fiber volume ratio increased. Furthermore, Shiping et al. (2021) [34]

investigated the tensile response of TRM coupons made of hybrid carbon and AR-glass fiber textile and fiber reinforced cementitious matrix, after their exposure to 50, 75, and 100 freeze-thaw cycles in a sodium sulfate solution. It was concluded that the average coupons' tensile strength decreased as the number of cycles increased; however, the strength decay was important only for the maximum number of cycles (this outcome also applied to the first crack stress). In addition, the authors highlighted that irrespective of the number of cycles, all specimens presented a strain hardening response. Dalalbashi et al. (2022) [35] studied the tensile response of TRM coupons made of coated AR-glass fiber textile and lime-based matrix after their exposure to 0, 60, 120, 180, 240, 300, and 360 freeze-thaw cycles. It was noticed that in comparison to the unexposed specimens, the average first crack stress of the exposed ones decreased after 60 cycles, increased after 120 to 240 cycles, and significantly decreased after 300 and 360 cycles. In addition, the authors proposed the comparison of the exposed specimens at 180 and 360 cycles with the control ones at the same age (i.e., age equal to the curing time plus the time needed for the implementation of each number of cycles), ending up as the same as the previous notation regarding the first crack stress (i.e., higher/lower in exposed specimens at 180/360 cycles compared to that of the control ones at the same age). Finally, Xu et al. (2023) [36] carried out uniaxial tensile tests with TRM dog-bone shaped specimens made of coated basalt or dry carbon fiber textile and fiber reinforced cementitious matrix. The specimens were previously exposed to 0, 100, 200, and 300 freeze-thaw cycles according to the provisions of GB/T 50082-2009 [37]. In comparison to the unexposed specimens, the average tensile strength of the exposed ones slightly increased for 100 cycles due to the late hydration of the matrix and decreased by around 3% and 20% for 200 and 300 cycles.

Based on the aforementioned studies regarding the tensile response of TRM systems after exposure to various numbers of freeze-thaw cycles, it is deduced that there is a critical number of cycles beyond which the decrease of TRM strength or first crack stress is irreversible. It also appears that the pre-cracking of the TRM and the increase of its fiber volume ratio are both beneficial for its post-frost tensile response (note: these two parameters can be considered beneficial within the examined range of their values). The studies discussed in this section are summarized in Table 1.

Table 1. Summary of studies regarding the post-frost tensile response of TRM systems.

Study	TRM system		Specimen	Freeze-thaw cycles		Reduction of tensile strength (%)****
	Textile/fiber (T/Y/FS)*	Matrix (Fl/CS)**		Temperature range/duration/freezing-thawing fluid (standard/recommendation)	Number***	
[22]	Coated/AR-glass (TS 820 MPa)	Cementitious (Fl/CS 13.6/97.5 MPa)	Coupon	−18 to +4 °C/5 h/water–water (ASTM C 666: Procedure A [32])	0, 25, 50, 75, 100, 150, **500**	21
[33]	Coated/E-glass (-)	Cementitious (Fl/CS 11.5/122.7 MPa)	Dog-bone	−18 to +20 °C/6 h/air–water	0, 50, **100**, 150	46
[34]	Dry/carbon & AR-glass (hybrid) (YS 3600 MPa)	Fiber-reinforced cementitious (-)	Coupon	(-)/(-)/Na_2SO_4 solution–Na_2SO_4 solution	50, 75, **100**	25
[35]	Coated/AR-glass (TS 875 MPa)	Lime-based (Fl/CS 4.5/16.8 MPa)	Coupon	−10 to +30 °C/16 h/air {60% relative humidity-RH}–air {90 % RH}	0, 60, 120, 180, 240, **300**, 360	36
[36]	Coated/basalt (FS 1700 MPa)	Fiber-reinforced cementitious (-)	Dog-bone	−18 to +5 °C/6 h/water–water (GB/T 50082-2009 [37])	0, 100, 200, **300**	20
[36]	Dry/carbon (FS 3400 MPa)	Fiber-reinforced cementitious (-)	Dog-bone	−18 to +5 °C/6 h/water–water (GB/T 50082-2009 [37])	0, 100, 200, **300**	20

*Note: Depending on the available data, T/Y/FS is the tensile strength [S] of the textile [T] or of each yarn [Y] or of each fiber [F] in the load-bearing direction. **Note: Depending on the available data, Fl/CS is the flexural [Fl] and/or the compressive [C] strength of the matrix at 28 days. ***Note: The number in bold signifies the number of cycles corresponding to the first statistically significant reduction of the tensile strength; beyond this number, the reduction is getting higher.****Note: The reduction is calculated in relation to the tensile strength corresponding to 0 freeze-thaw cycles, except for [34] where reduction is calculated in relation to the strength corresponding to 50 cycles, and corresponds to the number of cycles that signals the first statistically significant reduction of the tensile strength.

2.2. Flexural response

Yin et al. (2019) [38] implemented flexural tests employing TRM specimens made of hybrid carbon and E-glass fiber textiles (impregnated with epoxy resin and coated with sand), as well as cementitious matrix. The specimens were previously exposed to 0, 50, 70, and 90 freeze-thaw cycles in sodium chloride solution according to GB/T 50082-2009 [37]. It emerged that the flexural strength decreased significantly (by almost 30%) only after exposure to 90 cycles. The authors attributed the reduction of flexural strength to the expansion of the matrix and hence the decrease of its compression strength (which rendered the matrix less capable of carrying the stresses in the compression zone during bending of the TRM specimens). They also highlighted that the yarn-to-matrix bond did not affect the specimens' flexural response, since the strength resulting from pull-out tests was not reduced after freeze-thawing (see also Section 2.3). Yin et al. (2021) [34] also investigated the flexural response of TRM specimens made of hybrid carbon and AR-glass fiber textile and fiber reinforced cementitious matrix, after their exposure to 50, 75, and 100 freeze-thaw cycles in sodium sulfate solution. It was concluded that the average specimens' flexural strength as well as the initial cracking load decreased as the number of cycles increased, with the decrease being significant only for the maximum number of cycles considered. Based on this conclusion and on what was discussed previously (see Section 2.1), it is highlighted that the effect of the number of cycles was the same for both the flexural and tensile strength of the studied TRM system. In addition, Xu et al. (2023) [36] carried out flexural tests with TRM specimens made of coated basalt or dry carbon fiber textile and fiber-reinforced cementitious matrix. The specimens were previously exposed to 0, 100, 200, and 300 freeze-thaw cycles according to the provisions of GB/T 50082-2009 [37]. In comparison to the unexposed specimens, the average tensile strength of the exposed ones decreased for all numbers of cycles examined, while the reduction was significant (>20%) for 200 and 300 cycles. For the implementation of flexural tests, Cai et al. (2023) [39] prepared two series of TRC specimens made of coated basalt fiber textile embedded in a concrete matrix with an air-entraining agent and characterized by different fiber content. The specimens were previously exposed to 0, 20, 40, 60, 80, and 100 freeze-thaw cycles according to GB/T 50082-2009 [37]. As the number of cycles increased, the flexural strength decreased; regarding the specimens with the low fiber content, the strength reduction was important only for 100 cycles, while the strength of the specimens with the high fiber content started to decrease significantly, already after exposure to 40 cycles. It is noted that the findings related to the flexural response of the specimens with the low fiber content did not harmonize with those of pull-out tests conducted in the context of the same study (see also Section 2.3).

Based on the aforementioned studies regarding the flexural response of TRM systems after exposure to various numbers of freeze-thaw cycles, it is deduced that there is a critical number of cycles beyond which the decrease of TRM strength is irreversible, as also concluded from the results of the post-frost tensile tests. In addition, it appears that the effect of freeze-thawing on the flexural strength of a TRM system is not always related to the residual yarn-to-matrix pull-out strength of the same system; the harmonization of the results of the flexural and pull-out tests probably depends on the fiber content of the composite. The studies discussed in this section are summarized in Table 2.

Table 2. Summary of studies regarding the post-frost flexural response of TRM systems.

Study	TRM system		Specimen	Freeze-thaw cycles		Reduction of flexural strength (%)****
	Textile/fiber (T/Y/FS)*	Matrix (Fl/CS)**		Temperature range/duration/freezing-thawing fluid (standard/recommendation)	Number***	
[38]	Epoxy-impregnated & sand-coated/carbon & E-glass (hybrid) (YS 4203MPa)	Cementitious (CS 52.8 MPa)	Coupon-beam	−18 to +5 °C/3 h/NaCl solution–NaCl solution (GB/T 50082-2009 [37])	0, 50, 70, **90**	29
[34]	Dry/carbon & AR-glass (hybrid) (YS 3600 MPa)	Fiber-reinforced cementitious (-)	Coupon-beam	(-)/(-)/Na_2SO_4 solution–Na_2SO_4 solution	50, 75, **100**	35
[36]	Coated/basalt (FS 1700 MPa)	Fiber-reinforced cementitious (-)	Beam	−18 to +5 °C/6 h/water–water (GB/T 50082-2009 [37])	0, 100, **200**, 300	23
[36]	Dry/carbon (FS 3400 MPa)	Fiber-reinforced cementitious (-)	Beam	−18 to +5 °C/6 h/water–water (GB/T 50082-2009 [37])	0, 100, **200**, 300	28
[39]	Coated/basalt (fiber content 3.6K) (YS 2100 MPa)	Concrete with air-entraining agent (CS 40.6 MPa)	Coupon-beam	−16 to +3 °C/4 h/water–water (GB/T 50082-2009 [37])	0, 20, 40, 60, 80, **100**	31
[39]	Coated/basalt (fiber content 10.8K) (-)	Concrete with air-entraining agent (CS 40.6 MPa)	Coupon-beam	−16 to +3 °C/4 h/water–water (GB/T 50082-2009 [37])	0, 20, **40**, 60, 80, 100	30

*Note: Depending on the available data, T/Y/FS is the tensile strength [S] of the textile [T] or of each yarn [Y] or of each fiber [F] in the load-bearing direction. **Note: Depending on the available data, Fl/CS is the flexural [Fl] and/or the compressive [C] strength of the matrix at 28 days. ***Note: The number in bold signifies the number of cycles corresponding to the first statistically significant reduction of the flexural strength; beyond this number, the reduction is getting higher.****Note: The reduction is calculated in relation to the flexural strength corresponding to 0 freeze-thaw cycles, except for [34] where reduction is calculated in relation to the strength corresponding to 50 cycles, and corresponds to the number of cycles that signals the first statistically significant reduction of the tensile strength.

2.3. Yarn-to-matrix bond

Yin et al. (2019) [38] performed pull-out tests using TRM notched coupons with a rectangular cross-section made of hybrid carbon and E-glass fiber textile (impregnated with epoxy resin and coated with sand), as well as cementitious matrix. The specimens were previously exposed to 0, 50, 70, and 90 freeze-thaw cycles in sodium chloride solution according to GB/T 50082-2009 [37]; it turned out that their average post-frost pull-out strength remained unaffected in comparison to that of the reference specimens. The TRM specimens used by Dalalbashi et al. (2021) [40] and Dalalbashi et al. (2022) [35] for the implementation of pull-out tests consisted of a matrix prism and a yarn protruding from the inside of the prism. The matrix was a lime-based mortar, and the yarn was coated and made of AR-glass fibers. In the study of Dalalbashi et al. (2021) [40], various yarn configurations were examined, namely a single yarn, a single yarn with transversal elements and a double yarn (two yarns connected with transversal elements); for the first configuration, various yarn's bond lengths (50, 75, and 100 mm) were considered too. The specimens were tested after their exposure to 0, 60, 180, 300, and 360 freeze-thaw cycles. The authors also tested some unexposed specimens that had the same age as those exposed to 360 cycles. This choice was dictated by the fact that lime-based mortars harden over time under the combination of hydration and carbonation. Regarding the effect of the bond length, it occurred that the average bond strength of specimens with the shortest bond length decreased, while the strength of the rest specimens increased after exposure to 360 cycles. However, when comparing the bond strength of the specimens exposed to 360 cycles with that of the unexposed ones of the same age, it appears to be identical, irrespective of the bond length considered. Regarding the specimens with different yarn configurations, it appears that only the bond strength of those with the double yarns exposed to 360 cycles decreased in comparison to the strength of the unexposed ones (of the same age or age equal to the curing time). The study of Dalalbashi et al. (2022) [35] adopted the results of the specimens with the 50 mm long single yarn presented in [40] and enriched them with that of specimens exposed to 120 and 240 cycles, as well as with that of unexposed specimens, which had the same age as those exposed to 180 cycles. The additional finding was that the bond strength of specimens exposed to 180 cycles was lower than that of the unexposed ones of the same age. Therefore, depending on the age of lime-based mortar, the deterioration of the bond strength can be attributed to the effect of freeze-thawing and/or the shrinkage of the mortar. For the implementation of pull-out tests, Cai et al. (2023) [39] prepared two series of TRC notched coupons made of coated basalt fiber textile and concrete matrix with air-entraining agent; each series was characterized by different fiber content. The specimens were previously exposed to 0, 20, 40, 60, 80, and 100 freeze-thaw cycles according to GB/T 50082-2009 [37]. It was found that for both fiber contents examined, the freeze-thawing resulted in the reduction of the residual yarn-to-matrix bond strength, which was higher as the number of cycles increased. The authors attributed this phenomenon to the weakening of the bonding surface as the cycles increased, while they also highlighted the increase in cracks and holes in the matrix.

Based on the aforementioned studies regarding the yarn-to-matrix bond of TRM systems after exposure to various numbers of freeze-thaw cycles, it appears that the type of mortar used as a matrix decisively affects the pull-out strength of the yarn. The studies discussed in this section are summarized in Table 3.

Table 3. Summary of studies regarding the post-frost yarn-to-matrix bond of TRM systems.

Study	TRM system		Specimen (yarn's bond length)	Freeze-thaw cycles		Reduction of pull-out strength (%)****
	Textile/fiber (T/Y/FS)*	Matrix (Fl/CS)**		Temperature range/duration/freezing–thawing fluid (standard/recommendation)	Number***	
[38]	Epoxy-impregnated & sand-coated/carbon & E-glass (hybrid) (YS 4203 MPa)	Cementitious (CS 52.8 MPa)	Notched coupon (20 mm)	−18 to +5 °C/3 h/NaCl solution–NaCl solution (GB/T 50082-2009 [37])	0, 50, 70, **90**	2
[40]	Coated/AR-glass (TS 875 MPa)	Lime-based (Fl/CS 4.5/16.8 MPa)	Matrix prism with protruding <u>single</u> yarn (50mm)	−10 to +30 °C/16 h/air {60 % RH}–air {90 % RH}	0, 60, 180, **300**, 360	34
[40]	Coated/AR-glass (TS 875 MPa)	Lime-based (Fl/CS 4.5/16.8 MPa)	Matrix prism with protruding <u>double</u> yarn (50mm)	−10 to +30 °C/16 h/air {60 % RH}–air {90 % RH}	0, 60, **180**, 300, 360	40
[35]	Coated/AR-glass (TS 875 MPa)	Lime-based (Fl/CS 4.5/16.8 MPa)	Matrix prism with protruding single yarn (50 mm)	−10 to +30 °C/16 h/air {60 % RH}–air {90 % RH}	0, 60, 120, 180, 240, **300**, 360	34
[39]	Coated/basalt (fiber content 3.6K) (YS 2100 MPa)	Concrete with air-entraining agent (CS 40.6 MPa)	Notched coupon (160 mm)	−16 to +3 °C/4 h /water–water (GB/T 50082-2009 [37])	0, **20**, 40, 60, 80, 100	25
[39]	Coated/basalt (fiber content 10.8K) (-)	Concrete with air-entraining agent (CS 40.6 MPa)	Notched coupon (160 mm)	−16 to +3 °C/4 h/water–water (GB/T 50082-2009 [37])	0, **20**, 40, 60, 80, 100	24

*Note: Depending on the available data, T/Y/FS is the tensile strength [S] of the textile [T] or of each yarn [Y] or of each fiber [F] in the load-bearing direction. **Note: Depending on the available data, Fl/CS is the flexural [Fl] and/or the compressive [C] strength of the matrix at 28 days. ***Note: The number in bold signifies the number of cycles that corresponds to the first statistically significant reduction of the pull-out strength; beyond this number, the reduction is getting higher. ****Note: The reduction is calculated in relation to the pull-out strength corresponding to 0 freeze-thaw cycles and corresponds to the number of cycles that signals the first statistically significant reduction of the tensile strength.

2.4. TRM-to-substrate bond

2.4.1. Concrete substrate

Yin et al. (2018) [41] adopted the double-lap/single-prism setup for the implementation of shear bond tests. To this purpose, the authors used concrete prisms bilaterally reinforced with precast TRM sheets (bonded on the substrate using the same mortar as the one used as matrix of the overlay). The TRM system was identical to that used in [38]. Prior to mechanical testing, specimens were exposed to 0, 40, and 60 chloride freeze-thaw cycles according to [37]. Except for the number of cycles, additional examined parameters were the pre-cracking degree of the TRM sheets, the addition of short-cut fibers in the matrix, the compressive strength of the substrate, and its surface treatment. The dominant failure mode of both the untreated (reference) and treated specimens was due to the detachment at the TRM-to-substrate interface. The main outcome was that the freeze-thaw cycles did not seriously deteriorate the integrity of the TRM sheets, but they significantly reduced the bond strength of the TRM-to-substrate interface. It was also found that the bond strength of this interface could be improved by increasing the concrete strength, roughening the substrate's surface, and adding short-cut fibers in the matrix. Regarding the pre-cracking degree of the TRM sheets (i.e., the number of cracks developed due to loading of the overlay up to 20%, 40%, and 60% of its bending strength before its application to the substrate), it was found to be beneficial to some extent. Al-Jaberi et al. (2019) [42] studied the effect of weather conditions simulated by freeze-thaw, as well as high temperature and relative humidity cycles on the bond performance of two TRM systems, when applied to concrete masonry units through the cast-in-place method. It is specified that pre-testing specimens' weathering included sequentially: 50 freeze-thaw cycles, 150 high temperature (from 27 to 50 °C), and relative humidity (from 60% to 100%) cycles, 50 freeze-thaw cycles. The composites consisted of dry PBO or carbon fibre textiles embedded in cementitious mortars of different compressive strengths. All exposed specimens failed due to detachment at the textile-to-matrix interface, as did the reference ones. The bottom matrix layer of the TRM systems remained always bonded to the substrate. The bond strength of both TRM systems was not significantly affected by the weather exposure scenario. However, the textile slip at failure was significantly increased for exposed specimens in comparison to the unexposed ones. It is highlighted that in the context of this study, the effect of freeze-thawing cannot be isolated from that of high temperature and humidity cycles. Askouni and Papanicolaou (2021) [43] also used the single-lap/single-prism setup to study the in-plane bond of TRM overlays applied on concrete prisms through the cast-in-place method. Two TRM systems were examined; they shared the same textile (made of yarns with dry carbon fibers) and comprised cementitious matrices of different densities (a normal-weight with limestone sand and a lightweight one with pumice sand). Before mechanical testing, specimens were exposed to 0, 10, 30, 50, 60, and 70 freeze-thaw cycles according to Procedure B of the ASTM C 666 recommendation [32]. The failure mode of the reference specimens was due to tensile failure of the textile. The treated specimens exposed to 10 to 60 cycles failed due to the textile's failure (in case of TRM with normal-weight or lightweight matrix) or sliding of the textile within the matrix (in case of TRM with lightweight matrix). The specimens exposed to 70 cycles failed due to detachment at the TRM-to-substrate interface (irrespective of the matrix examined). Cycles' increase resulted in the intensification of partial detachment phenomena at textile-to-matrix interface and the weakening of the textile-to-matrix bond, with the lightweight matrix being more prone to these effects. Therefore, freeze-thawing led to a change in the failure mode of the specimens and the deterioration of both TRM systems' integrity. In addition, Verre and Cascardi (2022) [44] implemented the single-lap/single-prism test for the investigation of the bond of single or double TRM overlays with concrete. The composite consisted of PBO or dry carbon fiber textile and cementitious matrix, while it was applied on sandblasted concrete prisms through the cast-in-place method. The specimens were tested after their exposure to 0 and 20 freeze-thaw cycles according to the provisions of CNR-DT 215/2018 [45]. All specimens (both exposed and unexposed) failed due to textile sliding within the matrix, while no detachment phenomena at textile-to-matrix or TRM-to-substrate interface were observed. Freeze-thawing did not change the failure mode of the specimens and had a slightly positive effect on their bond capacity, irrespective of the fibers' type and the TRM overlay number. The increase in the specimens' bond strength due to freeze-thawing, although systematic, was statistically insignificant. The post-frost good performance of TRM systems was attributed, among others, to the matrix and substrate materials' compatibility (both based on cement) as well as to their low permeability. Finally, Karakasis et al. (2024) [46] also used the single-lap/single-prism setup to study the in-plane bond of single or double TRM overlays applied on concrete prisms through the cast-in-place method. Two TRM systems were examined; they consisted of the same dry carbon fiber textile, but their cementitious matrices were of different compressive strengths. Prior to mechanical testing, specimens were exposed to 0, 40, and 80 freeze-thaw cycles according to Procedure B of the ASTM C 666 recommendation [32]. The failure mode of the reference specimens was due to tensile failure of the textile and sliding of the textile within the matrix, which, in some cases, was accompanied by breaking off of the top matrix layer. The treated specimens exposed to 40 cycles were characterized by the same failure mode as the untreated ones, while in the case of some single or double TRM overlays with low strength matrix, this failure mode was combined with interlaminar crack (at textile-to-matrix interface). The specimens exposed to 80 cycles failed as the untreated ones too, suffering moreover damage at the textile-to-matrix interface and/or detachment (partial or complete) at the TRM-to-substrate interface. The increase in the number of TRM overlays was beneficial for specimens exposed to 40 cycles, irrespective of the matrix strength; regarding the specimens exposed to 80 cycles, the same conclusion was reached only for specimens reinforced with TRM of high strength. In addition, there was no correlation between the strength of the matrix and the bond capacity of the TRM-to-concrete joints. Although freeze-thawing did not have a severe effect on the bond strength, it led to a change in the failure mode of the specimens. The studies discussed in this section regarding the TRM-to-concrete bond after exposure to freeze-thaw cycling, are summarized in Table 4.

Table 4. Summary of studies regarding the post-frost TRM-to-concrete bond.

Study	TRM system		Specimen		Freeze-thaw cycles		Reduction (-) or increase (+) of bond strength****** (%)	Failure mode*******
	Textile/fiber (T/Y/FS)*	Matrix (Fl/CS)**	Set-up***	Bond length [mm]	Temperature range/duration/freezing–thawing fluid (standard/recommendation)	Number*****		
[41]	Epoxy-impregnated & sand-coated/carbon & E-glass (hybrid) (1 textile strip) (YS 4100 MPa)	Cementitious (CS 52 MPa)	DL/SP	200****	–18 to +6 °C/(2–4) h/NaCl solution–NaCl solution (GB/T 50082-2009 [37])	0, 40, 60	–65	[0-60 cycles]: DTRMS
[42]	Dry/PBO or carbon (1 textile strip) (-)	Cementitious (CS 35/15 MPa for PBO/carbon textile)	SL/SP	100	–17.8 to +4.4 °C/2.7 h/air–air	0, 100 (+150 high temperature-humidity cycles)	–10 or –11 (PBO or carbon fibers textile)	[0, 100 cycles] DTM
[43]	Dry/carbon (1 textile strip) (TS 830 MPa)	Cementitious/normal-weight or lightweight (Fl/CS 5/50 MPa or Fl/CS 3/50 MPa)	SL/SP	400	–18 to +4 °C/4 h/air–water (ASTM C 666: Procedure B [32])	0, 10, 30, 50, 60, **70**	–68 or +46 (normal-weight or lightweight matrix)	[0-60 cycles]: FT or ST [70 cycles]: DTRMS
[44]	Dry/PBO or carbon (1 or 2 textile strips) (TS 3400 or 780 MPa)	Cementitious (Fl/CS 7.08/44.2 MPa or Fl/CS 7.77/45.47 MPa for PBO or carbon textile)	SL/SP	260	–18 to +38 °C/16 h/air–air {90 % RH} (CNR-DT 215/2018 [45])	0, 20	+3/+8 or +14/+7 [PBO or carbon fibers textile (1/2 textile strips)]	[0, 20 cycles] ST

Continued on next page

Study	TRM system		Specimen		Freeze-thaw cycles		Reduction (-) or increase (+) of bond strength****** (%)	Failure mode*******
	Textile/fiber (T/Y/FS)*	Matrix (Fl/CS)**	Set-up***	Bond length [mm]	Temperature range/duration/freezing–thawing fluid (standard/recommendation)	Number*****		
[46]	Dry/carbon (1 or 2 textile strips) (TS 2574 MPa)	Cementitious/high-strength or low strength (Fl/CS 4.31/74.8 MPa or Fl/CS 3.69/45 MPa)	SL/SP	400	−18 to +4 °C/4.8 h/air– water (ASTM C 666: Procedure B [32])	0, **40**, **80**	–20/–12 or –13/–12 [high- or low-strength matrix (1/2 textile strips)]	[0 cycles]: FT or ST [40 cycles]: as in 0 cycles + phenomena of DTM [80 cycles]: as in 0 and 40 cycles + DTRMS

*Note: Depending on the available data, T/Y/FS is the tensile strength [S] of the textile [T] or of each yarn [Y] or of each fiber [F] in the load-bearing direction. **Note: Depending on the available data, Fl/CS is the flexural [Fl] and/or the compressive [C] strength of the matrix at 28 days. ***Note: DL/SL = double-lap/single-prism set-up, SL/SP = single-lap/single-prism set-up). ****Note: Not explicitly mentioned. *****Note: The number in bold signifies the number of cycles corresponding to the change of failure mode. ****** Note: Change of bond strength corresponding to the maximum number of cycles examined. *******Note: The observed failure mode is detachment at TRM-to-substrate interface (DTRMS) or detachment at textile-to-matrix interface (DTM) or tensile failure of textile within the matrix (FT) or sliding of textile within the matrix (ST).

2.4.2. Brick/masonry substrate

Ombres and Verre (2022) [47] used the single-lap/single-prism setup for the implementation of bond tests in TRM-to-masonry joints. The composite consisted of dry carbon fiber textile and cementitious matrix, while it was applied on wallettes made of solid clay bricks and M5 joints mortar through the cast-in-place method. The specimens were tested after their exposure to 0 and 20 freeze-thaw cycles according to CNR-DT 215/2018 [45]. All specimens (both exposed and unexposed) failed due to textile sliding within the matrix or tensile failure of the textile, while no detachment phenomena at the textile-to-matrix or TRM-to-substrate interface were mentioned. The reduction of the specimens' bond strength due to freeze-thawing was statistically insignificant. However, the authors highlighted that the initial stiffness of the response curves of the exposed specimens (which represents the "stiffness" of the textile-to-matrix interface) was substantially lower than that of the reference ones. Finally, Dalalbashi et al. (2022) [35] also adopted the single-lap/single-prism setup for the performance of bond tests in TRM-to-brick joints. The composite was made of coated AR-glass fiber textile and lime-based matrix, while it was applied on sandblasted solid clay bricks through the cast-in-place method. The specimens were tested after their exposure to 0, 60, 120, 180, 240, 300, and 360 freeze-thaw cycles. Additionally, the authors tested some unexposed specimens that had the same age as those exposed to 180 and 360 cycles. As mentioned, this choice was dictated by the fact that lime-based mortars harden over time under the combination of hydration and carbonation. During mechanical testing, no detachment took place at the TRM-to-substrate interface due to the surface treatment of the bricks, as well as the coefficient of thermal expansion of the matrix, which was comparable to that of the bricks. All specimens (both treated and untreated) failed due to textile sliding within the matrix, while for specimens previously exposed to 120 to 300 cycles, the textile sliding was followed by yarn rupture. It was found that the bond strength of specimens exposed to 180/360 cycles was higher/almost equal than/to that of the unexposed ones of the same age. Therefore, it appears that the residual bond capacity of treated specimens was mainly governed by the age of the matrix. The studies discussed in this section regarding the TRM-to-brick/masonry bond after exposure to freeze-thaw cycling, are summarized in Table 5.

Table 5. Summary of studies regarding the post-frost TRM-to-brick/masonry bond.

Study	TRM system		Specimen		Freeze-thaw cycles		Reduction of bond strength***** (%)	Failure mode******
	textile/fiber (T/Y/FS)*	matrix (Fl/CS)**	set-up***	bond length (mm)	temperature range/duration/freezing-thawing fluid (standard/recommendation)	number****		
[35]	coated/AR-glass (1 textile strip) (TS 875 MPa)	lime-based (Fl/CS 4.5/16.8 MPa)	SL/SP	100	−10 to +30 °C/16 h/air {60 % RH}–air {90 % RH}	0, 60, *120, 180, 240, 300*, 360	−56 or +8 (compare to unexposed control or aged specimens)	[0–360 cycles]: ST (+ *yarns' rupture*)
[47]	dry/carbon (1 textile strip) (TS 1520 MPa)	Cementitious (Fl/CS 6.7/23 MPa)	SL/SP	300	−18 to +38 °C/16 h/air–air {90 % RH} (CNR-DT 215/2018 [45])	0, 20	−13	[0, 20] cycles: FT or ST

*Note: Depending on the available data, T/Y/FS is the tensile strength [S] of the textile [T] or of each yarn [Y] or of each fiber [F] in the load-bearing direction. **Note: Depending on the available data, Fl/CS is the flexural [Fl] and/or the compressive [C] strength of the matrix at 28 days. ***Note: DL/SL = double-lap/single-prism set-up, SL/SP = single-lap/single-prism set-up. ****Note: The number in bold signifies the number of cycles that corresponds to the change of failure mode, while the numbers in italics regard only [35] and correspond to the numbers of cycles related to additional failure phenomena. *****Note: Change of bond strength corresponding to the maximum number of cycles examined. ******Note: The observed failure mode is sliding of textile within the matrix (ST) or tensile failure of textile within the matrix (FT).

2.4.3. General remarks

The effect of freeze-thawing is reflected in the residual bond strength of the TRM-to-substrate joints. In some cases, it is also observed that as the number of cycles increases, the failure mode characterizing the shear bond tests alters. However, the investigation of a greater number of cycles could provide more instructive results in the context of some studies where the TRM overlays remained intact and their bond strength was not substantially changed after specimens' exposure. Further comparative consideration of the results presented in Tables 4 and 5 would not be reliable enough since the features of cycles, the treatment of the textile (coated, impregnated or made of dry fibers), the method of application, and the bond length of the TRM overlays on the substrate are different.

The examined parameters in the discussed studies are:

- The type of textile's fiber;
- The number of TRM overlays (number of textile strips);
- The density of the matrix;
- The compressive strength of the matrix;
- The age of the specimens;
- The number of freeze-thaw cycles.

It is concluded that the type of matrix (cementitious or lime-based) and its physical characteristics (density) are more crucial in comparison to the type of textile's fibers regarding the residual bond strength, while the correlation of matrix mechanical characteristics with this strength is not apparent. There is also an indication that the residual TRM bond decreases less when double instead of single TRM overlays are employed. Regarding the number of cycles, it appears that their increase leads to the progressive degradation of the stiffness of the textile-to-matrix and the TRM-to-substrate interface. Finally, the studies of [44] and [47], in which the same TRM systems were applied to concrete prisms and masonry wallettes, respectively, and the specimens were exposed to the same freeze-thaw regime, provide a hint about the role of the substrate in the residual TRM's bond strength. Future studies could investigate, among others, the effect of the matrix-to-substrate compatibility (in terms of, e.g., coefficient of thermal expansion [35], permeability, and stiffness) on the post-frost bond performance of TRM-to-substrate joints.

3. Residual capacity of TRM-strengthened members after freeze-thaw cycling

3.1. Concrete members

Aljazaeri and Myers (2017) [48] studied the fatigue and post-fatigue flexural behavior of RC beams strengthened with one or four TRM overlays. The TRM was made of a dry PBO fiber textile and a cementitious matrix, while it was applied through the hand lay-up technique to the bottom (tensioned) surface of each beam. It is noted that before strengthening, each beam had been sandblasted. Prior to the mechanical testing, the beams had been exposed to various consecutive environmental cycles. The exposure regime simulated real weather conditions (Missouri State, USA) and consisted of: 100 freeze-thaw cycles and 150 high temperature and relative humidity cycles (as in [42]). The experimental process included: Pre-cracking of the RC beams; TRM strengthening; curing for 28 days under lab conditions; maintenance under lab conditions or exposure to weather conditions under either self-weight or sustained flexural loading; flexural fatigue test; and post-fatigue flexural monotonic test up to failure. The failure mode of specimens strengthened with one TRM overlay was due to textile sliding within the matrix, while the failure mode of specimens strengthened with four TRM overlays was due to the composite's detachment from the substrate. The authors highlighted that specimens' weathering did not affect their failure mode. It was concluded that the exposed specimens strengthened with one or four TRM overlays presented higher ultimate loads compared to the corresponding unexposed/strengthened specimens. This phenomenon was attributed to the specimens' post-curing resulting from their exposure to high temperature and humidity cycles. It was also observed that the unexposed/strengthened specimens presented lower stiffness degradation compared to the exposed/strengthened ones, while sustained loads further reduced the stiffness of the exposed specimens strengthened with one TRM overlay. The residual strength of the strengthened RC beams versus the number of freeze-thaw cycles examined in [48] is presented in Figure 1. It appears that TRM can ensure the maintenance of the flexural capacity of strengthened beams after their exposure to the combined action of sustained load and weather conditions, including, among others, freeze-thaw cycles. However, it should be pointed out that in the context of this study, the effect of freeze-thawing cannot be isolated from that of high temperature and humidity cycles.

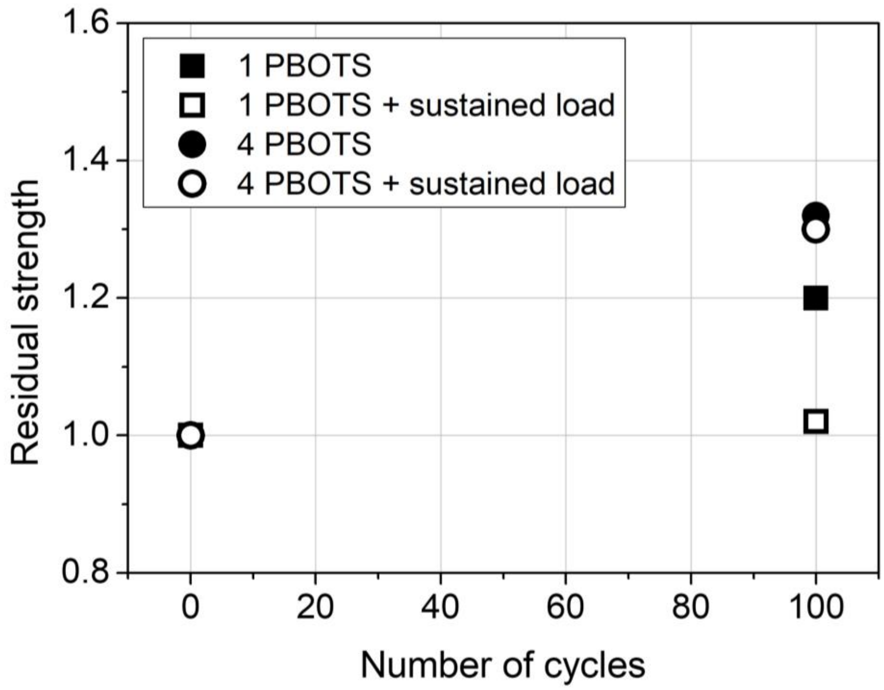

Figure 1. Residual fatigue and post-fatigue flexural strength of RC beams examined in [48] after exposure to weathering conditions, including freeze-thaw cycles. Note: PBOTS = PBO fiber textile strip.

Yin et al. (2017) [49] investigated the flexural response of RC beams strengthened with a TRM system comprised the same textile and matrix as those used in [38]. Two cast-in-place TRM overlays were applied to the bottom surface of each beam that had been previously roughened. The beams were mechanically tested after their exposure to the coupling action of chloride freeze-thaw cycles and sustained load. The frost process included 40 cycles according to the provisions of GB/T 50082-2009 [37], and it was combined with various ratios of sustained load (each ratio was equal to a percentage of the calculated ultimate load of the reference strengthened beam). It is noted that the reference specimen was free of load during its hygro-thermal treatment. All specimens failed in shear. The authors attributed this result to the reduction of the tensile strength of concrete caused by the freeze-thaw cycling. Increased sustained load entailed a higher degree of concrete deterioration manifested through the decrease of the beams' shear capacity and the increase of the maximum crack width and mid-span deflection. The TRM system maintained its integrity and remained bonded to the substrate; according to the authors, this was the reason why the TRM protected the bending section of the beams. Sheng et al. (2021) [50] complemented the testing program of Yin et al. (2017) [49] with five additional specimens. Specifically, Sheng et al. (2021) [50] prepared four TRM-strengthened and one un-strengthened beam. Three of the strengthened beams were exposed to the freeze-thawing process (identical to that adopted in [49]), being free of sustained load, while the fourth strengthened beam was not exposed to freeze-thawing prior to flexural testing. Two of the strengthened beams were exposed to 20 or 60 cycles, whereas the third was exposed to 40 cycles after its reinforcement with an epoxy-bonded/precast TRM plate (instead of the cast-in-place overlays). The unexposed beams (both un-strengthened and strengthened) failed in flexure, while the exposed/strengthened beams suffered shear failure. All cast-in-place TRM overlays remained bonded to the beams except the precast TRM plate that was partially detached from the substrate prior to the specimen's failure. The ultimate load of the exposed/strengthened beams decreased with increasing numbers of freeze–thaw cycles. The residual strength of all strengthened RC beams versus the number of freeze-thaw cycles examined in [49] and [50] is presented in Figure 2. Regarding the experimental program presented in these studies, it is concluded that the freeze-thaw cycling changed the failure mode of the TRM-strengthened beams from flexural to shear, whereas increasing the number of cycles and the level of sustained load has a negative effect on the beams' capacity. It is also observed that the method of TRM application to the substrate (cast-in-place versus epoxy-bonded/precast plate) decisively influences the TRM-to-substrate bond. However, it is noted that the role of TRM overlays could be better illuminated if exposed/un-strengthened specimens were also examined and compared with the exposed/strengthened ones.

Xu et al. (2023) [36] examined the flexural response of prisms made of cementitious mortar and strengthened with TRM systems. As mentioned, each system is composed of coated basalt or dry carbon fiber textile and fiber-reinforced cementitious matrix. Three groups of prisms were created; in each group, the degree of roughness of the strengthened surface was different (zero, low, high). Before the flexural test, the reinforced specimens were exposed to 0, 100, 200, and 300 freeze-thaw cycles according to GB/T 50082-2009 [37]. All specimens experienced flexural failure. After exposure to 100 cycles, the flexural capacity of the specimens slightly increased, irrespective of the type of textile and the degree of roughness of the substrate. For 200 and 300 cycles, the flexural capacity decreased, while the reduction was important for 300 cycles, and in general, it was getting lower as the roughness increased. The residual strength of the mortar prisms versus the number of freeze-thaw cycles examined in [36] is presented in Figure 3. It is interesting to note that the roughness of the strengthened surface enhances the TRM-to-substrate bond quality and results in lower reduction of the flexural strength due to freeze-thawing.

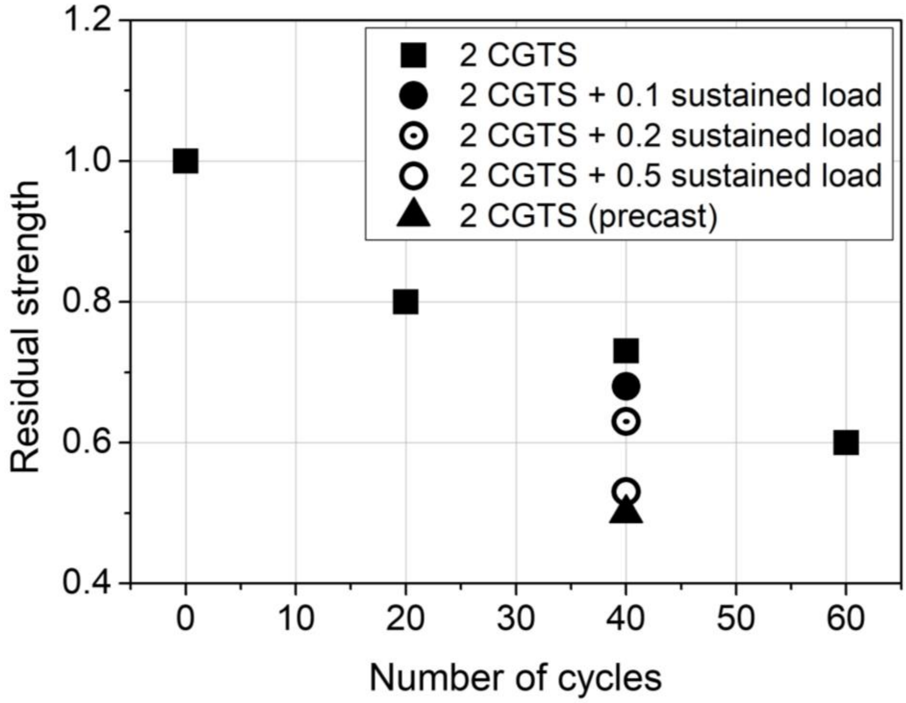

Figure 2. Residual flexural strength of RC beams examined in [49, 50] after exposure to freeze-thaw cycles. Note: CGTS = hybrid carbon & E-glass fiber textile strip.

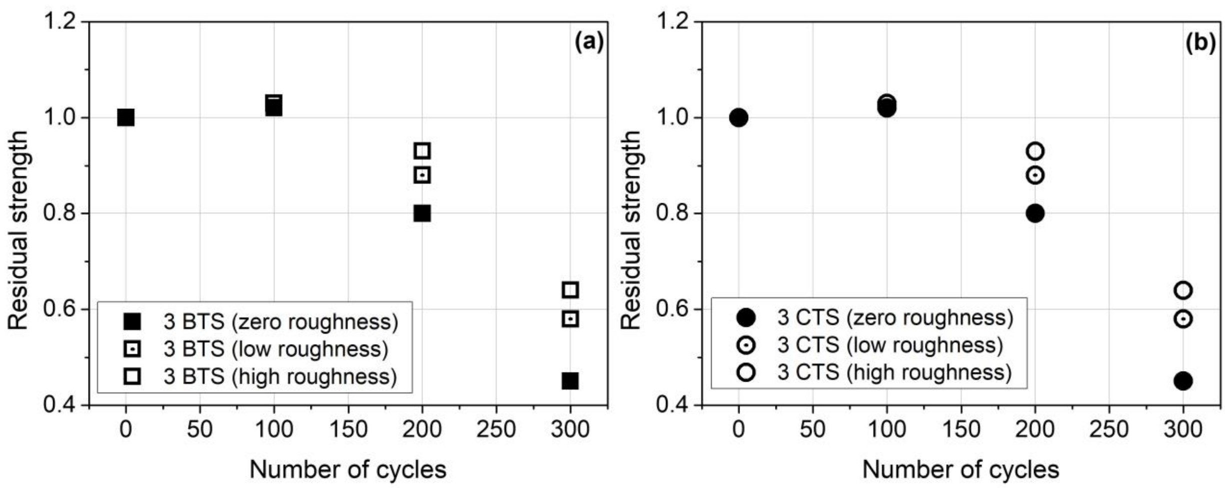

Figure 3. Residual flexural strength of mortar prisms examined in [36] after exposure to freeze-thaw cycles. Note: (a) BTS = basalt fiber textile strip, (b) CTS = carbon fiber textile strip.

3.2. Masonry members

Al-Jaberi and Myers (2018) [51] investigated the out-of-plane flexural response of reinforced masonry walls (piers) subjected to cyclic loading. The walls were made of concrete masonry units and cementitious joints' mortar, while they were unilaterally strengthened with two alternative TRM systems as those used in the study of Al-Jaberi et al. (2019) [42] (i.e., dry PBO or carbon (C) fiber textiles embedded in cementitious mortars of different compressive strengths, named as PBOTRM and CTRM in the following). After strengthening and before mechanical testing, the specimens were exposed to weather conditions as those adopted by Al-Jaberi et al. (2019) [42] (i.e., freeze-thaw, as well as high temperature and relative humidity cycles). It is also noted that during flexural testing, the stresses at the tension zone of the specimens were acting perpendicular to the walls' bed joints (i.e., failure plane parallel to bed joints). The failure mode of the PBOTRM-strengthened specimens before and after weathering changed from sliding to detachment (at the textile-to-matrix interface), while the failure mode of CTRM-strengthened specimens, which was due to detachment at the textile-to-matrix interface, did not change. It was found that the flexural capacity of the unexposed/strengthened specimens remained almost unaffected or slightly decreased compared to the capacity of the exposed counterparts equipped with carbon or PBOTRM system, respectively. The residual strength of the strengthened walls versus the number of freeze-thaw cycles examined in [51] is presented in Figure 4. Specimens' weathering affected only the failure mode of the walls strengthened with PBOTRM systems, but did not substantially affect the flexural strength of any of the specimens. The results in [51] are not incompatible with those presented in [42]. It is noted that the residual bond strength of the same TRM systems, when applied to the same masonry units after exposure to the same weathering conditions, was identical to that of the corresponding unexposed specimens, while the most critical interface was the textile-to-matrix one. As also applied to the results in [42] and [48], in the context of the study of [51], the effect of freeze-thawing cannot be isolated from that of high temperature and humidity cycles.

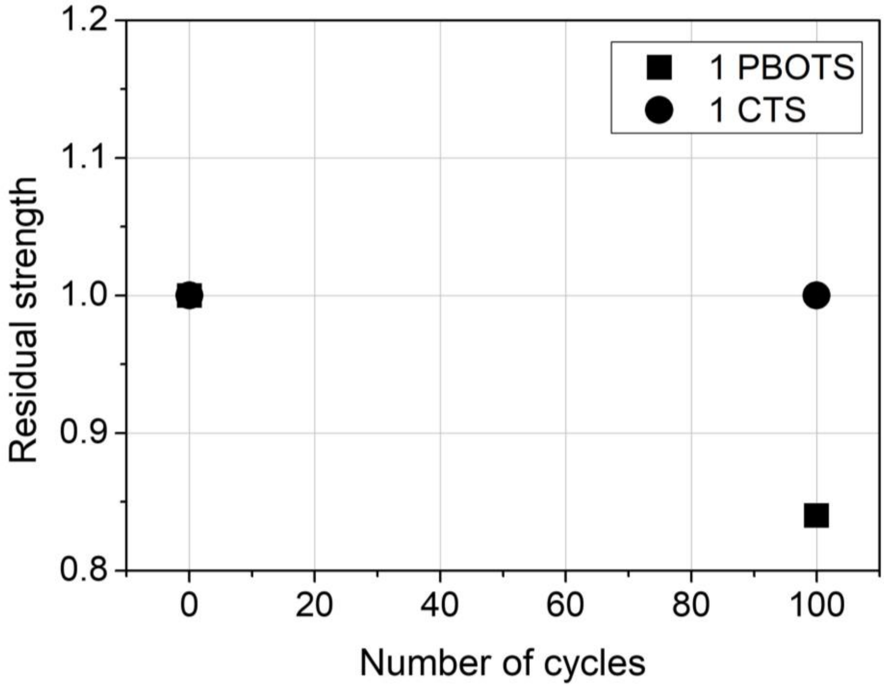

Figure 4. Residual out-of-plane flexural strength of reinforced masonry walls examined in [51] after exposure to weathering conditions, including freeze-thaw cycles. Note: PBO/CTS = PBO or carbon fiber textile strip.

Dalalbashi et al. (2022) [35] implemented diagonal compression tests using bilaterally TRM-strengthened or un-strengthened masonry panels made of sandblasted solid clay bricks and lime-based joints' mortar. In the context of this study, flexural tests were also implemented for the study of the out-of-plane response of unilaterally TRM-strengthened masonry panels of the same kind. It is noted that two types of flexural tests were performed; in the first, the tensile stresses of the specimen were acting perpendicular to the bed joints, while in the second, parallel to them (i.e., failure plane parallel and perpendicular to bed joints, respectively). The TRM system comprised a coated AR-glass fiber textile and a lime-based matrix, and it was the same as the one used in [35] for the implementation of the previously discussed tensile, pull-out, and shear bond tests. The specimens were tested after their exposure to 0 and 360 freeze-thaw cycles, while unexposed specimens that had the same age as those exposed to 360 cycles were also tested. As mentioned, this choice was dictated by the fact that lime-based mortars harden over time under the combination of hydration and carbonation. Regarding the failure mode of specimens subjected to diagonal compression, it was found that all un-strengthened panels (both unexposed and exposed) failed due to sliding along the mortar joint. The failure mode of the corresponding strengthened panels was characterized by the formation of diagonal cracks in the TRM, the tensile failure of the textile, and the development of diagonal cracks, while no detachment phenomena at the TRM-to-substrate interface were observed. It is interesting to note that the maximum load (as well as shear strength) of the un-strengthened control specimens decreased in comparison to the load of both the corresponding exposed specimens and their un-exposed counterparts (of the same age), due to the deterioration of the brick-to-mortar bond. However, the TRM jackets protected both the aged and exposed strengthened panels, as their load (and strength) was comparable to that of the control strengthened panels. The failure mode of all un-strengthened specimens subjected to out-of-plane bending was dominated by the weakness of the brick-to-mortar bond, too. During the failure of the corresponding strengthened specimens (control, aged, exposed), the textile rupture was also achieved, while TRM remained attached to the substrate. The maximum load of both strengthened and un-strengthened control specimens decreased compared to that of the corresponding aged and exposed ones. As pointed out by the authors, the matrix aging affected the response of both aged/unexposed and exposed specimens since the saturation level of the latter during the frost treatment was not sufficient (the relative humidity of the used climate chamber was equal to 90% during the thawing phase). The residual strength of the walls versus the number of freeze-thaw cycles examined in [35] is presented in Figures 5 and 6.

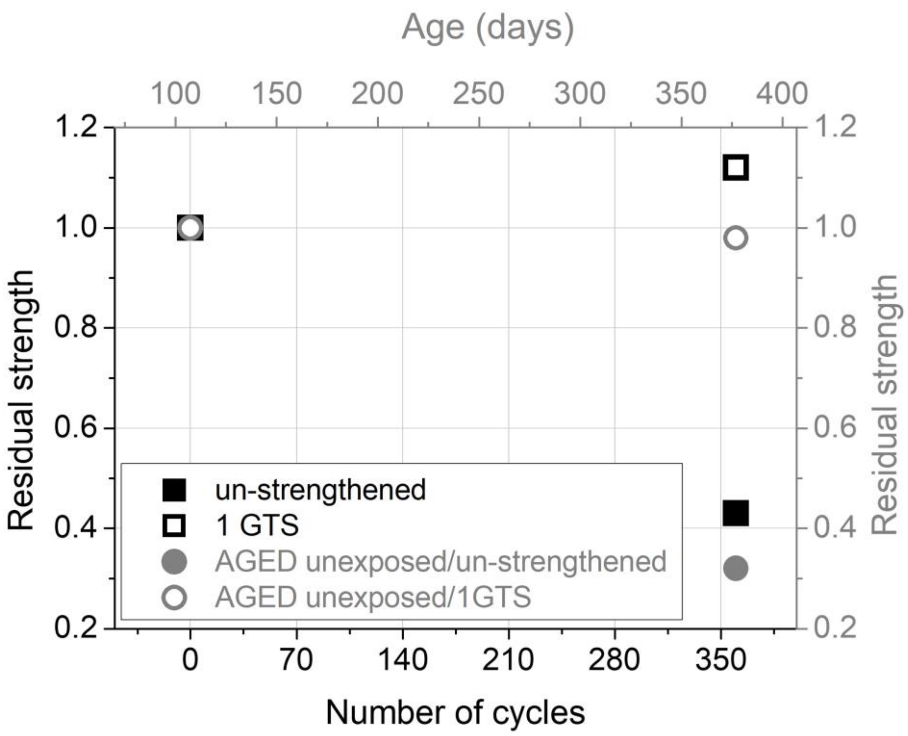

Figure 5. Residual strength in diagonal compression of masonry panels examined in [35] after exposure to freeze-thaw cycles. Note: GTS = glass fiber textile strip.

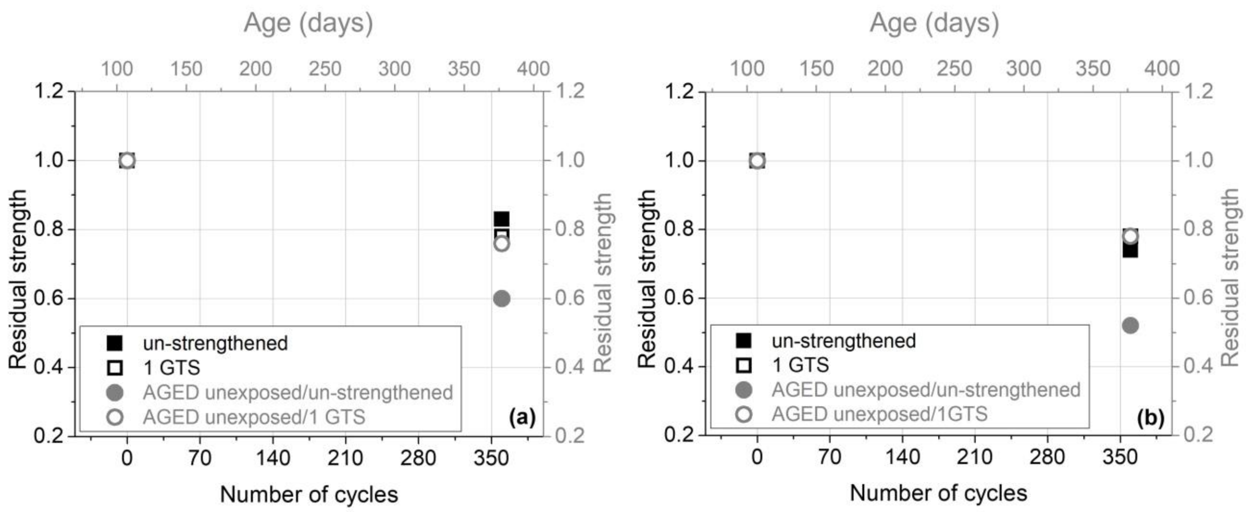

Figure 6. Residual out-of-plane flexural strength of masonry panels examined in [35] after exposure to freeze-thaw cycles: Failure plane (a) parallel and (b) perpendicular to bed joints. Note: GTS = glass fiber textile strip.

3.3. General remarks

The studies discussed in this section regarding the TRM-strengthened members after exposure to freeze-thaw cycling, are summarized in Table 6. The experimental database of the topic needs to be further enriched; there are 3 and 2 studies regarding RC and masonry members, respectively. Among them, the features and the number of freeze-thaw cycles are different. Based on [35], it appears that the regulation of these features is crucial in order a sufficient saturation level of the specimens to be achieved. Except for the cycles' features, the results of [48] and [51] imply that the specimens' curing conditions can also affect the outcome of the freeze-thawing. In addition, the presence of salts during cycles [49,50] is an important parameter that possibly further degrades the residual capacity of the members; it is expected that the capacity of a member after exposure to a certain number of cycles will be less if salts are used due to the development of osmotic pressures in the voids of the porous materials (concrete or clay bricks and mortar regarding the substrate and the strengthening overlay, respectively).

Table 6. Summary of studies regarding the post-frost capacity of TRM-strengthened members.

Study	TRM system		Test		Freeze-thaw cycles		Failure mode***
	Textile/fiber (T/Y/FS)*	Matrix (Fl/CS)**	Specimen	Loading	Temperature range/duration/freezing-thawing fluid (standard/recommendation)	Number	
[48]	Dry/PBO (1 or 4 textile strips) (-)	Cementitious (CS 31 MPa)	RC beam	Fatigue and post-fatigue flexure	−17.8 to +4.4 °C/2.7 h / air–air	0, 100 (+150 high temperature -humidity cycles)	[0, 100 cycles & 1 textile strip]: ST [0, 100 cycles & 4 textile strips]: DTRMS
[49] & [50]	Epoxy-impregnated & sand-coated/carbon & E-glass (hybrid) (2 textile strips) (YS 4203 & 4100 MPa)	Cementitious (CS 53 MPa)	RC beam	Monotonic flexure	−18 to +5 °C/(3–4) h/NaCl solution–NaCl solution (GB/T 50082-2009 [37])	0, 20, 40, 60	[0 cycles]: flexural failure [20–60 cycles]: shear failure
[36]	Coated/basalt (3 textile strips) (FS 1700 MPa)	fiber-reinforced cementitious (-)	Cementitious mortar prism	Monotonic flexure	−18 to +5 °C/6 h/water–water (GB/T 50082-2009 [37])	0, 100, 200, 300	[0–300 cycles]: flexural failure

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Study	TRM system		Test		Freeze-thaw cycles		Failure mode***
	Textile/fiber (T/Y/FS)*	Matrix (Fl/CS)**	Specimen	Loading	Temperature range/duration/freezing-thawing fluid (standard/recommendation)	Number	
[36]	Dry/carbon (3 textile strips) (FS 3400 MPa)	Fiber-reinforced cementitious (-)	Cementitious mortar prism	Monotonic flexure	−18 to +5 °C/6 h/water–water (GB/T 50082-2009 [37])	0, 100, 200, 300	[0–300 cycles]: flexural failure
[51]	Dry/PBO or carbon (1 textile strip) (FS 5800 or 4800 MPa)	Cementitious (CS 35/15 MPa for PBO/carbon textile)	Reinforced masonry wall	Monotonic out-of-plane flexure (failure plane//to bed joints)	−17.8 to +4.4 °C/2.7 h/air–air	0, 100 (+150 high temperature -humidity cycles)	[0 cycles & PBO fiber textile]: ST [100 cycles & PBO fiber textile]: DTM [0, 100 cycles & carbon fiber textile]: DTM
[35]	Coated/AR-glass (1 textile strip) (TS 875 MPa)	Lime-based (Fl/CS 4.5/16.8 MPa)	Masonry panel	Diagonal compression	−10 to +30 °C/16 h/air {60 % RH}–air {90 % RH}	0, 360	[0, 360 cycles; strengthened specimens]: FT
[35]	Coated/AR-glass (1 textile strip) (TS 875 MPa)	Lime-based (Fl/CS 4.5/16.8 MPa)	Masonry panel	Monotonic out-of-plane flexure (failure plane//to bed joints)	−10 to +30 °C/16 h/air {60 % RH}–air {90 % RH}	0, 360	[0, 360 cycles; strengthened specimens]: FT
[35]	Coated/AR-glass (1 textile strip) (TS 875 MPa)	Lime-based (Fl/CS 4.5/16.8 MPa)	Masonry panel	Monotonic out-of-plane flexure (failure plane⊥to bed joints)	−10 to +30 °C/16 h/air {60 % RH}–air {90 % RH}	0, 360	[0, 360 cycles; strengthened specimens]: FT

*Note: Depending on the available data, T/Y/FS is the tensile strength [S] of the textile [T] or of each yarn [Y] or of each fiber [F] in the load-bearing direction. **Note: Depending on the available data, Fl/CS is the flexural [Fl] and/or the compressive [C] strength of the matrix at 28 days. ***Note: The observed failure mode is detachment at TRM-to-substrate interface (DTRMS) or detachment at textile-to-matrix interface (DTM) or tensile failure of textile within the matrix (FT) or sliding of textile within the matrix (ST).

Although in [36] the substrate is a mortar prism, it emerges that, in some cases, the positive effect of TRM's late hydration dominates the TRM mechanical degradation due to frost action up to a certain number of cycles. Based on [36,49,50], the method of TRM application to the substrate (cast-in-place versus epoxy-bonded/precast plate), as well as the roughness of the strengthened substrate, decisively influences the TRM-to-substrate bond. The cast-in-place application of TRM to a roughened substrate enhances the bond quality of the TRM-to-substrate interface and renders the textile-to-matrix interface the most critical one during specimens' failure, which is desirable in terms of energy consumption. Finally, as it results from [49], the simultaneous action of frost and sustained load is more aggravating for the residual capacity of strengthened members.

4. Discussion

In the absence of an established standard for the assessment of the residual capacity of TRM-strengthened members after exposure to freeze-thaw cycles, scientists rely on various national standards/recommendations [32,37,45]. In the context of these standards/recommendations, the proposed features of the freeze-thaw cycles differentiate, rendering the comparison of the related experimental results difficult. It is also noted that some researchers have defined their own frost regime.

The degradation of the mechanical characteristics of the TRM systems at the material level due to frost action is significant since the used matrices are porous materials [20,21], and the fibrous yarns provide extra channels for the water flow inside the matrix when it cracks [22,43]. However, when TRM is used as an external reinforcement for strengthening concrete or masonry members can provide a protective barrier for the substrate against frost damage. As it appears in most of the previously discussed studies, TRM can remain attached to the substrate during freeze-thaw action, under the condition that the parameters affecting the TRM-to-substrate bond have been properly evaluated. In most studies, it is also noticed that TRM can maintain its integrity after the exposure of the strengthened members to various frost conditions. It is highlighted that in most of the studies, the capacity of the exposed/strengthened specimens has been compared only with that of unexposed/strengthened counterparts. It is proposed that the role of TRM overlays will be better illuminated if future studies also compare the performance of exposed/strengthened specimens with that of exposed/un-strengthened ones.

5. Conclusions

In this paper, I investigate the effectiveness of TRM as a strengthening intervention in existing concrete or masonry structural members and a protective overlay against frost damage. The major conclusions are the following:

1. Based on the studies regarding the tensile or flexural response of TRM systems after exposure to various numbers of freeze-thaw cycles, it is deduced that there is a critical number of cycles beyond which the decrease of the respective TRM strength is irreversible. In addition, the studies that regard the post-frost yarn-to-matrix bond of various TRM systems suggest that the pull-out strength of the yarn is highly affected by the type of mortar used as matrix.

2. Based on the studies examining the post-frost TRM-to-substrate bond performance, it emerges that the type of matrix (cementitious or lime-based) and its physical characteristics (density) are more crucial in comparison to the type of textile's fibers, regarding the residual bond strength, while the correlation of matrix mechanical characteristics with this strength is not apparent. There are also indications that the residual TRM bond decreases less when double instead of single TRM overlays are employed. Regarding the number of cycles, it appears that their increase leads to the progressive degradation of the stiffness of the textile-to-matrix and TRM-to-substrate interface. Finally, some of these studies provide a hint about the role of the matrix-to-substrate physical and mechanical compatibility in the residual TRM's bond strength.

3. In the absence of an established standard for the assessment of the residual capacity of TRM-strengthened members after exposure to freeze-thaw cycles, scientists rely on national standards/recommendations. In the context of these standards/recommendations, the proposed features of the freeze-thaw cycles differentiate, rendering the comparison of the related experimental results difficult. It is also noted that some researchers have defined their own frost regime. Despite the absence of an established standard and the post-frost degradation of the mechanical characteristics of the TRM systems at the material level, when TRM is used as external reinforcement of concrete or masonry members, it can simultaneously provide a protective barrier of the substrate against frost damage. In most of the related studies, the adopted TRM systems remained attached to the substrate during freeze-thaw action, while these composites also maintained their integrity after the exposure of the strengthened members to various freeze-thaw conditions.

For future research, the role of TRM overlays will be better illuminated if the next studies compare the performance of exposed/strengthened specimens not only with that of unexposed/strengthened counterparts (as in the studies currently discussed) but also with that of exposed/un-strengthened ones.

Use of AI tools declaration

The author declares she has not used Artificial Intelligence (AI) tools in the creation of this article.

Conflict of interest

The author declares no conflict of interest.

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