Experimental investigation on salt frost scaling of textile-reinforced concrete

Julian Konzilia | Matthias Egger | Jürgen Feix

Unit of Concrete Structures and Bridge Design, University of Innsbruck, Innsbruck, Austria

Correspondence
Julian Konzilia, Unit of Concrete Structures and Bridge Design, University of Innsbruck, Technikerstraße 13, 6020 Innsbruck, Austria
Email: julian.konzilia@uibk.ac.at

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Abstract
With the aim of reducing life cycle costs and dead weight, there are various concepts for replacing bridge pavements and sealants with high-performance concrete. The corrosion resistance of textile reinforcements allows the realization of thin reinforcement layers that fulfill this objective. However, the textile-reinforced concrete used as a road surface must meet the particular requirements relating to frost resistance and, specifically, scaling. An investigation on an existing structure indicated the influence of textile reinforcements on frost resistance. Therefore, the present investigations focus on the frost scaling of different combinations of a carbon reinforcement and fine-grained concrete. For this purpose, a multistage research design is used. First, the influence of the reinforcement and the concrete mix on the capillary porosity is investigated. The capillary porosity of concrete is directly related to its resistance to freeze–thaw scaling. This resistance is examined using the slab-test method. Finally, the influence of the frost exposure on the pull-off strength, which is crucial for the strengthening of structures, is determined.

1 | INTRODUCTION

Structural concrete used in civil infrastructure, is exposed to severe environmental attacks. One of the most significant exposures is freeze–thaw de-icing salt (FTDS) attack. The permeation of water and de-icing salt into concrete causes its structural damage and surface scaling owing to the freezing process of the solution. Concurrently, de-icing agent have a highly corrosive effect on steel, which in the past has led to severe damage of the reinforcements of civil infrastructure.1,2

Therefore, in bridge construction, a bituminous sealant is used to prevent the permeation of de-icing salt solution into concrete. This sealant must, in turn, be protected from the mechanical deterioration of the road surface. The sealant and road surface of a bridge are wearing parts that have to be replaced regularly.3 This leads to considerable costs and traffic obstructions during the rehabilitation of bridges. Therefore, recently numerous approaches have been developed to avoid the need for sealants and pavements by replacing them by thin layers of high performance-concrete.4–8 In other approaches, the structural concrete is reinforced with corrosion-resistant rebars or solely prestressed with particularly protected prestressing cables.9,10
2  |  REHABILITATION OF ROAD SURFACE USING TEXTILE-REINFORCED CONCRETE

Owing to the corrosion resistance of textile reinforcements, textile-reinforced concrete (TRC) offers many advantages compared with conventional steel reinforcements when directly exposed to a corrosive environment.\(^{11}\) Therefore, TRC is particularly suitable for use in civil infrastructure. These properties have been used and investigated in the past in first-time applications to bridge structures in which the sealant and the road surface were completely replaced by a TRC layer.\(^{12,13}\)

In addition, the application of a TRC layer allows significant strengthening against bending, shear, and torsion.\(^{14}\) Owing to the crack-bridging properties of TRC, it is also possible to strengthen cracked reinforced concrete and achieve a positive effect on crack distribution. This was investigated in particular for civil infrastructure. Depending on the type of failure, a significant level of strengthening was achieved.\(^{15}\) Further investigations showed that TRC layers can be realized for strongly exposed components without additional sealing or road surfaces.\(^{16,17}\)

A new approach has been developed at the University of Innsbruck that uses a TRC layer to strengthen and rehabilitate existing bridges. This method employs the mechanical properties and corrosion resistance of textile reinforcements to replace the road surface and sealant of a bridge. This can not only increase the load-bearing capacity of a bridge and reduce the dead load but also extend the service life. Thus, rehabilitation intervals can be extended and the life cycle costs of the structure can be reduced.\(^{18–20}\)

An additional requirement for using TRC layer as a sealant is that the crack openings should be small to avoid the permeation of water. By applying textile reinforcement, the crack width can be significantly reduced and the required fine crack pattern can be achieved.\(^ {21}\) Thus, the combination of a high-performance concrete with textile reinforcement can strongly reduce the permeation of water compared to conventional reinforced concrete.\(^ {22}\) Therefore, a thin TRC layer in the range of 3.0 cm is sufficient for preventing the structural concrete below it from water penetration and entrainment of harmful ions. However, the influence of the capillary water absorption by the reinforcement on the depth of water permeation in cracked concrete layers must be considered.\(^ {23}\)

### 2.1 Frost scaling of concrete

When concrete is used in infrastructure projects, it is exposed to direct weathering. One of the most significant exposures of concrete is repeated freeze–thaw cycling with and without de-icing agents. The research on TRC mainly focuses on the effect of frost damage on the mechanical properties of textile reinforcement, such as the bonding and tensile bearing behavior.\(^ {24–27}\) Several investigations have been conducted under different exposure conditions. These indicate a minor influence of frost exposure on the bond and tensile bearing behavior of TRC members.\(^{28–30}\)

However, frost exposure causes structural damage to concrete, and in particular, scaling of the concrete surface if de-icing agents (e.g., NaCl) are used. In case of concrete used in infrastructural applications, this is a crucial environmental impact. Various models are available to explain different aspects of frost damage and its causes.\(^ {31}\) A prerequisite for frost damage is saturation of the concrete with the de-icing salt solution. This occurs through the absorption of the de-icing salt solution from the surface during freezing. Thus, for scaling concrete, the surface must be exposed to cyclic freezing in the presence of a salt solution. Surface scaling is based on complex surface physics phenomena that occur in the sub-micro-scale of the pore structure of the hardened cement paste. These processes lead to an expansion as a result of ice growth in the capillary pores of the cement paste of the concrete. In German-speaking countries, this mechanism is known as micro-ice-lens formation.\(^ {32}\) Furthermore, current investigations show that during freezing, the lower-lying concrete shrinks, whereas expansion occurs near the surface. The resulting stress difference leads to the scaling of the surface layers.\(^ {33}\)

### 2.2 Damage characteristics and problems encountered in initial applications

Figure 1a–c shows the observed degradation of the road surface at the Gschwandtkopf-bridge in Seefeld (Austria). It is a frame bridge over three spans with an overall length of approximately 30 m The bridge was rehabilitated in 2014, including the application of a TRC layer on site as an addition to the conventional concrete slab of the bridge.\(^ {19}\) The figures show the frost scaling of the TRC surface recorded over the years 2015 (a), 2016 (b), and 2019 (c). This example shows, that a combination of inadequate concrete and textile reinforcement components or poor execution of the TRC layer in combination with high mechanical impact on the surface can lead to significant defects.

The cause of the damage can be attributed to the pore system of the concrete. Capillary pores (10 nm–100 μm) are crucial for the transport processes in concrete, and
thus, for the durability of the TRC layer. They are generated by the hydration of the cement paste component, and therefore, depend significantly on the ratio of water to cementitious materials (w/cm) of the concrete. A precise determination of the pore size distribution, and thus, the capillary pore content of the concrete is complex. Experimental procedures are available, e.g., mercury isometry and scanning electron microscopy. However, these methods can be distorted by the pore shapes (bottleneck pores), and owing to their complexity, do not present a method for the classification of concrete onsite. In fact, their suitability is uncertain owing to the small sample size used within the size range of the aggregates. Therefore, comparatively simpler test methods were utilized for the assessment of the frost damage shown in Figure 1a–c, which allowed a qualitative assessment of the open porosity and particularly the capillary porosity. Because the porosity of the aggregates is lower than that of the hardened cement paste, the porosity of the cement stone is decisive for the porosity of the entire concrete.

The open porosity of the concrete is determined experimentally by vacuum saturation. For this experiment, samples were taken from damaged areas by core drilling, and the porosity was determined according to OENORM EN 1936. Owing to the discontinuity of the layer structure, the porosity was investigated layer-wise for two cores. The results are shown in Figure 2.

The pores in concrete are not evenly distributed. Normally the surface zone of approximately 20 mm shows the highest porosity. Unlike the latter, the porosity profile shows that the layer with the integrated textile reinforcement has a higher porosity than the regular concrete. Because of the influence of the capillary porosity of the concrete on the FTDS resistance, this peculiarity may be of importance. In a first investigation, a qualitative correlation between the open porosity, which can be obtained relatively easily experimentally, and the capillary porosity was determined. Since capillary water absorption and the capillary pore system are strongly related, measurements of capillary absorbency can provide qualitative information about the capillary pore

FIGURE 1 Progressive frost damage from 2016 (a), 2018 (b), and till 2019 (c) for review only

FIGURE 2 Layer-wise porosity of drilling cores, dimensions in millimeter
There is also a direct correlation between the capillary water absorption and frost resistance of a specific concrete.39,40

The aim of further investigations was to identify possible causes of frost scaling in the application of a TRC as a road surface and sealant. For this purpose, the effects of various types of concretes and textile reinforcements on the FTDS resistance of the concretes were analyzed. In particular it was determined, whether the structural disturbance of the concrete (increased open porosity) in the layer of the textile reinforcement has an additional contribution. The focus of the investigation was on surface scaling and the influence of FTDS on the delamination resistance of the TRC specimens.

3 | MATERIALS AND METHODS

Because a TRC is a composite material of a textile reinforcement and concrete, a detailed investigation of the concrete, the reinforcement, and their interaction is necessary to determine the deterioration mechanism. Various concrete mixes and reinforcements were used to investigate their effects on durability. The used materials are described in the following.

3.1 | Concrete

Three different concrete mixes were used in the experimental program, referred to as a, b, and c. Types a and b were developed at the University of Innsbruck. The mixture compositions of all concretes are listed in Table 1. The data for concrete c are taken from Lieboldt.42 It should be noted that for the determination of the w/cm-ratios of mixtures a and b, the k-value for microsilica is chosen as 2.0 according to OENORM B 4710.41 However, for concrete c it is calculated according to DIN EN 20643 as \( k = 1.0 \) for microsilica and \( k = 0.4 \) for fly ash.

Figure 3 shows the grain size distributions of all concrete mixtures. The fresh concrete properties listed in Table 2 were determined according to OENORM EN 1015-1 to 744 and OENORM EN 12350-5.45 The experimental assessment of the consistency showed mix-specific properties. Concrete mix a had a very soft consistency with a flow table class of F59. Although concrete b was assigned to F45, its compactability was limited owing to the high air content. Concrete c was assigned to flow table class F52; however, it was highly sticky. A visual description of the different flow table classes is given in Figure 4.

The properties of the hardened concrete listed in Table 2 were determined using mortar prisms with dimensions \( 40 \times 40 \times 160 \text{ mm}^3 \) according to OENORM EN 196.46 In addition, the open porosity was measured according to OENORM EN 1936.36

### Table 1 | Concrete mixtures

| Ingredient                  | Unit   | a    | b    | c    |
|-----------------------------|--------|------|------|------|
| Aggregate Diabas 0/2        | kg/m³  | 1600 | 1560 | –    |
| Aggregate Sand 0/1          | kg/m³  | –    | –    | 1122.4|
| Cement CEM II/B-S 42.5 N    | kg/m³  | 575  | 410  | –    |
| Cement CEM I 32.5 N         | kg/m³  | –    | –    | 564.8|
| Microsilica (powder)        | kg/m³  | 25   | 30   | –    |
| Microsilica (slurry)        | kg/m³  | –    | –    | 56.6 |
| Fly ash                     | kg/m³  | –    | –    | 253.1|
| Air entrainment MasterAir 9060 | kg/m³ | 1.3  | 1.2  | –    |
| Plasticizer ACE 430, BASF   | kg/m³  | 6.3  | 3.5  | –    |
| Plasticizer MasterSure 911, BASF | kg/m³ | 3.1  | –    | –    |
| Plasticizer FM30, BASF      | L/m³   | –    | 12.0 | –    |
| Effective water content     | –      | 0.36 | 0.45 | 0.36 (0.30) |

3.2 | Textile reinforcement

In general, various fiber materials can be used as textile reinforcements. However, owing to the advantages of carbon, it is currently the most suitable nonmetallic reinforcement material for load-bearing components in structural engineering.47,48 The properties of carbon reinforcements vary depending on the type of production and impregnation.49 The latter influences in particular durability-relevant
properties, such as the density of the roving, and thus, the water absorption and impermeability of the reinforcement. Owing to the damage mechanism of an FTDS-attack, in reinforced concrete, the capillary porosity of the reinforcement and its influence on the concrete are of particular interest. In addition to the impregnation material, the roving cross-section, expressed in textile terms of fineness, and the quality of the impregnation of the roving are decisive. The fineness is expressed by the linear density and measured in the unit tex. One tex equals 1 g/1000 m of roving.

Therefore, an approach of using reinforcements with different impregnations and resulting varying water absorption was adopted in order to obtain a generalized trend of the effects of textile reinforcements on durability under an FTDS attack.

Three different types of reinforcements were used, which differ in their impregnations and fineness. These are listed in Table 3 and are referred to as numbers 01, 02, and 03 in the following. The reinforcements differ in fineness of 3200 tex or 6400 tex, and the impregnations, are styrene–butadiene rubber (SBR), epoxy resin (EP), or a combination of a thermoplastic with epoxy resin (TP & EP). The latter reinforcement was developed as a part of several research projects at the University of Innsbruck. As rovings do not have a uniform diameter, the carbon cross-section of the mesh reinforcement is determined from the linear density of the roving and the net density of the carbon fiber. The reinforcement cross-section is given per linear meter.

4 | EXPERIMENTAL PROGRAM AND RESULTS

A multistage approach was used for the study. From the concrete parameters—consistency and open porosity—

| Property                          | Unit     | a   | b   | c   |
|-----------------------------------|----------|-----|-----|-----|
| Air content in fresh concrete     | vol%     | 3.0 | 11.5| 3.8 |
| Fresh concrete density            | kg/m³    | 2370| 2150| 2205|
| Flow table test                   | cm       | 58  | 48  | 50  |
| Compressive strength              | N/mm²    | 82.8| 60.6| 109.1|
| Flexural strength                 | N/mm²    | 11.1| 8.3 | 9.3 |
| Density                           | kg/m³    | 2341| 2111| 2199|
| Open porosity                     | vol%     | 18.3| 23.8| 18.0|

FIGURE 3  Grain size distributions of concrete mixtures

FIGURE 4  Results of flow table test F59 for mixture a (a), F45 for mixture b (b), and F52 for mixture c (c)
and the tests on the capillary water absorption, conclusions were drawn about the capillary porosity relevant for durability. Subsequently FTDS tests were conducted to determine the performance of the concrete exposed to an FTDS attack, which, in turn, is directly related to the capillary porosity. Finally, pull-off tests were performed to investigate the effects of an FTDS exposure on the delamination resistance of the reinforcement layer.52,53

### 4.1 Experiments on capillary water absorption

To obtain qualitative information about the capillary pore fraction of the open porosity and the related capillary water absorption of the concretes and reinforcements, capillary absorption tests were conducted.

#### 4.1.1 Test program

The test setup for capillary water absorption was based on the experiments by Mechtcherine and Lieboldt22 in accordance with OENORM EN ISO 15148.54 For this purpose, cuboid TRC specimens with a cross-sectional dimension of 100 × 30 mm² and a length of 180 mm were prepared. For the reinforced specimens, two layers of the textile reinforcement were integrated with uniform spacing. The specimens were produced by laminating the different layers. After 24 h, the specimens were demoulded and submerged in water at 20°C until the 7th day. Subsequently they were stored in a climatic chamber at 20°C and 65% relative humidity until the 28th day. Following this, the samples were dried at 40°C in a forced air drying oven until the change in mass in 24 h was less than 0.1%. For easy handling and to ensure an open pore structure on the face side, the specimens were cast as strips of appropriate widths and cut to length by sawing. To ensure that the water was absorbed solely through the sawn face, the side surfaces were sealed with the epoxy resin Sikafloor®-156. For testing, a specimen conditioned to the equilibrium humidity of the room (20°C, 55% relative humidity) was immersed in water on the face side, and the capillary water absorption was measured by weighing the specimens after 5 min/20 min/60 min/2 h/4 h/8 h/24 h/72 h. A scheme of the experimental setup is shown in Figure 5.

To draw conclusions about the effects of the concrete and the reinforcement, different configurations were tested. The variants are listed in Table 4. For each configuration, three test specimens were used.

#### 4.1.2 Results

The results of the capillary water absorption tests are shown in Figure 6. The water absorption of the test specimens over time shows the following trend. After an initial strong increase, the graph becomes almost linear. Only configuration a-01 is an exception. It is almost linear from the beginning. The reason for this is the high capillary water absorption of the reinforcement used in this series.

Figure 6 also shows the water absorption coefficient, \( W_{w,24} \), of the specimens calculated using Equation (1).

\[
W_{w,24} = \frac{\Delta m_{wf}}{\sqrt{24}},
\]

where

\[
\Delta m_{wf} = \frac{M_{wf} - M_i}{A_w}.
\]
For the determination of the surface-related mass increase \( (\Delta m_{tf}) \), the amount of absorbed water, \( M_{tf} / C_0 M_i \), is related to the water-absorbing surface \( (A_w) \).

Concrete \( a \) in general shows the lowest relative water absorption. Reinforced variants \( a-02 \) and \( a-03 \) do not show increased water absorption compared to the unreinforced specimen. In contrast, reinforcement variant \( 01 \) leads to a drastic increase in the capillary suction. With this variant, water drainage is observed at the top end of the rovings after 8 h. The capillary water absorption reaches 233\% of that of the unreinforced reference specimen. The capillary suction of concrete \( c \) is approximately 25\% higher than that of concrete \( a \). In opposition to mixture \( a \), influence of the reinforcement on the water absorption can be observed. Thus, the specimens of series \( c-02 \) show an approximately 74\% and of series \( c-03 \) an approximately 34\% higher capillary absorption. The limit for water absorption of category R4 repair mortar according to ÖNORM EN 1504 3\textsuperscript{55} for particular exposure and loads is 0.5 kg/(m\(^2\) √h). This requirement is met by all three concrete mixes. Compared with the standardized test procedure according to ÖNORM 13507,\textsuperscript{56} the performed test procedure differs only slightly. Instead of circular specimens with a diameter of 100 mm and a thickness of 25 mm, cuboid specimens, as described above, were used.

### 4.2 FTDS tests

To determine the FTDS resistance of the TRC layers, the slab test method for frost classes XF2 and XF4 according to ÖN 23303\textsuperscript{57} was used. In this method, the frost resistance of the test specimens is assessed by comparing the mass of the weathered material with that of the reference specimen made of a so called zero concrete. The frost resistance of this reference concrete is determined in ÖN 23303\textsuperscript{57} by defining certain properties such as flow table class, cement content, w/cm ratio, air content in fresh concrete and air void characteristics. The test specimens are considered frost-resistant if their scaling is on average less than 200 g/m\(^2\) higher than that of the zero concrete, which has a frost scaling of less than 300 g/m\(^2\). If the scaling of the zero concrete is higher than 300 g/m\(^2\), an excess of 100 g/m\(^2\) is permissible.\textsuperscript{57}

### Table 4 Test program for capillary water absorption of TRC samples

| Label | Concrete mix | Reinforcement type | Layers of reinforcement | Degree of reinforcement \( \rho (\%) \) |
|-------|--------------|--------------------|-------------------------|---------------------------------------|
| a     | a            | –                  | –                       | –                                     |
| a-01  | a            | 01                 | 2                       | 0.67                                  |
| a-02  | a            | 02                 | 2                       | 0.57                                  |
| a-03  | a            | 03                 | 2                       | 0.90                                  |
| b     | b            | –                  | –                       | –                                     |
| c     | c            | –                  | –                       | –                                     |
| c-02  | c            | 02                 | 2                       | 0.60                                  |
| c-03  | c            | 03                 | 2                       | 0.94                                  |

### Figure 6 Results of capillary water absorption of TRC samples\textsuperscript{53}
Concurrently, pull-off tests were conducted, to reveal the structural damage of the TRC specimens by an FTDS attack.

4.2.1 | Test program

For the investigation of the TRC frost resistance, the concrete as well as the reinforcement were varied based on the previously described experiments. Recalling, the specimens contained two layers of reinforcement; however, the thickness of the concrete cover was varied. The specimens were produced by lamination, demoulded after 24 h, and stored under water until the seventh day. Subsequently, the specimens were cured in a climatic chamber at 20°C and 65% relative humidity. At the start of the tests, the specimens had a concrete age of 36 days. For each variant two specimens were tested. The different variants are listed in Table 5. The varying concrete cover is indicated in the brackets.

In the slab test method, the frost exposure was applied on slabs with dimensions of 15 × 15 cm². According to ONR 23303,⁵⁷ the slab thickness has to be 5 cm. However, to reflect real service conditions, it was reduced to a thickness of 3 cm, which is common for TRC components. Owing to the use of fine-grain concretes with a maximum grain size of 1 mm or 2 mm, the above thickness is sufficient to comply with the geometrical boundary conditions of the concretes. Only the reference specimens of the zero concrete had a thickness of 5 cm for comparing the test method. Another difference from the guideline was in the surface finish of the specimens. The test instruction specifies that the frost exposure should be applied on a sawn surface. However, to mimic the real service conditions for a concrete pavement, floated surfaces were used. However, the reference specimens, were manufactured with a sawn surface in accordance with the Austrian standard.

Concrete specimens must be specifically prepared for the test procedure. For this purpose, a sponge rubber seal was applied to all sides except the test surface. To ensure that the heat is only conducted by the test surface, the sealed sides were additionally thermally insulated. Three days prior to the start of the FTDS attack, the surface to be tested was immersed in an approximately 3-millimeter-deep layer of deionized water (67.5 ml), which was replaced by a 3% NaCl solution 15 min before the start of the test, which was kept on the surface throughout the test procedure. Subsequently, the test specimens were placed in a climatic chamber and subjected to an FTDS temperature curve. Each temperature cycle lasts 24 h. A schematic of the preparation of the test specimens and the applied temperature cycle is shown in Figure 7. The temperature was measured in the center of the specimen surface. The measurement is derived from an analogous series with similar filling of the freezer and the same specimen parameters. To determine the scaling of the test specimens, the scaled material was brushed off the test surface after 7/14/28/42/56 cycles and weighed after drying to constant mass at 105°C.

4.2.2 | Results

To determine whether a concrete is frost resistant, the area-related scaling after 56 FTDS is needed. It is calculated by dividing the summed mass loss after 56 cycles (M₅₆) by the exposed area (A_FT):

\[ S_{56} = \frac{M_{56}}{A_{FT}}. \]  

The crucial criterion for determining frost resistance is comparison with the zero concrete. However, because a weathering of only 5 g/m² was measured, the tested TRC concretes may have a maximum weathering of 205 g/m² to ensure an equivalent resistance to exposure class XF4. The average results of all samples and the limit value for the assessment of frost resistance are shown in Figure 8.

| Label (concrete cover) | Concrete mix | Reinforcement type | Layers of reinforcement | Concrete cover (mm) |
|------------------------|--------------|--------------------|------------------------|--------------------|
| a                       | a            | –                  | –                      | –                  |
| a-01 (8 mm)             | a            | 01                 | 2                      | 10                 |
| a-01 (5 mm)             | a            | 01                 | 2                      | 5                  |
| a-01 (13 mm)            | a            | 01                 | 2                      | 15                 |
| a-03 (7 mm)             | a            | 02                 | 2                      | 10                 |
| b                       | b            | –                  | –                      | –                  |
| c-02 (8 mm)             | c            | 02                 | 2                      | 10                 |
| c-03 (8 mm)             | c            | 03                 | 2                      | 10                 |
| Zero-concrete           | –            | –                  | –                      | –                  |
Only the specimens of concrete a meet the criterion of frost resistance of exposure class XF 4. The other specimens are above the limit. Particularly noticeable is the scaling of concrete b, which exceeds the required limit value by a factor of six. Furthermore, specimens a-01 and a-03 with textile reinforcements show increased scaling of the surface compared to the unreinforced reference. The progression of surface scaling of some tested specimens after 28 and 56 FTSW can be seen in Figure 9. A detailed interpretation of the results obtained and the effects of the concrete and the reinforcement on frost resistance is provided subsequently in Section 5.

### 4.3 Pull-off tests

To investigate the effects of frost exposure on the delamination strength of the concretes, pull-off tests were performed on the specimens used for the frost scaling tests. These were compared to reference tests without FTDS exposure.

#### 4.3.1 Test program

The pull-off tests were conducted according to ONR 23303.57 These tests to determine the pull-off resistance of interfaces, and are therefore, suitable for characterizing the discontinuity caused by textile reinforcements. For this purpose, drill cores with a diameter of 50 mm were taken from test slabs, and steel discs were bonded to both sides. Subsequently they were pulled apart using a tensile testing machine. The applied force was displacement-controlled at a rate of 0.25 mm/min. Near-surface failure of the concrete, failure of the adhesive, or delamination in the reinforcement layer could be observed, because a textile reinforcement represents a weak point in a concrete structure.58 The concrete age during testing was 94 days. The pull-off tests were performed for all the different variations of concrete and reinforcement used for the FTDS tests. Three individual tests were conducted for each configuration. The test setup as well as different failure modes can be seen in Figure 10.

#### 4.3.2 Results

Based on the ultimate load \( F_{\text{ul}} \), the pull-off stress of each specimen \( f_{\text{ul}} \) is determined using Equation (3) by dividing the load by the gross cross-sectional area of the drill core.
Figure 11 provides the pull-off stress and failure mode of the tested specimen. The mean pull-off strength, the change of it as well as the minimum values are given in Table 6. Owing to the damage of the concrete structure caused by the FTDS, a decrease in the ultimate pull-off strength can be observed throughout. Only the series of concrete mix \( b \) is an exception. The reason for this is that in the reference tests, failure occurred in the adhesive, whereas in the FTDS exposed specimens, it occurred on the frost scaled surface.

5 | DISCUSSION

Owing to the complex microstructure of concrete, consisting of hardened cement paste, aggregates, and pores, often only a qualitative assessment is possible. An exception is the classification of the tests on FTDS resistance. Because this is a performance-based test method, the concrete can be classified into categories. However, by linking the different experiments conducted, it is possible to determine different influences on the microstructure of the concrete and assess their effects on frost scaling.

5.1 | Relation between open porosity and capillary water absorption

Based on the results of the open porosity, the following trend can be seen. Owing to the high cement content in the concretes, a relatively high open porosity is measured for all three mixtures. Concrete \( b \) shows the highest porosity because of the high w/cm ratio and the substantial air content in the fresh concrete. Mixtures \( a \) and \( c \) show almost identical open porosity at different w/cm ratios. Although mixture \( c \) has a 32% higher cement content than mixture \( b \), it has a lower w/cm ratio; thus, it has the same open porosity as mixture \( b \) at approximately 18%.

A comparison of the capillary water absorption of the different concrete mixtures provides a clear trend. According to Wesche, the proportion of chemically bound water and gel water is approximately 38% of the...
cement mass at complete hydration. Accordingly, capillary pores are formed only if the w/cm ratio exceeds 0.38. Therefore, theoretically, only concrete mix b contains capillary pores. However, in practice, complete hydration is not achieved, and capillary pores are also found in concrete mixes a and c. However, the capillary water absorption tests show that the capillary suction in them is significantly lower than that in concrete b. It is determined that concrete c has a 22.6% higher water absorption than concrete a at almost the same open porosity. This indicates a higher capillary pore fraction for the former than that for the latter. The high capillary water absorption of the rovings treated with impregnation 01 shows that SBR impregnations leave voids in the roving, which increase the capillary water absorption. The water absorption of the EP-impregnated reinforcement variants varied significantly depending on the concrete used. For mix a, the difference in the areal water absorption of reinforcements 02 and 03 after 24 h is 0.0 kg/(m²·h). This indicates that the reinforced specimens do not absorb more water than the unreinforced reference specimen. Therefore, the roving cross-section can be considered impermeable. In contrast, for concrete mix c, reinforced specimen c-02 shows a 74% higher water absorption and variant c-03 a 34% higher water absorption than the unreinforced reference. One possible reason for the observed higher water absorption could be defects in the impregnation of the reinforcement. However, when the reinforcement was inspected prior to concreting, no notable defects were observed in the reinforcement grid; therefore, this reason can be almost excluded. Concurrently, it is suspected that the increased water absorption resulted from the defects in the specimens due to manual production in the lamination process using trowels. Concrete c had a very sticky consistency and had to be worked into the reinforcement.

FIGURE 10  Test setup (a), delamination of the textile layer (b), and concrete failure (c) of pull-off tests

FIGURE 11  Results of pull-off tests
grid with considerable force. It is quite possible that the desired degree of compaction was not achieved and that the interface between the concrete and the reinforcement in particular had high porosity or voids, and thus, increased the water absorption. In addition, the floating finish of the surface may have affected the microstructure.

Owing to the correlation between the capillary water absorption and the FTDS resistance, a reinforcement that enables a high capillary water absorption of the concrete must be considered critical with regard to frost resistance.

### 5.2 | FTDS scaling

A closer examination of the scaling of the different configurations of concrete mix a in Figure 12 shows that the amount of scaling after 56 FTSW is the lowest for the reference specimen without reinforcement. For variant a-01, the amount of scaling depends on the concrete cover of the textile reinforcement. It reaches a minimum of 12 g/m² with a 5-mm-thick concrete cover and a maximum value of 65 g/m² when the concrete cover is increased to 13 mm. Although reinforcement 01 (SBR) and 03 (TP&EP) show different capillary water absorption properties, the amount scaled after 56 FTSW differs only insignificantly. The type of impregnation, and thus, the porosity of the reinforcement do not seem to have any influence on the frost scaling. Therefore, the cause of the increased scaling as a function of the concrete cover is related to the concrete. The possibility of the addition of fibers to concrete affecting its durability was recognized early and is of particular importance in the case of fiber concretes. Although various studies on this in the literature, there is a lack of clarity in the results. Studies by Zaki et al.⁶⁰ suggested that the use of steel fibers causes an increase in the frost scaling, whereas Balaguru and Ramankrishnan⁶¹ found that they have only a minor influence compared to the air content of the fresh concrete. Hähne et al.⁶² investigated the properties of concrete reinforced with polycrylonitrile fibers. No influence of the polycrylonitrile fibers on the frost resistance was found when air-entraining agents were added. In the present study the influence of textile reinforcements on the pore systems of the concretes cannot be excluded; however, it seems to be relatively smaller than the effect of the concrete mix.

In contrast to the clear influence of the concrete mixture, the absolute change in the amount of scaled material within the test series due to the integration of a textile reinforcement is small. The total increase amounts in the scaling for concrete mix a compared to the unreinforced reference were 8, 28, and 61 g/m² for 5, 8, and 13 mm concrete covers. The proportionality of the concrete cover and the FTDS scaling indicates a change in the pore structure of the concrete due to the integration of the textile reinforcement. This inference has already been discussed for capillary water absorption in Section 4.1. Because the scaling of variant a-03 with a measured concrete cover approximately 7 mm is approximately 30 g/m², and therefore 17% higher than expected, no general conclusion can be drawn. As described before, the reinforcement in this variant differs in various parameters. To determine how the properties of the reinforcement influence the pore structure of the concrete,
and therefore, the scaling, further investigations are necessary.

5.3 | Pull-off tests

In the pull-off tests, in most cases, failure occurred in the interface of the textile reinforcement. In the existing codes, failure at the reinforcement interface is generally not considered, because in the case of strengthening with steel-reinforced concrete, failure occurs either in the bond joint to the existing concrete or at the treated surface. Therefore, the pull-off strength of the reinforcement interface should reach the strength required for these cases to prevent an early failure due to the delamination of the textile-reinforced layer.

There is no uniform criterion for assessing the pull-off strength. However, standards and technical regulations provide various guide values, which can be used for classification. For example, ÖNORM EN 1504-3 requires a pull-off strength of at least 2.0 MPa after 28 days for the repair mortar of class R4. In Austria, RVS 15.02.34 is also relevant for the strengthening of bridges using a top concrete. It sets the minimum value for the pull-off strength as 1.5 MPa.

Table 6 shows that before the FTDS exposure, all specimens are above these limits. After the FTDS, a decrease in the pull-off strength to approximately 60% is observed for concrete mix a, with the failure mechanism changing from delamination in the textile layer to failure of the frost-scaled surface. The decrease in the pull-off strength is particularly large for mixture c. In this case, it drops to approximately 30% of the initial strength. This indicates a strong degradation of the concrete by the FTDS, which is already evident from the amount of the scaled material. The residual strength also drops below the minimum values required in ÖNORM EN 1504-3 as well as in RVS 15.02.34, although frost exposure is only conditionally required in the regulations. In this case, the failure is due to the delamination in the interface of the textile reinforcement. The strong decrease in both the pull-off strength and adhesive tensile strength in the interface, analogous to the increased capillary water absorption, could be owing to the previously described problem in the manufacture of the test specimens and the resulting increased porosity of the interface.

5.4 | Encountered problems

The FTDS resistance tests showed problems when very little scaling occurred. This was particularly problematic with concrete mix a. It was frequently difficult to weigh the amount of the scaled material, because it was less than 0.05 g. Owing to the small test surface of $2 \times 0.15 \times 0.15 \text{ cm}^2$, the chipping of individual aggregates led to a strong increase of the upsized amount of scaled material per square meter. Furthermore, for test configuration c-03, a strongly nonuniform scaling of the two test specimens was observed. Test specimen 01 showed a mass loss of 1000.53 g/m², whereas test specimen 02 only had a scaling of 103.57 g/m². Both test specimens originate from the same concrete slab and were stored next to each other in a climate chamber. In the opinion of the authors, a test-related cause can be excluded. The cause for the strong deviation is currently not clear and subject of further research.

6 | CONCLUSION

During the inspection of the Gschwandtkopf-bridge, damage of the TRC surface was observed. Further investigations showed increased porosity in the textile reinforcement layer. To investigate the effects of this anomaly on the durability, capillary water absorption, FTDS resistance, and pull-off tests were conducted. Three different concrete mixes and carbon reinforcements with three different impregnations were used for this purpose. The most important conclusions that were drawn from the test program are as follows:

1. Capillary water absorption is strongly influenced by the textile reinforcement used, and particularly the type of impregnation is decisive. The epoxy resin-impregnated reinforcements show almost no capillary water absorption, whereas the SBR impregnations lead to increased water absorption.

2. The integration of a textile reinforcement affects the concrete microstructure depending on the consistency of the concrete. Even when using carbon rovings, which have a dense cross-section, the capillary water absorption can increase owing to the interference layer of the reinforcement.

3. A reinforcement, or the integration of a reinforcement, probably affects the pore structure of the concrete. For the SBR-impregnated reinforcement, a correlation between the concrete cover and the frost scaling is observed in the FTDS resistance tests. However, further investigations with other impregnation variants are necessary to draw a general conclusion.

4. Frost resistance XF4 is only achieved with concrete mix a. Mixture b is not frost resistant. Mixture c, which according to the information of the manufacturer has frost resistance class XF4, is not confirmed in the test. However, no reference tests are conducted
with this concrete. This means only the reinforced samples are available to assess the frost resistance. The reason for the amount of scaled material may be the disturbance zone of the pore structure caused by the reinforcement. A large effect of the textile reinforcement on the concrete structure is also observed in this concrete mix in the capillary water absorption tests and is probably related to the sticky consistency of the concrete, which makes it difficult to apply the concrete using the lamination method.

5. The pull-off strengths of the reference samples consistently show higher values than required. However, the FTDS exposure leads to a decrease in the pull-off strength, and particularly the delamination resistance of the textile layer. This causes a reduction of the pull-off strength up to 30%. If a sufficiently frost-resistant concrete is used, the residual strength is approximately 60%. In this case, instead of delamination of the textile layer, a pull-off failure of the frost-loaded surface occurs.

Further tests to clarify the validity of the relationship between the concrete cover and the FTDS resistance for the epoxy resin-impregnated reinforcements are being planned.

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Research data are not shared.

ORCID
Julian Konzilia https://orcid.org/0000-0002-0796-5206

REFERENCES
1. Schiessl P, Mayer T. Lebensdauermanagementsystem—Teilprojekt A2. Schlussberichte zur ersten Phase des DAStb/BMBF-Verbundforschungsvorhabens Nachhaltig Bauen mit Beton: Vol. 572. Schriftenreihe des DAStb. Berlin: Beuth Verlag GmbH; 2007. p. 49–100.
2. Schießl-Pecka A, Willberg U, Rausch A, Bäumler W. 100 Jahre Dauerhaftigkeit für Brücken- und Tunnelbauwerke. Beton Stahlbetonbau. 2018;113(10):746–55. https://doi.org/10.1002/best.201800032
3. Wicke M, Kirsch P, Straning W, Scharitzer B. Kostenmodell für den Funktionserhalt von Straßenbrücken. Bauingenieur. 2001;76:86–91.
4. Feix J. UHPC—Aufbetone. Tagungsband 11. Münchener Massivbauseminiar: zum 80. Geburtstag von em. Univ.-Prof. Dr.-Ing. Dr.-techn. h.c. Herbert Kupfer. München: Technische Universität München; 2007. p. 1–20.
5. Feix J, Andreatta A. Strengthening of existing bridge decks by additional concrete layers—new research results and design rules. In: Strauss A, editor. Life-cycle and sustainability of civil infrastructure systems: proceedings of the third international symposium on life-cycle civil engineering, Hofburg palace, Vienna, Austria, 3–6 October 2012. Boca Raton, FL: CRC Press; 2013. p. 358–64.
6. Feix J, Andreatta A, Niederegger C. Strengthening of bridges with high performance concrete (HPC). In: A. Zingoni, editor. Recent developments in structural engineering; Rotterderdam: Millpress; 2007. p. 743–44.
7. Feix J, Strobl G. HPC—bridge decks without additional sealing. In: Albrecht G, Japanese German Bridge Symposium, editors. 6th Japanese German bridge symposium: proceedings. Munich: Univ. der Bundeswehr; 2005.
8. Hadl P, Della Pietra R, Hoang KH, Tue NV, Pileh E. Anwendung von UHPC als direkt befahren Außbeton bei der Integralisierung eines bestehenden Brückenbauwerks in Österreich. Beton Stahlbetonbau. 2015;110(2):162–70. https://doi.org/10.1002/best.201400991
9. Berger J, Bruschetini-Amбро SZ, Kollegger J. An innovative design concept for improving the durability of concrete bridges. Struct Concr. 2011;12(3):155–63. https://doi.org/10.1002/suco.201100022
10. Berger J, Kollegger J. Spannglieder mit Kunststofffuhloehren zur Herstellung von Bricken ohne Betonstahlbewehrung. Beton Stahlbetonbau. 2009;104(6):349–56. https://doi.org/10.1002/best.200900006
11. Hegger J, Horstmann M, Voss S, Will N. Textilbewehrter Beton: Tragverhalten, Bemessung und Anwendung. Beton Stahlbetonbau. 2007;102(6):362–70. https://doi.org/10.1002/best.200700552
12. Hegger J, Goralski C, Kulas C. Schlanke Fußgängerbrücke aus Textilbeton. Beton Stahlbetonbau. 2011;106(2):64–71. https://doi.org/10.1002/best.201000081
13. Helbig T, Unterer K, Kulas C, Rempel S, Hegger J. Fuß- und Radwegebrücke aus Carbonbeton in Albstadt-Ebingen. Beton Stahlbetonbau. 2016;111(10):676–85. https://doi.org/10.1002/best.201600058
14. Brückner A, Ortlepp R, Curbach M. Textile reinforced concrete for strengthening in bending and shear. Mater Struct. 2006;39(8):741–748. https://doi.org/10.1617/s11527-005-9027-2
15. Herbrand M, Adam V, Clasen M, Kueres D, Hegger J. Strengthening of existing bridge structures for shear and bending with carbon textile-reinforced mortar. Materials. 2017;10(9):1099. http://doi.org/10.3390/ma10091099
16. Farwig K, Neumann J, Schneider R, Breitenbücher R, Curbach M. Instandsetzung von gefugten Betonflächen mit zusätzlichen TextilbemUSTER. Beton Stahlbetonbau. 2020;115(10):768–78. https://doi.org/10.1002/best.202000048
17. Schumann A, Michler H, Schladitz F, Curbach M. Parking slabs made of carbon reinforced concrete. Struct Concr. 2018;19(3):647–55. https://doi.org/10.1002/suco.201700147
18. Feix J, Hansl M. Zur Anwendung von Textilbeton für Verstärkung im Brückenbau: Festschrift zum 60. Geburtstag
19. Feix J, Hansl M. Pilotanwendung von Textilbeton für Verstärkung im Brückenbau. In: Curbach M, editor. Tagungsband 25. Dresdner Brückenbausymposium: Institut für Massivbau, Freunde des Bauingenieurwesens e.V., 09. und 10. März 2015. Dresden: Technische Universität Dresden; 2015. p. 99–110.

20. Hansl M. Textilbewehrte Betone zur Instandsetzung und Verstärkung von Fahrbahnplatten aus Stahlbeton (Dissertation). Innsbruck: Leopold-Franzens-Universität Innsbruck; 2014.

21. Hansl M, Feix J. Untersuchung der Rissbreiten in textilebewehrten Betonen. Beton Stahlbetonbau. 2015;110(6):410–8. https://doi.org/10.1002/best.201400122

22. Mechtcherine V, Lieboldt M. Permeation of water and gases through cracked textile reinforced concrete. Cem Concr Compos. 2011;33(7):725–34. https://doi.org/10.1016/j.cemconcomp.2011.04.001

23. Lieboldt M, Mechtcherine V. Capillary transport of water through textile-reinforced concrete applied in repairing and/or strengthening cracked RC structures. Cem Concr Res. 2013;52:53–62. https://doi.org/10.1016/j.cemconres.2013.05.012

24. Al-Lami K, Calabrese AS, Colombi P, D’Antino T Effect of Wet-Dry Cycles on the Bond Behavior of Fiber-Reinforced Inorganic-Matrix Systems Bonded to Masonry Substrates. Materials. 2021;14(20):6171. http://doi.org/10.3390/ma14206171

25. Colombo IG, Colombo M, Di Prisco M. Tensile behavior of textile reinforced concrete subjected to freezing–thawing cycles in un-cracked and cracked regimes. Cem Concr Res. 2015;73:169–83. https://doi.org/10.1016/j.cemconres.2015.03.001

26. Yin S, Jing L, Yin M, Wang B. Mechanical properties of textile reinforced concrete under chloride wet–dry and freeze–thaw cycle environments. Cem Concr Compos. 2019;96(4):118–27. https://doi.org/10.1016/j.cemconcomps.2018.11.020

27. Yin S, Yu Y, Na M. Flexural properties of load-holding reinforced concrete beams strengthened with textile-reinforced concrete under a chloride dry–wet cycle. J Eng Fibers Fabrics. 2019;14(1):1558925019845902. https://doi.org/10.1177/1558925019845902

28. Al-Lami K, D’Antino T, Colombi P. Durability of fabric-reinforced cementitious matrix (FRCM) composites: a review. Appl Sci. 2020;10(5):1714. https://doi.org/10.3390/app10051714

29. Alma’aithah M, Ghiassi B, Dalalbashi A. Durability of textile reinforced concrete: existing knowledge and current gaps. Appl Sci. 2021;11(6):2771. https://doi.org/10.3390/app11062771

30. Dalalbashi A, Ghiassi B, Oliveira DV. Influence of freeze–thaw cycles on the pull-out response of lime-based TRM composites. Construct Build Mater. 2021;313(4):125473. https://doi.org/10.1016/j.conbuildmat.2021.125473

31. Müller M, Ludwig H-M, Ehrhardt D. Frost-Tausalz-Angriff auf Beton. Beton Stahlbetonbau. 2019;114(6):392–400. https://doi.org/10.1002/best.201800096

32. Sezger MJ. Micro-ice-lens formation in porous solid. J Colloid Interface Sci. 2001;243(1):193–201. https://doi.org/10.1006/jcis.2001.7828

33. Liu Z, Hansen W. A hypothesis for salt frost scaling in cementitious materials. J Adv Concrete Technol. 2015;13(9):403–14. https://doi.org/10.3151/jact.13.403

34. Stark J, Wicht B. Dauerhaftigkeit von Beton (2, aktualisierte und erweiterte Auflage). Berlin, Heidelberg: Springer Vieweg; 2013. https://doi.org/10.1007/978-3-642-35278-2

35. Gluth GIG. Die Porenstruktur von Zementstein und seine Eignung zur Gastrennung (Dissertation). Berlin: TU Berlin; 2011.

36. ÖNORM EN 1936:2007. Natural stone test methods—Determination of real density and apparent density, and of total and open porosity. German version. Vienna: Austrian Standards Institute.

37. Martin WD, Kaye NB, Putman BJ. Impact of vertical porosity distribution on the permeability of pervious concrete. Construct Build Mater. 2014;59:78–84. https://doi.org/10.1016/j.conbuildmat.2014.02.034

38. Parrott LJ. Variations of water absorption rate and porosity with depth from an exposed concrete surface: effects of exposure conditions and cement type. Cem Concr Res. 1992;22(6):1077–88. https://doi.org/10.1016/0008-8846(92)90038-W

39. Gagné R, Houehanou E, Jolin M, Escaillit P. Study of the relationship between scaling resistance and sorptivity of concrete. Can J Civil Eng. 2011;38(11):1238–48. https://doi.org/10.1139/l11-084

40. Liu Z. Frost deterioration in concrete due to deicer salt exposure: mechanism, mitigation and conceptual surface scaling model (Dissertation). Ann Arbor, MI: University of Michigan; 2014.

41. ÖNORM B 4710-1:2018. Concrete—Specification, performance, production, use and conformity—Part 1: Rules for the implementation of ÖNORM EN 206 for normal and heavy concrete. German version. Vienna: Austrian Standards Institute.

42. Lieboldt M. Feinbetonmatrix für Textilbeton. Beton Stahlbetonbau. 2015;110(S1):22–8. https://doi.org/10.1002/best.201400100

43. DIN EN 206:2017–01. Concrete — Specification, performance, production and conformity; German version EN 206:2013+A1: 2016. Berlin: Beuth Verlag GmbH

44. ÖNORM EN 1015. Methods of test for mortar for masonry—Part 1-7. German version. Vienna: Austrian Standards Institute.

45. ÖNORM B 12350-5:2019. Testing fresh concrete—Part 5: Flow table test. German version. Vienna: Austrian Standards Institute.

46. ÖNORM EN 196-1:2016. Methods of testing Cement—Part 1: Determination of strength. German version. Vienna: Austrian Standards Institute.

47. Kirsten M, Freudenberg C, Cherif C. Carbonfasern, der Werkstoff des 21. Jahrhunderts. Beton Stahlbetonbau. 2015;110(S1):16–22. https://doi.org/10.1002/best.201400105

48. Younes A, Seidel A, Rüttner S, Cherif C, Thyroff R. Innovative textile Bewehrungen für hochbelastbare Betonbauteile. Beton Stahlbetonbau. 2015;110(S1):16–21. https://doi.org/10.1002/best.201400101

49. Reichenbach S, Preinstorfer P, Hammerl M, Kromoser B. A review on embedded fibre-reinforced polymer reinforcement in structural concrete in Europe. Construct Build Mater. 2021;307(7):124946. https://doi.org/10.1016/j.conbuildmat.2021.124946
50. Lieboldt M. Transport von Flüssigkeiten und Gasen in Textilbeton (Dissertation). Dresden: TU Dresden; 2012.
51. Egger MG. Gesteckte textile Bewehrung (Dissertation [unpublished]). Innsbruck: Universität Innsbruck; 2022.
52. Fritsch BJ. Experimentelle Untersuchungen zur Dauerhaftigkeit von gestickter Carbonbewehrung in Betonbauteilen Textilbetonschichten: Frostbeständigkeit dünner Textilbetonschichten (Masterarbeit). Innsbruck: Universität Innsbruck; 2021.
53. Zingerle F. Experimentelle Untersuchungen zur Dauerhaftigkeit von gestickter Carbonbewehrung in Betonbauteilen Textilbetonschichten: Wasserdurchlässigkeit dünner Textilbetonschichten (Masterarbeit [unveröffentlicht]). Innsbruck: Universität Innsbruck; 2021.
54. ÖNORM EN ISO 15148:2016. Hygrothermal performance of building materials and products—Determination of water absorption coefficient by partial immersion (ISO 15148:2002 + Amd 1:2016). German version. Vienna: Austrian Standards Institute.
55. ÖNORM EN 1504-3:2006. Products and systems for the protection and repair of concrete structures - Definitions, requirements, quality control and evaluation of conformity - Part 3: Structural and non structural repair. German version. Vienna: Austrian Standards Institute.
56. ÖNORM EN 13057:2002. Products and systems for the protection and repair of concrete structures - Test methods - Determination of resistance of capillary absorption. German version. Vienna: Austrian Standard Institute.
57. ÖNORM EN 13057:2002. Products and systems for the protection and repair of concrete structures - Test methods - Determination of resistance of capillary absorption. German version. Vienna: Austrian Standard Institute.
58. ÖNORM EN 13057:2002. Products and systems for the protection and repair of concrete structures - Test methods - Determination of resistance of capillary absorption. German version. Vienna: Austrian Standard Institute.
59. ÖNORM EN 13057:2002. Products and systems for the protection and repair of concrete structures - Test methods - Determination of resistance of capillary absorption. German version. Vienna: Austrian Standard Institute.
60. ÖNORM EN 13057:2002. Products and systems for the protection and repair of concrete structures - Test methods - Determination of resistance of capillary absorption. German version. Vienna: Austrian Standard Institute.
61. ÖNORM EN 13057:2002. Products and systems for the protection and repair of concrete structures - Test methods - Determination of resistance of capillary absorption. German version. Vienna: Austrian Standard Institute.
62. ÖNORM EN 13057:2002. Products and systems for the protection and repair of concrete structures - Test methods - Determination of resistance of capillary absorption. German version. Vienna: Austrian Standard Institute.
63. RVS 15.02.34. Berechnungs- und Bemessungshilfen, Bemessung und Ausführung von Aufbeton auf Fahrbahnplatten. Vienna: FSV; 2011.

AUTHOR BIOGRAPHIES

Julian Konzilia, PhD student, Unit of Concrete Structures and Bridge Design, University of Innsbruck, Technikerstraße 13, 6020 Innsbruck, Austria. Email: julian.konzilia@uibk.ac.at.

Matthias Egger, PhD student, Unit of Concrete Structures and Bridge Design, University of Innsbruck, Technikerstraße 13, 6020 Innsbruck, Austria. Email: matthias.g.egger@uibk.ac.at.

Jürgen Feix, Full professor at the University of Innsbruck and Head of the Unit of Concrete Structures and Bridge Design, University of Innsbruck, Technikerstraße 13, 6020 Innsbruck, Austria. Email: juergen.feix@uibk.ac.at.

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