OKU Fen Bilimleri Enstitüsü Dergisi
8(1): 82-99, 2025

OKU Journal of The Institute of Science and Technology, 8(1): 82-99, 2025

Osmaniye Korkut Ata Üniversitesi Fen Bilimleri Enstitüsü Dergisi

Osmaniye Korkut Ata University Journal of The Institute of Science and Technology

Suya Daldırma ve Donma-Çözülme Döngülerinin Betona Yapıştırılan FRP Epoksinin Çekme Dayanımına Etkisi

Metehan ÇALIŞ[1]*
[1]Türk Standardları Enstitüsü, Yangın ve Akustik Laboratuvarı, 34953, Tuzla/İstanbul

[1]https://orcid.org/0000-0003-1169-6413
*Sorumlu yazar: mcalis@tse.org.tr

Araştırma Makalesi

Makale Tarihçesi:
Geliş tarihi: 01.06.2024
Kabul tarihi: 12.08.2024
Online Yayınlanma: 15.01.2025

Anahtar Kelimeler:
Fiber takviyeli polimer
Donma ve çözülme
Suya daldırma
Pull-off
Yapısal güçlendirme
Yapı malzemeleri

ÖZ

Fiber Takviyeli Polimer (FRP) kompozitlerin çeşitli çevresel koşullar altında beton yapıların güçlendirilmesindeki dayanıklılığı, uzun vadeli etkinlikleri için çok önemlidir. Bu çalışma, suya daldırma ve donma-çözülme döngülerinin epoksi bağlı FRP beton plakaların çekme mukavemeti üzerindeki etkilerini incelemekte ve sahil yapılarında yaygın olan koşulları temsil etmektedir. Beton plakalar, Duratek® AV21 epoksi reçinesi kullanılarak Bazalt (BFRP), Cam (GFRP) ve Karbon Fiber Takviyeli Polimer (CFRP) levhalarla güçlendirilmiş ve suya daldırma ve donma-çözülme döngüsü testlerine maruz bırakılarak şartlandırılmıştır. Çekme testleri, kontrol numunelerinde beton için 3.26 N/mm² ve epoksi reçine için 3.97 N/mm² ortalama çekme mukavemetleri ile beton alt tabakada kohezif arızalar olduğunu ortaya koymuştur. Suya daldırma, CFRP ve GFRP için çekme mukavemetinde hafif düşüşlere neden olurken, BFRP'de artışa neden olmuştur. Donma-çözülme döngüsü tüm FRP tiplerinde çekme mukavemetini arttırmıştır. Sonuçlar, EN 12004-2 standardına göre seçilen suya daldırma ve donma-çözülme koşullarının FRP-beton bağının sağlamlığını gösteren gerekli 2.5 MPa'nın üzerinde kalan tüm test sonuçları ile FRP takviyeli betonun çekme mukavemetini minimum düzeyde etkilediğini göstermektedir. Çalışma, zorlu ortamlarda yapısal takviye için FRP kompozitlerinin kullanılmasını desteklemekte ve olumsuz koşullar altında kullanım esnekliklerini vurgulamaktadır.

Effect of Water Immersion and Freeze-Thaw Cycles on Pull-off Strength of FRP Epoxy Bonded on Concrete

Research Article

Article History:
Received: 01.06.2024
Accepted: 12.08.2024
Published online: 15.01.2025

Keywords:
FRP
Freeze and tow
Water immersion
Pull-off
Structural strengthening
Construction materials

ABSTRACT

Fiber Reinforced Polymer (FRP) composites' durability in reinforcing concrete structures under various environmental conditions are crucial for their long-term effectiveness. This study examines the effects of water immersion and freeze-thaw cycles on the pull-off strength of epoxy-bonded FRP concrete slabs, representing conditions common in waterfront structures. Concrete slabs were reinforced with Basalt (BFRP), Glass (GFRP), and Carbon Fiber Reinforced Polymer (CFRP) sheets using Duratek® AV21 epoxy resin and exposed to water immersion and freeze-thaw cycling tests. Pull-off tests revealed cohesive failures in the concrete substrate, with average pull-off strengths of 3.26 N/mm² for concrete and 3.97 N/mm² for epoxy resin in control samples. Water immersion caused slight decreases in pull-off strength for CFRP and GFRP, while BFRP increased. Freeze-thaw cycling increased pull-off strength across all FRP types. The results suggest that the selected water immersion and freeze-thaw requirements according to the EN 12004-2 minimally impact the pull-off strength of FRP-reinforced concrete, with all test results remaining above the required 2.5 MPa, demonstrating the FRP-concrete bond's robustness. The study supports using FRP composites for structural reinforcement in harsh environments, emphasizing their resilience under adverse conditions.

To Cite: Çalış M. Effect of Water Immersion and Freeze-Thaw Cycles on Pull-off Strength of FRP Epoxy Bonded on Concrete. Osmaniye Korkut Ata Üniversitesi Fen Bilimleri Enstitüsü Dergisi 2025; 8(1): 82-99.

1. Introduction

The conservation of natural resources has become a pressing issue because of rapid urbanization and industrial growth. The construction sector significantly influences sustainable resource management. Construction processes, ranging from new developments to the upkeep and refurbishment of existing buildings, have a significant impact on the environment. The industry is a substantial consumer of natural resources, including water, minerals, and timber, and contributes considerably to environmental degradation through deforestation, pollution, and waste production. Therefore, it is crucial to implement strategies that mitigate these effects and promote resource conservation.

The conservation of natural resources and extension of building lifespans are critical considerations in the construction industry. Tran et al. (2023) highlighted the need for an integrated framework to assess building sustainability, emphasizing the importance of environmental, economic, and social aspects in the decision-making process. Ayoub et al. (2022) presented a framework for evaluating the application of sustainable construction principles in government-building projects, focusing on environmental, economic, and social sustainability throughout the project's life cycle. Renovation of existing structures conserves resources by reducing the need for new materials and waste production. This approach preserves cultural heritage, extends building lifespans, and mitigates environmental impact. Sustainable development is further promoted by maintaining and retrofitting older buildings and ensuring their functionality and resilience to harsh conditions. Regular maintenance and timely repair prolong building life, contribute to resource conservation, and reduce the ecological footprint of the construction industry.

Numerous elements can damage or reduce the strength and durability of civil structures. In addition to design loads, environmental factors such as harsh conditions and additional loads during the lifespan of a structure can have negative impacts. The advancement of composite materials and their integration into construction has garnered significant attention from researchers and industries in recent years. Fiber-reinforced polymer composites have gained popularity for structural repair and retrofitting of reinforced concrete buildings. Composite systems are frequently used to enhance the ductility, rigidity, and strength of reinforced concrete structures that lack these qualities. To strengthen these structures, fiber-reinforced polymer (FRP) systems are well-suited for specialized civil engineering applications. FRP composites are composed of high-strength fibers embedded in a polymer matrix, such as epoxy, vinyl ester, or polyester thermosetting plastic. However, epoxy resins are the most commonly used matrices. The polymer matrix, which is typically stiff but weak, is combined with a high-tensile reinforcing material to create a final product that exhibits the desired mechanical or material properties such as high strength and elasticity.

Several studies have evaluated the FRP-concrete bond degradation under hygrothermal conditions. Zheng et al. simulated the hygrothermal climate characteristics of a region in South China and CFRP-bonded concrete specimens exposed to six different temperature and humidity conditions (Zheng et al. 2016). In their study, two types of tests were conducted: pull-off and single-shear. The results showed that the bond behavior decreased up to 27.9% after exposure to high temperatures and humidity (5°C to 50°C, 70%RH to 95% RH) for a period of 14 days. Lai et al. performed a long-term durability study on CFRP–concrete direct shear pull-off tests, and the specimens were immersed in water at 25°C, 40°C, and 60°C for 5, 15, 30, and 50 weeks (Benzarti et al. 2011). The test results showed a reduction of up to 30% in load-bearing capacity. Benzarti et al. (2011) studied the bonding strength of CFRP on concrete with a longer period of exposure to 95% RH at 40°C. The decrease in the pull-off test results was approximately 58%. Dai et al. (2010) studied the effect of moisture on the bond behavior of FRP to concrete interfaces (Dai et al., 2010). The main focus of this study was the effects of moisture at the time of FRP installation and the effect of moisture on service life. Pull-off tests were conducted at the beginning and again after 8 months, 14 months and 2 years of wet-dry and thermal cycling. The marginal effect was on up to 90% RH-cured concrete surfaces, and FRP composites adversely affected the bonding performance of the FRP-concrete interfaces.

In addition to humidity and temperature effects, FRP system behavior at low temperatures is also important, especially for applications in cold climate conditions. Green et al. (2006) studied the behavior of large- and small-scale FRP-confined concrete columns under extreme conditions (Green et al. 2006). Small-scale test samples of concrete cyclinders wrapped with FRP and exposed to temperatures as low as -40°C or up to 300 freeze-thaw (-18°C to 15°C). GFRP and CFRP sheets were used to confine the concrete cylinders, and the compressive strengths of the exposed and unexposed test samples were compared. The results of this study showed that FRP-confined concrete columns have adequate compressive strength under several extreme conditions. Freeze-thaw cycling did not reduce the compressive strength significantly, and at low temperatures, it showed an increase in strength. In addition to laboratory studies, the long-term durability of externally bonded FRP systems via field assessments is important. Yun and Wu's study aimed to investigate the durability of the FRP-concrete bond interface under freeze-thaw cycling, considering exposure conditions, concrete grade, and the number of freeze-thaw cycles as parameters (2010). The behavior of the carbon FRP (CFRP)–concrete bond interface was evaluated through single-face shear tests. Similarly, Bisby and Green conducted flexural tests on 39 small-scale flexural beams reinforced in tension with externally bonded FRP sheets (2002). The study presented the results of an experimental and theoretical investigation into the effects of freeze-thaw cycling on the FRP-concrete bond.

Yaman et al. (2022) investigated the performance of C16 and C25 concrete samples reinforced with BFRP under freeze–thaw cycles and elevated temperatures. Cylindrical samples were exposed to temperatures of 25°C, 60°C, 100°C, and 150°C for 12 h and subjected to 30, 60, 90, and 120 freeze/thaw cycles. Changes in the compressive strength, relative masses, resonance frequencies, and dynamic modulus of elasticity were compared with those of the reference samples. The results showed that the BFRP reinforcement increased the compressive strength compared with the non-reinforced samples.

However, the performance decreased with increasing freeze/thaw cycles and temperature, although the BFRP-reinforced samples maintained a higher strength than the non-reinforced samples, even under harsh conditions. Allen and Atadero's study was collecting pull-off strength data in situ, where FRP repair had been applied eight years before the study on an arch bridge (Allen and Atadero, 2012). Tests were conducted according to ASTM D7522 (2009), and this study also considered a newer version of the standard ASTM D7522 (2021). According to this study, because of the difficulties on site measurements, the pull-off results varied drastically for locations within close proximity, and there was no clear conclusion regarding which material was deteriorating: the substrate, filler resin, or FRP.

In this study, the effects of water immersion and freeze-thaw cycles on epoxy-bonded FRP concrete slabs were investigated. The significance of this study is heightened by the growing demand for a robust and long-lasting infrastructure in the face of increasing environmental challenges. Enhancing the endurance and dependability of FRP-concrete bonds can substantially reduce the maintenance expenses and bolster the security of buildings subjected to adverse weather conditions. Furthermore, this study expands the existing body of knowledge by providing empirical data on the durability of FRP-concrete bonds, which can inform guidelines and standards for the use of FRPs in construction. By bridging the knowledge gap regarding the behavior of these materials under freeze-thaw and water immersion conditions, this study supports the creation of a more resilient infrastructure, thereby contributing to the sustainability and safety of the built environment. The findings of this research can aid engineers and policymakers in making well-informed decisions regarding the utilization of FRPs in various applications, ensuring that structures can withstand the rigors of environmental exposure without compromising performance. The results will also elucidate the behavior of the pull-off performance of FRP systems used to strengthen waterfront concrete structures, such as piles, beams, and decks.

2. Materials and Methods

2.1. Materials

2.1.1. Concrete Substrate

According to the standard products and systems for the protection and repair of concrete structures, part 4: structural bonding EN 1504-4 (2005), the reference concrete for pull-off testing is described as MC (0.40) in the EN 1766 (2017) reference concrete for testing (Figure 1). Type MC (0.40) is concrete with a water/cement ratio of 0.40 and contains 455/470 kg/m^3 cement in the mix. The reference concrete has a median bonding strength determined by pull-off testing according to EN 1542 with a value of greater than 2.5 MPa (N/mm^2). The pull-off test results for the concrete substrates are listed in Table 1.

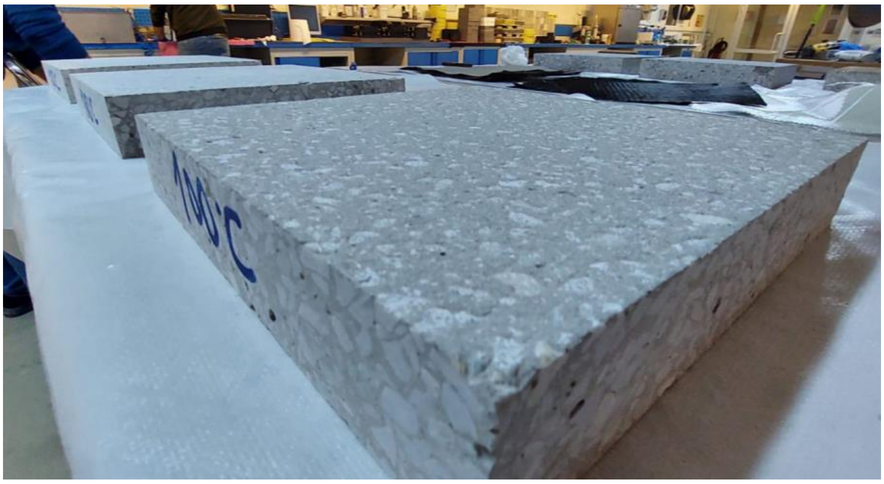

Figure 1. Reference Concrete Substrate Type MC (0,40)

The concrete substrates used for testing had dimensions of 300 mm × 300 mm × 50 mm, differing from the standard thickness of 100 mm. The surface has a roughness created by grit blasting equipment, as described in the standard, which helps the cover layer bond to the concrete surface better.

Table 1. Pull-off Strength of Concrete Substrate

Test Sample No	Value (N/mm^2)
No:1	3.125
No:2	3.256
No:3	3.089
No:4	3.475
No:5	3.358
Average	**3.26**

2.1.2. Epoxy Resin Adhesive

Duratek® AV21 epoxy-based lamination system was used as an adhesive between the concrete and the FRP. The epoxy kit had two components (A: main component epoxy and B: hardener) with an A/B mixing ratio of 73/27 by weight. The contents of container B were added to container A and the two components were mixed for 2-5 min until a homogeneous appearance was achieved. The working environment temperature range was between 10°C and 30°C, and the test samples were prepared under standard laboratory conditions at 23±2°C. Before the fiber sheet was applied, the concrete surface was impregnated. Duratek® AV21 epoxy lamination resin has CE marking according to EN 1504-4 and the features of the product are listed in Table 2.

Table 2. Epoxy Resin (AV21) Technical Specification

Feature	Unit	Standart	Specimen (Epoxy + Hardener)
Density	kg/l	EN ISO 2811-1	1.10±0.05
Viscosity(@23°C)	mPas	ISO 2884-1	500-800
Pot Life (@23°C)	Min	EN 9514	450
Drying time	Min	TS 4317	
Touch Duration	Hour		24
Full Hardening (@23°C, %55 RH)	Week		1
Thermal Transition Temperature	°C	EN 12614	>50
Shrinkage (@23°C, 7 days)	%	EN 12617-1	<%0.1
Thermal Expansion Coeff.	10^{-6}/K	EN 1770	<100
Compressive Strength	N/mm^2	EN 12190	103.6±0.5
Adhesion Strength	N/mm^2	EN 12188	>14
Shear Strength	N/mm^2	EN 12188	>60
Modulus of Elasticity	N/mm^2	EN 13412	>2500
Reaction to fire	-	EN 13501-1	D-s2/d0

2.1.3. Fiber Reinforced Polymer (FRP) Sheets

Basalt, glass, and carbon fiber fabrics with epoxy resin were used on the concrete slab for reinforcement purposes. Ten test samples were prepared in total. The samples were first cut to a size of 30 x 30 cm, which was the same as the surface size of the concrete slab (Figure 2). The technical specifications of the FRP fabrics are listed in the following tables (Table 3-4).

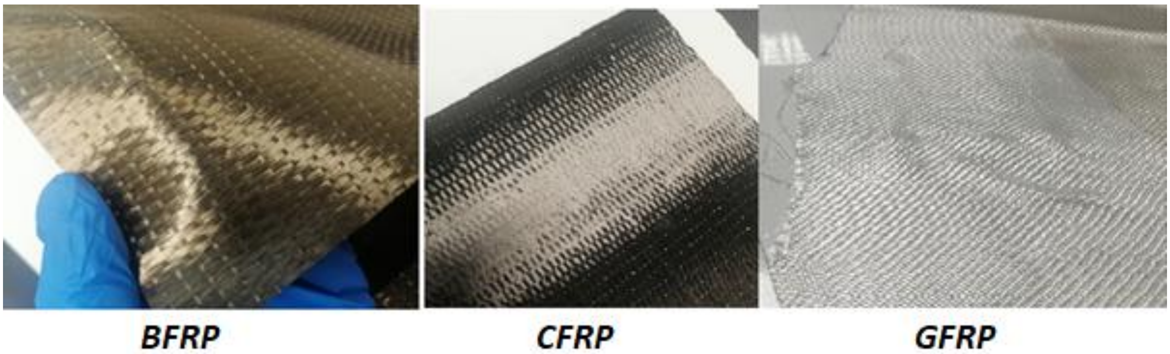

Figure 2. FRP Sheet Preparation (30cmx30cm)

Table 3. CFRP and BFRP Technical Specification

Spesification	CFRP	BFRP
Areal Weight (g/m^2)	300±5%	300±5%
Weave Style (-)	Unidirectional	Unidirectional
Density (g/cm^3)	1.80	2.63
Tensile Style (MPa)	5500	3000
E-Modulus (GPa)	250	90
Thread Count Warp (ends/10cm)	36.5±5%	12.5±5%
Thread Count Weft (ends/10cm)	10.0±5%	10.0±5%

Table 4. GFRP Technical Specification

Spesification	Value
Areal Weight (g/m^2)	300±5%
Density Warp (y/cm)	22±2%
Density Weft (y/cm)	21.4±2%
Weave Style	Satin 8
Glass Type (warp-weft)	e-glass
Tensile Strength Warp (N/cm)	587
Tensile Strength Weft (N/cm)	571

2.2. Test Sample Preparation and Test Methods

First, the FRP fabrics were cut using a 30 × 30 cm metal template. The concrete slabs were maintained in a standard laboratory environment (23±2°C, 50±5% RH) for at least 24 h and marked with a board pen to describe the experiments. Before starting the epoxy resin application, the fabric weights were measured and the amount of epoxy used was calculated based on the measured weight. Within the framework of the epoxy manufacturer's instructions, approximately 2.5-3 times the FRP surface weight of epoxy resin was used for each FRP type.

After mixing epoxy resins A and B at a specified ratio, the first layer was applied to the concrete slabs. In the first layer, slightly more than half of the consumption value of epoxy resin was used. This can be attributed to the fact that concrete absorbs some amount of resin from the surface and the effect of the epoxy resin applied to the substrate on the main adhesion strength. After the first layer was applied using a brush, FRP fabric was applied to the surface within 2 min. A force was applied both horizontally and vertically with a ribbed metal paddle roller (consolidation roller) to ensure that there was no air gap between the concrete surface and FRP fabric. This ensured that the FRP fabric adhered better to the surface and that the epoxy resin entered between the tows and fibers of the FRP fabric. After the application of the metal paddle roller, some epoxy resin reached the surface between the BFRP and CFRP fabrics. The GFRP fabric was directly incorporated with the epoxy resin and integrated with the epoxy resin to create a monolithic appearance.

After FRP fabric application, the remaining part of the calculated consumption amount was applied to the FRP fabric within 2 min. The surface was smoothed with a brush to avoid ripples and roughness. Afterwards, they were placed on test sample shelves and stored under laboratory conditions (23±2°C, 50±5% RH). The experimental flow applied to concrete slabs bonded with FRP fabrics is shown in Figure 3.

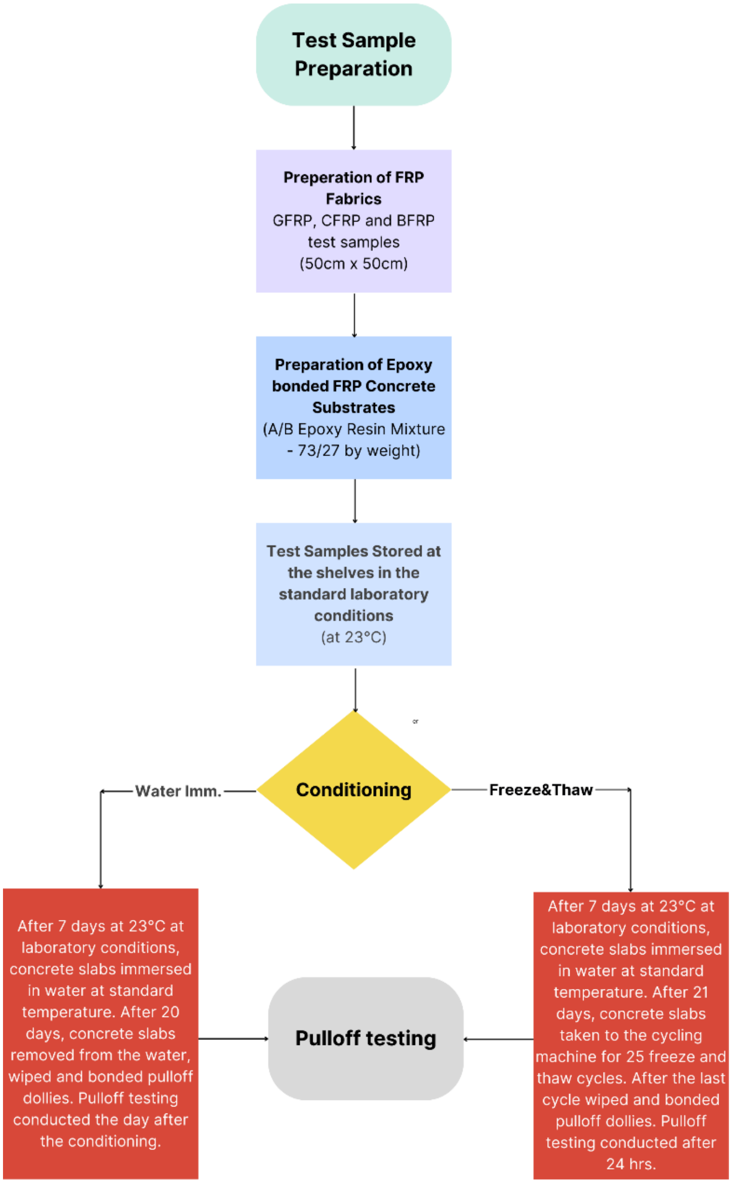

Figure 3. Testing Flow Chart

To determine the epoxy application amount according to the declaration of the epoxy resin manufacturer, weight measurements of the 30 × 30 cm FRP fabrics were performed, and the areal weight measurements of the FRP fabrics to be applied were within the declared values (g/m^2) of the FRP fabric manufacturers.

The standard, "EN 1542:1999 Products and systems for the protection and repair of concrete structures - Test methods- Measurement of bond strength by pull-off" is mainly used for concrete repair and protection systems, mortars, grouts, and the concrete itself (EN 1542, 1999).

The ASTM D 7522 Standard Test Method for Pull-off Strength for FRP Laminate Systems Bonded to Concrete or Masonry Substrates was used to determine the adhesion performance of the FRP laminate systems on concrete.

Both standards require a drill diameter and barrel dimensions of 50±10 mm and the depth of the drill through the concrete substrate should be 15±5 mm. An adhesive was applied to the surface of the drilled part of the test specimen and allowed to harden, in accordance with the manufacturer's instructions. The rate of the load applied on the dolly for pull-off testing according to EN 1542 must be continuous and at 0.05±0.01 MPa/s constant speed until failure occurs, but for ASTM D7522, limiting the rate of stress applied to the FRP-substrate interface being tested to less than or equal to 1 MPa/min (equal to 0.0167 MPa/s).

Another difference between these two standards is the method used to determine the failure modes. The failure modes according to ASTM D7522 are shown in Figure 4. The types of failure according to EN 1542 are listed in Table 5.

Table 5. Failure Modes according to EN 1542

A	Cohesion failure in the concrete substrate
A/B	Adhesion failure between the substrate and the first layer (e.g. primer, bonding slurry or mortar)
B	Cohesion failure in the first layer
B/C	Adhesion failure between the first and second layer
C	Cohesion failure in the second layer
-/Y	Adhesion failure between the last layer and adhesive layer (e.g. C/Y in a two-layer repair system)
Y	Cohesion failure in the adhesive layer
Y/Z	Adhesion failure between the adhesive layer and the dolly (which is Z)
If there is a combination of given failure modes, a visual inspection for the percentage of each type of failure must be conducted, for example; A : A/B : B = % 40 : % 10 : % 50	

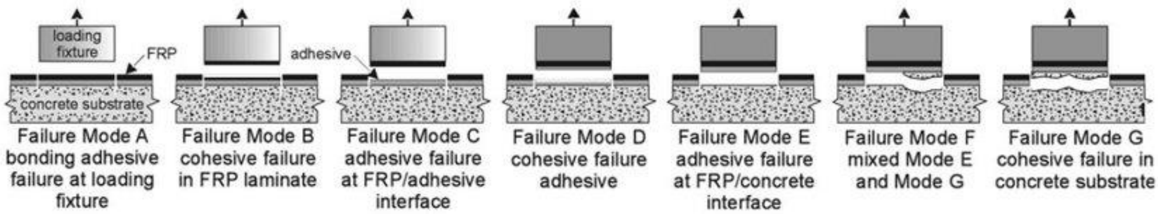

Figure 4. Failure Modes according to ASTM D 7522

For both standards, although the figures and names differ, three failure modes are commonly described: adhesive, cohesive, and substrate modes. Adhesive failure is undesirable, whereas cohesive and substrate failure modes are desirable as a result of the conducted tests. The drill holes and bonded dollies used for pull-off testing are shown in Figure 5-6.

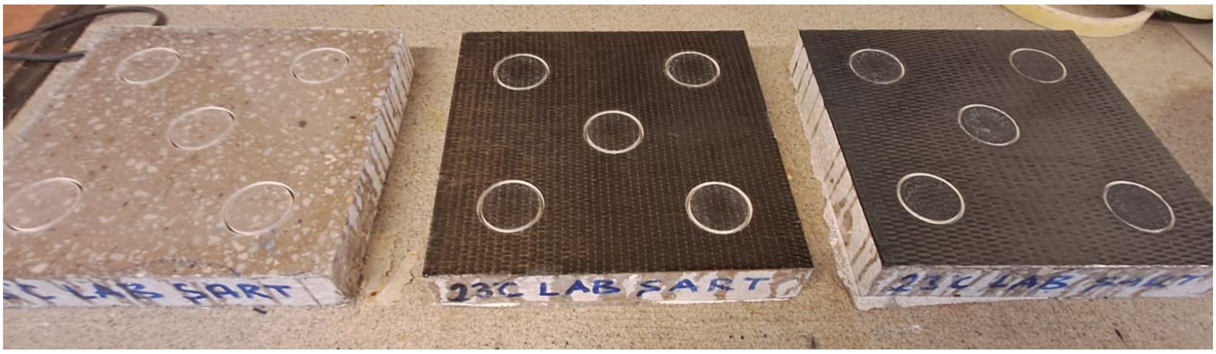
Figure 5. Sample Drilled

Figure 6. Orientation of Dollies on Pull-off Test Sample

2.3. Testing Procedure and Conditioning

Tests were conducted according to EN 1542 and for the tests conducted in this research the preload value is taken as 3,0 N and the test speed was 0,05 N/mm^{2}s using ZWICK Z100 model universal tensile and compression testing machine.

In addition to conditioning the prepared samples under normal laboratory conditions, the methods used for tile adhesives in the EN 12004-2 (2017) standard for water immersion (Figure 7) and freeze-thaw cycling (Figure 8) were considered. It is assumed that the exposure conditions of the ceramics coated on reinforced concrete are the same as those of the FRP fabrics under the environmental conditions specified in the standard. Test samples were exposed to 25 freeze–thaw cycles, as declared in the standard.

For each freeze–thaw cycle, the following steps were followed and repeated 25 times (EN 12004-2, 2017):

1) remove the test units from the water and place in a cold chamber to achieve a steady cabinet temperature of (−15 ± 3) °C within 2 h ± 20 min;

2) maintain the test units at (−15 ± 3) °C for 2 h ± 20 min;

3) immerse the test units in water at (20 ± 3) °C and raise the temperature to (15 ± 3) °C;

4) maintain the test units at (15 ± 3) °C for a minimum 2 h before commencing the next freeze–thaw cycle.

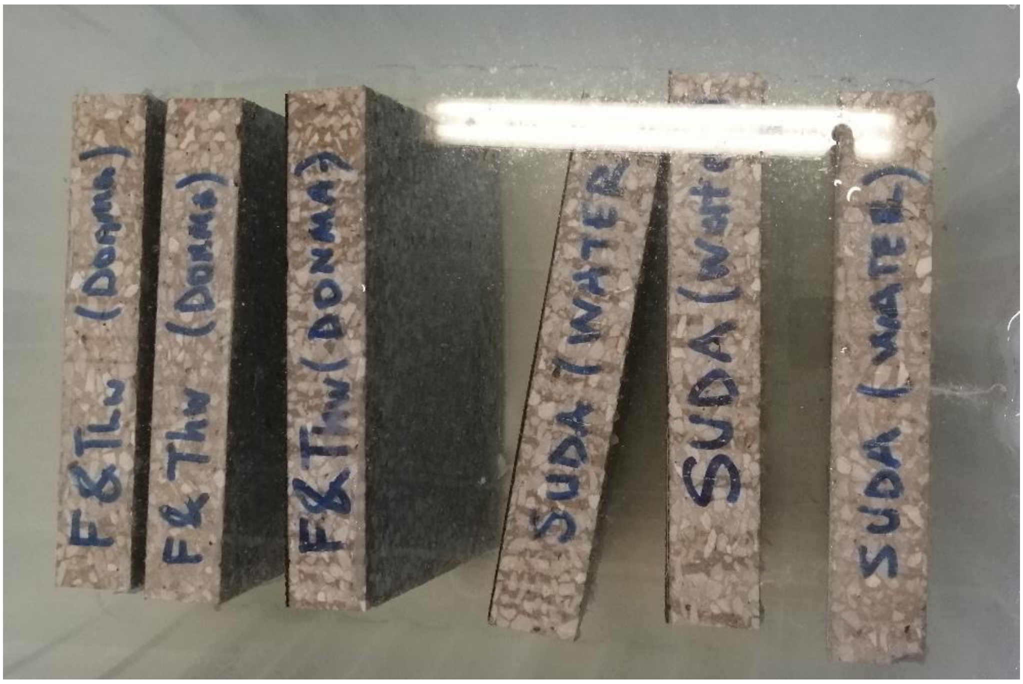

Figure 7. Water Immersion of Test Samples

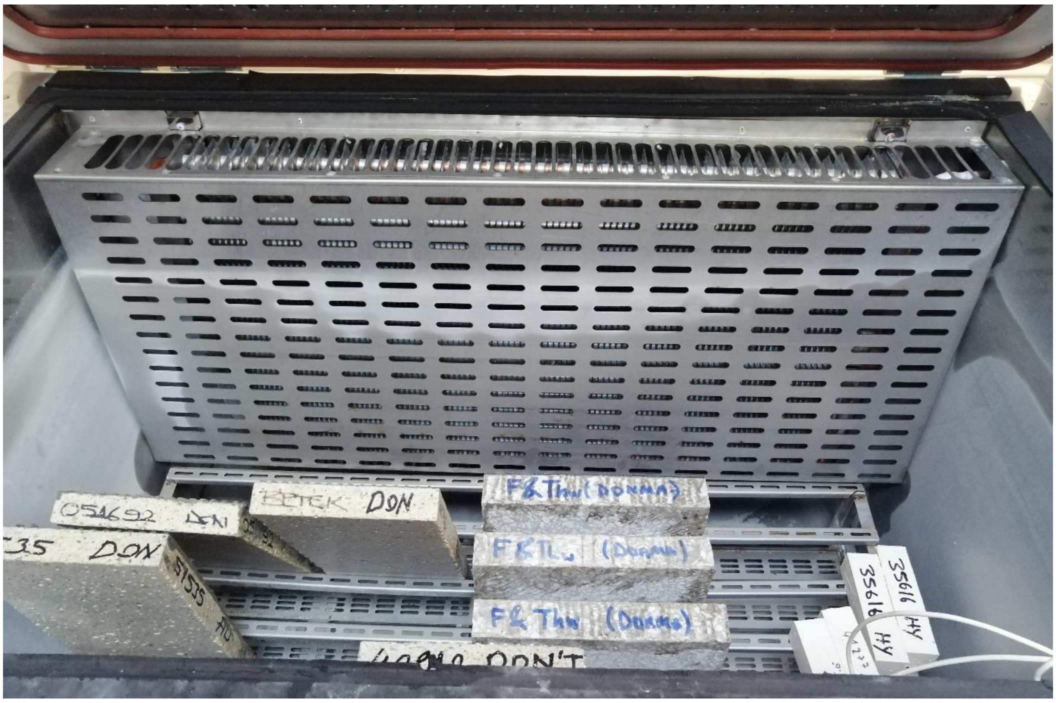

Figure 8. Test Samples placed in Freeze-Thaw Cycle Testing Machine

The table specifying the test plans for various temperature levels, and the corresponding numbers of test samples are presented in Table 6.

Table 6. Test Sample Plan for each Temperature

FRP Type	CFRP	BFRP	GFRP	Epoxy Resin
Lab. Conditions (23°C)	√	√	√	√
Water Immersion	√	√	√	-
Freeze - Thaw Cycling	√	√	√	-
# of Concrete Slabs	3	3	3	1
Total # of Concrete Slabs			10	

3. Results and Discussion

The average pull-off test results are presented in Tables 7 and Table 10–11. As shown in the figures, the failure modes were the same for all tests and were called cohesive failures from the substrate (Figure 9-10). The failure mode was denoted as "A" according to EN 1542 and as "G" according to ASTM D 7522.

Table 7. Pull-off Strength of Epoxy resin

Test Sample No	Value (N/mm^2)
No:1	3.333
No:2	3.616
No:3	4.125
No:4	3.820
No:5	4.932
Average	**3.97**

Table 8. Water Absorption amount for Freeze and Thaw Testing Samples (21 days)

FRP Type	Unit	Initial Weight	Final Weight	Value
CFRP	kg	11.05	11.17	0.12
BFRP	kg	10.98	11.10	0.12
GFRP	kg	10.85	10.95	0.10

Table 9. Water Absorption amount for Water Immersion Testing Samples (21 days)

FRP Type	Unit	Initial Weight	Final Weight	Value
CFRP	kg	11.07	11.15	0.08
BFRP	kg	10.90	11.00	0.10
GFRP	kg	10.80	10.90	0.10

The water absorption amounts for both the water immersion and freeze-thaw cycle test samples were approximately the same at approximately 0,10 kg per concrete slab (Table 8-9). In other words, the effect of water absorption on pull-off test results can be neglected.

Table 10. Pull-off Strength of Water Immersion Concrete Slabs

Test Sample No	GFRP (N/mm^2)	BFRP (N/mm^2)	CFRP (N/mm^2)
No:1	3.196	3.303	3.685
No:2	3.517	3.639	3.385
No:3	4.043	4.134	**5.125***
No:4	3.165	4.029	3.988
No:5	3.544	3.272	3.056
Average	**3.49**	**3.97**	**3.53**

* These values were omitted because they were more than %25 above or below average. The new average value was calculated, and is presented in table.

GFRP ***BFRP*** ***CFRP***

Figure 9. Pull-off Failure Pattern for Water Immersion

Table 11. Pull-off Strength of Freeze-Thaw Concrete Slabs

Test Sample No	GFRP (N/mm^2)	BFRP (N/mm^2)	CFRP (N/mm^2)
No:1	4.086	3.442	3.990
No:2	3.729	3.580	4.178
No:3	4.261	4.418	4.254
No:4	3.390	3.437	3.605
No:5	3.599	3.465	4.080
Average	**3.81**	**3.67**	**4.02**

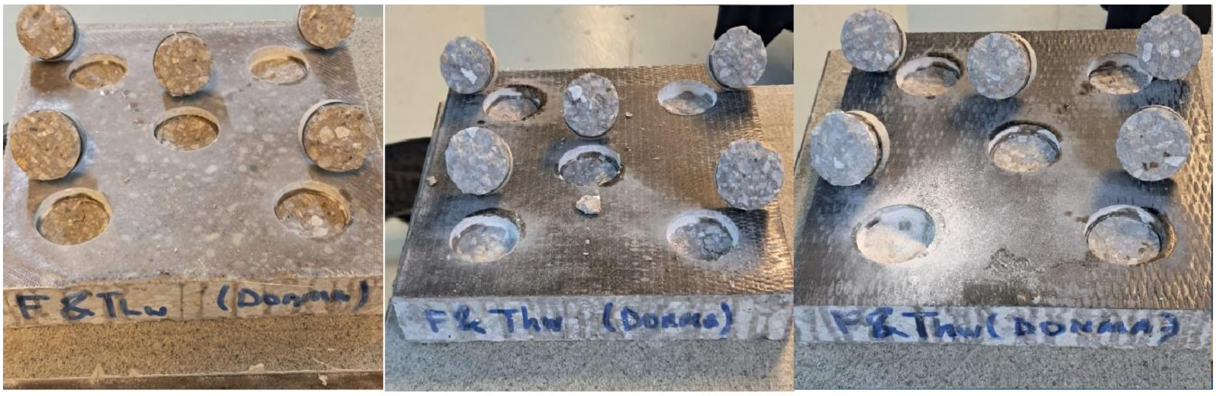

Figure 10. Pull-off Failure Pattern for Freeze-Thaw Cycle

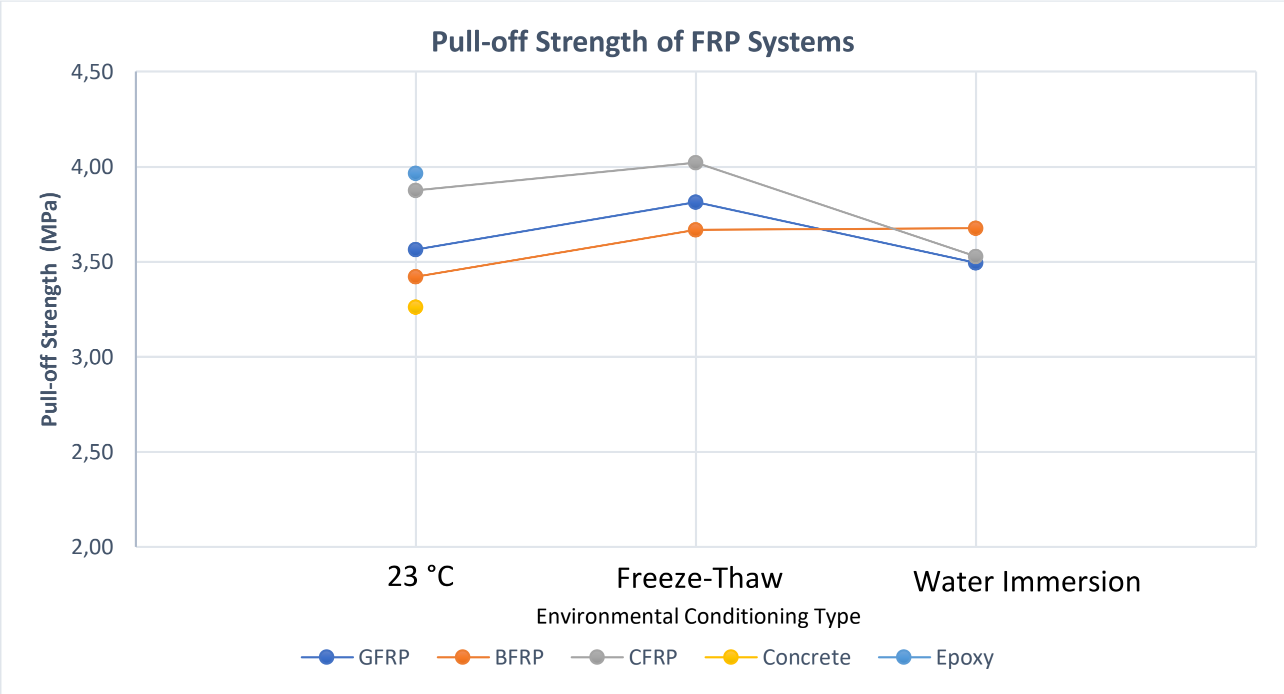

Figure 11. Pull-off Strength for Each Environmental Conditioning Type

As seen on the Figure 11,

- The water immersion pull-off test results were lower than the freeze–thaw cycle test results. With respect to the literary analysis, it is not possible to make a direct comparison between the two test results.
- All the initial, water immersion, and freeze-thaw cycle pull-off test results for all FRP types lie between the pull-off test results of epoxy (without FRP) and the concrete slab itself. Essentially, the effect of environmental conditioning on the degradation of pull-off test outcomes was negligible.
- All FRP types showed an increase in the pull-off test results after 25 freeze-thaw cycles when compared to the initial pull-off test results. This increase was approximately 7%, 7,3%, and 3,75% for GFRP, BFRP, and CFRP, respectively. The curing process of the adhesive under

standard laboratory conditions followed by exposure to low temperatures may potentially enhance its bonding capability by further hardening the adhesive.

- Only BFRP exhibited an increase in the average pull-off strength for both freeze-thaw cycles and water immersion. This result might be due to the mechanical properties of BFRP (stiffer and harder to bend) when compared to GFRP and CFRP. The inherent flexibility of BFRP, owing to its lower modulus of elasticity, might allow it to better accommodate the expansion and contraction of concrete during freeze-thaw cycles without cracking or debonding.
- Water immersion for 21 d had an adverse effect on the CFRP and GFRP. The decrease was approximately 9% for CFRP and 2% for GFRP compared to the initial pull-off test results. The Differential expansion due to water absorption may be the reason for this difference in the results. Both CFRP and GFRP might absorb more moisture than BFRP, leading to swelling and the creation of internal stresses that weaken the bond between the composite and concrete. Additionally, swelling of the matrix owing to water absorption can induce microcracks or delamination at the fiber-matrix interface, reducing the pull-off strength.

In contrast to the results obtained in this study, Yun and Wu (2010) reported a decrease in bond strength, stiffness, and interfacial fracture energy, as well as an increase in cracking and effective bond length with more freeze-thaw cycles. The main difference between this research was the test method and the number of test cycles, as well as the testing type (shear pull-off). Bisby and Green (2002), however, indicated little to no damage from freeze-thaw cycling on the FRP-concrete bond, similar to the results of this study. Similarly, Green et al. (2006) suggested that the bond between carbon FRP strips and concrete was not significantly damaged by up to 300 freeze-thaw cycles. Interestingly, while some studies report a deterioration in bond strength due to freeze-thaw cycling (Yun and Wu, 2010), others show minimal impact (Bisby and Green, 2002; Green et al., 2006). In contrast to the results of this research, Benzarti et al. reported that the bonding strength of CFRP on concrete with a longer period of exposure to 95% RH at 40°C showed a 58% decrease in the pull-off test results (2011).

The reason for this general result is that some adhesives may perform better at lower temperatures than others do. For example, certain epoxy resins can exhibit increased stiffness and strength at lower temperatures, which may contribute to the higher pull-off results. Moodi et al. (2023) indicated that the presence of water, especially under water-filled conditions, deteriorates the bond characteristics of epoxy resins. However, this study also found that lower temperatures prolong the curing process, which could imply that bond strength development may be affected by the temperature during the curing phase. If the adhesive underwent a curing process under standard laboratory conditions and was then exposed to low temperatures, the transition might have further hardened the adhesive and enhanced its bonding capability. Both the FRP material and adhesive may become stiffer and stronger at lower temperatures. This increased stiffness can lead to a better load transfer and improved interfacial bond strength.

The results of the study conducted by Allen and Atadero (2012) on in situ pull-off strength testing of an arch bridge showed a significant variation, although the test method was similar to that employed in this study. The reasons for this variation are not clear and may be attributed to various factors, such as the application quality, environmental conditions, and chosen bonding materials.

5. Conclusions

The effects of water immersion and freeze-thaw cycling on the bond strength of fiber-reinforced polymer (FRP) composites are critical for assessing the durability of structures reinforced with these materials. Studies have shown varying effects on the FRP-concrete bond interface when subjected to these conditions. The primary reasons for these discrepancies in results are the differences in the sources of the standard methods employed, properties of the fabric or adhesive utilized in the experiments, and specifics of the environmental conditions (such as the number of cycles and temperature points) that were applied. Nevertheless, it is evident that a small number of freeze-thaw cycles, which correspond to approximately 50 years, do not significantly reduce the adhesion strength of FRP fabrics. This suggests that FRP fabrics remain effective in protecting structures against earthquakes for an extended period even when subjected to severe conditions. The following conclusions were drawn from the results of the pull-off tests of this study performed as a preliminary investigation:

1. 21 days of water immersion after seven days of FRP application to the concrete slab did not have an adverse effect on the reinforced concrete structures. Each test result was still higher than the required pull-off strength of 2.5 MPa.
2. Similar to the results of Green et al.'s study on the effect of low temperature, an increase in the compressive strength and freeze-thaw cycling affected the pull-off strength positively in this study.
3. Studies show that even with long-term exposure to extreme moisture or freeze-thaw cycling, the low performance cannot be directly attributed to epoxy resin, FRP sheets, concrete, or labor.

In addition to this study, it is recommended that further studies be conducted to evaluate the long-term performance of water immersion testing and more than 25 freeze-thaw cycles with thermocouples inside the concrete slab, between the FRP Sheet and concrete slab surface. In this way, it is also possible to evaluate the thermal gradient inside the concrete slabs so that we can have a better understanding of whether the FRP system behaves as a thermal shield for concrete.

Acknowledgements

The author is sincerely grateful to the Turkish Standards Institution for allowing the use of the laboratory infrastructure and Eng. A. Fazıl KARA and Mr. Osman AYDOĞDU for their collaboration in conducting the laboratory tests at the Turkish Standards Institution (TSE).

Statement of Conflict of Interest

The author declare the following financial interests/personal relationships which may be considered as potential competing interests:

Metehan CALIS reports equipment, drugs, or supplies (only epoxy resins) was provided by DURATEK. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Author's Contributions

Metehan ÇALIŞ: Writing–Reviewing and Editing, Visualization, Conceptualization, Investigation, Data curation, and resources.

References

Allen DG., Rebecca AA. Evaluating the long-term durability of externally bonded FRP via field assessments. Journal of Composites for Construction 2012; 16(6): 737-746.

ASTM D7522. Standard test method for pull-off strength for FRP laminate systems bonded to concrete or masonry substrates. ASTM International, 2021.

Ayoub H., Sweis G., Abu-Khader W., Sweis R. A framework to evaluate sustainable construction principles in government building projects: the case of Jordan. Engineering, Construction and Architectural Management 2022; 30(9): 4080–4098.

Benzarti K., Sylvain C., Marc Q., Céline M., Christophe A. Accelerated ageing behaviour of the adhesive bond between concrete specimens and CFRP overlays. Construction and Building Materials 2011; 25(2): 523–538.

Bisby L., Green M. Resistance to freezing and thawing of fiber-reinforced polymer-concrete bond. ACI Structural Journal 2002; 99(2): 215-223.

Dai JG., Hiroshi Y., Mitsuyasu I., Ema K. Experimental investigation of the influence of moisture on the bond behavior of FRP to concrete interfaces. Journal of Composites for Construction 2010; 14(6): 834-844.

EN 1504-4. Products and systems for the protection and repair of concrete structures- Definitions, requirements, quality control and evaluation of conformity- Part 4: Structural bonding, 2005.

EN 1542. Products and systems for the protection and repair of concrete structures- Test methods- Measurement of bond strength by pull-off, 1999.

EN 1766. Products and systems for the protection and repair of concrete- Test methods- Reference concretes for testing, 2017.

EN 12004-2. Adhesives for ceramic tiles- Part 2: Test methods, 2017.

Green MF., Luke AB., Amir ZF., Venkatesh KRK. FRP confined concrete columns: Behaviour under extreme conditions. Cement and Concrete Composites 2006; 28(10): 928–937.

Lai WL., Kou SC., Poon CS., Tsang WF., Lee KK. A durability study of externally bonded FRP-concrete beams via full-field infrared thermography (IRT) and quasi-static shear test. Construction and Building Materials 2013; 40: 481-491.

Moodi F., Bagheri M., Dashti P., Ramezanianpour AA. Mechanical properties and durability of injected SCC panels by epoxy against freezing and thawing. International Journal of Adhesion and Adhesives 2023; 124: 103380.

Tran DB., Nguyen VT., Tran VT., Pham XA. A General framework for sustainability assessment of buildings: A life-cycle thinking approach. Sustainability 2023; 15(14): 10770.

Yaman Z., Öztürk İŞ., Emiroğlu M. Donma/çözülme ve sıcaklığın BFRP kompozitlerle güçlendirilmiş betonların davranışlarına etkisi. Osmaniye Korkut Ata Üniversitesi Fen Bilimleri Enstitüsü Dergisi 2022; 5(2): 551-569.

Yun Y., Wu YF. Durability of CFRP–concrete joints under freeze–thaw cycling. Cold Regions Science and Technology 2010; 65(3): 401-412.

Zheng XH., Huang PY., Guo XY., Huang JL. Experimental study on bond behavior of FRP-concrete interface in hygrothermal environment. International Journal of Polymer Science 2016; 2016(5): 1–12.