The Effects of Extreme Environments on Concrete Surface Layer and Durability and Using Permeability-Reducing Admixtures to Prevent permeability of Harmful Liquids

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Abstract:

Extreme environmental conditions negatively impact the mechanical properties of concrete, leading to reduced durability. Among these conditions, freeze-thaw cycles are particularly detrimental, as they cause the expansion of micro-cracks in the concrete, eventually resulting in serious damage. Therefore, in such harsh environments, materials that reduce the permeability of water, oil, or other harmful liquids in concrete are necessary. It is important to note that studying surface strength is meaningful because the top layer of concrete is directly exposed to the environment and is most affected by external conditions. In this study, we measured surface strength and concrete permeability using novel twist-off and cylindrical chamber tests. We then evaluated the impact of extreme environmental conditions on these parameters. Finally, we enhanced concrete durability against the permeability of harmful substances by using a permeability-reducing admixture. Our findings indicate that fibrous microsilica gel can be used as a permeability-reducing admixture to mitigate the negative effects of extreme environments on concrete surfaces. Additionally, water permeability in concrete surfaces increases rapidly during the first 50 freeze-thaw cycles but gradually decreases thereafter. The permeability of plain concrete was found to be 13.3 mL, whereas it was 6.6 mL for concrete containing permeability-reducing admixtures. The results show that the permeability of concrete with permeability-reducing admixtures is approximately 50% less than that of plain concrete.

Keywords:

Concrete surface layer; Extreme environment; Water; Durability.

1. Introduction

Permeability is one of the most important factors used to evaluate concrete durability [1]. Under extreme environmental conditions, concrete loses its strength and durability, allowing materials such as water, oil, and other liquids to permeate. Factors affecting concrete permeability depend on the chemical and physical properties of the concrete and the types of tests performed [2]. Several factors influence the permeability of concrete, including the use of admixtures [3], concrete microstructure [4], aggregate size and weight [5,6], temperature [7], water-to-cement ratio [8], and applied stresses [9]. Furthermore, the cement matrix significantly affects concrete permeability, especially in the transition zone between the aggregate and the cement paste [10,11].

Permeability-reducing admixtures (PRAs) are important for preventing the ingress of harmful materials into concrete. Acting as fillers, PRAs fill the pores within the concrete, thereby reducing its permeability. Fibrous microsilica gel is a novel additive used in concrete to reduce permeability. Microsilica gel is produced by combining plasticizers such as polycarboxylate with silica fume and polypropylene fibers. These components collectively contribute to reducing concrete permeability. The plasticizer increases the fluidity of the concrete, allowing fine particles of silica fume or microsilica powder to fill the voids between the coarser aggregates. As a result, the concrete becomes denser and achieves greater strength. A previous study observed that the reduction in water permeability within concrete is due to decreased porosity [12].

One study investigated the impact of freeze-thaw cycles on chloride permeability in concrete. This numerical study considered the propagation of macrocracks and discussed in detail the effects of various pore structure parameters. The results indicated that freeze-thaw cycles significantly influence chloride transport; specifically, the number of freeze-thaw cycles is positively correlated with both the chloride concentration and permeability depth. As freeze-thaw cycles increase, macrocrack propagation occurs, affecting chloride transport not only within the crack itself but also throughout the entire diffusion zone [13].

In another work presents a multi-phase and multi-component ionic transport model of concrete under freeze-thaw action in ocean environments, in which the modified binding isotherm considers the time-varying porosity. Based on a systematical study of a series of influencing factors, the following conclusions is drawn, the influence of freeze-thaw action on chloride binding capacity has two stage: freeze-thaw action first increases binding capacity by greater diffusivity and second decreases binding capacity by fewer solid phase. Besides, freeze-thaw action significantly increases the concentration and permeability depth of bound and free chlorides [14]. In another study, it was done on a numerical study on chloride diffusion in freeze-thaw affected concrete. the following conclusions can be drawn, the number of FTCs has a positive correlation with both chloride concentration and permeability depth in concrete, which indicates that the frozen concrete has higher chloride permeability than the ordinary one. A further quantitative investigation concludes that the effect of number of FTCs is not only greater than that of diffusion time, but also amplifies the effect of diffusion time on chloride penetration [15].

Based on the type of chemical and physical structure of water, this liquid can permeate in craze cracks. When the amount of water entering concrete increases, it causes more damage to concrete. Also, water causes organic and mineral compounds to penetrate the concrete, by dissolving them in itself [16]. A lot of research is conducted on the impact of freezing and thawing cycles on concrete strength. In one research, it was observed that concrete freezing causes a reduction in the strength and the quality of mechanical bonds in concrete [17-18]. Regarding concrete strength, concretes with 35 MPa strength and more are more durable against extreme environmental conditions [19]. Various freezing cycles cause the expansion of craze cracks in the transition zone, in addition to reducing the concrete strength [20-21]. In another research, it was shown that the mechanical bonds of concrete to CFRP have caused about 20 percent reduction during 60 to 180 cycles.

Adding to the evaluation of mechanical properties and concrete durability, devices that help in measuring these factors are of much importance. The twist-off test is a new and in situ test for measuring the surface strength of layers [22]. This test is also used in other research to evaluate the mechanical properties of some materials. The results of one research show that there is a coefficient of correlation of more than 93 percent between the results of twist-off test and standard tests [23]. Also, in another research finite element modeling is used to evaluate the accuracy of the twist-off test and the results indicate the high accuracy of this method [24]. One of the new tests for the evaluation of concrete permeability is a cylindrical chamber device [25]. In the past, some researches were conduct-ed using the cylindrical chamber test. The results of a research show that the relation be-tween volume and permeability of water into concrete can be obtained with high accuracy using a cylindrical chamber test [26]. In another research, it was observed that by increasing the curing period and compressive strength, the volume of water permeability in concrete reduces [27]. Also, the permeability of concretes containing pozzolan is less than that of plain concretes [28].

Currently, no in-situ tests are available that can measure the compressive strength and permeability of concrete directly at the project site in a cost-effective and non-destructive manner, regardless of location or temperature. Therefore, this research employs two modern tests known as Twist-off and cylindrical chamber, which can directly measure surface strength, the volume of water permeability, and the depth of water permeability into the concrete. These tests utilize simple devices, and their advantages and comparison with existing standard methods are discussed in subsequent sections. Furthermore, this study investigates the impact of fibrous microsilica gel on concrete's permeability and surface strength under normal and acute conditions in light of the development of new materials used to reduce concrete permeability.

In another study, the effects of freeze-thaw cycles on the thermophysical and mechanical properties of concrete were investigated, including mass loss, specific heat capacity, thermal conductivity, thermal expansion coefficient, compressive strength, tensile strength, flexural strength, elastic modulus, and stress-strain relationship. The study also analyzed the effects of water-cement ratio, air content, number of freeze-thaw cycles, degree of saturation, and several other factors [29]. Another study developed a freeze-thaw damage model by considering the non-uniform temperature field distribution in reinforced concrete (RC) beam-column connections under freeze-thaw cycles. The investigations showed that the water-cement ratio significantly affects the resistance of concrete to damage caused by freeze-thaw cycles [30]. Yet another study investigated the damage mechanisms and models of concrete under freeze-thaw cycles, finding that the deterioration of concrete microstructures during freeze-thaw cycles is the main reason for the reduced service life of concrete [31].

In one study, concrete samples were prepared using fly ash, granulated blast furnace slag, and rice husk ash as supplementary cementitious materials. The mechanical properties and permeability of concrete subjected to freeze-thaw cycles were investigated. The results showed that increasing the number of cycles leads to increased permeability and decreased compressive strength of concrete. However, the use of rice husk ash mitigated the loss of mechanical properties [32]. Another study examined the effect of freeze-thaw cycles on geopolymer mortars, including the role of polypropylene fibers in their response to the number of cycles [33]. In yet another study, the effects of freeze-thaw cycles on the mechanical properties and cracking characteristics of concrete were investigated. Samples previously exposed to different numbers of freeze-thaw cycles were tested under uniaxial compression. It was found that the compressive strength of concrete decreases with the increasing number of freeze-thaw cycles [34].

This article's innovation lies in estimating the depth of water penetration and the compressive strength of concrete without the need to break the sample. Additionally, we investigated permeability-reducing materials that are abundantly available in the Iranian market under severe conditions. These new materials are widely used and require thorough investigation. Tests were conducted on concretes of different grades to ensure the reliability of the results.

In this research, ASTM C666 [29] is used for the appliance of freezing and thawing cycles. Using new twist-off and cylindrical chamber tests, the surface strength and permeability of concrete are measured. Then, the impact of extreme environmental conditions on the mentioned items is investigated. Eventually, the concrete durability against the permeability of harmful materials into it is increased using a permeability-reducing ad-mixture. Figure 1 shows the flowchart of the research method.

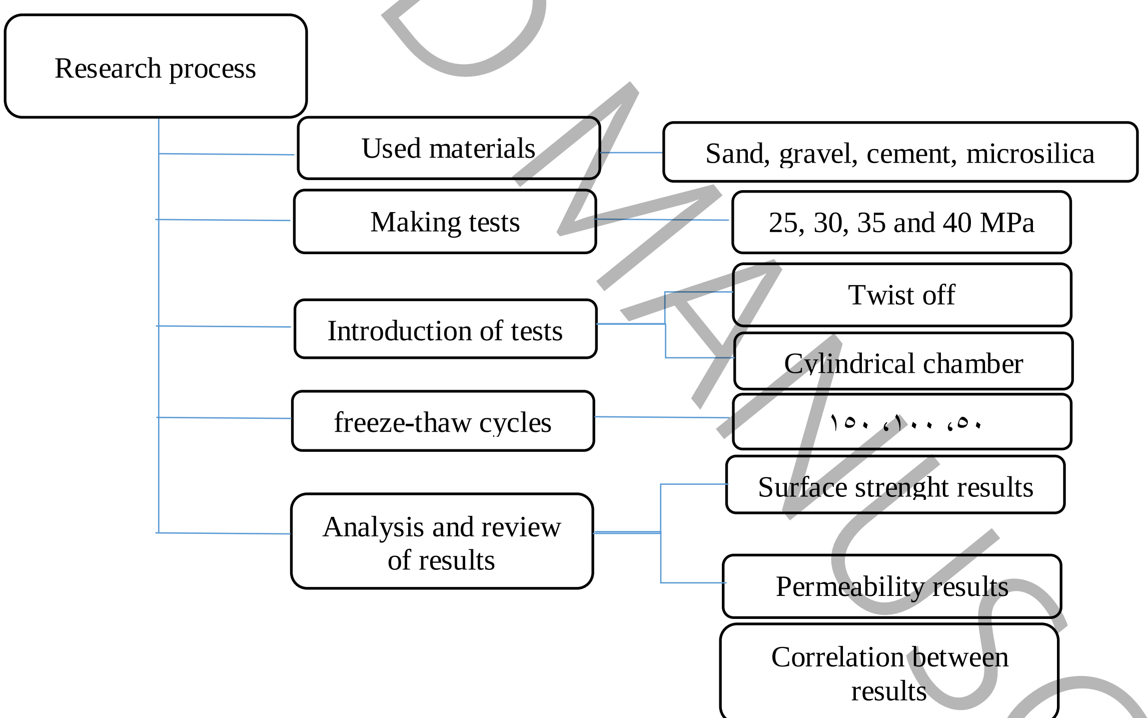


Figure 1. The flowchart of the research method

2. Experimental works

2.1. Used materials

To conduct cylindrical chamber and twist-off tests on concrete Portland cement type 2, crushed gravel and sand, drinking water, superplasticizers, special adhesive, and permeability-reducing admixtures are used. In table 1, the chemical properties of the used cement are presented.

Table 1. Chemical properties of cement (%).

Fe_2O_3	SiO_2	MgO	CaO	Al_2O_3	K_2O	Na_2O	SO_3	Alkali as Na_2O	Loss on ignition
4.52	20.23	2.14	63.86	4.86	0.71	0.21	2.12	0.21	1.2

For the gradation of gravel and sand, ASTM C136 [36] is used. ASTM C127 [37] and ASTM C128 [38] are used to measure the density and the amount of water permeability. The water permeability of gravel and sand are 2 and 2.5 percent, respectively; And, the density was obtained to be 2582 and 2463 kg/m^3, respectively. The gradation diagram of fine-grain and coarse-grain is illustrated in figure 2.

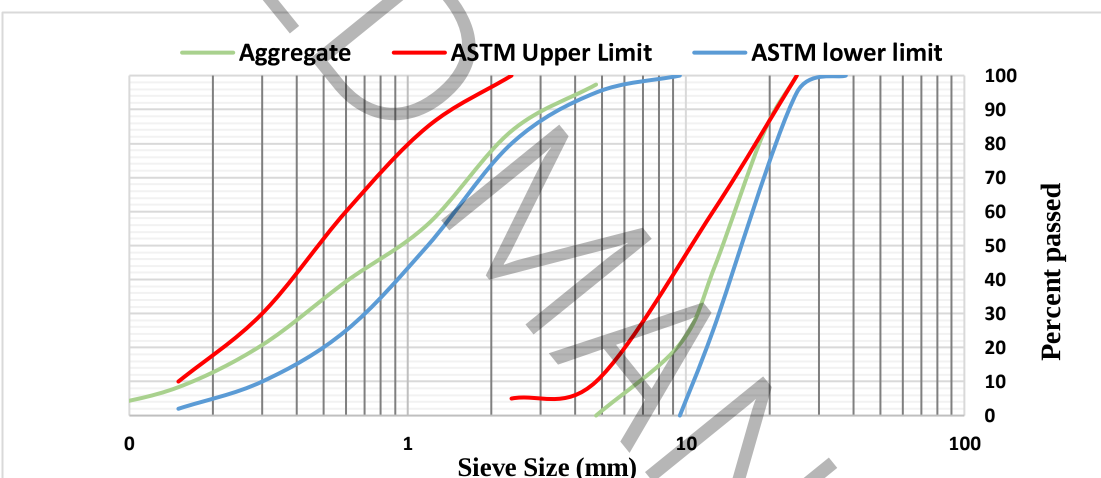


Figure 2. The gradation diagram.

The special glue used in this research is epoxy resin; its properties are presented in table 2.

Table 2. Specifications of the adhesive.

Setting time		Shear strength (MPa)	Shear strength (MPa)	Modulus of elasticity (MPa)	compressive strength (MPa)
35 ºC	25 ºC				
4 h	10 h	15 MPa	15	12750 MPa	70 MPa

The intended mix designs are defined according to ACI211.1 [39]. The design of the concrete specimens' mixture can be seen in table 3.

Table 3. mix designs (Kg/m^3).

Compressive Strength	Cement	Water	Gravel	Sand	W/C	Specific weight
C40	476	195	677	851	0.41	2199
C35	440	198	686	862	0.45	2186
C30	416	206	687	864	0.49	2173
C25	381	211	699	879	0.55	2170

Utilized materials for the reduction of permeability are fibrous micro silica gel, whose properties are given in table 4. According to ASTM C1202 [40] and ASTM C494 [41], and also based on the descriptions of the producer company, the usage amount of this material is 6 percent of cement's weight. Microsilica gel is a material that can reduce the permeability of concrete and is produced using plasticizers such as polycarboxylate, silica fume, and polypropylene fibers. These plasticizers help to make the concrete more fluid, allowing fine particles of silica fume or microsilica powder to move into empty spaces between coarser aggregates, filling them and increasing the concrete's impermeability and strength. When using microsilica gel, it is recommended to mix it with the concrete mixing water before adding it to the dry components of concrete. The mixing process involves precisely measuring the materials used to make the concrete. Initially, sand is poured into the mixer, followed by a quantity of water needed to reach the moisture content of the aggregates to the state of SSD (saturated with the dry surface). The mixture is then mixed for 30 seconds. Next, cement is added to the mixer, and water is gradually added while the mixture is mixed for two minutes. Finally, microsilica gel is mixed with some remaining water and added to the mixture in the last stage. The mixing process then continues for another two minutes.

Table 4. Specifications of microsilica gel.

Fiber	Type	Special Weight (gr/cm^3)	Colour
Polypropylene	Slurry or jelly	1.35	Dark grey

2.2. Defining tests

Twist-off method

The Twist-off test, illustrated in Figure 3, is a novel method for evaluating the surface strength of concrete. The test involves attaching a steel cylinder with a diameter of 4 cm and a height of 3 cm to the surface of the concrete (Figure 3-a). To ensure that the cylinder adheres to the concrete surface, an adhesive with higher shear and compressive strength than that of concrete must be used. This is because the concrete may break or the adhesive may separate during the test, leading to inaccurate results that cannot be relied upon. Accordingly, an adhesive with a shear strength of 15 MPa and a compressive strength of 70 MPa was employed, as specified in Table 2 provided in the preceding sections.

Care should be taken to ensure that adhesive is thoroughly mixed to produce a fully homogeneous paste. The 'hardener' and 'base' components should be stirred thoroughly in order to disperse any settlement before mixing them together. The two components should be mixed together in a 1:1 ratio, by volume, until a uniform consistency and grey colour is achieved. Due to the easy workability of the product, a variety of instruments such as trowel, scraper or filling knife can be used.

In Figure 3-b: How to apply glue on the steel cylinder can be seen. Based on Figure 3-c, a torsional anchor is inserted into the cylinder until it fails using a simple torque meter. The resulting outcome is shown in Figure 3-d. To determine the surface strength of concrete in accordance with Equation 1, the reading obtained from the torque meter must first be converted to the shear strength of the concrete surface. Subsequently, comparable samples are placed beneath the concrete breaker jack, and a calibration diagram is produced to establish the relationship between the Twist-off test results and concrete compressive strength. Consequently, the compressive strength of similar concretes can be measured with high precision by performing the Twist-off test without placing the sample under the concrete breaker jack. These findings are presented in the following sections.

$$\tau_{E-max} = \frac{Tr}{J}, \; J = \frac{\pi r^4}{2} \; \rightarrow \; \tau_{E-max} = \frac{2T}{\pi r^3} \qquad (1)$$

Where T, r, τ, and J present momentum, radius, strength, and second polar moment of the surface, respectively.

(**a**) steel cylinder (**b**) Applying glue on the cylinder (**c**) the torsional moment (**d**) the final result

Figure 3. Perform the twist-off test.

Previously, the Twist-off test has been utilized to conduct various studies on concrete, which have been published in esteemed international journals. In 2013, Naderi investigated the adhesion between concrete and CFRP plates under acute temperature fluctuations, as well as wet and dry conditions and freezing and thawing, utilizing the Twist-off test in a research study [42]. In a study conducted the Twist-off method that produces maximum shear stresses along the edges of the bonded FRP-concrete systems can be used to measure the adhesion along the interfaces. In a study conducted in 2011, the Twist-off test was employed to determine the strength of regular concrete under various curing [43], The results obtained compared with the surface strength of the concretes cured under standard conditions (i.e., immersion in drinking water), concretes covered with wet hessian and polythene sheet produced slightly higher surface strength. Twist-off test was used to measure the in-situ strength of concrete in another research [22], The results obtained the accuracy attainable using Twist-off method is better than that of some other partially destructive methods, and it is more versatile than most, requiring no advance planning.

In a study conducted in 2021, the Twist-off test was utilized to determine the compressive strength of various stones, yielding highly precise outcomes [11]. Moreover, other research endeavors have implemented this test to evaluate the mechanical properties of certain materials, and the findings indicate a strong correlation coefficient of 93% between the results of the Twist-off test and those obtained from standardized tests [23]. A study employed finite element modeling to assess the precision of the Twist-off test, and the outcomes demonstrated the method's high degree of accuracy [24].

While laboratory-based strength tests for materials and constructions have been conducted for a considerable period, there has been a recent surge of interest in in-situ tests. This shift has resulted from the emergence of novel materials and unforeseen structural damage in numerous buildings and edifices. Consequently, in addition to laboratory testing, assessing the strength of materials on-site has become a vital requirement for the upkeep of buildings and constructions. The Twist-off test is deemed highly reliable since failure transpires within the object being tested. Consequently, the results derived from this method are considered to be more trustworthy than tests evaluating surface hardness or those that determine material strength indirectly.

The Twist-off test has several advantages based on the equipment and procedure utilized, including:

- Compared to similar tests, the equipment required for the Twist-off test is simple, inexpensive, and readily available.
- The test exhibits a high degree of accuracy.
- Once the epoxy adhesive has been set, the test can be conducted in a brief period of approximately 10 minutes.
- The test results are straightforward and require no specialized interpretation.

- Torsional anchor failure can directly evaluate the strength of materials.
- By inducing failure within the tested specimen, this test can directly measure its resistance without relying on external factors.
- Damage is minimal and superficial.
- Individuals can perform the test without advanced expertise.

Cylindrical chamber test

Permeability is conducted according to some standards, including BS EN 12390-8 [44] and DIN 1048-5 [45]. In Cylindrical chamber test, the steel plate is attached to the concrete surface at first and then the cylindrical chamber device is installed on it and it is filled with water (Figure 4-a). The hand lever should be turned to set the pressure to 5 bars (Figure 4-b). The water permeability volume and water permeability rate are simply measured respectively using Equations 2 and 3.

$$V = h \times A \quad (2)$$

$$Q = \frac{V}{t} \quad (3)$$

V is permeated water volume (mm^3), h represents micrometer reading (mm), A represents the cross-section under pressure (mm^2), Q represents water permeability rate (mm^3/s), and t represents time (s).

(**a**) Steel rings (**b**) The device

Figure 4. Cylindrical chamber.

After determining the permeability of the specimens, according to figure 5-a, the specimens are divided into two sections and according to figure 5 -b the amount of water penetration depth in concrete is measured.

(**a**) Concrete under the jack (**b**) Measurement permeability

Figure 5. Measurement penetration depth.

Table 5 shows some advantages of the cylindrical chamber method over the standard test of BS EN 12390-8 [44].

Table 5. Advantages of the "cylindrical chamber" test over BS EN 12390-8 test

Advantage	Cylindrical chamber test	BS test	BS EN 12390-8 note
The ability to repeat the test	✓	×	Sample should be split in half to measure penetration depth based on BS test instructions.
The ability to do in-situ tests	✓	×	BS test equipment is bulky and not portable.
Portability of the apparatus	✓	×	BS test equipment is bulky and not portable.
Being cost-effective	✓	×	BS test equipment is expensive.
No limitation of the sample size to do the test	✓	×	Sample should be placed in a mold with specific dimensions based on BS test instructions.
The ability to do the test on any inclined surfaces	✓	×	BS test equipment is bulky.
The ability to do the test in places where sampling is impossible	✓	×	BS test equipment is bulky.
Doing the test in a semi-destructive manner	✓	×	Sample should be split in half based on BS test instructions.

Compressive strength test

To measure the compressive strength of concrete specimens EN 12390-3 [44] is used. To conduct the test, 10-cm cubic specimens are constructed, applied to different freezing and thawing cycles, and then placed under a 200-Ton concrete breaker.

2.3. Methodology

To conduct this study, 150 concrete specimens with dimensions of 150×150×150 mm are constructed. Also, 2 different concretes were used, i.e., plain concrete and concrete containing micro silica gel, and various freezing and thawing cycles were applied, i.e., 0, 50, 100, and 150. Conducting all the tests took more than 6 months.

ASTM-C666 [29] standard has been used to investigate the effect of melting and freezing on concrete. According to this standard, the melting process is in water, but the freezing process of concrete takes place in the air.

To conduct freezing and thawing cycles, concrete specimens are placed at -18 degrees for 4 hours and then at 4.5 degrees for 4 hours. The number of freezing and thawing cycles applied to a concrete specimen are 0, 50, 100, and 150.

3. Results and Discussion

3.1. Volume of water permeability in concrete in different cycles of freezing and thawing

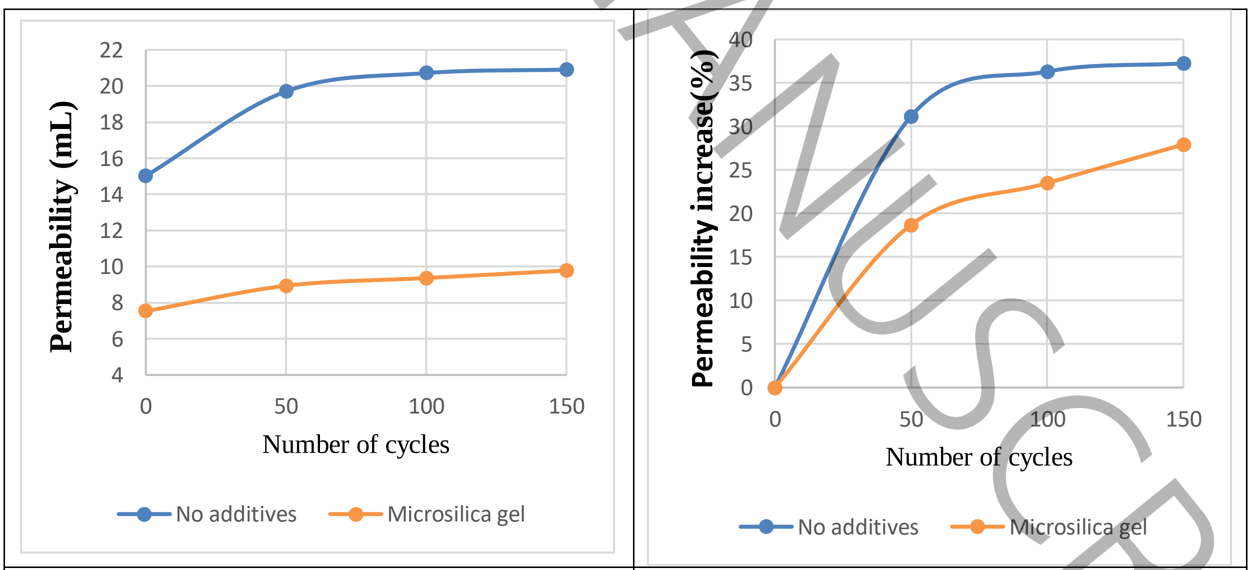
The value of permeability of concretes with different strength measured by cylindrical chamber test is shown in Figure 6. Since the purpose of this section is to investigate the effect of acute conditions on the permeability of normal concrete and concrete containing fibrous microsilica gel, the graphs presented reflect the average results of the permeability of concretes with different strengths analyzed separately.

According to Figure 6-a, the permeability of 25 MPa grade concrete under 50, 100 and 150 cycles is 19.71, 20.72 and 20.91 ml, respectively. Observing that with the increase in the number of cycles, the permeability value has increased. Also, according to Figure 6-b, by comparing C25 concrete under normal conditions with concrete under acute cycles, it can be seen that under the above cycles, the permeability value has increased by 31.2, 36.3 and 37.2%, respectively. By adding fibrous microsilica gel to concrete, the amount of permeability has decreased significantly. It can be seen that for C25 concrete, with the addition of fibrous microsilica gel, the permeability of concrete has decreased by more than 2 times under ice cycles and ice removal. According to figures 6-c to 6-h, the same trend can be seen for concretes with 30, 35 and 40 MPa categories.

It is observed that the water permeates the concrete at higher paces at first but as the pores are filled, the pace of water permeability becomes a constant value. Also, the amount of permeated water in plain concretes is more than in concretes containing permeability-reducing admixtures.

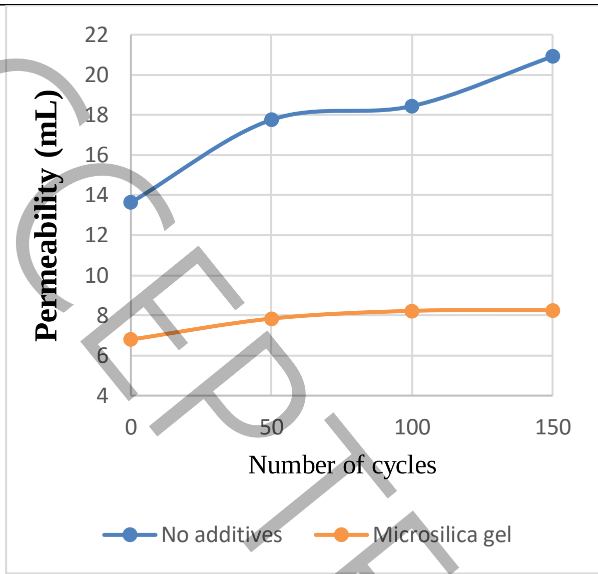
In general, considering that freezing and thawing cycles increase the craze cracks in concrete, more water permeates into the concrete and this is one of the main factors in concrete durability reduction. Fibrous micro silica gel, as a filler, causes the concrete pores to be filled and therefore affects positively the concrete permeability. It was observed in one research that one of the reasons for the reduction of water permeability inside the concrete, is the reduction of concrete pores [46]. Also, it was observed in other researches that concretes applied to freezing and thawing cycles have more cracks than plain concrete [20], which causes an increase in the permeability of water into concrete. The results obtained from other researches show that materials that reduce concrete pores can cause a reduction in water permeability [47-48]. Also, concrete with high strength can have more tolerance against freezing and thawing cycles [19].

In another study [49], using the "cylindrical enclosure" test, almost similar results were obtained that the permeability values of concrete with a strength of 30 MPa at the age of 28 days were equal to 7 mm, and the results of the present study were equal to 6.8 mm. liter, the difference between the two is very small. It was also observed in other researches that the permeability decreases with the increase of the compressive strength of concrete, and in this research, the permeability value also decreases with the increase of the compressive strength [50-51].

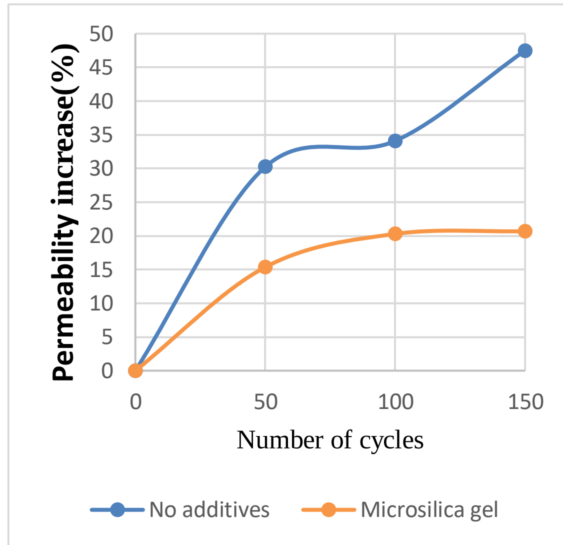


(a) Permeability value changes (25Mpa)

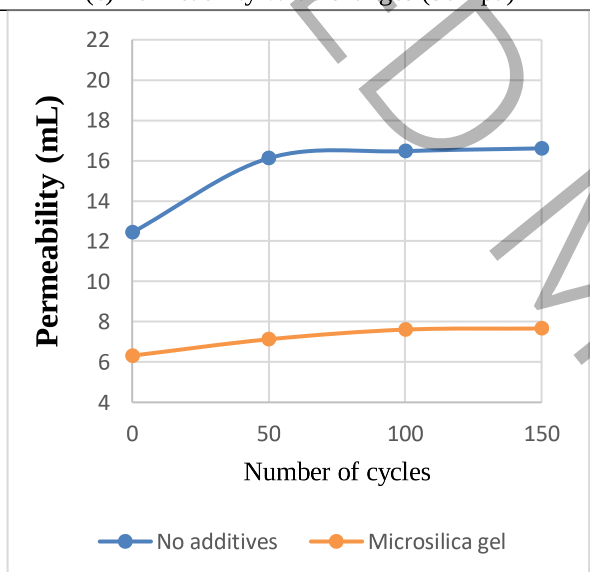
(b) Changes in percentage increase (25Mpa)



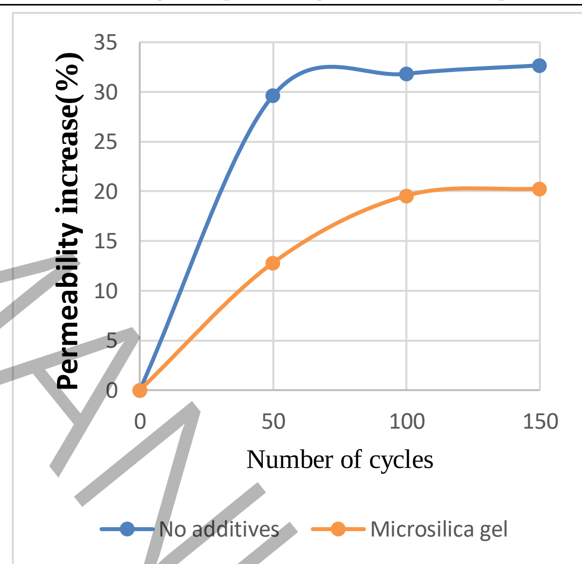
(c) Permeability value changes (30Mpa)



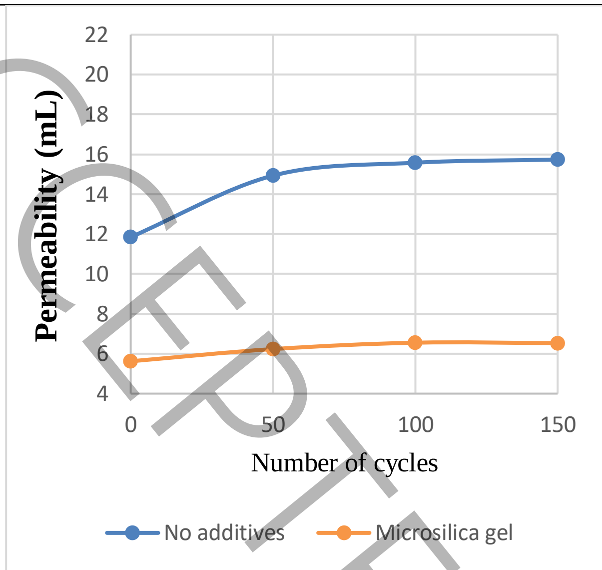
(d) Changes in percentage increase (30Mpa)



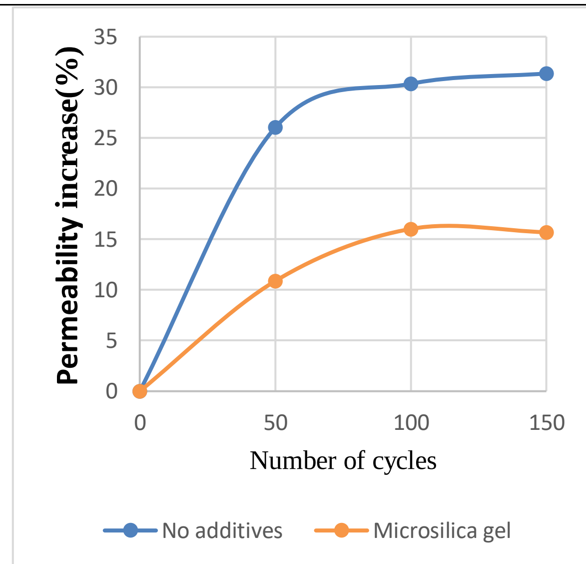
(e) Permeability value changes (35Mpa)



(f) Changes in percentage increase (35Mpa)



(g) Permeability value changes (40Mpa)



(h) Changes in percentage increase (40Mpa)

Figure 6. Permeability value in different cycles of freezing and thawing.

After conducting a permeability test, the concrete specimen is divided into two parts. Then, the maximum depth of water permeability in concrete is measured. In figure 7, the relation between permeability depth and permeability of specimens is illustrated. By conducting a new cylindrical chamber test concrete permeability depth can be measured using Equation 4, with high accuracy, and without cracking the concrete specimen. x is the permeability obtained from the cylindrical chamber test; By implementing this value in the equation, the amount of water permeability in concrete without breaking the specimen is calculated.

$$y=2.63x+1.74 \tag{4}$$

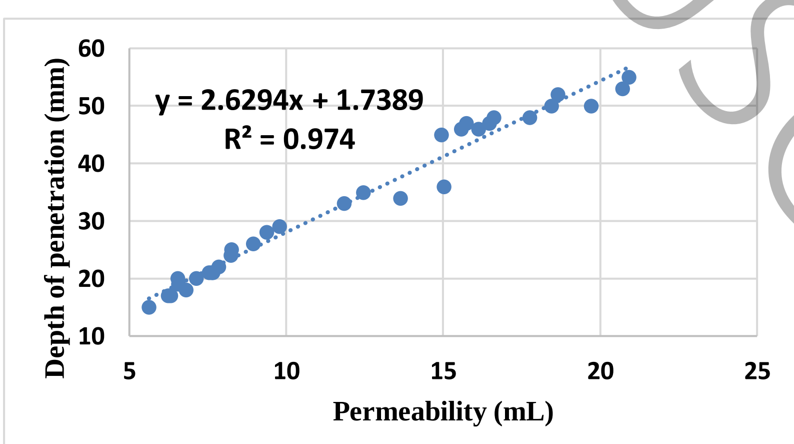
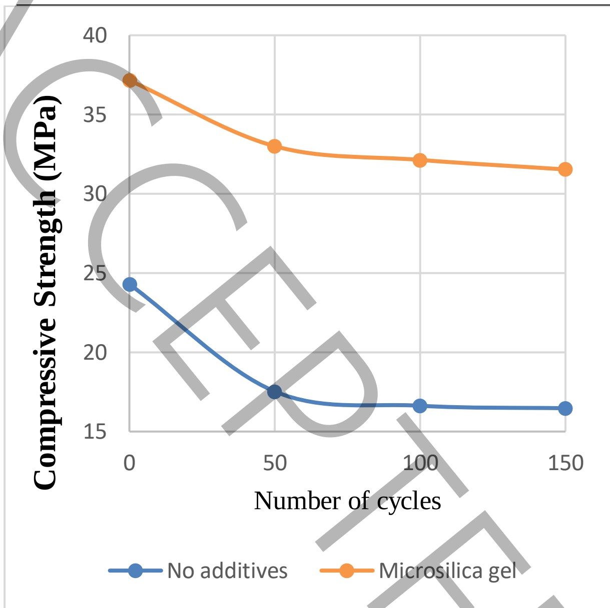


Figure 7. permeability depth and permeability relationship.

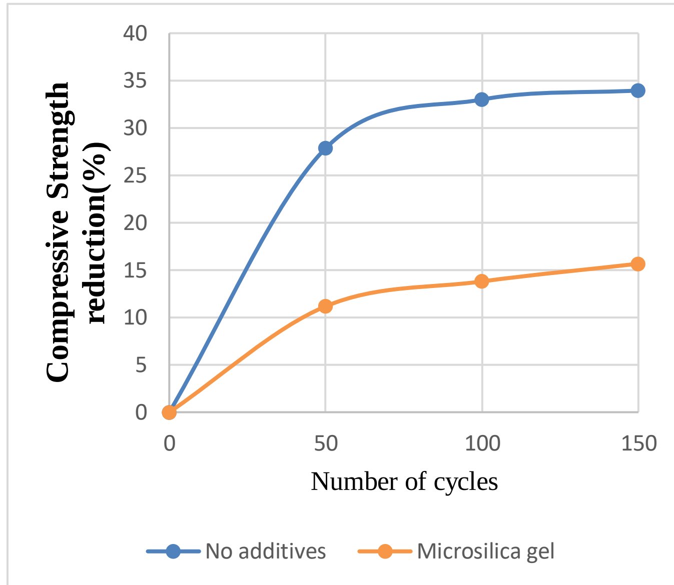
3.2. Permeability of concretes with different strengths

As mentioned above, concretes used in this research have strength classes of 25, 30, 35, and 40 MPa. As can be seen in figure 8, the value of water permeability in plain concrete in the mentioned classes is obtained to be equal to 15.1, 13.6, 12.4, and 11.9 mL, respectively. As can be observed, permeability has an inverse correlation with compressive strength. The volume of water permeated in concrete with 40 MPa strength is about 21 percent less than water permeated in concrete with 25 MPa strength. This trend also applies to concrete containing permeability-reducing admixtures. The value of water permeability for concrete containing permeability-reducing admixtures for strength classes of 25, 30, 35, and 40 are obtained to be equal to 7.5, 6.8, 6.3, and 5.6 mL, respectively (Figure 8).

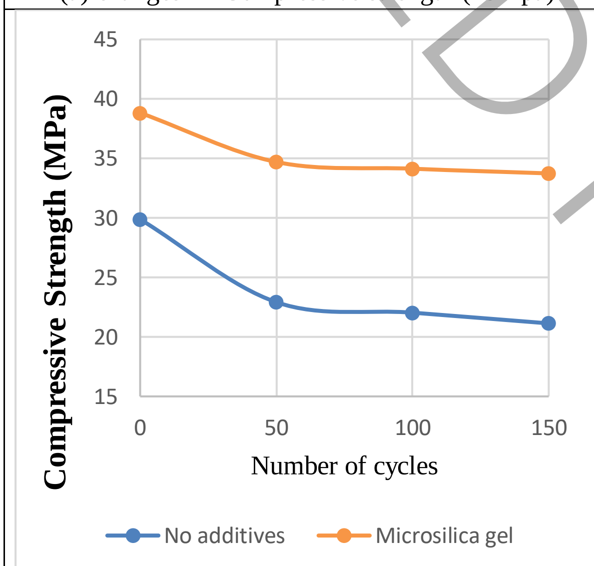
It was also observed in other researches that the permeability decreases with the increase of the compressive strength of concrete, and in this research, the permeability value also decreases with the increase of the compressive strength [50-51]. In general, it is observed that permeability has an inverse correlation with compressive strength. The reason that the water permeated in concretes with high strength has reduced is that the permeability of the cement matrix has an inverse correlation with the progress of the hydration process. By the progression of cement hydration, the amount of water permeated in concrete reduces greatly because the net gel volume is almost 2 times the volume of unhydrated cement. Therefore, it gradually occupies some of the empty spaces filled with water and therefore causes a reduction in water permeated in concrete. Also, it was observed in one research that the permeability of concrete is dependent on the water-cement ratio [52-54]. Reducing the value of the water-cement ratio in concrete increases the density of the cement matrix and decreases the space available for water. Also, by blocking micropores, the permeability reduces [55].



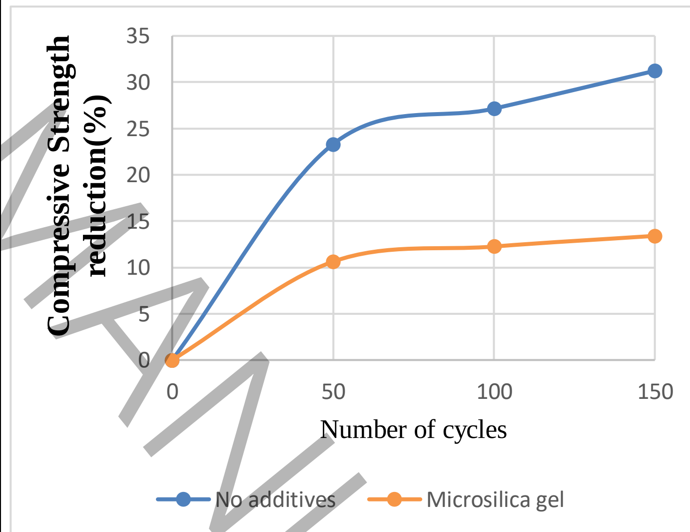
(a) changes in Compressive strength (25Mpa)



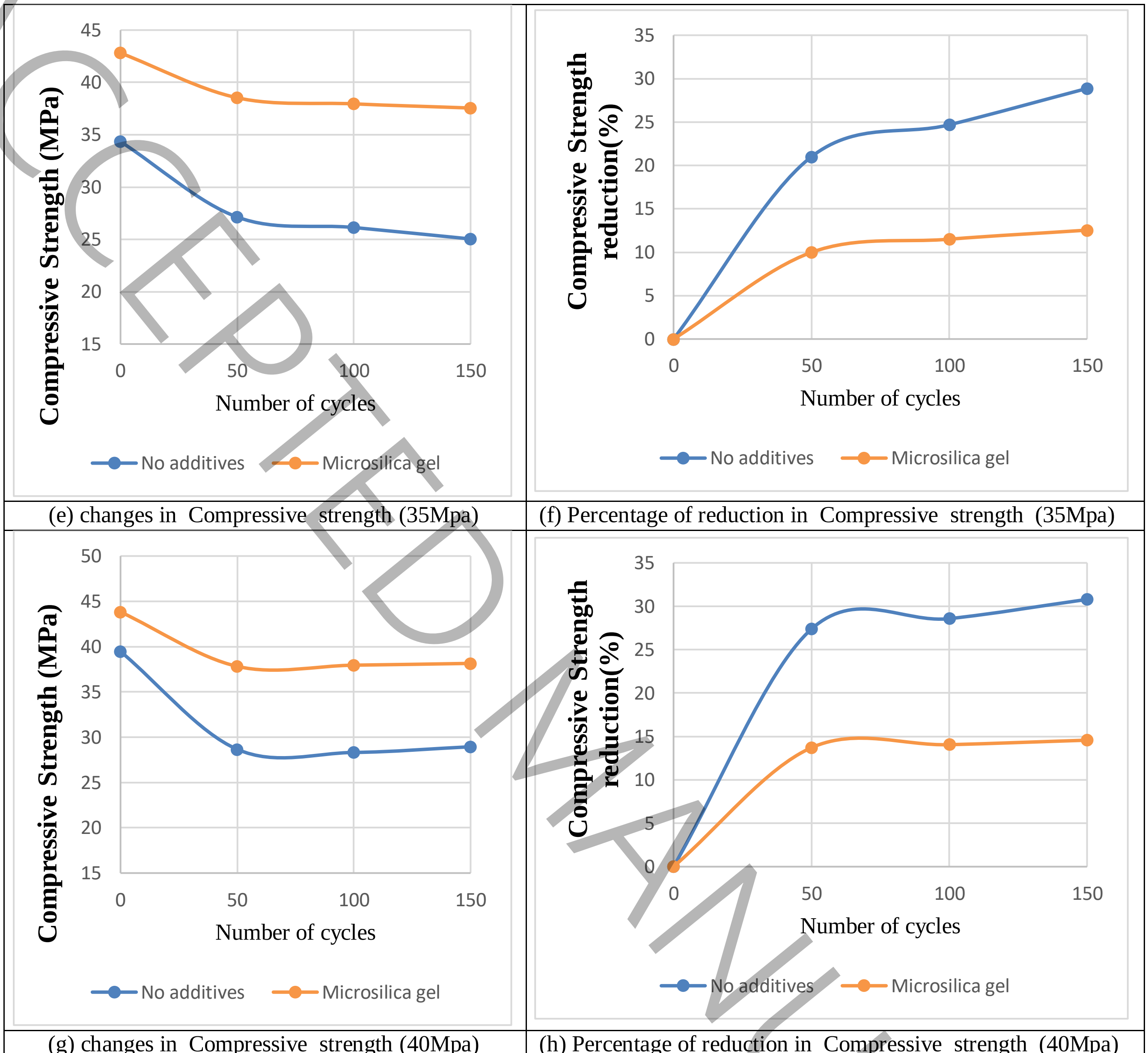
(b) Percentage of reduction in Compressive strength (25Mpa)



(c) changes in Compressive strength (30Mpa)



(d) Percentage of reduction in Compressive strength (30Mpa)



(e) changes in Compressive strength (35Mpa)

(f) Percentage of reduction in Compressive strength (35Mpa)

(g) changes in Compressive strength (40Mpa)

(h) Percentage of reduction in Compressive strength (40Mpa)

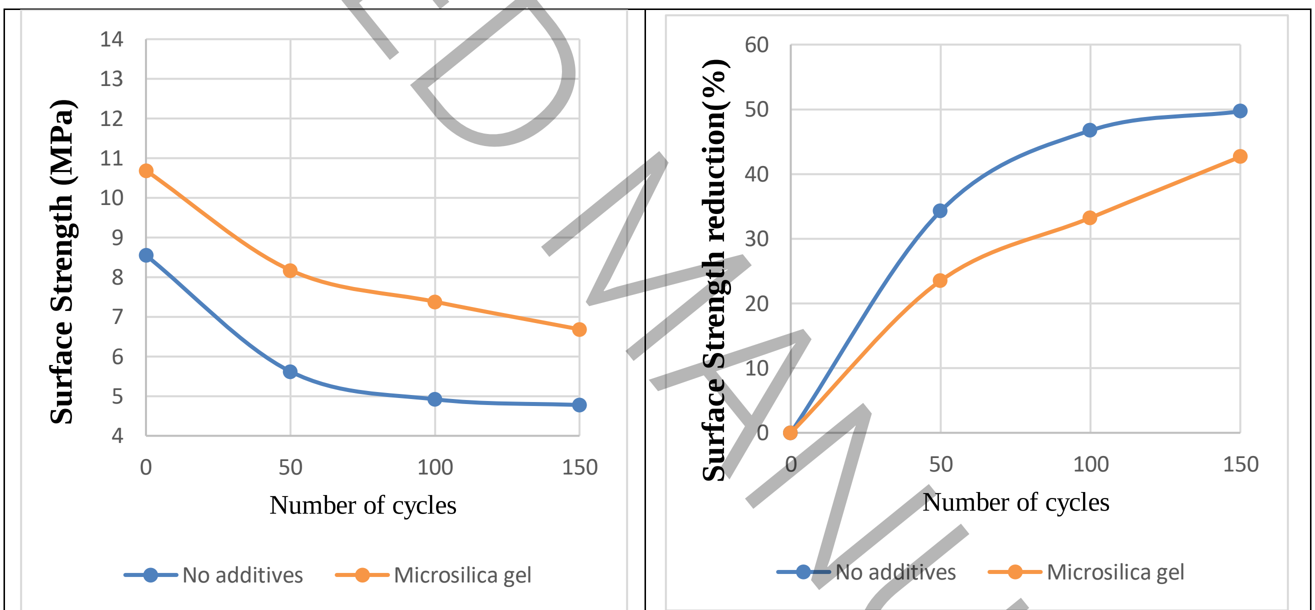
Figure 8. The results obtained from the Compressive Strength test in different freezing and thawing cycles.

3.3. Surface strength of concrete under different cycles of freezing and thawing

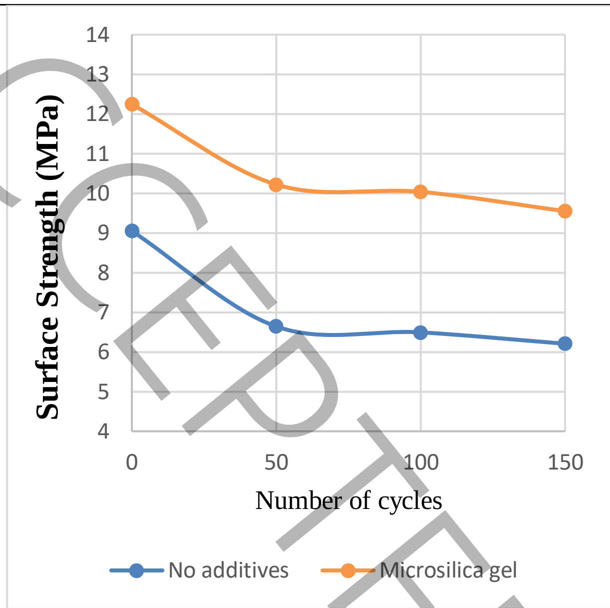
According to figure 9, the results obtained from the twist-off test show that the reduction in surface strength of plain concrete is more than specimens containing permeability-reducing admixtures.

According to Figure 9-a, the surface resistance value of C25 concrete under normal conditions is equal to 8.6 MPa, while the surface resistance value of C25 concrete under 50, 100 and 150 cycles is 5.6, 4.9 and

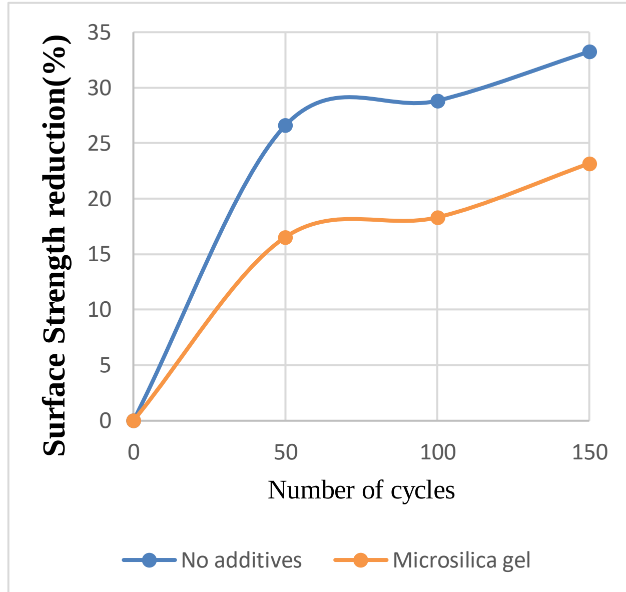
4.8 MPa, respectively. In other words, the above cycles have increased the value of surface resistance to 34.3, 46.7 and 49.7%. It can also be seen that with the increase in compressive strength, the amount of surface resistance has also increased. The reason for this reduction is the progress of the cement hydration process, which has led to an increase in the compressive strength and surface resistance of concrete [56]. With the passage of time and the progress of the hydration reaction, the empty pores are filled with the products of this reaction, and in the same way, the resistance increases. Also, in the hydration process, the bonding strength of the particles in the cement paste increases and the voids between the particles in the cement paste decrease. The spaces in the fresh cement paste, which are filled with water from the beginning, are filled with the products resulting from the hydration interactions of the cement, and hence, the strength of concrete increases [57].



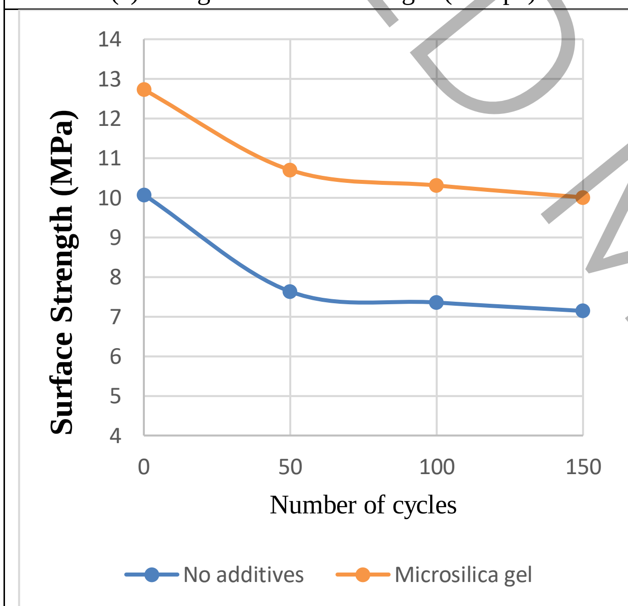
(a) changes in surface strength (25Mpa) | (b) Percentage of reduction in surface strength (25Mpa)



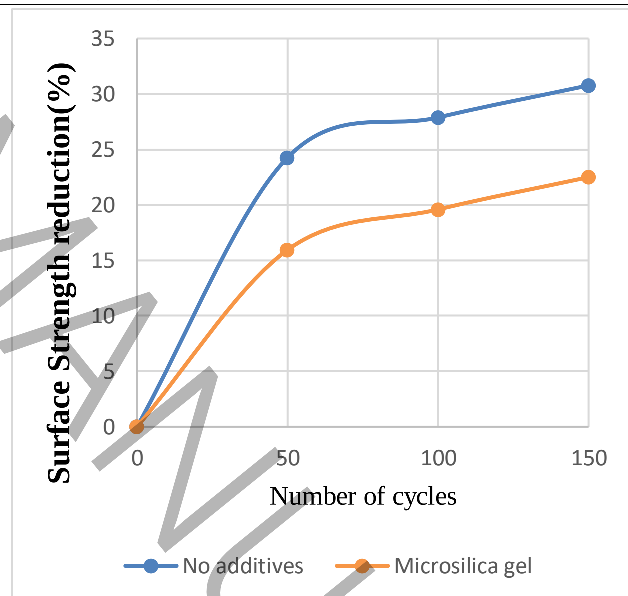
(c) changes in surface strength (30Mpa)



(d) Percentage of reduction in surface strength (30Mpa)



(e) changes in surface strength (35Mpa)



(f) Percentage of reduction in surface strength (35Mpa)

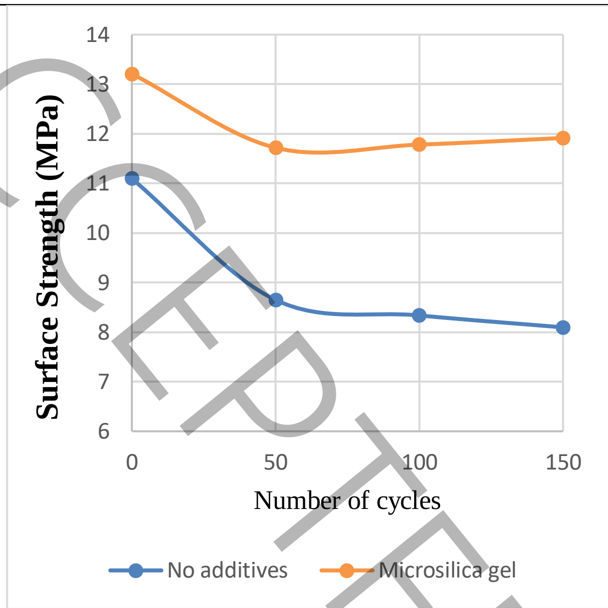
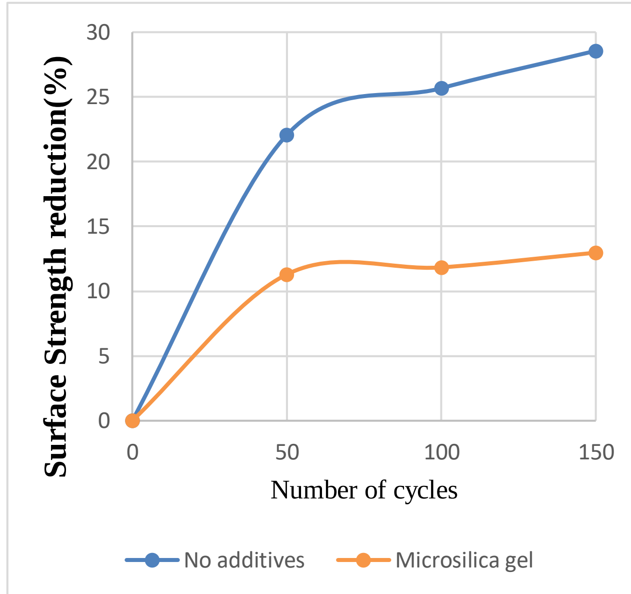
	
(g) changes in surface strength (40Mpa)	(h) Percentage of reduction in surface strength (40Mpa)

Figure 9. The results obtained from the twist-off test in different freezing and thawing cycles.

4. Results

In this research, surface strength and concrete permeability were measured using novel twist-off and cylindrical chamber tests. The effects of extreme environmental conditions on these parameters were then investigated. Finally, concrete durability against the permeability of harmful substances was enhanced using a permeability-reducing admixture. Based on the results obtained:

- Fibrous microsilica gel can be used as a permeability-reducing admixture to mitigate the negative effects of extreme environments on concrete surfaces.

- Water permeability into concrete surfaces increases rapidly until the 50th freeze-thaw cycle, after which the rate of increase becomes more gradual. The water permeability of plain concrete surfaces increases by about 36%, while that of concrete surfaces containing microsilica gel increases by about 22%.

- The permeability of plain concrete was found to be 13.3 mL, whereas that of concrete containing the permeability-reducing admixture was 50% less.

- The compressive strength of concrete surfaces decreases sharply until the 50th freeze-thaw cycle, after which it becomes more gradual. Approximately 78% of the reduction in compressive strength occurs during the first 50 cycles, with the remaining 22% occurring over the next 100 cycles.

- The permeability has an inverse relation with compressive strength. The amount of water permeated in concrete with a strength of 40 MPa is about 21 percent less than the water permeated in concrete with a strength of 25 MPa.

- Using the new cylindrical chamber test the permeability depth of concrete can be measured with the equation y=2.63x+1.74, with high accuracy, and without cracking the concrete specimen. x is the value of permeability obtained from the cylindrical chamber test; importing this in the equation gives the water permeability depth in concrete without breaking the specimen.

Reference

[1] Kaboudan, A. Naderi, M. and Amin Afshar, A. The efficiency of Darcy and two-dimensional diffusion flow models toestimate water penetration into concrete. Journal of Building Engineering. 34(3), (2021). 1-12.

[2] Akkaya, A. and Çağatay, I.H. Investigation of the density, porosity, and permeability properties of pervious concrete with different methods, Construction and Building Materials, 294(6), (2021) 123-139.

[3] Amadi, I.G. and Amadi-Oparaeli, K.I. Effect of admixtures on strength and permeability of concrete, The International Journal of Engineering and Science, 7(7), (2018), 1-7.

[4] Zhang, Y. Xu, Sh. Fang, Zh. Zhang, J. and Mao, Ch. Permeability of Concrete and Correlation with Microstructure Parameters Determined by HNMR. Advances in Materials Science and Engineering. 8(3), (2020), 1-12.

[5] Kong, L. and Ge, Y. Mechanism study of effect of coarse aggregate size on permeability of concrete, ACI Materials Journal, 112(6), (2015), 767-774.

[6] Liu, H. Luo, G. Wei, H. and Yu, H. Strength, permeability, and freeze-thaw durability of pervious concrete with different aggregate sizes, porosities, and water-binder ratios, Applied Sciences, 8(8), (2018), 1-16.

[7] Sakai, Y. Yokoyama, Y. and Kishi, T. Relationship among the permeation rate of water into concrete, the mix design, curing, and the degree of drying, Journal of Advanced Concrete Technology, 15(10). (2017), 595-602.

[8] Dashtibadfarid, M. and Afrasiabi, M. Low-permeability concrete: Water-to-cement ratio optimization for designing drinking water reservoirs, Int. J. Innov. Eng. Sci, 2(2), (2017), 20-24.

[9] Xue, W. Zhang, H. Li, H. and Xu, W. Effect of early age loading on the subsequent mechanical and permeability properties of concrete and its mechanism analysis, Journal of Materials Research and Technology, 14 (2021) 1208-1221.

[10] Liang, M. Feng, K. He, C. Li, Y. An, A. and Guo, W. A meso-scale model toward concrete water permeability regarding aggregate permeability, Construction and Building Materials, 261(3), (2020), 1-15.

[11] Naderi, M. and Kaboudan, A. Experimental study of the effect of aggregate type on concrete strength and permeability. Journal of Building Engineering. 37(2), (2021), 1-11.

[12] Naderi, M. and Bonyadi, A. Comparison of Mix-Design and Compressive Strengths of Leca, Scoria and Perlite

Lightweight Concretes with Using Twist-off Method, Civil Engineering Journal of Mashhad Ferdowsi, 23(2), (2012), 71-90.

[13] Lin-jie, Li. Qing-feng, L. Luping, T. Zhe, H. Yong, W. and Peng, Zh. Chloride penetration in freeze-thaw induced cracking concrete: A numerical study. Constr Build Mater, 302, (2021), 124291.

[14] Wen-qiang, J. Xiao-han, Sh. Shuxian, H. Zi-yan, W. and Qing-feng, L. Binding capacity and diffusivity of concrete subjected to freeze-thaw and chloride attack: a numerical study. Ocean Engineering, 186, (2019), 106093.

[15] Wen-qiang, J. Xiao-han, Sh. Jin, X. Li-xuan, M. Jian, Y. and Qing-feng, L. A numerical study on chloride diffusion in freeze-thaw affected concrete. Construction and Building Materials, 179, (2018), 553–565.

[16] Houaria, M.B.A. Abdelkader, M. Marta, C. and Abdelhafid, K. Comparison between the permeability water and gas permeability of the concretes under the effect of temperature, Energy Procedia, 139, (2017), 725-730.

[17] Naderi, M. and Smailzadeh, S. Ultimate strength of concrete beams strengthened by CFRP fabric and laminates, at high and freezing temperatures. Amirkabir Journal of science and Research, 48(1), (2016), 17-20.

[18] Cao, D. Liu, J. Zhou, Y. Ge, W. and Zhang, X. Experimental Study on the Effect of Freeze-Thaw Cycles on Axial Tension and Compression Performance of Concrete after Complete Carbonization. Advances in Civil Engineering, (2021), 1-16.

[19] Etman, A. and Ahmed, C. Effect of freezing-thawing on concrete behavior. CHALLENGE JOURNAL OF CONCRETE RESEARCH LETTERS. 9(1), (2018), 21–36.

[20] Boyd, J. and Leone, A. Effect of freeze-thaw cycling on fatigue behaviour in concrete, IOP Conf. Series: Materials Science and Engineering 652, (2019), 012028.

[21] Lee, S. Park, S. Kim, D. and Kang, J. Effect of Freeze–Thaw Cycles on the Performance of Concrete Containing Water-Cooled and Air-Cooled Slag. Appl. Sci. 72(11), (2021), 1-13

[22] Naderi, M. New twist-off method for the evaluation of in-situ strength of concrete. Journal of Testing and Evaluation, 35(6), (2007), 602-608.

[23] Varzaneh, A.S. and Naderi, M., Determination of Shrinkage, Tensile and Compressive Strength of Repair Mortars and Their Adhesion on the Concrete Substrate Using "Twist-off" and "Pull-off" Methods. 45(2), (2021) 2377–2395.

[24] Varzaneh, A.S. and Naderi, M., Experimental and Finite Element Study to Determine the Mechanical Properties and Bond Between Repair Mortars and Concrete Substrates. J. Appl. Comput. Mech. 8(2), (2022), 493-509.

[25] Naderi, M. Determine of concrete, stone, mortar, brick and other construction materials permeability with cylindrical chamber method, Registration of Patent in Companies and industrial property Office, (2010).

[26] Naderi, M. and Kaboodan, A. Investigating the effect of resistance, time and amount of water pressure and concrete pouring direction on concrete permeability. Amirkabir Engineering Journal, 52 (9), (2019), 2379-2398.

[27] Naderi, M. and Kaboudan, A. The effect of mineral admixtures on permeability, porosity and electrical resistivity of concrete. Amirkabir J. Civil Eng., 54(3), (2022), 191-194.

[28] Naderi, M Kaboudan, A. and Kargarfard, K. Studying the compressive strength, permeability and reinforcement corrosion of concrete samples containing silica fume, fly ash and zeolite. Journal of Structural and Construction Engineering, 8(2), (2022), 25-43.

[29] Zheng, Xinyu, Yingrui Wang, Shaoqi Zhang, Fei Xu, Xinping Zhu, Xi Jiang, Long Zhou et al. "Research progress of the thermophysical and mechanical properties of concrete subjected to freeze-thaw cycles." Construction and Building Materials 330 (2022): 127254.

[30] Rong, Xian–Liang, Lei Li, Shan–Suo Zheng, Feng Wang, Wei–Yuan Huang, Yi–Xin Zhang, and Dong Lu. "Freeze–thaw damage model for concrete considering a nonuniform temperature field." Journal of Building Engineering 72 (2023): 106747.

[31] Guo, Jinjun, Wenqi Sun, Yaoqun Xu, Weiqi Lin, and Weidong Jing. "Damage mechanism and modeling of concrete in freeze–thaw cycles: a review." Buildings 12, no. 9 (2022): 1317

[32] Zhao, H., Geng, Q., & Liu, X. (2023). Influence of freeze–thaw cycles on mechanical properties of pervious concrete: From experimental studies to discrete element simulations. Construction and Building Materials, 409, 133988.

[33] Zhang, Hongen, Wei Chen, Bei He, Xinping Zhu, and Zhengwu Jiang. "Compressive behaviour and microstructure of geopolymer mortar subjected to cryogenic freeze-thaw cycle: Effects of cycles and polypropylene fiber." Cement and Concrete Composites 149 (2024): 105505.

[34] Lian, Shuailong, Yu Zhao, Jing Bi, Chaolin Wang, and Yan sen Huang. "Investigation the effect of freeze–thaw cycle on fracture mode classification in concrete based on acoustic emission parameter analysis." Construction and Building Materials 362 (2023): 129789.

[35] ASTM C666, Standard Test Method for Resistance of Concrete to Rapid Freezing and Thawing, ASTM International, West Conshohocken, PA, (2017).

[36] ASTM C136-01, Standard Test Method for Sieve Analysis of Fine and Coarse Aggregates, ASTM International, West Conshohocken, PA, (2001).

[37] ASTM C127, Standard test method for density, relative density (specific gravity), and absorption of Coarse aggregate, (2015).

[38] ASTM C128-15, Standard Test Method for Density, Relative Density (Specific Gravity), and Absorption of Fine Aggregate, ASTM International, West Conshohocken, PA, (2015).

[39] ACI 211.1, Concrete Mix Design, ACI Committee 211, Standard Practice for Selecting Proportions for Normal Heavyweight, and Mass Concrete. (1997).

[40] ASTM C1202, Standard test method for electrical indication of concrete's ability to resist chloride ion penetration, American Social Test. Materials, 4(2) (2012) 1-8.

[41] ASTM C494, Standard specification for chemical admixtures for concrete, in, ASTM West Conshohocken, PA, USA, 2005.

[42] Naderi, M. ans Hajinasri, S.A. Using Twist-off Method for Measuring CFRP/Concrete Adhesion when Exposed to Cyclic Temperature Changes, Wet-Dry and Freeze-Thaw. The Journal of Adhesion, 89(7), (2013), 559-577.

[43] Naderi, M. Using Twist-Off Method for Measuring Surface Strength of Concretes Cured under Different Environments. J. Mater. Civ. Eng. 23(4), (2011), 385-392.

[44] BS EN 12390-8. Testing Hardened Concrete, Part 8 Depth Of Penetration Of Water Under Pressure. BRITISH STANDARD. (2009).

[45] DIN 1048-5. Testing Concrete: Testing of Hardened Concrete (Specimens Prepared in Mould). Germany. (1991).

[46] Ghiasvand, E. Zaree, B. Sharifi, P. and Saraee, E. Effect variation of maximum of size of aggregate on permeability of common concretes", 7th annual national concrete conference, Tehran, (2015).

[47] Final Report National concrete pavement technology center. Investigation into freezing-thawing durability of low-permeability concrete with and without air entraining agent. Tehran, (2009).

[48] Tao, J. Preliminary study on the water permeability and microstructure of concrete incorporating nano-sio2. Cement and Concrete Research, 35(3), (2005), 1943-1947.

[49] KABOUDAN., A. Experimental and theoretical study of the effect of concrete constituent materials on the permeability of hardened concrete using "Cylindrical chamber" method. Ph.D. Student. Imam Khomeini International University (2020).

[50] Naderi, M., Kaboudan, A., & Akhavan Sadighi, A. Comparative study on water permeability of concrete using cylindrical chamber method and British standard and its relation with compressive strength. Journal of Rehabilitation in Civil Engineering, 6(1) (2018) 116-131.

[51] Naderi, M., B. Maleki, and A. F Amini. ASSESSING THE PERMEABILITY OF THE OIL AND IT S COMPONENTS INTO POROUS CONCRETE USING NEW CYLINDRICAL CHAMBER METHOD. Sharif Journal of Civil Engineering 33, no. 1.1 (2017): 89-93.

[52] Kolias, S. and Georgiou, C. The effect of paste volume and of water content on the strength and water absorption of concrete. Journal of Cement & Concrete Composites. 27(5), (2005), 211-216.

[53] Ahmad, S. Azad, A.K. and Loughlin, K.F. A study of permeability and tortuosity of concrete. 30th Conference on Our World in Concrete & Structures, Singapore. (2005), 23 - 24.

[54] Hefnawy, E. and Ibrahim, A.A. Comparative study on strength, permeability and sorptivity of concrete and their relation with concrete durability. International Journal of Engineering and Innovative Technology (IJEIT). 4(4), (2014), 123-131

[55] Building and Housing Research Center, National durability of concrete code in Persian Gulf and Oman Sea, Issue: 428. Tehran. Building and Housing Research Center pub. (2014), 34-35.

[56] Naderi, M., Kaboudan, A. R., & Amin Afshar, M. STUDYING THE STRENGTH AND DIFFUSION AND PERMEABILITY COEFFICIENTS OF CONCRETES CONTAINING SILICA FUME, FLY ASH, ZEOLITE AND LIMESTONE POWDER. Sharif Journal of Civil Engineering, 36(2) (2020) 13-25.

[57] Kim, J., & Choi, S. Fractal-based microstructure reconstruction to predict the permeability of cement pastes. Construction and Building Materials, 366(5) (2023) 130157.