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Calculating the Compressive Strength of Concrete Structures Using Effects of Freeze-Thaw Cycles on Electrical Resistivity

Soroosh Sobhkhiz[1*], Mohammad Hossein Eftekhar[2] and Mohammad Shekarchi Zadeh[2]

[1]School of Civil Engineering, College of Engineering, University of Tehran, Iran

[2]Institute of Construction Materials, University of Tehran, Tehran, Iran

*Corresponding author: Soroosh Sobhkhiz, School of Civil Engineering, College of Engineering, University of Tehran, Iran, Tel: +989128996097;

E-mail: sorouhsobhkhiz@ut.ac.ir

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Abstract

Traditionally, one of the influential parameters in concrete structures sustainability has been the number of freeze-thaw cycles over the life period of concrete structures. Since some regions in the world have highly variable climates, freeze-thaw cycles are one of the most important factors that decreases the lifetime service of structures. In this paper, samples were exposed to freeze-thaw cycles after 28 days of treatment, in order to investigate the effect of freeze-thaw cycles on sustainability and durability of concrete. Their Electrical Resistivity (ER) and compressive strength were measured at different cycles. Afterwards, the extent of reduction in compressive strength and ER were compared with each other considering, to the number of freeze-thaw cycles. The results indicated both, concrete ER and compressive strength were decreasing in each cycle, where these reductions were calculated for five different water-cement (W/C) ratios. Hence, a relationship between compressive strength and ER can be correlated.

Keywords: Sustainability; Concrete structures; Freeze-thaw cycles; Electrical resistivity; Compressive strength

Introduction

Emergence and first practical application of concrete as a construction material goes back to the early 19th century. Since then, it has befitted as one of the most applicable materials, widely used around the world. Improved standards of society and growth in developed and developing countries has resulted in an ever-increasing demand for concrete materials. It has been predicted that this trend would make concrete the most popular material [1]. However, dams of hydropower plants, bridges across rivers, lighthouses, and other concrete structures have been constructed to serve human beings, while they are constantly exposed to harms caused by the environment. Sustainable development involves meeting present needs without compromising the ability of future generations to meet their needs [2]. The ecological criteria for sustainable development are the preservation of biodiversity and adoption of human activities to the natural resources and tolerance of nature [3].

Fatigue-induced damages are one of the main contributor factors in structural components failure [4-6]. Particularly for concrete elements, freeze-thaw cycles in humid and cold regions are one of the main factors for concrete destruction. The American Concrete Institute (ACI) has listed some specifications for protection of concrete against cold climates. This institute has defined cold climate as a period when the temperature of more than three days is lower than 4.5°C. Accordingly, a thorough understanding of plain concrete properties after freeze-thaw cycles to predict structural reaction and its lifetime is of great importance [7]. Concrete sustainability against freeze-thaw cycles in colder-climate countries including Russia, China, Northern Europe, and cold and humid regions in Iran, such as Kordestan and Tabriz, has great significance [8]. The destruction is caused by water freezing due to cold temperatures and its subsequent melting in response to heat and warm weather. Transition of concrete phase is accompanied by variations in dimensions and internal tensions. Freeze-thaw cycles can result in concrete sample break down [9].

Similar to the way stone capillary tubes freeze, when tough and saturated concrete temperatures decline during exploitation, the water in the capillary pores of cement solidified dough freezes and expands. If another freezing occurs after melting, further expansion happens. This indicates that freeze-thaw cycles have a cumulative effect, happening mostly in toughened cement dough. Larger pores of concrete created by incomplete compression are usually filled with air, and they are not significantly exposed to the effect of freezing.

Concrete sustainability [10] is its ability to preserve its primary form and quality with no considerable defect in the long term. The factors behind concrete structure damage during its lifetime can be divided into two groups: Physical factors (such as erosion and damage caused by freeze-thaw cycles) and chemical factors (such as sulfate attack and corrosion of steel bars). Since concrete is widely used as the foundation of construction, all properties of concrete sustainability for frequent usage is of significance. Regarding the need of practical programs, a large number of armed concrete structures constructed in cold regions are nonetheless exposed to freeze-thaw cycles [11-15]. One of the main problems in sustainability of armed concrete structures is damage caused by thawing and freezing.

Previous works addressing cement-based materials' sustainability against different freeze-thaw cycles were focused on various factors including mechanical property destruction (e.g., module and resistance) [16-18], weight change [19-21], length change [21,22], microstructural variations [23], and ultrasonic sign change [24]. However, supervision on freeze-thaw cycles was not addressed very often.

Another motivation for studying the progression of damage of samples during freeze-thaw cycles is result of recent study, which showed that the financial viability of heated pavement systems [1], especially electrical conductive concrete, which is continually gaining attention as a desirable alternative for conventional snow removal systems [1,10,12,13,25]. This study, by establishing an integrated stochastic method in estimating benefits and costs for the whole life cycle of heated pavements operations, showed that if such systems would be implemented in large-scale airports millions of dollars would be saved annually [1]. Furthermore in **Table 2**, the mentioned study highlights the impact of maintain heated pavement systems on the whole life-cycle costs [1]. Freeze-thaw cycles is an important factor in maintaining operation of such systems [23].

To study the progression of damage of samples during freeze-thaw cycles, a non-destructive and sensitive real-time test method is required. This paper uses Electrical Resistivity (ER) measurement as a non-destructive test. Although this method has previously been used for supervision on the trend of concrete freezing [26], the connection between reduction of compressive strength and ER of concrete during freeze-thaw cycles has not been investigated so far.

Materials and Methods

Mixing design

In this research, five series of mixing design with W/C of 0.4, 0.45, 0.5, 0.55, and 0.6 were prepared and investigated. A summary of mixing designs and the ages of every experiment are provided in **Table 1**. The concrete samples consist of Portland cement type 2, which are produced by Firoozkooh factory, and broken coarse aggregates, which have a max size of 19 mm and include round-cornered sand. The granularity series used for coarse grain consists of 1-to-3 combination of pea-to-almond sand, within the standard range of ASTM C33. To achieve a desirable efficiency, a naphthalene-based super lubricant was used. To construct and treat concrete samples, Tehran's potable water was utilized.

Table 1 Employed mixing designs.

Super plasticizer (Kg/m^3)	Gravel (Kg/m^3)	Sand (Kg/m^3)	W/C	Amount of cement (Kg/m^3)	Mixing design code
4	692	1057	0.4	400	C 0.4
3.2	689	1052	0.45	400	C 0.45
2	681	1043	0.5	400	C 0.5
0.8	678	1041	0.55	400	C 0.55
0	673	1038	0.6	400	C 0.6

Table 2 Aggregate gradation. Granularity combination of stone materials is listed in **Table 2**.

	0.75 mm	0.15 mm	0.3 mm	0.6 mm	1.18 mm	2.36 mm	4.75 mm	9.5 mm	12.5 mm	19 mm	25 mm
Sand	1.7	3.4	14.3	25	35	56	86	100	100	100	100
Mid aggregate	0	0	0	0	0	4.6	15.5	86	100	100	100
Coarse aggregate	0	0	0	0	0	0.1	0.1	4	33	96	100

Details of experimental procedure

After compression with vibrating table and molding, the samples were maintained at standard conditions for 24 hrs. After molding, the samples were placed into a lime-saturated water solution. Experiments were conducted inside 17-degree centigrade water. To enhance accuracy, three square samples were made per each experiment of freeze-thaw cycles.

75 square samples with 15 × 15 × 15 cm dimensions were prepared according to standard ASTM C192. Freeze-thaw cycles were then conducted according to standard method ASTM-C666 [27]. Every sample was frozen in a cooling device and then was placed in warm water to go through the melting stage, where, according to standards, cooling and warming time of samples was 4 hrs. Compressive strength of samples was measured at the beginning and after 50, 100, 150, and

200 cycles. The extent of compressive strength and ER drops in samples before and after test cycles were considered as the criterion for measuring concrete sustainability.

Test methods (concrete sustainability against freezing).

In order to determine concrete sustainability against freezing there are numerous methods, the most important of which is ASTM-C666 instructions. Some examples of these instructions are discussed below:

a) Instruction A: Concrete samples are subject to freeze cycles between -17 and +4 degree centigrade. The number of cycles is 300, where sample freezing and melting are performed in the vicinity of water.

b) Instruction B: Instruction B is the same as Instruction A: the only difference is that sample freezing and melting are done in the presence of water and air, respectively. After completion of freeze-thaw cycles, the degree of destruction in samples is measured by various criteria, mainly consisting of:

- Variations in compressive strength: a drop of more than 10% is an indicator of destruction.
- Sample weight change: a drop of more than 5% is an indicator of destruction. If separation of some components from the sample is visible, in case it is significant, it can be labelled as destruction.
- Variations in wave response: When ultrasonic waves passed through the sample before and after the experiment, if a 40% reduction was observed in the velocity of waves, the sample would be considered destructed.
- Variations in dimensional length of the sample: Sample strains are measured by accurate instruments. If the values transgress recommended values, the sample is destructed.

The experiment shown in **Figure 1** was used for determining ER with the two-point method; for each specimen, two samples were used for measuring the amount of ER. After determining the ER, it is obtained by formula 1 [24].

ρ=R.A/L

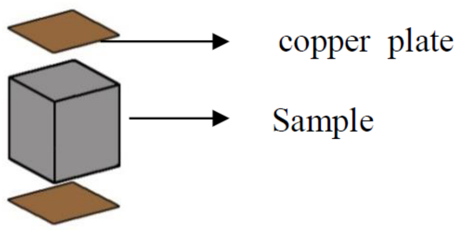

Figure 1 Schematic Illustration of the concrete specimens for Electrical Resistivity measurements with two point probe resistance.

Results and Discussion

The obtained results are listed in **Tables 3-7**.

Table 3 Electrical resistivity and compressive strength measured with W/C=0.4.

Number of freeze-thaw cycles (N)	0	50	100	150	200
Measured compressive strength (Mpa)	36.8	36.02	34.2	33.18	32.19
Reduction percentage of compressive strength	0	2.14	7.09	9.84	12.53
Measured electrical resistivity (kΩ.cm)	10.29	9.45	8.71	8.15	6.86
Reduction percentage of	0	8.21	15.41	20.81	33.36

Table 4 Electrical resistivity and compressive strength measured with W/C=0.45.

Number of freeze-thaw cycles (N)	0	50	100	150	200
Measured compressive strength (Mpa)	29.1	27.94	26.36	26.06	24.56
Reduction percentage of compressive strength	0	4.02	9.42	10.45	15.62
Measured electricalresistivity (kΩ.cm)	7.81	7.01	6.54	5.79	5.15
Reduction percentage of electrical resistivity	0	10.34	16.28	25.93	34.18

Table 5 Electrical resistivity and compressive strength measured with W/C=0.5.

Number of freeze-thaw cycles (N)	0	50	100	150	200
Measured compressive strength (Mpa)	29.1	27.67	26.13	25.48	23.51
Reduction percentage of compressive strength	0	4.94	10.24	12.47	19.24

Measured electrical resistivity (kΩ.cm)	7.81	6.83	6.37	5.27	5.01
Reduction percentage of	0	12.64	18.46	32.63	35.93

Table 6 Electrical resistivity and compressive strength measured with W/C=0.55.

Number of freeze-thaw cycles (N)	**0**	**50**	**100**	**150**	**200**
Measured compressive strength (Mpa)	22.3	21.14	19.54	17.9	17.63
Reduction percentage of compressive strength	0	5.23	12.41	19.74	20.96
Measured electrical resistivity (kΩ.cm)	6.84	5.91	5.43	4.59	3.82
Reduction percentage of electrical resistivity	0	13.62	20.72	32.95	44.29

Table 7 Electrical resistivity and compressive strength measured with W/C=0.

Number of freeze-thaw cycles (N)	**0**	**50**	**100**	**150**	**200**
Measured compressive strength (Mpa)	22.3	20.61	19.22	17.23	15.76
Reduction percentage of compressive strength	0	7.61	13.84	22.77	29.35
Measured electrical resistivity (kΩ.cm)	6.84	5.72	5.01	4.57	2.82
Reduction percentage of electrical resistivity	0	16.48	26.77	33.21	58.78

According to the obtained results, it can be concluded that as W/C increases, so does the destruction. There is also a direct connection between reduction percentage of ER and compressive strength. Since the possibility of sampling and conducting compressive strength pressure is more di icult and has more restrictions, one suitable solution is conducting an ER test. According to the obtained results, as there is a direct connection between reduction percentage of compressive strength and ER, it is required that this connection be expressed as an equation. This relation has been calculated and demonstrated in **Figures 2-7**.

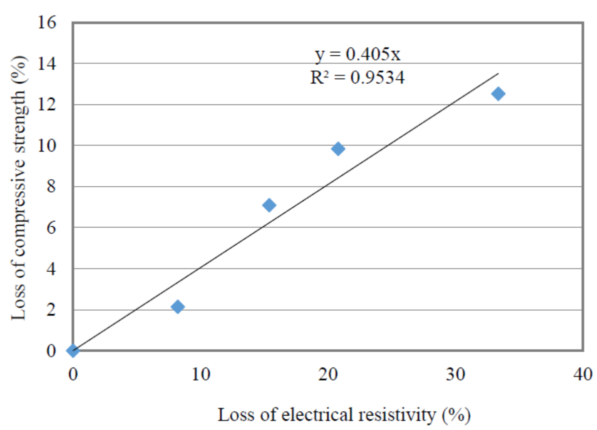

Figure 2 The connection between reduction percentage of electrical resistivity and compressive strength with W/C=0.4.

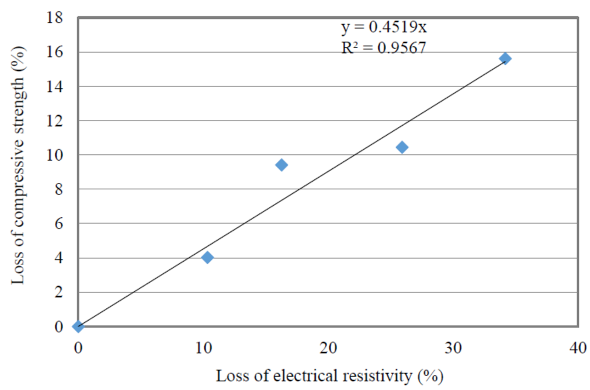

Figure 3 The connection between reduction percentage of electrical resistivity and compressive strength with W/C=0.45.

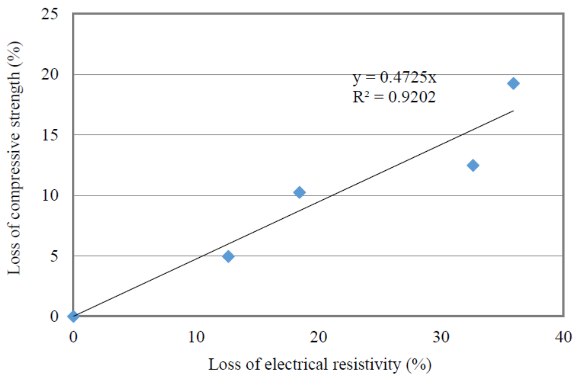

Figure 4 The connection between reduction percentage of electrical resistivity and compressive strength with W/C=0.5.

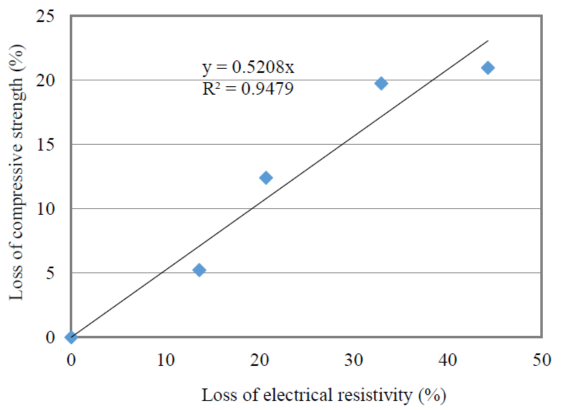

Figure 5 The connection between reduction percentage of electrical resistivity and compressive strength with W/C=0.55.

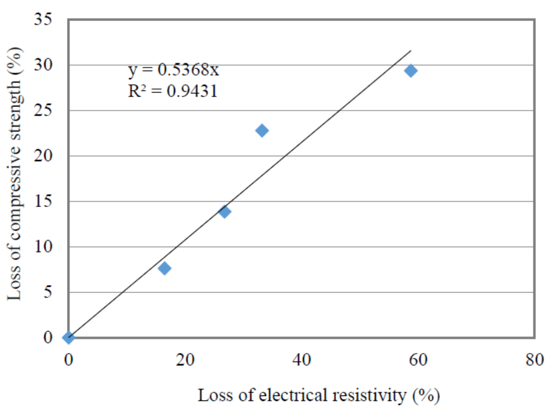

Figure 6 The connection between reduction percentage of electrical resistivity and compressive strength with W/C=0.6.

Figures 2-6 presents percentage reduction of ER against percentage reduction of compressive strength, where every point in the diagram represents the number of freeze-thaw cycles from zero to 200, respectively. In every diagram, the best possible line has been fitted. These diagrams illustrate that if W/C is known for each sample, along with reduction percentage of ER of any sample affected by freeze-thaw cycles, reduction percentage of compressive strength is easily extractable. In every diagram, regardless of the number of freeze-thaw cycles, by setting reduction percentage of ER as "X" reduction percentage of compressive strength is obtained as "Y''. Obtaining the formula

Table 8 shows the all of the formulas together. To obtain a certain final formula, the effect of W/C ratio should calculate on the rate of changes.

Table 8 The connection between electrical resistivity and compressive strength with different W/C.

	The connection between reduction percentage
W/C ratio	Electrical resistivity (X) and compressive
	Strength (Y)
0.4	y=0.405x
0.45	y=0.4519x
0.5	y=0.4725x
0.55	y=0.5208x
0.6	y=0.5368x

The final formula contains 2 variables: W/C ratio as "X_1" and reduction percentage of ER as "X_2". The effect of W/C ratio was calculated on the formula by using the total least squares method. **Figure 7** shows the effect of W/C on the formula ratio.

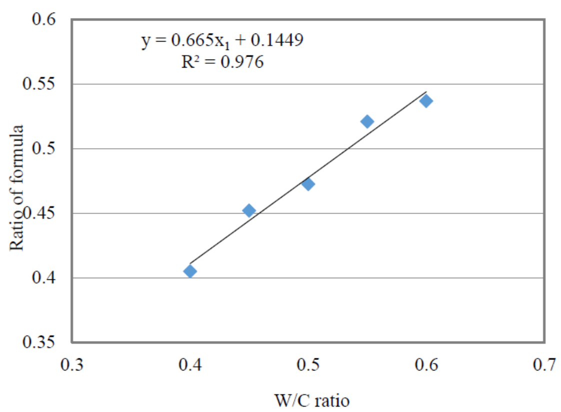

Figure 7 Effect of W/C on the formula ratio.

Figure 7 presents the connection between the W/C and ratio of the final formula. The final formula is shown as formula 2:

$y=(0.66x_1+0.15)x_2$

Where x_1 is W/C ratio, x_2 is reduction percentage of ER and y is reduction percentage of compressive strength.

Conclusion

As one of the easiest methods for calculating electrical resistivity of concrete structures is conducting *in-situ* experiments, then it is of great significance to know that the value of current compressive strength is easily calculable by using initial compressive strength and reduction percentage of electrical resistivity.

- By increasing the W/C, electrical resistivity reduction and compressive strength also grow under the influence of freeze-thaw cycles.
- Electrical resistivity reduction and compressive strength are directly correlated in freeze-thaw cycles.
- This connection is, in general, calculated as equation 3: $=(0.66x_1+0.15)x_2$.

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