

An Experimental Study on Concrete's Durability and Mechanical Characteristics Subjected to Different Curing Regimes

Edgar L. S. Borrero¹, Visar Farhangi^{1*}, Kazem Jadidi¹, Moses Karakouzian¹

¹ Department of Civil and Environmental Engineering and Construction, University of Nevada, Las Vegas, NV, 89119, United States.

Received 08 January 2021; Revised 21 March 2021; Accepted 26 March 2021; Published 01 April 2021

Abstract

Considering a constant demand in construction of concrete structures to develop novel approaches for predicting the concrete's properties, a host of investigations were performed on concrete's mechanical properties and durability under various curing regimes. However, few studies were concerned with evaluating the concrete's durability using non-destructive concrete surface resistivity tests by applying various curing conditions. The present study compares the influence of different curing regimes on durability and compressive strength of concrete to recommend the most effective curing conditions on concrete's characteristics. Five curing conditions including ambient, laboratory, dry oven, wet oven and 7-days were analyzed. Accordingly, a non-destructive concrete surface resistivity test was performed on the concrete specimens using hand-held Wenner Resipod probe meter as a reliable and rapid approach. To analyze specimen's durability, results of the surface sensitivity tests were correlated to chloride ion penetration rate based on the cylinder specimen dimensions and the degree of chloride ion penetration. The compressive strength tests were conducted on the specimens after 7, 28 and 56 days to determine the effect of curing conditions at different ages. Based on the reported outcomes, applying the wet oven curing regime results in higher compressive strength and durability compared to the other curing conditions.

Keywords: Concrete Curing; Compressive Strength; Durability; Electrical Resistivity.

1. Introduction

Various factors contribute to the degradation of the concrete specimens. Chloride ion penetration in concrete [1], weak materials [2], environmental conditions and curing conditions [3] are among these factors. There are several tools and techniques to measure the chloride penetration in concrete. The Rapid Chloride Penetration Test (RCPT) is the most popular chloride permeability measuring test [4]. Wenner Resipod probe meter as a novel approach provides non-destructive measurements which can be used to determine the surface sensitivity and chloride ion penetration [5]. The resistivity is determined by equation 1, as follows:

$$\rho = 2\pi LP/I \quad (1)$$

Where ρ is the sensitivity Ω , L is the distance between two probes in meter, P is the potential in V and I is the applied current in the cross section [3]. Based on Florida Department of Transportation which is a premier in developing this method, surface resistivity of 12 or less should be considered as high chloride ion penetration, and consequently low concrete quality [6]. Electrical resistance could be used to control the durability of concrete specimens during

* Corresponding author: farhangi@unlv.nevada.edu

 <http://dx.doi.org/10.28991/cej-2021-03091681>



© 2021 by the authors. Licensee C.E.J, Tehran, Iran. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC-BY) license (<http://creativecommons.org/licenses/by/4.0/>).

construction. It is possible to correlate the electrical resistivity directly to compressive strength, porosity and water absorption in concrete specimens [7, 8].

Concrete's durability is governed by its penetration resistance to the harmful chemicals [9], and is affected by physical characteristics of concrete [10]. Using environmentally-friendly approaches such as incorporating fly ash in the concrete can reduce the harmful effect of concrete [11, 12]. Moreover, concrete members' characteristics such as energy absorption can be improved by enhancing the durability and incorporating methods such as increasing the opening length in the layer concrete [13]. Concrete specimens manufactured with fine aggregate contribute to higher rate of chloride absorption and lower rate of durability [14]. Higher w/c ratio and porosity are the two other factors which could lead to lower durability in the final concrete product [15]. Improving the durability of concrete is achievable by adding the admixtures such as super plasticizers [16].

Curing condition is another factor with significant influence on concrete sample's durability and strength [17], and permeability [18], especially in hot weather condition [19]. The effect of curing conditions on concrete's performance, mechanical properties and durability of concrete specimens manufactured by recycled aggregate were investigated in some studies [20, 21]. In this regard, Thomas et al. [22] investigated effect of permeability on durability of recycled concrete specimens subjected to the corrosive condition. They exposed the specimens with various weights of the recycled aggregates along with different water/cement ratios to the marine environment. After curing the specimens in a humidity chamber, the durability of the aggregate concrete material reduced. Based on their research, cement paste's quality affects the permeability of the specimens subjected to the aggressive environment. It was observed that the low water/cement ratios enhanced the specimens' durability, considering the capillarity effect. Moreover, exposing to temperature is an influential parameter on concrete's strength properties [23], and apparent resistivity [20]. Sabbağ and Uyanık [24] evaluated both unreinforced and reinforced concrete's strength according to the apparent resistivity variations [25] and curing conditions. Both types of concrete samples were subjected to air and water cure. The potential differences on samples' surfaces were measured using the electrical resistivity approach up to 90 days of curing in water saturated and dry conditions. They asserted that different curing condition affects concrete's strength and apparent resistivity. Based on their study, increasing the compressive strength of concrete reduces the resistivity in the air cure; while it enhances it in the water cure. Appropriate curing leads to a significant improvement in concrete compressive and flexural strengths [26]. In addition, aggregate type and particle size are among other factors affecting the concrete properties such as the compressive strength [27, 28].

Curing is a necessary step to reach the acceptable compressive strength. It is also crucial to satisfy the minimum durability requirements. Curing conditions have significant influence on durability and strength of concrete specimens [29]. Various curing methods were investigated to enhance the concrete's mechanical characteristics. For instance, the steam curing has been gained a wider attention to prepare precast structural elements with considerable strength at early ages. However, the steam curing adversely affects concrete's properties by causing thermal damage on its microstructure. Therefore, application of other curing regimes on enhancing the concrete mechanical properties can be further investigated. In this context, Zou et al. [30] investigated the influence of subsequent curing on compressive strength and surface permeability of concrete subjected to steam curing. They measured surface permeability indexes regarding the air and permeation in concrete. Following the outcomes of their study, the subsequent curing regime significantly enhances concrete's compressive strength and permeability. Accordingly, the surface indexes were improved by 88.0 %. They reported the calcium hydroxide's continuous dissolution as the main agent that can deteriorate the strength and impermeability of concrete during the steam curing. In another effort, Velandia et al. [31] performed a research study regarding the effect of curing, compressive strength and mix design on durability of concrete in the presence of fly ash. They asserted that the outdoor curing enhances permeability of concrete specimens. Moreover, they reported that the durability parameters are directly correlated with the compressive strength by using Portland cement in the concrete. Based on their observations, the microstructural agents affect the durability characteristics. Hassan et al. [32] casted Ultra-high performance concrete (UHPC) specimens reinforced with fibers to evaluate the effect of long-term curing in a 360-day period at 10, 20, 30, 90 °C temperatures. They researched the effect of low temperatures (10-30 °C) on tensile and compressive strength of the reinforced UHPC. Additionally, the outcomes were compared to the specimens subjected to the elevated temperature of 90 °C. They concluded that the maximum strength for the curing at 90 °C can be achieved at early ages (7 days). Also, specimens exposed to the lower temperatures reached to the acceptable compressive strength of 45 MPa in this period. Falliano et al. [26] conducted a study to assess flexural and compressive strengths of lightweight concrete using different curing conditions. They considered three curing conditions (water, air, and cellophane) with different dry density and fiber contents. The reported negligible difference in the flexural strength of concrete specimens under different curing conditions. In another research, Hiremath et al. [33] investigated the influence of various curing conditions and duration on strength of reactive powder concrete at early ages. They asserted that the hot water bath curing regimes further enhances the concrete's strength compared to standard water curing regime. Based on their results, the compressive strength of reactive powder concrete can be improved by almost 63% compared to the standard curing. Incorporating the most suitable curing condition is also beneficial in the precast concrete members.

1.1. Research Significance

Various studies have investigated the concrete's mechanical characteristics and durability under different curing conditions. However, application of non-destructive concrete surface resistivity tests under various curing regimes to predict the concrete's durability is not comprehensively studied. Furthermore, the present study. This research, compares the effect of different curing conditions on durability and compressive strength of concrete. The prime objective of this study is to recommend the most influential curing conditions. Accordingly, the required concrete properties in the construction process of concrete structures can be optimized by applying the effective curing conditions in the absence of additional harmful chemicals. In this context, an improvement on concrete's mechanical characteristics without using additives can be deemed not only as a cost-effective method, but also an environmentally-friendly approach without incorporating harmful additive chemicals in the cement. Furthermore, the use of ordinary Portland cement, as the most common cement type, extends the applicability of the reported outcomes in this research. In addition, evaluating the effect of various curing regimes on mechanical properties of concrete results in improving the construction methods of pre-cast concrete members. In this regard, most suitable in-situ curing conditions can be applied to the pre-cast members by providing a controlled environment during the fabrication process. The present research study is devoted to evaluate the influence of various curing conditions on durability and mechanical characteristics of concrete using a hand-held Wenner Resipod probe meter. This electrical resistivity test as a reliable, non-destructive, and rapid method.

2. Materials and Methods

In the absence of any specified approach in the design codes on evaluation of durability behavior of concrete structures, characteristics of chloride diffusivity has been increasingly adopted as a performance-based approach to determine the durability of concrete structures, specifically in hazardous environment [34]. The concrete's electrical resistivity can be characterized as the resistance versus the electrical current's flow. Parameters such as the cement type, hydration degree, pozzolanic additives along with the water/cement ratio govern the concrete's resistivity. Determination of concrete properties is achievable using the electrical resistivity test as a reliable, non-destructive, rapid method [35]. In addition, portable devices for measuring the resistivity can be used on either site or in-situ tests. Based on the developed specifications on the Wenner approach by ASTM, the relationship within the surface resistivity (Wenner four electrode approach) and the bulk resistivity (Wenner two electrode approach) is determined. Moreover, the relationship between the diffusivity and electrical resistivity is established by the Nernst-Einstein function [36], as follows:

$$D_i = \frac{T \times R}{F^2 \times Z^2} \left[\frac{t_i}{\rho \gamma_i c_i} \right] \quad (2)$$

In this equation, the D_i stands for the ion's diffusivity, R, F, Z are gas constant, Faraday constant, and ionic valence respectively. γ_i , and t_i are respectively activity coefficient and ion's transfer number. Also, ρ indicates the electrical resistivity and c_i shows the ion's concentration (i) in the pore water. It should be noted that for a specific curing condition a specific ion; other parameters such as faraday and gas constants as well as transfer number, activity coefficient, and ionic valence are assumed constant. Accordingly, the constant parameters are expressed using the K parameter to simplify the Equation 2 to the form below. For each of the three proposed mix designs, the ion concentration in the pore water remains constant [37].

$$D = K \left(\frac{1}{\rho} \right) \quad (3)$$

Where K is the equivalent constant of the linear slope's correlation within the electrical conductivity and diffusivity equal to the inverse amount of electrical resistivity. Considering the constant values of the mentioned parameters, the quality of electrical connection between the electrodes and concrete is mainly the function of distance between the electrodes [38] and geometry of the concrete specimens affects the test outcomes. Another important factor that governs the outcome of the resistivity test, is the environmental condition. Both the geometrical specification and environmental conditions (curing regimes) were considered in this study.

The electrical flow is carried through the pore solution by charged dissolved ions. In this regard, the electrical resistivity can be deemed as an index of concrete's pore structure. The electrical resistivity test was performed by a hand-held Wenner Resipod probe meter with 1K.

During this research investigation, three concrete mix were prepared to perform the experiments. Table 1 presents the properties and the combination of the materials used for each mix. Total of 135 specimens were prepared for this experiment which includes 45 for each mix design. All the prepared specimens were 4×8 cylinders, which were made according to the ASTM C172/C172M-17 specifications [39].

Table 1. Mix properties

Mix 1	Mix 2	Mix 3
¾ Rock	¾ Rock	¾ Rock
Type V – Cement	Type V – Cement	Type V – Cement
Apex Sand	Sand	Con Sand-3
Fly Ash	Fly Ash	Fly Ash
Water Reducer WRDA 64	Water Reducer Type A and E	Con Sand-2 (crushed)
-	Retarder	-
Water Cement Ratio (0.36)	Water Cement Ratio (0.46)	Water Cement Ratio (0.45)

In order to investigate the effects of curing conditions on concrete's durability and compressive strength, the following five curing conditions were established:

- Ambient condition: the samples were remained in ambient condition without any curing process;
- 7-days curing condition: the samples were covered with a wet burlap and wet mat, in order to keep them in constant moist condition for a 7-day period;
- Dry-oven condition: the specimens were kept in an oven and subjected to 120°F, during the performed experiment;
- Wet-oven condition: the specimens were kept in a wet oven under 120 °F in the experiment period;
- Laboratory standard condition: the specimens were placed in the standard moist room in the time of the experiment.

As presented in Figure 1, a step by step procedure was performed to collect the required data. The surface resistivity and compressive strength tests were conducted by maintaining the specimens in mentioned curing conditions for 7, 28 and 56 days. Figure 2 demonstrates resistivity test process. In order to perform this test, the surface of the concrete specimens was marked on the top circular finished surface, and then the resistivity test was conducted on each sample twice within approximately 5 minutes. After performing the resistivity test as a non-destructive experiment, the same samples were used for measuring the compressive strength test. In order to analyze the durability of the samples, the results of the surface sensitivity tests were correlated to chloride ion penetration rate based on the cylinder specimen dimensions and the degree of chloride ion penetration, in accordance with the AASHTO T358-19 specifications [40]. Sengul [41] reported the significant correlation of $R=0.98$ between the electrical conductivity and chloride diffusivity. The chloride diffusivity is a considerable factor for assessing the durability of concrete members. Various classifications are proposed for concrete's chloride penetration resistance [42, 43]. Considering the relationship of electrical resistivity and diffusivity, the concrete's resistivity can be applied to these classifications to indirectly evaluate the concrete's resistance against the chloride penetration. During the measurement of electrical resistivity by the resistance meter, an ammeter, constant direct current using a power supply, the NaCL solution for filling up the cells and two voltage cells are required according to the ASTM specifications. Some issues such as proper mounting the concrete specimens within the two voltage cells along with potential of NaCL solution leakage can delay the estimated time for completing the tests and requires additional attention and effort for enhancing the reliability of test outcomes. Moreover, the variations of temperature and moisture due to different environmental conditions affect the outcomes of the measured resistance. Such different environmental conditions were investigated in this study using five curing conditions.

The correlation between surface resistivity and chloride penetration is presented in Table 2.

Table 2. Correlation between surface resistivity and chloride ion penetration

Chloride ion penetration	Cylinder specimen (4" × 8")	Cylinder specimen (6" × 12")
High	<12	<9.5
Moderate	12 - 21	9.5 - 16.5
Low	21 - 37	16.5 - 29
Very low	37 - 254	299 - 199
Negligible	>254	>199

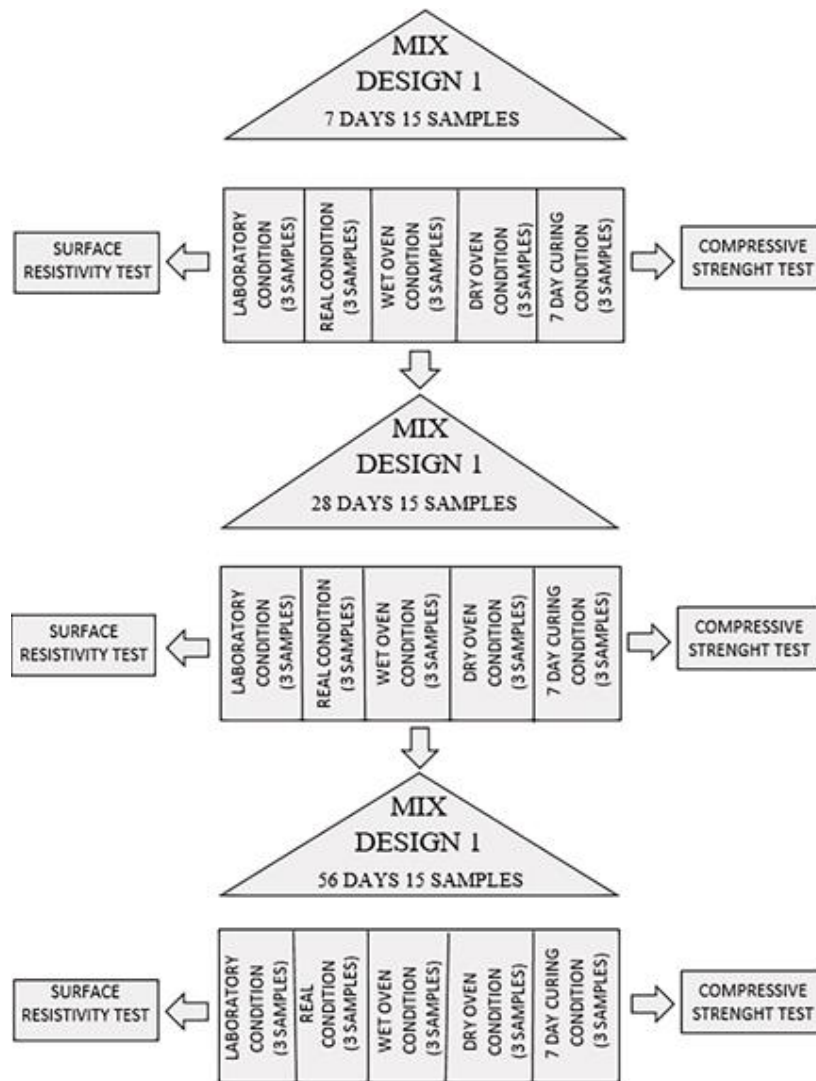


Figure 1. Experiment procedure, step by step (total of 45 samples)

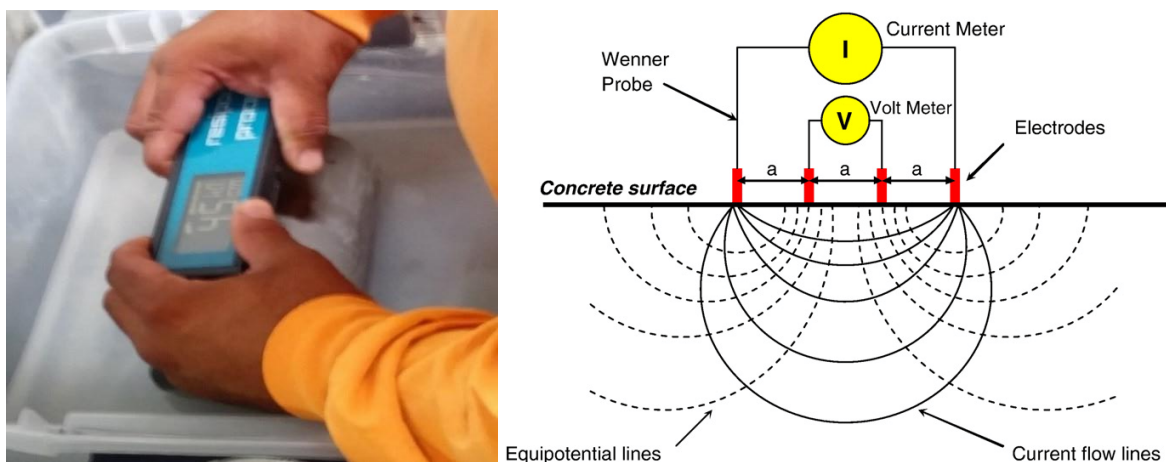


Figure 2. Electrical surface resistivity test process [44]

3. Results

3.1. Surface Resistivity Test

The surface sensitivity tests were conducted in two ranges, high and low ranges using three specimens, and the average measured values were considered. Figures 3, 4 and 5 demonstrate the results of sensitivity tests performed on specimens made with the mix 1, after 7, 28 and 56 days, respectively.

Concrete Mix Desgin 1, (7 days)

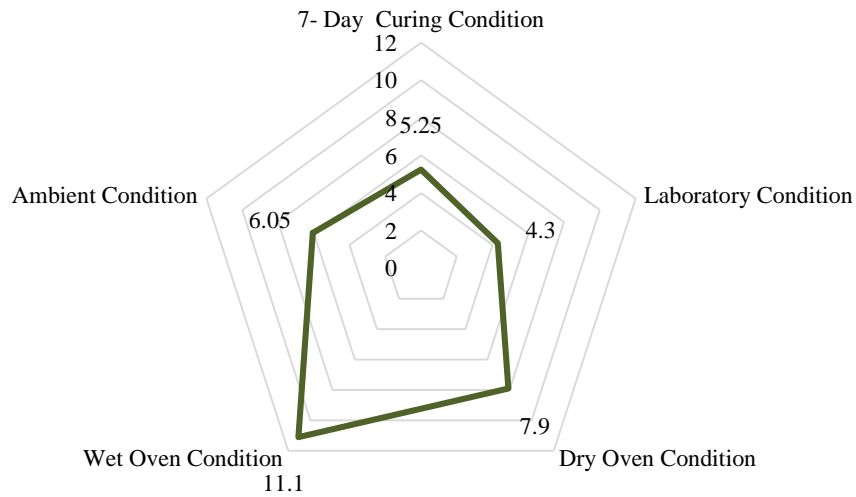


Figure 3. Surface resistivity test results on mix 1 after 7-day curing

Concrete Mix Desgin 1, (28 days)

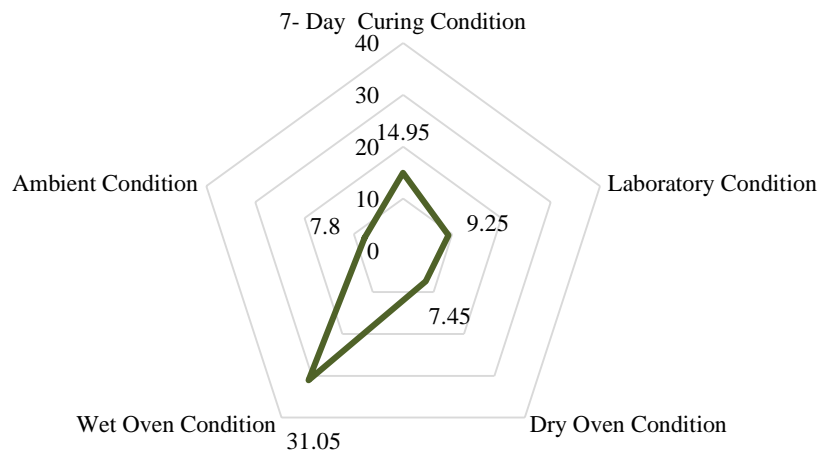


Figure 4. Surface resistivity test results on mix 1 after 28-day curing

Concrete Mix Desgin 1, (56 days)

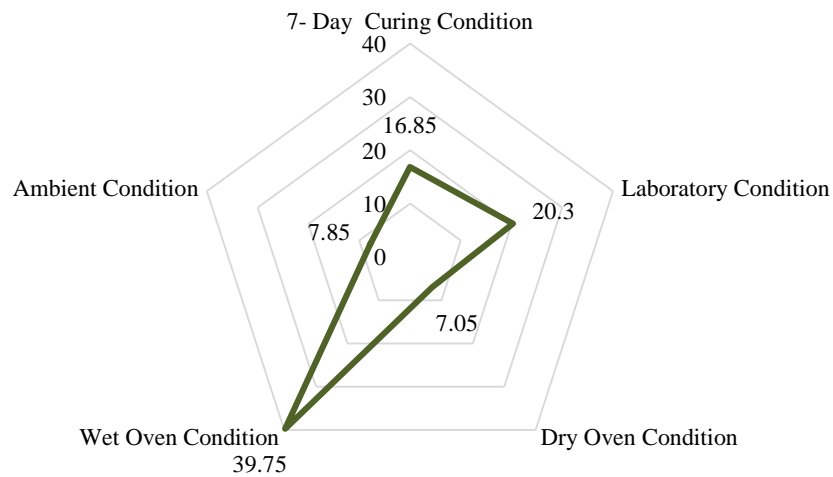


Figure 5. Surface resistivity test results on mix 1 after 56-day curing

Comparing Figures 3 to 5 reveals that the lowest surface resistivity was reported for tests performed after 7 days. This is regardless of the curing condition. Although wet oven curing specimens show slightly higher resistivity after 7-days curing the chloride ion penetration for all specimens are considered high e.g. low durability. The 28-day test results indicate significant improvement in surface resistivity of wet-oven cured specimens followed by 7-days cured samples. The resistivity of specimens subjected to the laboratory and ambient curing conditions was slightly improved slightly but still be considered as “high” in terms of chloride ion penetration rate. The resistivity rate of samples maintained in the dry oven condition was not improved. After the 56-day curing time, the resistivity of specimens under laboratory curing condition has improved by 200 percent, however; it is not comparable to the results of wet oven curing condition. The chloride ion penetration rate for both laboratory curing and 7-days curing conditions are considered moderate, while for wet oven curing condition this rate is very low and therefore the durability of samples kept in wet oven curing condition for 56 days is considered to be very high. Dry oven and ambient curing conditions lead to very low resistivity. Figures 6, 7 and 8 illustrate the resistivity test results on the mix design 2 samples.

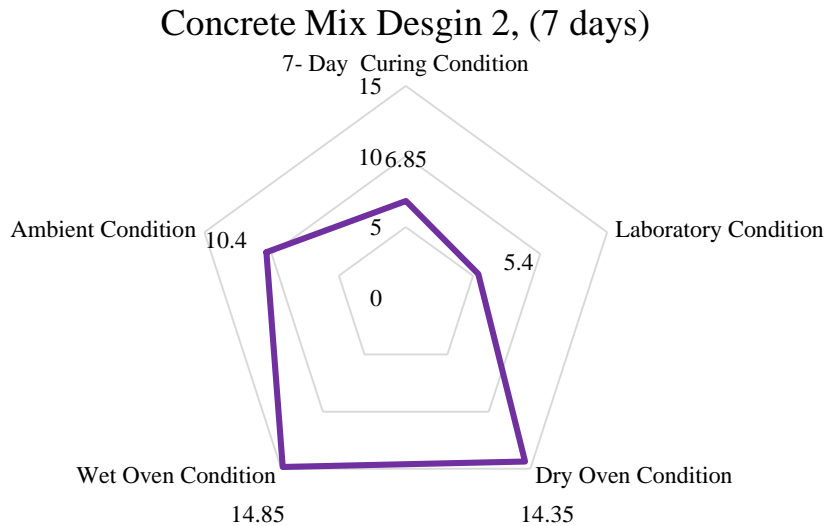


Figure 6. Surface resistivity test results on mix 2 after 7-day curing

Similar to the mix design 1, the test results after 7 days subjected to the different curing conditions indicate lower resistivity range compared to 28- and 56-days curing experiment periods. Wet oven and dry oven curing reveal higher resistivity compared to the standard, ambient and 7-day curing conditions. The durability for specimens under both wet and dry oven conditions are considered moderate. Specimens kept in wet oven curing condition present the highest surface resistivity after 28 and 56 days and the chloride penetration rate for both tests are considered very low. The specimens under 7-days curing conditions indicate better results for 28-days tests while the samples kept in standard laboratory condition show significant enhancement in resistivity rate after curing 56 days. Both dry oven and ambient curing conditions resulted in lower durability in comparison to the other curing conditions. Finally, Figures 9, 10 and 11 presents the performed test results regarding the mix design 3.

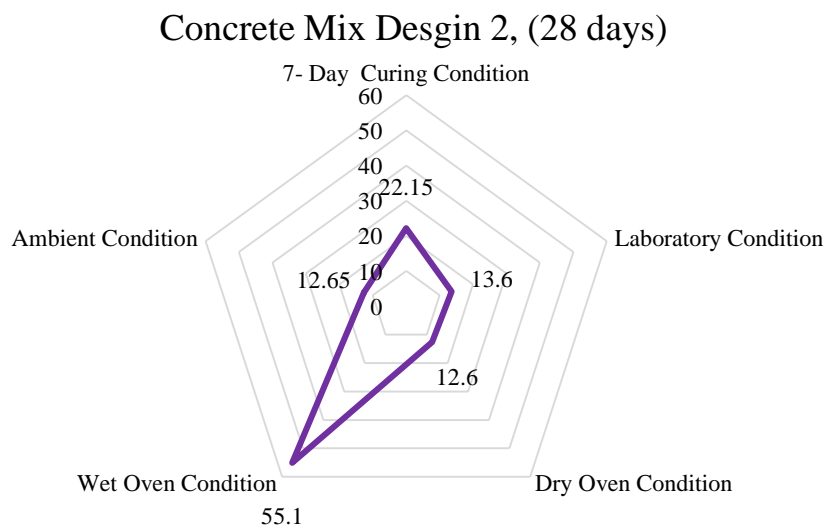


Figure 7. Surface resistivity test results on mix 2 after 28-day curing

Concrete Mix Design 2, (56 days)

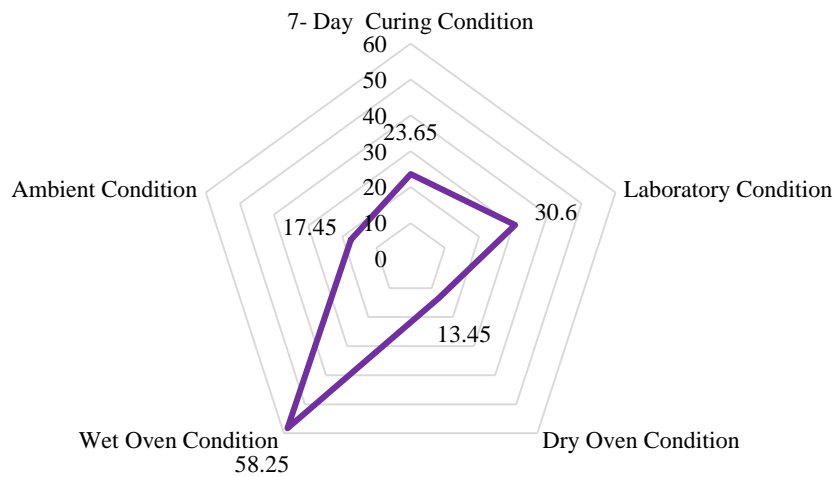


Figure 8. Surface resistivity test results on mix 2 after 56-day curing

Concrete Mix Design 3, (7 days)

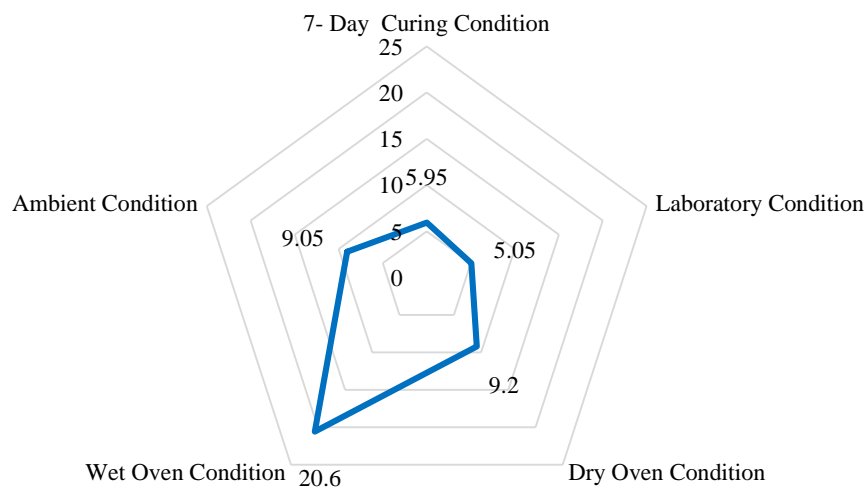


Figure 9. Surface resistivity test results on mix 3 after 7-day curing

Similar to the results presented for mix 1 and 2, the lower resistivity rates belong to the tests that performed on the samples being in curing condition for after 7 days. The reflected data on Figure 9 and Table 2 reveal such a resistivity rate, with exception for the wet oven curing condition; which shows moderate penetration rate. The other four curing conditions resulted in very low resistivity condition which indicates a high penetration rate. Based on the results of mix 3 experiments after 28 and 56 days of curing time, are presented in Figures 10 and 11, standard laboratory curing and 7-days curing follow the patterns similar to mix 1 and mix 2. On the other hand, laboratory curing condition has considerably lower penetration rate after being kept in curing condition for 56 days.

Concrete Mix Design 3, (28 days)

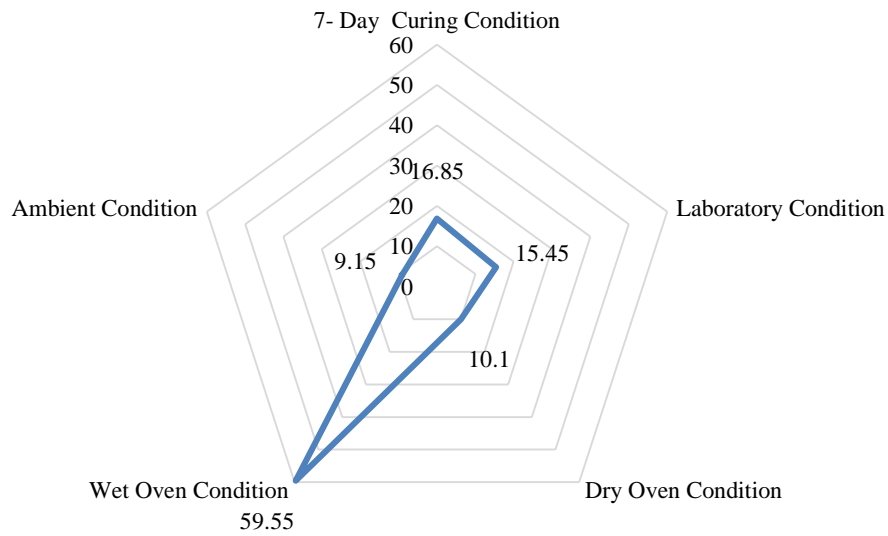


Figure 10. Surface resistivity test results on mix 3 after 28-day curing

Concrete Mix Design 3, (56 days)

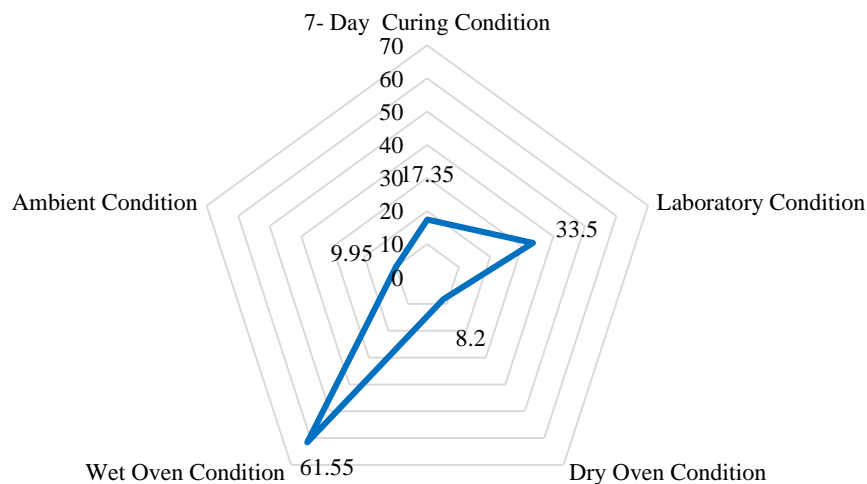


Figure 11. Surface resistivity test results on mix 3 after 56-day curing

3.2. Compressive strength Tests

In addition to the surface resistivity tests, the compressive strength tests were conducted on the specimens after 7, 28 and 56 days to determine the effect of various curing conditions at different ages on concrete samples.

As shown in Figure 12, the compressive strength values of the samples for mix design 1 at earliest curing period (7 days) is fairly comparable for samples under 7-day curing condition and laboratory condition. Similarly, dry oven and ambient curing regimes have close strength values at early ages. Accordingly, the minimum and maximum compressive strength values were measured 3310.64 and 457825 psi for specimens subjected to ambient and wet oven curing regimes, in the order given. Following the constructed tests after a 28-day period, the compressive strengths of specimens under 7-day and laboratory and wet oven conditions were improved by almost 25.14, 41.58, and 29.69%, compared to the 7-day experiment results, respectively. The maximum improvement between the 7 and 28 days was observed for the laboratory curing condition, which shows 1557.93 psi increase in the strength values. On the other hand, compressive strengths of specimens subjected to dry and ambient conditions is almost similar for the 7-day and 28-day test periods with the maximum improvement of 0.5 and 6.38% improvement, respectively. The similar trend of compressive strength enhancement was reported at the 56-day age, compared to the 7-day and 28-day ages. Based on the measurements on 56-day specimens, the maximum and minimum increases in the strength values were reported for

laboratory and dry oven conditions. This values show 25.62 and 3.66% enhancements compared to the 28-day specimens, respectively.

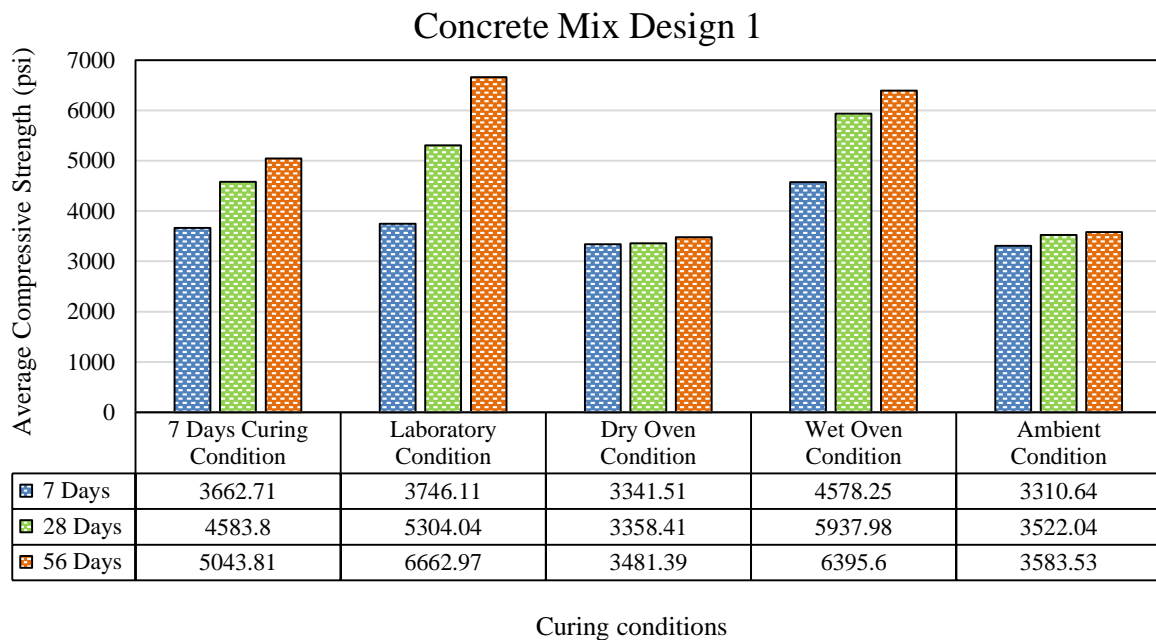


Figure 12. Compressive strength test results on mix 1, subjected to various curing conditions

Figure 13 illustrates compressive strengths of concrete mix design 2 in 7, 28, 56 days for the concrete specimens subjected to the 5 different curing regimes. At the earliest age, the wet oven curing condition results in the maximum compressive strength of 6054.63 psi, while the minimum strength value was reported for the dry oven curing regime, 4583.8 psi. In this period, the strengths of specimens under all curing conditions except the wet oven are comparable. For instance, the difference of 568 psi is reported between the 7-day curing and the dry oven curing regimes. Outcomes of the compressive strength measurements of the 28-day specimens shows similar improvements in comparison with 7-day specimens. In this period, the highest compressive strength is recorded for the wet oven curing method which has an almost 35 % of improvement compared to the 7-day period. In addition, the 7-day and laboratory curing conditions show more significant strength values compared to the dry oven and ambient curing regimes. The results of the compressive strength at the age of 56 days shows a similar trend to the 28-day specimens. At the 56-day age, wet oven and laboratory curing conditions has the most compressive strength values compared to the other curing methods. The lowest strengths in this period was recorded to the specimens cured by dry oven and ambient approaches.

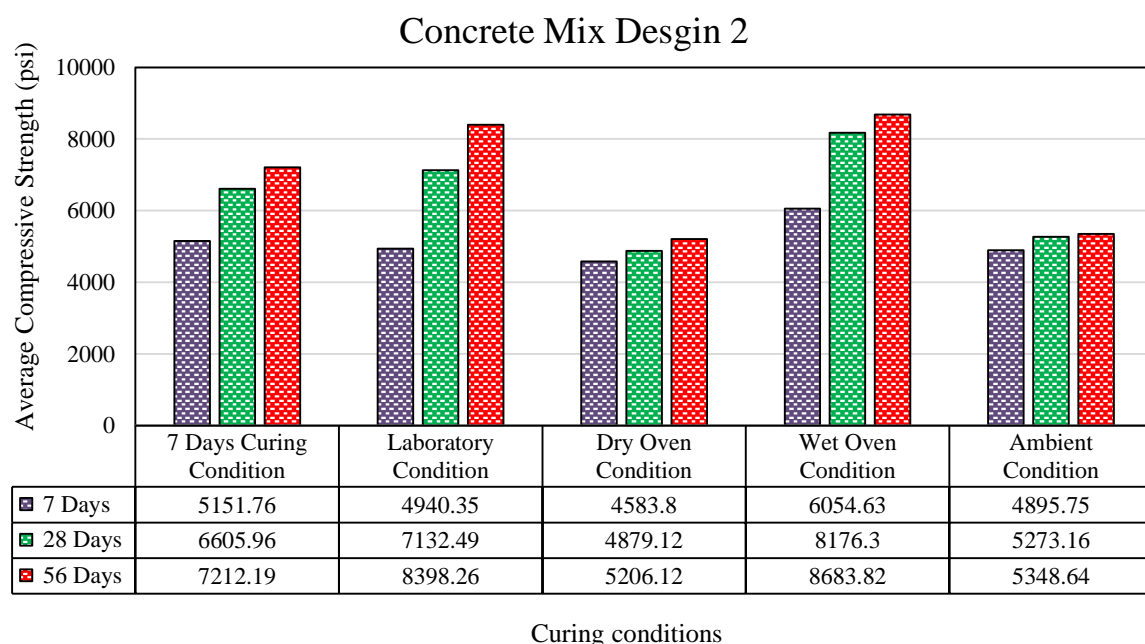


Figure 13. Compressive strength test results on mix 2, subjected to various curing conditions

Figure 14 presents the measured compressive strengths of the concrete specimens based on the mix design 3. In the 7-day curing period, the strength values of the specimen's cured under laboratory, and dry oven regimes are approximately similar, with less than 50 psi difference. In this period, curing by wet oven shows the most promising results, while the minimum strength value belongs to the specimens cured under ambient condition. In the 28-day period, the maximum improvements were recorded for the specimens subjected to the laboratory and wet oven curing regimes with 48.5% and 36.22% enhancements of compared to the 7-day, respectively. It was observed that the compressive strengths of specimens with dry oven and ambient condition have improved between the 7-day and 56-day curing periods by merely 5.7% and 16.73%, respectively. The most significant compressive strength was reported for specimens under laboratory and wet oven curing conditions with over than 7000 psi of compressive strength.

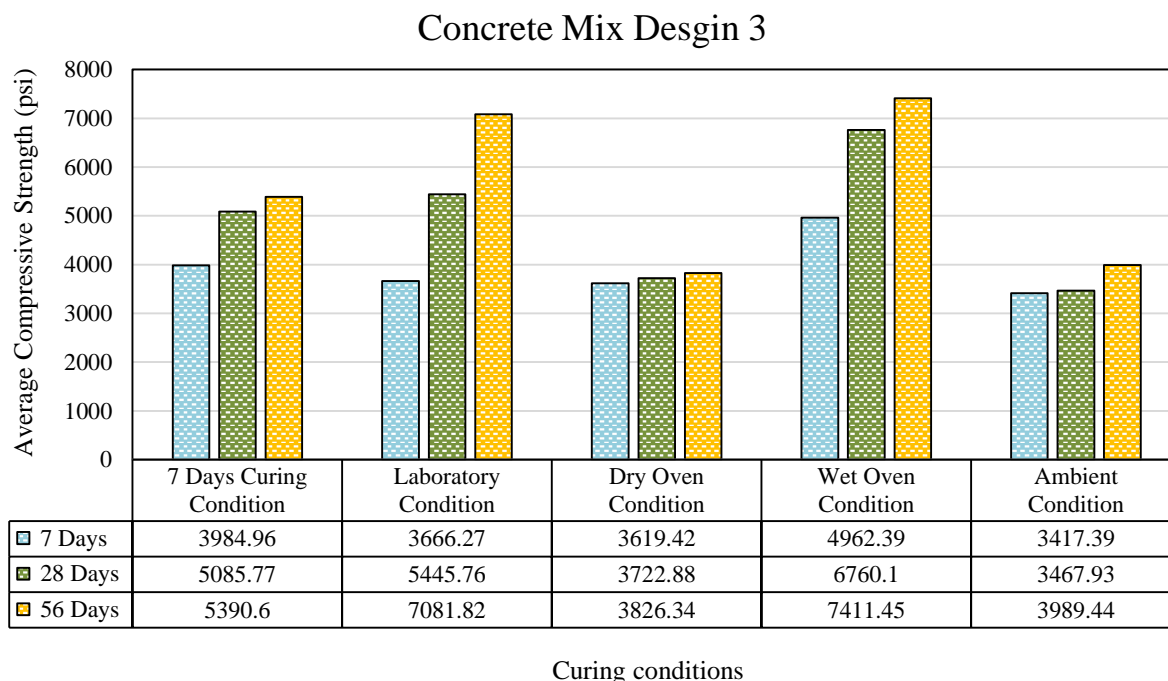


Figure 14. Compressive strength test results on mix 3, subjected to various curing conditions

Based on the presented measurements in Figures 12 to 14, the highest compressive strength was observed for specimens subjected to the wet oven condition, followed by laboratory curing condition for all the tested ages. In general, mix 1 specimens demonstrate lower compressive strength compared to the mix 2 and 3 for all curing conditions. Figures 12 and 14 illustrate that specimens kept in dry oven ambient curing condition did not meet the minimum required 4500 psi compressive strength, and are not acceptable. Moreover, it was observed that the aging has crucial impact on the compressive strength of the concrete. In this regard, almost all specimens present an improvement in compressive strength by increasing the curing period to 28 and 56 days.

4. Conclusions

In this study the influence of different curing conditions on the durability and compressive strength of concrete is investigated. Concrete specimens were prepared following the three different mix design types and were subjected to five curing conditions. In order to consider the effect of aging, the experiments were tested after 7, 28 and 56 days of being subjected to the curing process. The results of this investigation are summarized as follow:

- The presented test results show the importance of curing to achieve acceptable durability in the concrete samples;
- It was observed that the concrete specimens subjected to the wet oven curing condition has higher surface resistance compared to the other curing regimes. Correspondingly, for all the three mixes and at any testing age, the wet oven curing condition demonstrated significantly higher durability in comparison to standard laboratory curing condition;
- Specimens with wet oven curing has the most compressive strength values in the proposed mix designs compared to other implemented curing regimes. The laboratory curing procedure also demonstrate high compressive strength followed by 7-days curing condition;

- Concrete specimens which were maintained in either of ambient or dry oven conditions did not show a considerable resistance against the chloride ion penetration. This specimen had lower durability compared to specimens with other curing methods;
- Use of the dry oven and ambient curing regimes result in considerably low surface resistivity and compressive strengths. Accordingly, some specimens did not meet the minimum 4500 psi compressive strength failure criteria;
- The specimens under 7-day curing did not show remarkable surface resistance or compressive strength, however by increasing the curing period, the strength and durability of this specimens were considerably improved. Such an improvement resulted in higher compressive strength of 7-day curing after 28 and 56 days compared to the specimens with dry oven and ambient conditions at the same ages;
- Similarly, the surface resistivity of 7-day curing regime has considerably improved by aging and exceeds the resistance of dry oven and ambient regimes. For instance, in the mix design 1, the resistivity of concrete specimens under 7-day curing condition has improved by 184% and 220% at 28 and 56 days, compared to the earliest age.

5. Declarations

5.1. Author Contributions

Conceptualization, E.B., K.J., V.F. and M.K.; methodology, E.B., K.J., V.F. and M.K.; software, E.B., K.J., V.F. and M.K.; validation, E.B., K.J., V.F. and M.K.; formal analysis, E.B., K.J., V.F. and M.K.; investigation, E.B., K.J., V.F. and M.K.; resources, M.K.; data curation, E.B., K.J., V.F. and M.K.; writing—original draft preparation, E.B., K.J., V.F. and M.K.; writing—review and editing, V.F.; visualization, E.B., K.J., V.F. and M.K.; supervision, M.K.; project administration, E.B., K.J., V.F. and M.K.; funding acquisition, M.K. All authors have read and agreed to the published version of the manuscript.

5.2. Data Availability Statement

Data sharing is not applicable to this article.

5.3. Funding

The authors received no financial support for the research, authorship, and/or publication of this article.

5.4. Conflicts of Interest

The authors declare no conflict of interest.

6. References

- [1] Balestra, Carlos Eduardo Tino, Thiago Alessi Reichert, Wagner Alessandro Pansera, and Gustavo Savaris. "Evaluation of Chloride Ion Penetration through Concrete Surface Electrical Resistivity of Field Naturally Degraded Structures Present in Marine Environment." *Construction and Building Materials* 230 (January 2020): 116979. doi:10.1016/j.conbuildmat.2019.116979.
- [2] Lu, Caifeng, Wei Wang, Qingsong Zhou, Shenghuai Wei, and Chen Wang. "Mechanical Behavior Degradation of Recycled Aggregate Concrete after Simulated Acid Rain Spraying." *Journal of Cleaner Production* 262 (July 2020): 121237. doi:10.1016/j.jclepro.2020.121237.
- [3] Long, Guangcheng, Youjun Xie, Zhiyu Luo, Lu Qu, John L. Zhou, and Wengui Li. "Deterioration Mechanism of Steam-Cured Concrete Subjected to Coupled Environmental Acid and Drying Action." *Journal of Infrastructure Preservation and Resilience* 1, no. 1 (March 23, 2020). doi:10.1186/s43065-020-00001-2.
- [4] Kumar, Shashikant, Baboo Rai, Rahul Biswas, Pijush Samui, and Dookie Kim. "Prediction of Rapid Chloride Permeability of Self-Compacting Concrete Using Multivariate Adaptive Regression Spline and Minimax Probability Machine Regression." *Journal of Building Engineering* 32 (November 2020): 101490. doi:10.1016/j.job.2020.101490.
- [5] Azarsa, Pejman, and Rishi Gupta. "Electrical Resistivity of Concrete for Durability Evaluation: A Review." *Advances in Materials Science and Engineering* 2017 (2017): 1–30. doi:10.1155/2017/8453095.
- [6] FM5-578, Florida method of test for concrete resistivity as an electrical indicator of its permeability, Florida Department of Transportation. (2004) 4–7.
- [7] A. Malakooti, M. Maguire, R.J. Thomas, Evaluating Electrical Resistivity as a Performance based Test for Utah Bridge Deck Concrete (CAIT-UTC-NC35), Rutgers University. Center for Advanced Infrastructure and Transportation. (2018).

- [8] Karakouzian, Moses, Visar Farhangi, Marzieh Ramezani Farani, Alireza Joshaghani, Mehdi Zadehmohamad, and Mohammad Ahmadzadeh. "Mechanical Characteristics of Cement Paste in the Presence of Carbon Nanotubes and Silica Oxide Nanoparticles: An Experimental Study." *Materials* 14, no. 6 (March 11, 2021): 1347. doi:10.3390/ma14061347.
- [9] Elyasigorji, A., M. Rezaee, and A. Ghorbanpoor. "Magnetic Corrosion Detection in Concrete Structures." *International Conference on Sustainable Infrastructure 2019* (November 4, 2019): 175–184. doi:10.1061/9780784482650.018.
- [10] Salimi, Javid, Amir Mohammad Ramezani-pour, and Mohammad Javad Moradi. "Studying the Effect of Low Reactivity Metakaolin on Free and Restrained Shrinkage of High Performance Concrete." *Journal of Building Engineering* 28 (March 2020): 101053. doi:10.1016/j.jobe.2019.101053.
- [11] Roshani, Mohammad Mehdi, Seyed Hamidreza Kargar, Visar Farhangi, and Moses Karakouzian. "Predicting the Effect of Fly Ash on Concrete's Mechanical Properties by ANN." *Sustainability* 13, no. 3 (January 31, 2021): 1469. doi:10.3390/su13031469.
- [12] Ghaderi, Aref, Vahid Morovati, Pouyan Nasiri, and Roozbeh Dargazany. "Uncertainty Quantification in Predicting Behaviour of Rubber-Like Materials in Uni-Axial Loading." *Volume 12: Mechanics of Solids, Structures, and Fluids* (November 16, 2020). doi:10.1115/imece2020-24200.
- [13] Jomaah, Muyasser M., and Diyaree J. Ghaidan. "Energy Absorption Capacity Of Layered Lightweight Reinforced Concrete Beams With Openings In Web." *Civil Engineering Journal* 5, no. 3 (March 19, 2019): 690. doi:10.28991/cej-2019-03091279.
- [14] Farhangi, Visar, and Moses Karakouzian. "Effect of Fiber Reinforced Polymer Tubes Filled with Recycled Materials and Concrete on Structural Capacity of Pile Foundations." *Applied Sciences* 10, no. 5 (February 25, 2020): 1554. doi:10.3390/app10051554.
- [15] Karimipour, Arash, Mansour Ghalehnovi, and Jorge de Brito. "Mechanical and Durability Properties of Steel Fibre-Reinforced Rubberised Concrete." *Construction and Building Materials* 257 (October 2020): 119463. doi:10.1016/j.conbuildmat.2020.119463.
- [16] Cartuxo, Francisco, Jorge de Brito, Luis Evangelista, José Jiménez, and Enrique Ledesma. "Increased Durability of Concrete Made with Fine Recycled Concrete Aggregates Using Superplasticizers." *Materials* 9, no. 2 (February 8, 2016): 98. doi:10.3390/ma9020098.
- [17] Karimipour, Arash, Mansour Ghalehnovi, Jorge de Brito, and Mohammad Attari. "The Effect of Polypropylene Fibres on the Compressive Strength, Impact and Heat Resistance of Self-Compacting Concrete." *Structures* 25 (June 2020): 72–87. doi:10.1016/j.istruc.2020.02.022.
- [18] Sadrmomtazi, Ali, Behzad Tahmouresi, and Reza Kohani Khoshkbi-jari. "Effect of Fly Ash and Silica Fume on Transition Zone, Pore Structure and Permeability of Concrete." *Magazine of Concrete Research* 70, no. 10 (May 2018): 519–532. doi:10.1680/jmacr.16.00537.
- [19] Ibrahim, M., M. Shameem, M. Al-Mehthel, and M. Maslehuddin. "Effect of Curing Methods on Strength and Durability of Concrete Under Hot Weather Conditions." *Cement and Concrete Composites* 41 (August 2013): 60–69. doi:10.1016/j.cemconcomp.2013.04.008.
- [20] Silva, R.V., J. de Brito, and Nabajyoti Saikia. "Influence of Curing Conditions on the Durability-Related Performance of Concrete Made with Selected Plastic Waste Aggregates." *Cement and Concrete Composites* 35, no. 1 (January 2013): 23–31. doi:10.1016/j.cemconcomp.2012.08.017.
- [21] Afroughsabet, Vahid, Luigi Biolzi, and Togay Ozbakkaloglu. "Influence of Double Hooked-End Steel Fibers and Slag on Mechanical and Durability Properties of High Performance Recycled Aggregate Concrete." *Composite Structures* 181 (December 2017): 273–284. doi:10.1016/j.compstruct.2017.08.086.
- [22] Thomas, C., J. Setién, J.A. Polanco, A.I. Cimentada, and C. Medina. "Influence of Curing Conditions on Recycled Aggregate Concrete." *Construction and Building Materials* 172 (May 2018): 618–625. doi:10.1016/j.conbuildmat.2018.04.009.
- [23] Hong, Sungnam. "Influence of Curing Conditions on the Strength Properties of Polysulfide Polymer Concrete." *Applied Sciences* 7, no. 8 (August 14, 2017): 833. doi:10.3390/app7080833.
- [24] Sabbağ, Nevbahar, and Osman Uyanık. "Determination of the Reinforced Concrete Strength by Apparent Resistivity Depending on the Curing Conditions." *Journal of Applied Geophysics* 155 (August 2018): 13–25. doi:10.1016/j.jappgeo.2018.03.007.
- [25] Mehdipour, Sadegh, Iman.M. Nikbin, Soudabeh Dezhampannah, Reza Mohebbi, HamidHabibi Moghadam, Shahin Charkhtab, and Abolhasan Moradi. "Mechanical Properties, Durability and Environmental Evaluation of Rubberized Concrete Incorporating Steel Fiber and Metakaolin at Elevated Temperatures." *Journal of Cleaner Production* 254 (May 2020): 120126. doi:10.1016/j.jclepro.2020.120126.

- [26] Falliano, Devid, Dario De Domenico, Giuseppe Ricciardi, and Ernesto Gugliandolo. "Compressive and Flexural Strength of Fiber-Reinforced Foamed Concrete: Effect of Fiber Content, Curing Conditions and Dry Density." *Construction and Building Materials* 198 (February 2019): 479–493. doi:10.1016/j.conbuildmat.2018.11.197.
- [27] Miled, K., K. Sab, and R. Le Roy. "Particle Size Effect on EPS Lightweight Concrete Compressive Strength: Experimental Investigation and Modelling." *Mechanics of Materials* 39, no. 3 (March 2007): 222–240. doi:10.1016/j.mechmat.2006.05.008.
- [28] Gebretsadik, B., K. Jadidi, V. Farhangi, and M. Karakouzian. "Application of Ultrasonic Measurements for the Evaluation of Steel Fiber Reinforced Concrete." *Engineering, Technology & Applied Science Research* 11, no. 1 (February 6, 2021): 6662–6667. doi:10.48084/etasr.3915.
- [29] Cho, Young-Keun, Sung-Won Yoo, Sang-Hwa Jung, Kwang-Myong Lee, and Seung-Jun Kwon. "Effect of Na₂O Content, SiO₂/Na₂O Molar Ratio, and Curing Conditions on the Compressive Strength of FA-Based Geopolymer." *Construction and Building Materials* 145 (August 2017): 253–260. doi:10.1016/j.conbuildmat.2017.04.004.
- [30] Zou, Chao, Guangcheng Long, Cong Ma, and Youjun Xie. "Effect of Subsequent Curing on Surface Permeability and Compressive Strength of Steam-Cured Concrete." *Construction and Building Materials* 188 (November 2018): 424–432. doi:10.1016/j.conbuildmat.2018.08.076.
- [31] Velandia, Diego F., Cyril J. Lynsdale, John L. Provis, and Fernando Ramirez. "Effect of Mix Design Inputs, Curing and Compressive Strength on the Durability of Na₂SO₄-Activated High Volume Fly Ash Concretes." *Cement and Concrete Composites* 91 (August 2018): 11–20. doi:10.1016/j.cemconcomp.2018.03.028.
- [32] Hassan, A.M.T., G.H. Mahmud, A.S. Mohammed, and S.W. Jones. "The Influence of Normal Curing Temperature on the Compressive Strength Development and Flexural Tensile Behaviour of UHPFRC with Vipulanandan Model Quantification." *Structures* 30 (April 2021): 949–959. doi:10.1016/j.istruc.2021.01.063.
- [33] P.N. Hiremath, S.C. Yaragal, Effect of different curing regimes and durations on early strength development of reactive powder concrete, *Construction and Building Materials*. 154 (2017) 72–87. <https://doi.org/10.1016/j.conbuildmat.2017.07.181>.
- [34] Şengül, Ö. "Probabilistic Design for the Durability of Reinforced Concrete Structural Elements Exposed to Chloride Containing Environments". *Teknik Dergi/Technical Journal of Turkish Chamber of Civil Engineers* 22 (2011): 1461-1475
- [35] Wang, Zhendi, Qiang Zeng, Ling Wang, Yan Yao, and Kefei Li. "Characterizing blended cement pastes under cyclic freeze–thaw actions by electrical resistivity." *Construction and Building Materials* 44 (2013): 477-486. doi:10.1016/j.conbuildmat.2013.02.042.
- [36] Chidiac, S.E., and M. Shafikhani. "Electrical Resistivity Model for Quantifying Concrete Chloride Diffusion Coefficient." *Cement and Concrete Composites* 113 (October 2020): 103707. doi:10.1016/j.cemconcomp.2020.103707.
- [37] Cosoli, G., A. Mobili, N. Giuliotti, P. Chiariotti, G. Pandarese, F. Tittarelli, T. Bellezze, N. Mikanovic, and G.M. Revel. "Performance of Concretes Manufactured with Newly Developed Low-Clinker Cements Exposed to Water and Chlorides: Characterization by Means of Electrical Impedance Measurements." *Construction and Building Materials* 271 (February 2021): 121546. doi:10.1016/j.conbuildmat.2020.121546.
- [38] Thiyagarajan, Karthick, Parikshit Acharya, Lasitha Piyathilaka, and Sarath Kodagoda. "Numerical Modeling of the Effects of Electrode Spacing and Multilayered Concrete Resistivity on the Apparent Resistivity Measured Using Wenner Method." *2020 15th IEEE Conference on Industrial Electronics and Applications (ICIEA)* (November 9, 2020): 200–206. doi:10.1109/iciea48937.2020.9248217.
- [39] ASTM International, Designation: C172/C172M – 17, "Standard Practice for Sampling Freshly Mixed Concrete," *Annual Book of ASTM*. International Standard Worldwide (2009).
- [40] American Association of State and Highway Transportation Officials, AASHTO T 358-19-Standard Method of Test for Surface Resistivity Indication of Concrete's Ability to Resist Chloride Ion Penetration, (2019).
- [41] Sengul, Ozkan. "Use of Electrical Resistivity as an Indicator for Durability." *Construction and Building Materials* 73 (December 2014): 434–441. doi:10.1016/j.conbuildmat.2014.09.077.
- [42] Lim, Tze Yang Darren, Bahador Sabet Divsholi, and Susanto Teng. "In Situ Inspection of Ultra Durable Concrete Using Electrical Resistivity Technique." *Advanced Materials Research* 368–373 (October 2011): 1989–1992. doi:10.4028/www.scientific.net/amr.368-373.1989.
- [43] Spragg, R. P., J. Castro, T. Nantung, M. Paredes, and J. Weiss. "Variability Analysis of the Bulk Resistivity Measured Using Concrete Cylinders." *Advances in Civil Engineering Materials* 1, no. 1 (July 2012): ACEM–2012–0004. doi:10.1520/acem-2012-0004.
- [44] Sbartaï, Z.M., S. Laurens, J. Rhazi, J.P. Balayssac, and G. Arliguie. "Using Radar Direct Wave for Concrete Condition Assessment: Correlation with Electrical Resistivity." *Journal of Applied Geophysics* 62, no. 4 (August 2007): 361–374. doi:10.1016/j.jappgeo.2007.02.003.