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Chapter

Compressive Behavior of Concrete under Environmental Effects

Alireza Farzampour

Abstract

Concrete strength is fairly sensitive to environmental effects. Extreme weather conditions and changes in humidity rates significantly affect the concrete compressive strength development. Concrete as one of the substantial material used in residential buildings and infrastructures is subjected to a massive strength change under extreme weather conditions. For understanding, the different concrete's behavioral aspects, various commercial cement types under different temperatures, and humidity rates are investigated in this chapter. The experiments are aimed to investigate the concrete strength development over time when the material is cast at lower to mild temperatures and different humidity index rates. Results show that reducing the curing temperature more than 15° could result in 20% reduction in total compressive strength, while decreasing humidity rates by 50% leads to less than 10% drop in ultimate strength. To understand the strength developing process, maturity tests are conducted. It is shown that concrete is not able to reach to the expected ultimate strength if the temperature is significantly low regardless of curing time. The effect of temperature change during the curing process is more tangible on strength development compared to cement type and humidity rate values.

Keywords: compressive strength, environmental effects, maturity, durability

1. Introduction

There is significant need for evaluating the concrete behavior on-site without implementing experimental tools. Concrete if properly placed in extreme weather conditions is able to develop desired ultimate strength [1]. Temperature changes could cause cracks or sapling, distress, and aggregate expansion which leads to concrete strength deterioration. Many different procedures are recommended in codes to reduce the negative effects of low or high ambient temperature [1, 2]. High temperature, above 100°C, could lead to color changes in aggregates leading to abrupt loss of compressive strength. While, lower temperature, less than zero, usually ends up in cracking and low resistance against freeze-thaw effects [3–5]. A common practice to reduce the undesirable crack propagation in concrete mixtures under thermal effects is to use fibers due to having persistency in behavior under various environmental conditions [6].

The behavior of the concrete under high temperature values could be affected with several factors. The temperature rate, aggregate type, and stability of the mixture are among the most important factors to be considered under high temperature condition. It is noted that the abrupt temperature rise can cause thermal

shock, spalling, cracking, and aggregate expansion leading to high distress within the concrete [2, 3]. Therefore, the strength of concrete is reduced by any significant temperature increase. The strength degradation rate is depended on the initial compressive concrete strength [7]. Concrete in general provides one of the best fire resistance properties due to chemically combined material with thermal conductivity, and high heat capacity which leads to self-protection against extreme temperature conditions (e.g., fire).

On the other hand, the low temperature curing condition is a highly common issue affecting the strength development of the concrete. Pouring and curing concrete in extreme weather conditions require special attention to the code instructions for obtaining desirable performance in structures [1, 2]. The cold weather condition is defined previously as a period of time in which for more than three consecutive days, either average daily air temperature is less than 5°C or the air temperature is not greater than 10°C for more than one-half of any 24-h period. The cold condition limits the concrete capability to develop strength by causing significant decrease in hydration process. Another issue with cold ambient temperature is expansion of the water in concrete, especially in high water-cement ratio mixtures, leading to spalling and overall strength degradation [1, 7, 8]. It is well documented that if the concrete in plastic stage freezes, about 50% of the strength is expected to be reduced and durability loss is inevitable [2].

The durability of the concrete against freeze-thaw cycles is previously investigated as a major factor indicating the ability for resistance against weathering actions [9–11]. For durability improvements, the concrete mixture's water-to-cement ratio plays an important role which should be carefully considered [12, 13]. ACI guide [1] proposes procedures prior and after pouring concrete under harsh weather conditions to avoid any strength loss (**Figure 1**). It is generally recommended that to use lower water-to-cement design ratio, type-three cement and nonchloride admixtures for the best performance under cold weather conditions.

There are different factors which are indirectly affected by any change in environmental conditions. The setting time issue with cold weather would be twice by each 10°C, which causes the concrete to be exposed and vulnerable to ambient damages. Therefore, effectively protect the concrete from the harsh ambient conditions is necessary until it gains minimum strength of 3.5 MPa [1, 2, 14]. Additionally, under harsh environmental conditions, the inner parts of concrete would experience a different hydration process rather than the outer areas. The inner parts commonly have higher temperature due to hydration of the cement with water, while outer layers experience less temperature values. This phenomenon, especially under cold outside temperature, results in significant thermal



a) b)

Figure 1.
(a) Concrete in cold weather. (b) Cold weather curing.

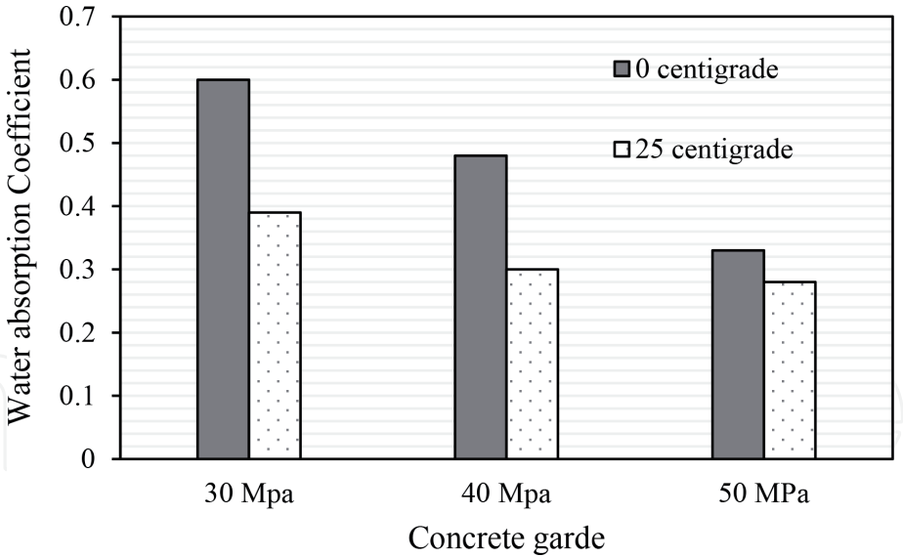


Figure 2.
Influence of the curing temperature on water absorption of the mixture.

cracks causing lower compressive strength values, generating microcracks and adversely affecting the interfacial zone (ASTM C 1074-04). Furthermore, at freezing temperatures, a reduction of 29% in stiffness after 28 days is expected since the vulnerability against cracks is reduced due to increase in water absorption of the hardened concrete [15]. **Figure 2** shows the water absorption coefficient is increased for three different concrete types under cold weather compared to mild weather conditions. These phenomena negatively change the compressive strength and vulnerability against crack propagation showing that water-cement ratio is one most important factors in strength development of the concrete [15, 16]. In addition, the concrete freezing at initial stages of strength development negatively reduces the capability of the cement matrix to maintain the mixture integrity against freeze-thaw cycles [16, 17].

In what follows, the ambient temperature and humidity index effects on various concrete types are investigated. The compressive strength development under temperature changes is discussed in detail. The overview of the harsh weather concreting is established in detail by elaborating on compressive strength, maturity index, and freeze-thaw experiments. The out of this chapter is to understand the behavior of the concrete under various ambient conditions as the most commonly used material for construction and residential buildings.

2. Material properties used for compressive strength investigation

To elaborately indicate compressive behavior of the concrete, the results for three different temperatures of 5, 10, and 25°C as well as two humidity rate index values are represented. Four cement types with low and high water-cement ratio are taken into account to understand the compressive behavior of the concrete in various environmental effects. The commercially available grout types of BASF, Dayton, Five Star, and Quickrete are prepared and cured with water-cement ratios of 0.12, 0.12, 0.18, and 0.18, respectively. The values of consistency, an indicator of the mobility or fluidity of the mortar, were checked to be in conformity with the limits set in ASTM standards. **Table 1** shows a detailed plan of testing plan with the number of samples. The mentioned mortar compositions are selected based on the applicability of them for harsh environmental condition in North USA.

Temperature during the first 7 days (°C)	Relative humidity during the first 7 days (%)	Temperature after 7 days (°C)	Relative humidity after 7 days (%)	Number of cubes (2 × 2 × 2 in.)	Number of cylinders (maturity)	Number of rectangular cubes (Freeze-thaw)
23	100	23	100	15	2	2
23	50		50	15	2	2
10				15	2	2
5				15	2	2

Table 1.
Testing plane for evaluating the effect of temperature and humidity index.

All the samples were prepared in molds accordingly and consolidated with tamping rods. Roding is done for each layer uniformly on the cross-sectional area with rounded end. The number of strokes varies depending on the type of molds used, which is based on ASTM standards [14]. The samples are subsequently covered with burlaps to effectively initiate the hydration process for 24 h. Subsequently, the samples are demolded after being cured for 24 h, and the compressive strength is monitored for 1, 3, 7, 14, and 28 days curing time based on the ASTM recommended procedure [14–16]. It is noted that the mixing procedure is based on the ASTM manuals [14–16] for simulating the actual behavior of the concrete under cold, mild, and moderate temperature conditions.

It is noted that samples are remained in temperatures shown in **Table 1** for a week and then moved to room temperature area with the same humidity afterward. In general, for each grout type at each time interval, three cubic and two cylinders as well as two large rectangular samples for freeze-thaw durability index test are made for compressive strength development investigations.

3. Investigation of cement matrix compressive strength development under various temperature conditions

Different concrete types are made and cured for compressive strength test. For each grout, 15 ASTM verified cubes are cured based on the material plan summarized in **Table 1**. The compressive behavior is evaluated with compressive test machine shown in **Figure 3** at each time interval of 1, 3, 7, 14, and 28. For each time interval, the average of three compressive values is selected for accuracy of the results. It is noted that the rate of the compressive loading based on the ASTM manuals [14–16] should be consistent for all the specimens, since the loading rate has a significant effect on the ultimate compressive strength. **Figure 3** shows the compressive test machine and cube samples for use in compressive test experiment.

The general behavior of the concrete under different environmental conditions is summarized in **Figure 4**. Based on the results, it is concluded that the concrete would develop desirable compressive strength at room temperature (23°C) and 100% humidity rate. The hydration process in which the cement matrix develops bonds between aggregates is highest before 14 days of curing. It is concluded that the temperature before 14 days of curing is highly important factor in general strength development compared to other factors (e.g., humidity index rate).

The strength behavior is highly affected by the temperature of curing as compared to humidity rate index value. The temperature of curing plays an undeniable role specifically at early stages of curing process. The temperature reduction of 15° generally ends up in more than 20% drop in ultimate strength regardless of the



Figure 3.
(a) Compressive test machinery. (b) Cube concrete samples.

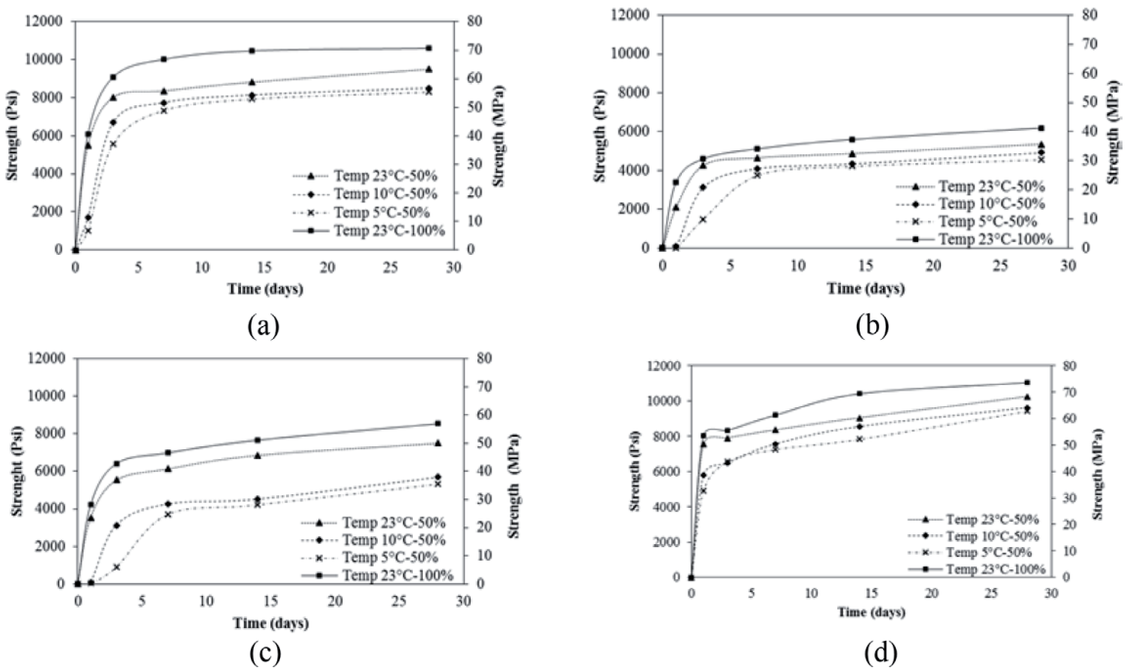


Figure 4.
The effect of temperature and humidity on various cement types. (a) BASF. (b) Five star. (c) Quickrete. (d) Dayton.

cement types. While, decreasing 50% of humidity rate leads to about 10% drop in ultimate strength values. Therefore, to reach to the specific ultimate compressive strength, the temperature should be controlled and monitored at different stages of curing. In addition, more than 75% of the total strength compressive strength development, for all the specimens, is occurred within the first 14 days of curing. The least compressive strength is associated with lower temperature and drier condition, while the most strength development is related to milder temperature and higher humidity condition.

4. Investigation of curing process and strength development of concrete with maturity method

In-place concrete strength evaluation is an important step in achieving the reliable performance of structures and construction scheduling [18, 19]. The level of maturity is in need of evaluation for deciding the forms' striping time, posttesting, protection

removal, and progressing with further construction plan. The minimum level of the strength required for concrete is required at different stages before further progress, which imposes careful monitoring of the strength evaluation through curing time. However, concrete under harsh environmental conditions normally experiences unexpected issues that decline the strength development. Significant expenses might be occurred if the concrete curing process is delayed under environmental effects to be assured that the concrete has reached the specified minimum strength.

Maturity in general is estimated by tracking the changes in strength development for fresh concrete under various temperatures over time intervals. As the cement hydrates, the strength increases; however, the amount of hydrated cement depends on many factors, specifically curing temperature. From the strength-maturity index curves of corresponding samples, the strength on-site could be predicted at any moment after concrete placement, which shows how far the hydration is processed. Usually, the concrete reaches the expected strength under warm weather condition, if the temperature is not abruptly increased. However, in cold temperature situation, the fluctuation in temperature during days and nights might stop the cement hydration process. For understanding, the reasonable evaluation of the strength of the placed concrete, maturity-meters shown in **Figure 5** are implemented at different stages of curing process.

The concrete strength is directly related to the curing time, humidity index, and temperature fluctuation. The maturity investigation is a method with which the early age concrete strength is monitored and the results subsequently could be implemented for in-site concrete placement [15, 17]. The main assumption with maturity concept is that the concrete is able to attain the same strength if the mixture reaches the same value of maturity index [18]. Another assumption with maturity evaluation is that the combination of temperature and time leads to the same strength for the considered concrete mixture. Therefore, strength development is a function of time and temperature. This function could be nonlinear or linear with respect to time and temperature. The instrument shown in **Figure 5** indicates how mature the concrete mix is which is represented as a number ultimately. The information is subsequently used for establishing maturity curves which are unique for any concrete mixture and related to compressive strength [19–21]. The schematic maturity curve is shown in **Figure 6**. The maturity curves are based on the time-temperature factor (TTF) which is compatible with the assumption that the maturity is a function of time and temperature.

In general, there are many common methods in obtaining the maturity level of the concrete. The general idea is based on the time-temperature factor which considers the proportional relation between combined temperature-time and compressive strength. The important issue related to this commonly used method shown in Eq. (1) is that the strength development in significantly higher or lower



Figure 5.
The maturity-meter device used for concrete strength evaluation.

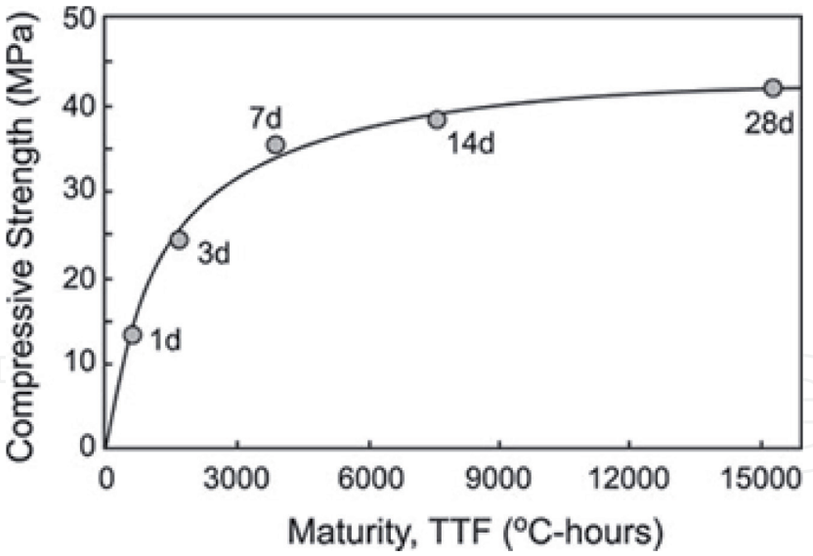


Figure 6.
The schematic maturity-meter curve showing the concrete maturity.

temperatures is not accurate; hence, the careful interpretation of the results in extreme temperature is inevitable.

$$M = \sum_{0}^{t} (T - T_0)\Delta t \tag{1}$$

where M is the maturity index in °C h, T is the average temperature in °C over time interval of Δt per hours, and T_0 is the datum temperature usually taken as 0°C at which the hydration is stopped and concrete does not gain any strength. M index is usually referred to as the maturity index related to TTF factor [2]. To understand the assumption in this method, **Figure 7** is shown in which the area of temperature over time for a specific mixture under cold condition is M_1, and under corresponding mild temperature condition is M_2. If M_1 and M_2, which represents the maturity index of a mixture, are equal, then the compressive concrete strength is expected to be the same. It is highly important that this assumption is only useful if the concrete does not experience any harsh environmental condition (e.g., excessive cold or hot temperature) during initial stages of the curing process.

To further investigate the effect of harsh environmental conditions on maturity and strength development of the concrete, the cylinder-shaped specimens are used for maturity evaluation of the four different concrete mixtures. Different temperatures and rates of humidity are considered for all the mixtures. **Figure 8** shows the maturity evaluation for all the concrete mixtures in which the compressive strength of the specimens are extracted at different time intervals. It is noted that the effect of significant humidity change, even though not considered in maturity concept formulation, is clearly observed. It is shown that environmental effects such as very dry conditions could tangibly change the strength development of the concrete; however, the change might not be as much as temperature variations. The lower water-cement ratio leads to significant gain in early stages of curing or lower TTF values, since all the cement materials actively participate in chemical hydration reactions. As the TTF increases or curing progresses, the rate of strength gain decreases until the concrete reaches the ultimate strength conditions.

Figure 8 shows the combined effect of temperature and time on compressive strength by using the maturity index. It is noted that temperature drop significantly affect the hydration process, which leads to less ultimate strength over the same period of the time. It is noted that if the harsh environmental condition such as

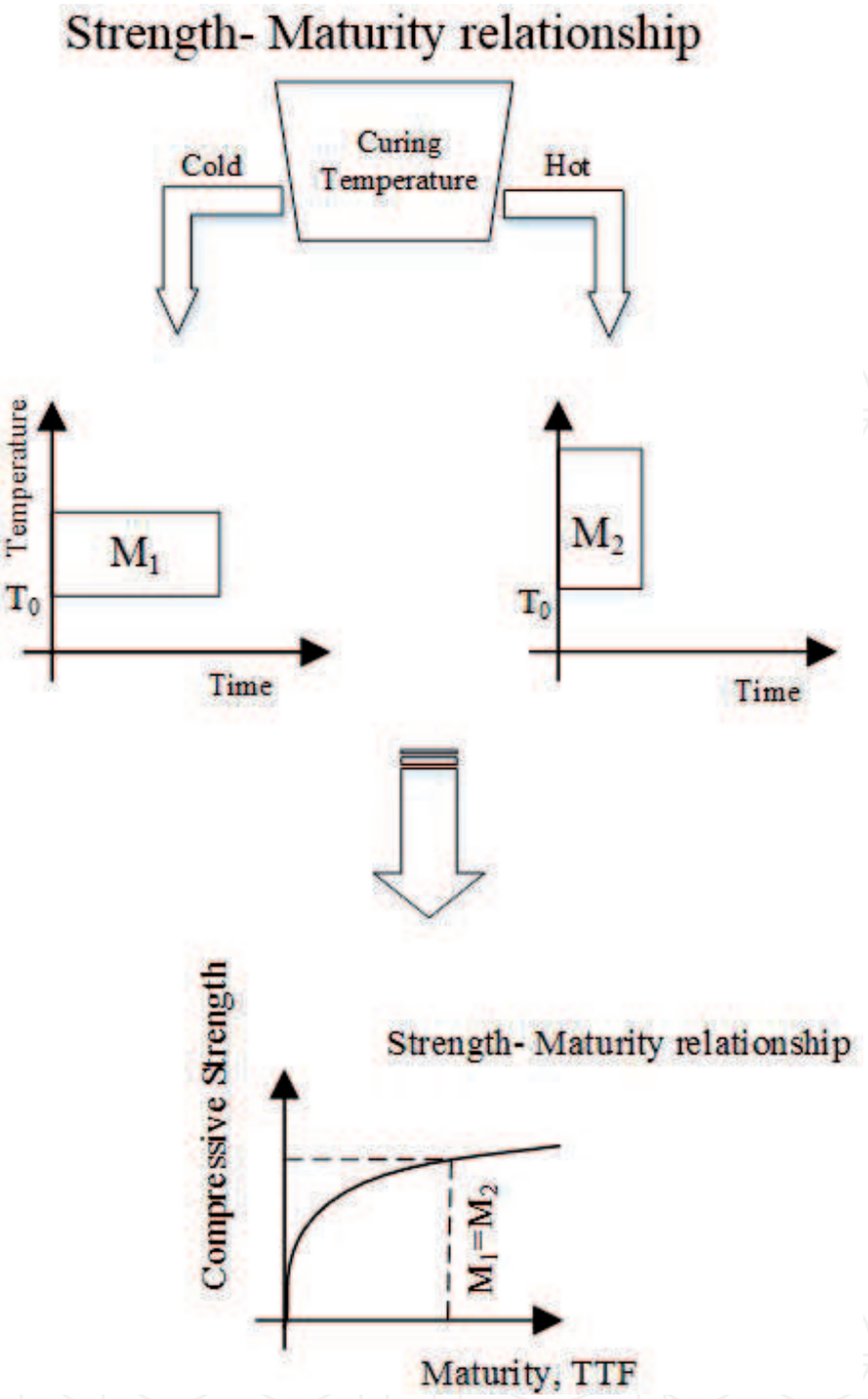


Figure 7.
The schematic representation of the maturity index assumption.

freezing temperature occurs, the hydration is stopped and the concrete would not be able to reach the ultimate expected strength even the sufficient amount of curing time is provided. In another words, the concrete would not develop the expected ultimate strength regardless of the curing time interval. This phenomena is important since the maturity formulation typically shows that by increasing the curing time, the effect of lower temperature could be compensated, which only is valid under specific environmental conditions (e.g., temperature over zero and sufficient humidity). From **Figure 8**, it is concluded that for all the cylinder samples, as the temperatures decrease significantly during the curing process, the bounding between cementious materials is not fully generated leading to lower ultimate strength even in large period of curing.

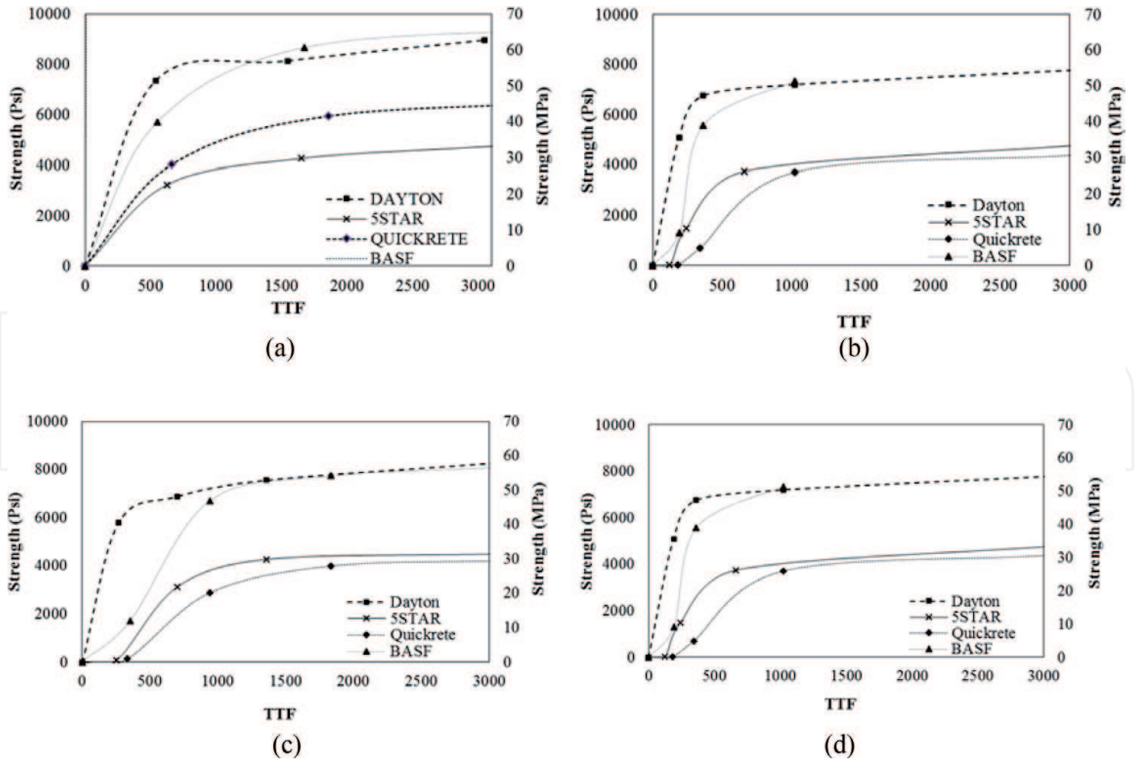


Figure 8.
Maturity evaluation of different cementious materials. (a) Temperature 23°C and RH 100%. (b) Temperature 23°C and RH 50%. (c) Temperature 10°C and RH 50%. (d) Temperature 5°C and RH 50%.

The strength of a given mixture placed and cured with the prescribed procedures is estimated from the temperature and time combinations. This method assumes that the only contributing factors to the strength development are time and temperature, while from the results of humidity rate study, it is shown that a drop of 50% in humidity index values would lead to average of 10% drop in compressive strength regardless of cement type.

In general, there are limitations of the maturity method implementation in estimating the concrete strength.

First, the implementation of this method is under the assumption that the placed concrete at the site has similar conditions to the concrete made in the laboratory. Any changes in batching accuracy, air content, and used materials could lead to different maturity curves and strength estimations.

Second, the areas that the maturity is evaluated within a specimen should not be only allocated to specific point. The hydration process within a large piece of concrete shows distinctive behavior aspects in outer and inner parts.

Third, the maturity method should be revised and carefully interpreted under extreme environmental conditions, which leads to incorrect estimation at early curing ages.

Fourth, the size of the concrete piece usually is larger than the samples, which means that the hydration process produces more heat and higher temperatures inside. This large temperature difference might affect the compressive strength development, which is not considered in laboratory samples.

5. Durability of the concrete under cyclic environmental conditions

The durability of cement mix is defined as the ability for resistance against weathering action, abrasion, and chemical reactions, or generally the processes that

deteriorate and affect the strength and stiffness. The durable concrete maintains the original quality and serviceability under environmental effects. Concrete is assumed durable if

1. Under extreme environmental effects (e.g., cycles of freeze-thaw), the deterioration is limited and controlled.

2. Minimum impurities such as chlorides, slit, and sulfates are existed.

3. The aggregates are clean and well graded; therefore, the concrete is less permeable.

4. The cement matrix is well structured and dense which appropriately bonds all the components together.

The durability of the concrete is highly depended on the cement content, water-cement ratio, curing process, cover, sufficient compaction, and appropriate mix design. In general, the outer causes of durability loss are: extreme weathering condition, abrupt temperature change, high humidity, chemical attacks, and ettringite formation. The inner causes are volume changes due to thermal properties of the aggregates and high water content, chemical reactions of ingredients, and steel reinforcement corrosion.

For durability assessment of the concrete, ASTM C666 [17] provides an equation which is shown in Eq. (2). If up to 300 cycles, significant cracks are not existed, then the concrete maintains its durability under environmental changes.

$$DF = PN/M \tag{2}$$

where DF is the durability factor of the specimen and P is relative dynamic modulus of elasticity. M is the specified number of cycles at which the exposure is terminated. N is the minimum of the cycles' number at which P reaches the specified minimum value for discontinuing the test, and the specified number of cycles at which the exposure is to be terminated. The general prepared specimens for durability investigation are shown in **Figure 9**.

For further investigations, the behavior of the concrete samples is monitored for cycles of freeze-thaw. For each type of cement, two specimens are made to sufficiently validate the results of the test. ASTM 666 procedures [17] to build and



Figure 9.
Durability investigation of the concrete, and freeze-thaw test.

test the specimens are considered, and the durability index is evaluated accordingly. **Figure 10** shows some of the specimens after significant number of freeze-thaw cycles. From this experiment, it is shown that the durability of the concrete is highly dependent on the cement matrix, water-cement ratio, exposure to harmful chemicals, extreme weathering, and concrete mix design.

The durability factor is obtained for each cement type at 30 each cycles, and the results are summarized in **Figure 11**. It is concluded that cement type and water-cement ratio has significant effect on the resistance and durability of the concrete. The high water-cement ratio would lead to higher permeability, which will be filled with water in the next cycles.

The water volume is expanded upon freezing and it is transformed to ice, which eventually causes microcrack propagation in concrete samples. Microcracks



Figure 10.
Significant number of freeze-thaw cycles.

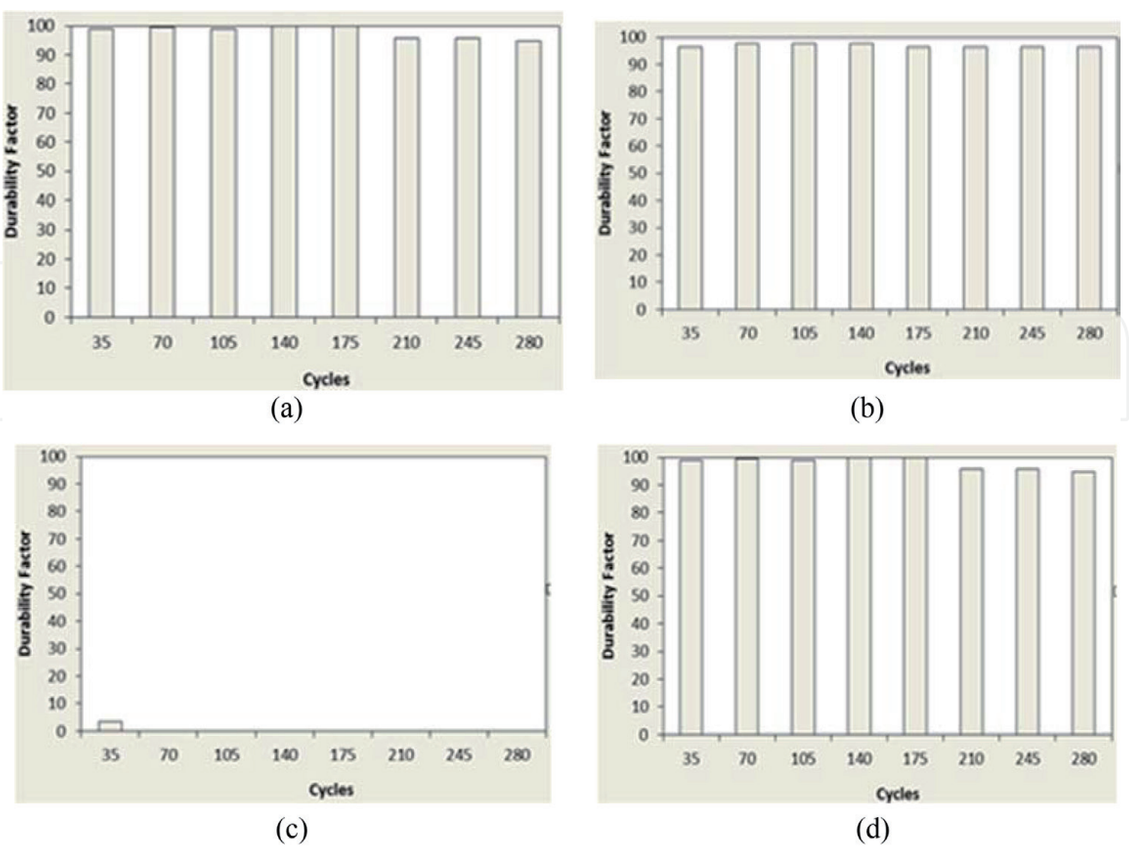


Figure 11.
Durability of the cement under freeze-thaw cycles. (a) BASF after 300 cycles. (b) Five star after 300 cycles. (c) Quickrete after 34 cycles. (d) Dayton after 300 cycles.

adversely change the concrete resistance against further freeze-thaw cycles leading to major cracks and abrupt loss of strength. It is recommended that lower water-cement ratio mix designs to be used under freeze-thaw possibility to limit the durability loss and maintain compressive strength.

6. Conclusion

The environmental conditions play an important role in compressive strength of concrete. Generally, the temperature during the curing time and humidity rate index value are among the most effective factors for achieving reliable concrete structure. It is shown that temperature if drops below the freezing condition, not only slows down the hydration process, but also reduces the durability of the concrete significantly. In general, for appropriately cured concrete, a temperature drop of 15° leads to 20%, and a 50% drop in humidity rate index ends up in 10% reduction in overall compressive strength, if the environmental conditions are not extreme. The concrete cured in significantly low temperature is not able to reach the same expected strength, whereas the higher cured temperature concrete could reach, regardless of the curing time. Therefore, it is recommend to pay close attention to curing procedures under extreme weather conditions. In addition, lower water-cement ratios have better performance under freeze-thaw cycles; however, in higher temperature condition, excessive heat is produced which could cause damages to other particles.

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Author details

Alireza Farzampour
Virginia Tech, Blacksburg, Virginia, USA

*Address all correspondence to: afarzam@vt.edu

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