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Temperature and humidity effects on behavior of grouts

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Abstract. Grouts compared to other material sources, could be highly sensitive to cold weather conditions, especially when the compressive strength is the matter of concern. Grout as one the substantial residential building material used in retaining walls, rebar fixation, sidewalks is in need of deeper investigation, especially in extreme weather condition. In this article, compressive strength development of four different commercial grouts at three temperatures and two humidity rates are evaluated. This experiment is aimed to assess the grout strength development over time and overall compressive strength when the material is cast at low temperatures. Results represent that reducing the curing temperature about 15 degrees could result in 20% reduction in ultimate strength; however, decreasing the humidity percentage by 50% could lead to 10% reduction in ultimate strength. The maturity test results represented the effect of various temperatures and humidity rates on maturity of the grouts. Additionally, the freeze-thaw cycle's effect on the grouts is conducted to investigate the durability factor. The results show that the lower temperatures could be significantly influential on the behavior of grouts compared to lower humidity rates. It is indicated that the maturity test could not be valid and precise in harsh temperature conditions.

Keywords: cold weather concrete; compressive strength; low temperature; humidity effect; maturity; freeze-thaw

1. Introduction

Due to time and equipment limitation, there is noticeable need to evaluate the concrete behavior on-site without any experimental test. Concrete can be placed in cold weather conditions provided that necessary precautions are taken to reduce the negative effects of low ambient temperatures. Pouring and curing concrete in cold weather require special procedures, which should be strictly followed to achieve determined performance of concrete and structure (ACI 2010, Krylov 2008). Appropriate procedures are extensively important in areas with seismic hazard potential (Farzampour and Kamali 2015). Studies accredited by cement and concrete organizations nationally and internationally have been prepared to address the cold weather concreting procedures (ACI 2010, Krylov 2008).

ACI (2010) defines cold weather concreting as a period when for more than three consecutive days, either the average daily air temperature is less than 5°C (40°F), or the air temperature is not greater than 10°C (50°F) for more than one-half of any 24-hour period. Under cold temperatures,

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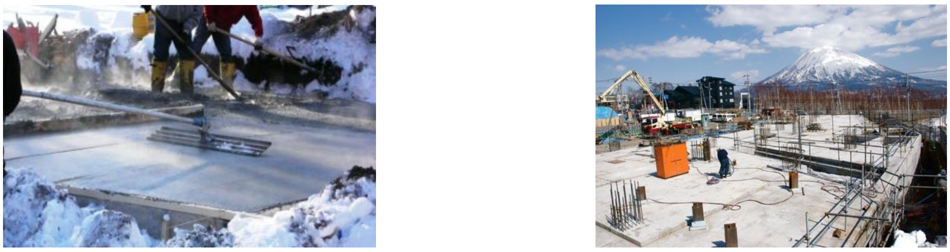


Fig. 1(a) Placement of concrete in cold weather (ACI 2010) (b) Curing of concrete in cold weather (Krylov 2008)

concrete gains very little strength (or even stops gaining strength) due to decrease in hydration process. At the same time, the forces generated by the expansion of ice compared to water could be highly detrimental to overall strength of concrete (ACI 2010, Kosmatka and Wilson 2011, ASTM C94). In plastic stage of concrete, if concrete freezes, 50% of the concrete strength would be reduced and problems associated with durability would be inevitable (Cold-Weather Concreting, Chapter 14). In addition, the setting time of the concrete would be twice by each 10°C decrease, leading to longer time of being vulnerable to ambient damage (ACI 2010, Kosmatka and Wilson 2011, ASTM C31). Therefore, it is important to protect the concrete from cycles of freeze-thaw until it gains minimum strength of 3.5 MPa (500psi).

Various procedures are proposed to improve the structural behavior (e.g., Farzampour and Kamali 2017); however, it is important to consider the durability of the material used in the structures. To efficiently improve the durability of the concrete products, a number of studies have been done previously (Güneyisi *et al.* 2014, Muhit *et al.* 2014, Gjørv 2013, Mansouri *et al.* 2017). It is represented that the durability of cementious material would be affected by environmental conditions (Zhang 2014, Zhang *et al.* 2016, Patila *et al.* 2014). In harsh environmental conditions, it is necessary to make sure ACI guide is fully understood and followed prior to and after pouring concrete in cold weather (Fig. 1). Generally, it is recommended that higher strength admixture mixes, lower water-cementious material ratios, adding non-chloride admixtures, and using type-three cement which is considered as the high-strength cement are considered in cold weather condition.

Another point of concern, especially in cold weather, is that the inner sides of the concrete would have higher temperature due to hydration of the cement with water, while the surface of the member would experience a significantly lower temperature. Significant temperature difference between interior sides and the interface of the concrete member would result in thermal cracks, leading to less compressive strength. Cold weather curing could lead to development of micro-cracks and adversely affects inter-facial zone (ASTM C 1074-04). In addition, at freezing temperatures, concreting could result in 20% stiffness reduction after 28 days, and the water absorption of hardened concrete would be increased as a result of cold-curing, leading to increase in vulnerability against cracks (ASTM C 1074-04) as indicated in Fig. 2. It is noted that concrete which is attained enough strength by appropriate curing conditions, could develop its potential against subsequent cold weather exposures (ASTM C 1074-04, ASTM C 109). It is noted that the water-cement ratio is significantly important in strength development behavior of the concrete structures, which is investigated in this study. Along the same lines, the freezing of the concrete at initial stages, before reaching to satisfactory strength, would significantly reduce the applicability of cement to resist against freeze-thaw cycles (ASTM C 109, ASTM C 666).

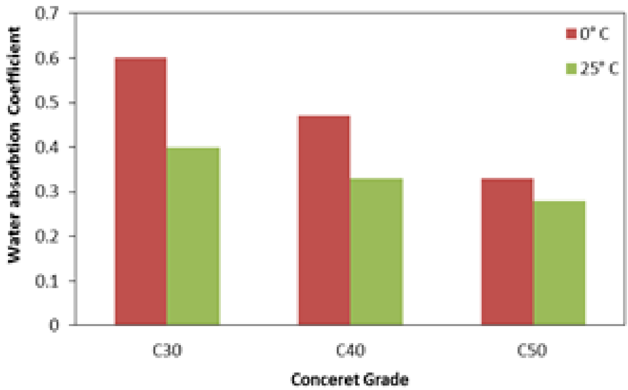


Fig. 2 The influence of curing temperature in water absorption for 30, 40, 50 MPa compressive strength samples (ASTM C 1611)

Table 1 The water-cement ratio of four investigated grouts

Grout	W/C
BASF	0.12
Dayton	0.12
Five Star	0.18
Quickrete	0.18

This research is conducted in three parts to thoroughly investigate the behavior of four commercially available grouts as one the most essential materials used in residential buildings, in extreme weather conditions. Retaining of walls, column-beam rebar fixation, sidewalks are among a number of implementations of this material. In the first part, the compressive strength development for each grout is indicated and compared, and the effect of water cement ratio, temperature, humidity and time on developing strength are considered. In second part, the maturity concept is investigated in harsh temperature condition, and the validity of the mentioned concept is investigated and recommendations are proposed. In the third part, the ductility ratios of the specimens are extracted based on the experiments done on specimens, and comparisons made regarding freeze-thaw cyclic testing procedures.

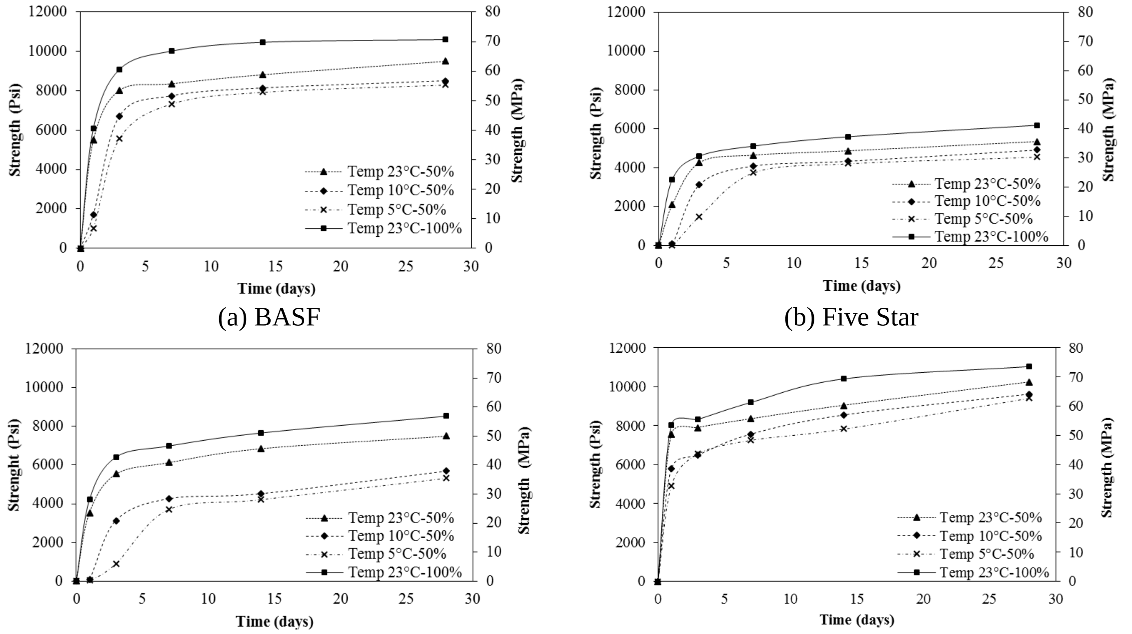
This paper provides a brief overview on cold-weather concreting along with experimental analysis of four commercially available grouts. The significant outcome of this research is to understand the compressive behavior of grouts in cold temperatures as one of the most common materials in constructions and residential buildings as well as to achieve higher safety at a specified time period. The results of this research could be followed in colder months where special concrete practices and appropriate planning are matters of concern, and the loss due to cold temperatures could be irreversible.

2. Materials and mixing procedure

Three different temperatures and two humidity indexes were investigated to assess the concrete member curing process in cold weather. Table 1 indicates four different grouts with the

Table 2 Temperature and humidity investigation plan

Temperature during the first 7 Days (ºC)	Relative Humidity during the first 7 Days (%)	Temperature after 7 Days (ºC)	Relative Humidity after 7 Days (%)	Number of Cubes (2×2×2in.)	Number of Cylinders (maturity)	Number of Rectangular Cubes (Freez-Thaw)
23	100%	23	100%	15	2	2
23	50%		50%	15	2	2
10				15	2	2
5				15	2	2



(a) BASF (b) Five Star

(c) Quickrete (d) Dayton

Fig. 3 The effect of temperature and humidity

recommended water cement ratios.

Table 2 indicates the testing regime regarding various temperatures, humidity rates and the number of samples. All the grout mixtures were designed based on the recommended cement ratios (ASTM C31, ASTM C94, ASTM C 109, ASTM C 1074-04, ASTM C 1611). The mixing procedure was based on ASTM manual (ASTM C 109, ASTM C 1074-04, ASTM C 1611). All samples were placed in molds and consolidated with tamping rod, and then they were immediately covered with wet burlap and plastic for 24 hours. Afterwards, samples are demolded at 24 hours curing and one-day compressive strength was tested according to ASTM C109 (ASTM C 1074-04). The compressive strength was tested at 3, 7, 14 and 28 days.

It should be mentioned that, the samples were kept in the specified temperatures mentioned in Table 2 for a week, and they transported to temperature 23(ºC) rooms with the same humidity rate afterwards. For each grout in each time interval three samples were tested to evaluate compressive strength. Two cylinders for maturity test, and 2 cylinders for freeze-thaw test were considered to have sufficient accuracy.

3. Strength development results

The strength behavior of four common types of grout at different temperatures and humidity rates are investigated in this section. Fig. 3 indicates the general behavior of grouts with time regarding four and two different temperature sand humidity rates, respectively.

According to the strength behaviour, the effect of temperature is significant. Considering the overall strength development of the grouts, reducing the curing temperature as much as 15 degrees could result in more than 20% reduction in ultimate strength; however, by decreasing the humidity percentage by 50% could lead to more than 10% reduction in ultimate strength. Therefore, the effect of temperature in reaching to specific ultimate strength level would be more significant than humidity regardless of the grout type.

4. Maturity investigation of different temperature-cured grouts

Determination of the strength of in-place concrete is significantly important to achieve sufficient performance, and avoid time mismanagement. Decisions on the time of striping forms from concrete members, post-tensioning, and when to terminate cold-weather protection are based on the level of maturity to obtain a minimum level of concrete strength. It is worthy of notice that timeline considerations of each project would impose the need to evaluate the strength trend through time at a specified temperature. Waiting for long periods of time to be completely assured about the performance of the member, or premature operation of the system causes significant expenses. Maturity is calculated by tracking changes in fresh concrete temperature over time. Strength increases as cement hydrates, and the amount of cement hydrated depends on how long the concrete has been cured and at what temperature. Since each concrete mix has its own strength-maturity relationship curve, we can use this curve to estimate the strength of that mix at any moment after placement, and how far hydration is processed.

It is important to understand the degree of hydration of cement in concrete, which dictates directly its strength development. In cold-weather, with fluctuations of temperature during days and nights, it is a hard task to make sure what the strength of concrete precisely is. To have a reasonable estimation about the strength of placed concrete, maturity-meters are highly suggested to be applied.

The maturity concept is associated with the fact that the concrete strength is directly related to time and temperature. This method can provide a reliable assessment of early-age concrete strength in regard to in-place construction (ASTM C 1074-04, ASTM C666). The maturity concept's main assumption is based on the attainment of same strength if the concrete mixture attains the same values of maturity index (Anderson *et al*. 2009, Technical bulletin 2006); in addition, it is assumed that combination of temperature with time would lead to the same strength for concrete mixtures. Therefore, maturity is related to the strength gain in the concrete as a function of time and temperature. Fig. 4 schematically shows the effect of temperature and time aggregation on compressive strength by using the maturity index as well as the maturity meter device used in this study.

Using different built-in programs, the instrument determines how mature the concrete is. The

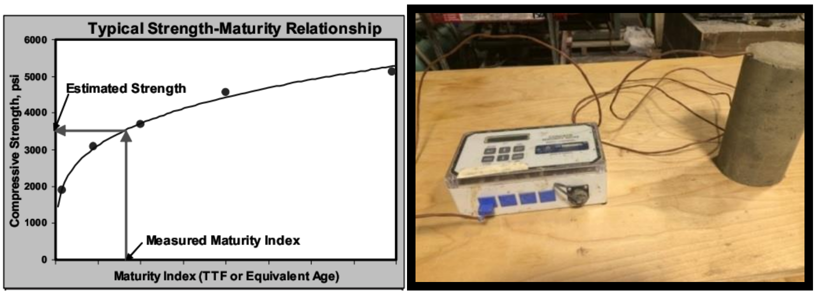


Fig. 4 Combined effect of time and temperature using maturity meter

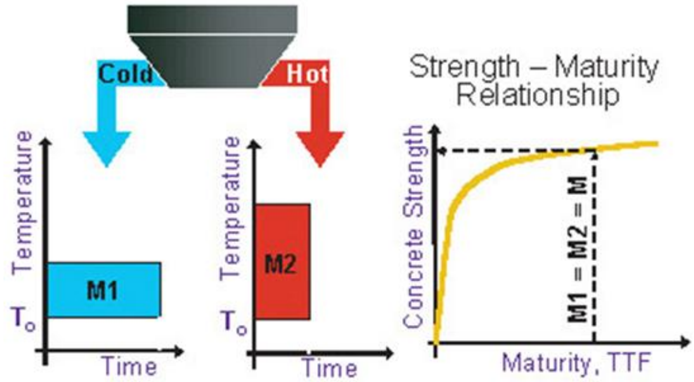


Fig. 5 Maturity method concept

output of the instrument is a number. Each concrete mix has a unique curve, relating its maturity index to compressive strength. It is required to obtain calibration curve of the used concrete. If the concrete mix is provided from local concrete mix providers, calibration curves should be asked for (Carino and Malhotra 2003).

There are two maturity methods to obtain maturity index of each mixture. First, time-temperature factor method (Nurse-Saul) which considers proportionate relation between time-temperatures-combination known as maturity index and compressive strength. This method is not able to specify strength development in higher temperatures; thus, an underestimation in results would be inevitable especially at high temperatures. Eq. (1) shows the maturity index formula.

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

where M is the maturity index in terms of °C.hr, T is the average temperature in degree centigrade during time interval of Δt per hours, and T_0 is the datum temperature usually taken as zero °C, at which the concrete strength gain ceases completely. This index is known by some different terms, such as the maturity index value, the time-temperature factor (TTF) or the maturity of the concrete (Krylov 2008). The concept of TTF procedure could be observed in Fig. 5, where the same surface of temperature versus time could lead to the same results in regard to concrete strength.

Second, the equivalent age maturity function (Arrhenius procedure) is another method to estimate the maturity of concrete mixtures. The Arrhenius equation is a better representation of time-temperature function than the Nurse-Saul equation when a wide variation in concrete temperature is expected. However, the Arrhenius equation is the most commonly used alternative to the Nurse-Saul equation. This homogenous formula could make some conflicts, as the cement is a multiphase material, and the process of cement hydration is not that simple. Therefore, homogenous reaction kinetics cannot be applied. Trost suggested implementation of Arrhenius equation despite the exponential format which is not compatible with chemical reactions. The only disadvantage of Arrhenius formula is that this equation can cause extreme over-prediction of concrete strength under certain unpredictable and uncontrolled conditions. Therefore, it is not as widely used as the Nurse-Saul equation indicated in Eq. (2).

$$t_e = \sum_{0}^{t} e^{-E(1/T_e - 1/T)\Delta t/R} \tag{2}$$

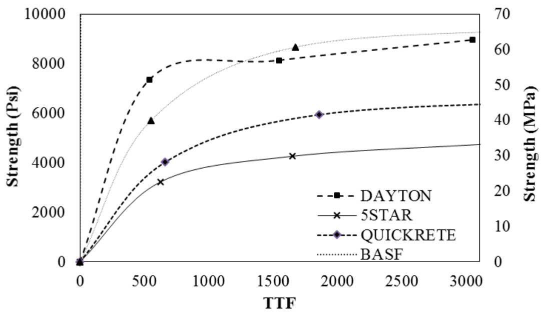
where E is the apparent activation energy (J/mol), R is the universal gas constant (8.31 J/mol.k), T is average temperature of the concrete, T_0 is the absolute reference temperature (Kelvin degree), T_e is the equivalent age at the reference temperature, and Δt is time interval (hours).

There are some limitations on usage of this method for concrete strength. The main limitation of usage of this method could be described that concrete used in structure could not be assumed to be exactly as the concrete used in laboratory, since any changes in materials, batching accuracy, air content, etc. could affect the ultimate compression strength. In addition, extreme temperatures at early curing age could result in incorrect estimations.

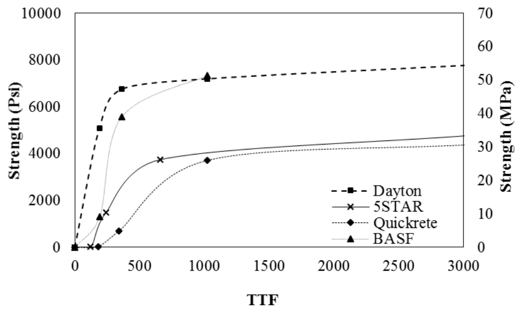
The strength of given mixture, which has been placed and cured in appropriate procedures, could be estimated from the combination of temperature and time. This fact is further investigated in details with representing results for different grout types. In addition, maturity concept presumes that all other factors affecting concrete strength are properly controlled, which is a simplification of the concrete behavior. Usage of datum temperature could not be adequately assessed and determined. In addition, different sample sizes are assumed not to have any effect on the maturity-strength relationship (Kwon 2013).

Fig. 6 indicates the maturity test regarding different temperatures and rates of humidity. The effect of humidity, although, is not noticeable in TTF formulation, it is obvious in the tests results. It is represented that the lower humidity could have tangible effect on ultimate strength reduction, but not as much as temperature effect. It is important to note that usage of lower water-cement ratio has led to significant strength gain specifically in lower TTFs. However, as the TTF increases, the rate of difference would be unchanged, meaning that the concrete has reached its ultimate strength. By lowering humidity rate it could be expected that concrete reaches to its ultimate strength in lower TTFs, as well as lower strength would be gained compared with higher humidity rates.

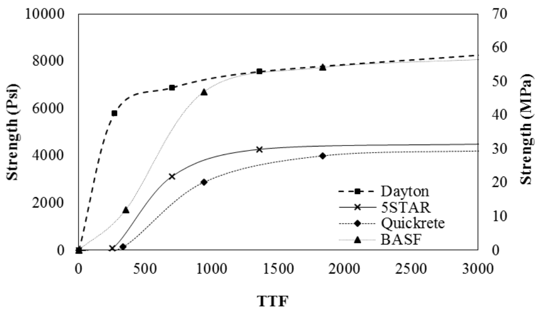
It is worthy of notice that temperature could have tremendous effect on the behavior of the concrete. If the concrete stays in cold temperature, the hydration of the cement could be reduced or get lower, leading to less strength. The important matter is that because the common TTF formulation is based on the linear mutilation temperature and time of curing, it could be misleadingly inferred that sooner or later the concrete would end up with the same strength; however, this is not correct. By lowering the temperature, the grout could never fully develop its strength at specified temperature due to having inappropriate initial condition for cement hydration; this would lead to the lower ultimate strength at the end of the curing procedure. It is represented that concrete cured in lower temperature could barely reach to the ultimate strength of a corresponding concrete cured in higher temperature, no matter how long the concrete is being



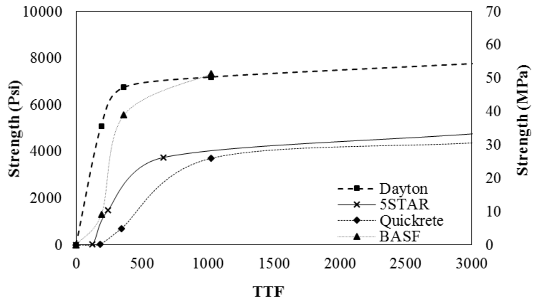
(a) Temperature 23°C and RH 100%



(b) Temperature 23°C and RH 50%



(c) Temperature 10°C and RH 50%



(d) Temperature 5°C and RH 50%

Fig. 6 Maturity evaluation of grouts

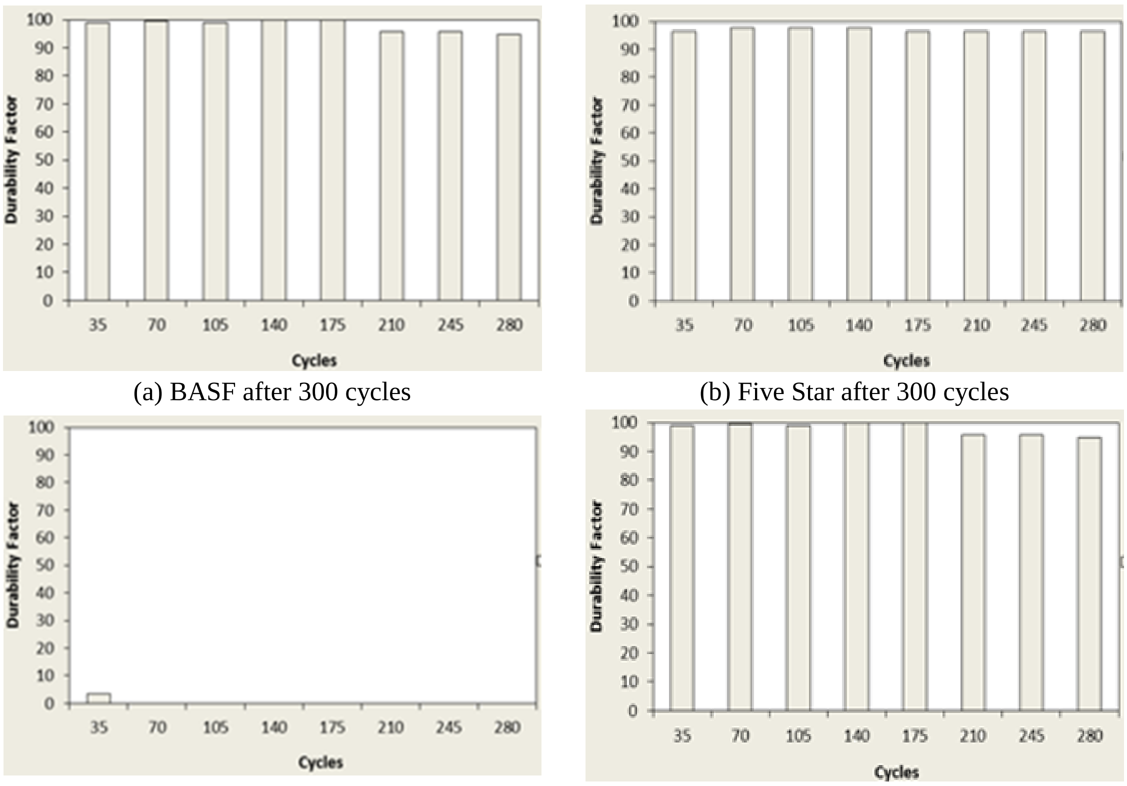
cured. As it is observed, reduction in curing temperature would result in huge decrease in ultimate strength development. In details, the reason of this strength reduction could be described as the curing temperature decreases, the hydration rate in early ages would be decreased and subsequently the bounding between cementious materials would not be fully initialized.

From the results of this part, it is concluded that the maturity concept could not be sufficiently precise in conditions of harsh temperatures or humidity rates since as the curing temperatures decreases significantly, the grout would not develop the same strength the higher-temperature-cured grouts could have developed in specified time, even after sufficient amount of time. In addition, the type of grout could be highly important in cold weather conditions. In this regard, Quickrete has better performance in the higher curing temperature; however, it could have much worse behavior in colder temperature. This unpredicted behavior in cold temperature could be highly influential especially in the case of freeze-thaw situation. It seems that curing in colder weather should have some specific precautions, due to immature strength development of cement matrix. In addition, Fig. 5 indicates that the maturity tests, indicated the curing temperature would be considered a highly important factor in gaining strength as compared to humidity rate. Results show that the common maturity assessment method might not sufficiently precise for extreme environmental conditions.

5. Freeze thaw investigation

In this part, the behavior of the grouts is investigated during cycles of freeze-thaw. For this, two similar specimens for each grout were made and tested based on the ASTM C 666 to increase the

Fig. 7 The specimens after significant number of freezing and thawing cycles



(a) BASF after 300 cycles (b) Five Star after 300 cycles

(c) Quickrete after 34 cycles (d) Dayton after 300 cycles

Fig. 8 The durability behavior of the grouts in specified number of freezing and thawing cycles

validity of the results. This method indicates grouts' resistance to rapidly repeated cycles of freezing and thawing. The effect of the water-cement ratio is investigated here. Fig. 7. Indicates the specimens after significant number of cycles.

All the specimens were tested until significant cracks would happen or the number of cycles got over 300 based on ASTM C666. The durability factor for each specimen is monitored and calculated based on the equations provided in ASTMC666 as indicated in Eq. (3).

$$DF=PN/M \quad (3)$$

where DF is the durability factor of the specimen, P is relative dynamic modulus of elasticity, N is the number of cycles at which P reaches the specified minimum value for discontinuing the test or the specified number of cycles at which the exposure is be terminated, whichever is the less, and M is specified number of cycles at which the exposure is to be terminated. The durability factor is used to determine the ability of the grout to resist the freeze-thaw cycles. In general, the durability factor of more than 85% is considered to be adequate for the freeze-thaw behavior.

For each grout type, the average value of the results are recorded after each 35 cycles. This experiment is designed to investigate the effect of freeze-thaw cycles on mitigation of cracks at appropriate room temperature of 23^{o} and humidity rate of 100%. Fig. 8 indicates the durability ratio estimated based on the ASTM C666 for different types of grouts with regard to cycle number of freezing and thawing.

From the results of this test, it is noted that the type of cement is significantly important to resist the cycles of freeze-thaw. Different types of cement need specific amount of water to have appropriate resistance behavior against these cycles. It is indicated that the lower water-cement ratio could be highly effective on improving the resistance and avoiding the ductility factor loss.

6. Conclusions

The strength development of four commercially available grouts was investigated at three different temperatures and two humidity rates. It is shown that the effect of humidity on curing regime of concrete is noticeable. However, it is not well addressed in the TTF maturity formulations. The effect of temperature on the overall maturity of the concrete is thoroughly investigated, and it is observed that the concrete cured at lower temperatures could never reach the same strength which the concrete with higher curing temperature could reach; therefore, curing temperature could be highly essential in strength of the grouts. In addition, the usage of lower water-cement ratios is recommended in cold weather curing, as the water turning to ice, the expanding forces would be increased, and damage would be inevitable. Therefore, lower water-cement ratios are strongly recommended, especially in cold weather condition. Additionally, this ratio would have significant effect on the durability of the grouts after certain number of freeze-thaw cycles.

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