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# Freezing and Thawing Durability of Very High Strength Concrete

Sameer Hamoush and Miguel Picornell-Darder,
Taher Abu-Lebdeh and Ahmed Mohamed
Department of Civil, Architectural and Environmental Engineering,
North Carolina A and T State University, NC 27411, Greensboro, USA

**Abstract: Problem statement:** The newly developed Very High Strength Concrete (VHSC), having compressive strengths of 29 ksi and flexural strengths of 6 ksi, represents a breakthrough in concrete technology. Study to further enhance the properties of this new concrete is continuing. **Approach:** The objective of this study is to investigate the effect of exposing Very High Strength Concrete (VHSC) specimens to rapid freeze/thaw cycles. Twenty one specimens were tested according to the Standards of the American Society for Testing and Materials ASTM C215, ASTM C666 and ASTM C78. **Results:** One hundred freeze/thaw cycles were performed on the VHSC specimens. Change in specimen's dimensions and material's properties were recorded at zero, forty, seventy and one hundred cycles. Dimensions and properties considered were: dimension of cross section, length, weight, Dynamic Moduli, Poisson's Ratio, durability factor and Modulus of Rupture. **Conclusion/Recommendations:** The test results indicated that VHSC is good freeze-thaw resistance (durability factor > 85%) and can avoid freeze/thaw damage. Freeze- thaw cycling did not significantly affect VHSC specimens' cross sectional dimensions, length, or Poisson's Ratio. However, there was a decrease in the specimens' weight with the increase in number of freeze/thaw cycles, but the decrease was very slim indicating little or no deterioration has occur. Moreover, the fine voids exist in VHSC greatly lower the freezing point of any trapped water, making the material less susceptible to Freeze-Thaw damage.

**Key words:** Very High Strength Concrete (VHSC), freeze/thaw cycles, Dynamic Modulus of Elasticity, Dynamic Modulus of Rigidity, Modulus of Rupture, Durability Factor (DF), reducing admixture, osmotic pressure, chemical attack

## INTRODUCTION

Very High Strength Concrete (VHSC) is a newly developed material by the U.S. Army Engineer Research and Development Center (ERDC). The unconfined compressive strength of VHSC can be five times the compressive strength of the conventional normal concrete and toughness of about eight times greater than that of conventional fiber reinforced concrete. These superior properties were achieved by considering several factors such as low flaws, particle packing, improved material homogeneity, low water cement ratio, mixing method and special curing treatment (Abu-Lebdeh *et al*., 2010a; 2010b; O'Neil *et al*., 1999; 2006; Hamoush *et al*., 2010; Ravichandran *et al*., 2009; Saravanan *et al*., 2010). To date, researchers continue working on enhancing the properties of this new concrete. One of such properties is the durability of the material. This study is an attempt to investigate the durability of Very High Strength Concrete (VHSC) subjected to rapid freeze/thaw cycles. Durability of concrete may be defined as the ability of concrete to resist weathering conditions, chemical attack and abrasion while maintaining its desired engineering properties. It can be measured by using the standards of the American Society for Testing and Materials (ASTM C-666) which defines the resistance of concrete to rapid freeze and thaw cycles. Durability of concrete is the percent ratio of the dynamic modulus of elasticity after a number of freeze and thaw cycles to the corresponding value before the freeze and thaw cycles. Further, there are many theories explaining how freezing and thawing causes damage to concrete. Such theories include: critical saturation, hydraulic pressure, ice accretion and osmotic pressure (Beaudoin *et al*., 2009; Mustafa *et al*., 2009). Critical saturation theory is

**Corresponding Author:** Taher Abu-Lebdeh, Department of Civil, Architectural and Environmental Engineering, North Carolina A and T State University 1601 E. Market Street Greensboro, Tel: (336) 334-7575 Fax: (336) 334-7126

based on the expansion of about 9 % in water volume when it freezes. Hydraulic pressure theory states that the buildup of hydraulic pressure from the resistance to flow of unfrozen water through capillaries causes damage to the concrete. Ice accretion and osmotic pressure theory was developed to solve some of the experimental results that were inconsistent with the hydraulic pressure theory. It states that "water travels from the gel pores to the capillary pores" and based on the laws of thermodynamics (diffusion from high to low free energy) and the theory of osmotic (diffusion along concentration gradients). Based on the above theories, damages occur due to the excessive internal stresses in concrete during the freeze and thaw cycles. Therefore, adding air entrained admixtures to the concrete mix will act as a release for these internal stresses.

A significant number of studies have been done on the durability of concrete and its ability to withstand severe weather conditions (Kumaran *et al*., 2008; Roshan *et al.*, 2010; Nagaradjane *et al*., 2009; Malhotra and Carino, 2004). The later presented a review of non-destructive testing methods used for determining the dynamic modulus of elasticity of concrete. They discussed factors that affect the dynamic modulus of elasticity, the correlations between dynamic modulus and static modulus of the concrete and the usefulness and limitations of the resonant frequency method. Kumar *et al.* (2006) performed non-destructive evaluation of dynamic properties of concrete. They investigated the dynamic modulus of elasticity of concrete with three different mixture proportions and using two different methods: the first method is the ASTM C215-02 (2002) , while the second method follows the test set up suggested by Jin and Li (2001) and comparable to the test setup by Leming *et al*. (1988). They observed that both the dynamic and static moduli of elasticity of concrete are largely influenced by the age and grade of concrete. Jin and Li (2001) compared static compressive and dynamic (sonic) modulus of elasticity and showed that the compressive modulus is lower than the dynamic and that both the age of the concrete and the magnitude of the modulus affect the ratio of the two values. Michael (2003) from Rhode Island Department of Transportation (RIDT) performed freeze/thaw tests on a Glass Fiber Reinforced Concrete mix (GFRC). The concrete was used in Washington bridge section, number 200. RIDT primary concern was to study the effect of using a special sealer on the durability of the GFRC concrete subjected the freeze and thaw cycles. They performed two studies: The first one is to evaluate dynamic modulus of elasticity, weight gain/loss, permeability, Bulk Specific Gravity, Compressive strength and Flexural strength. They noticed that the dynamic modulus results were unusual because there was an increase in the dynamic modulus with the increase in number of cycles. They reason this behavior to the fact that the specimens were not fully cured. In the second study, RIDT performed a second set of test to validate the results of the first study. Although, the final results of the dynamic modulus were above the stated minimum values (60% of the initial), they were also unusual because of the ups and downs in the values. Furthermore, RIDT reported that the weight gain, in both studies, was higher than anticipated, but it was lower in second study than that of the first one. This suggests that the concrete mix used in the second study has fewer voids.

In the present study, dynamic properties of Very High Strength Concrete (VHSC) have been evaluated through an experimental investigation to study the effect of rapid freeze and thaw cycles on the durability of VHSC. Flexural strength tests were also performed on selected specimens after specified number of cycles. The flexural tests were conducted according to ASTM C78-09 using third point loading conditions. Several studies have been conducted on the flexural strength of deteriorated concrete (Masti *et al*., 2008; Hashemi *et al*., 2007). Marini and Bellopede (2007) investigated the influence of the climatic factors on the decay of marbles. They conducted a laboratory flexural strength test to evaluate the decay before and after a period of four years cycles of natural exposition.

## MATERIALS AND METHODS

**Materials:** In this research, an experimental investigation was performed to study the effect of rapid freeze and thaw cycles on the properties of Very High Strength Concrete (VHSC). Twenty one specimens with dimensions of 3×4×16 inch were prepared to carry out the overall experimental program. The materials used in VHSC mix include sand, cement, silica flour, silica fume, high range water reducing admixture and water. The mix proportions were: 1.00 cement: 0.97 sand: 0.28 silica flour: 0.39 silica fume: 0.0206 High Range Water Reducing Admixture (HRWRA): 0.22 water. The specific gravity was 3.15, 2.65, 2.65, 2.22, 1.3 and 1.0 respectively.

**Specimen preparation:** The components of the mix were dry-mixed at a low rate for ten minutes and then the water / HRWRA were slowly added to the mix and mixed for about twenty two minutes (homogeneous mix). During casting, the specimens were vibrated for several minutes until the frequency of surfacing air bubbles significantly diminished. After casting and adequately vibrating the specimens, they were placed in plastic bags with wet burlap for 36 hours. Then, the specimens were removed from their molds and placed

Fig. 1: Freeze/thaw specimens

Fig. 2: Freeze/thaw machine

in a lime saturated water curing tank for 7 days at room temperature (23 ± 2°C). After the 7 days curing, the specimens were placed in a water filled tank which was placed in an oven set at 90°C for four days. After four days in the container, they were removed from t he water filled tank and returned to the oven at 90°C for an additional two days. It should be noted that twenty one specimens (Fig. 1) were prepared, although, ASTM 666 requires only eighteen specimens to run the freeze and thaw test.

**Test setup and testing procedures:** The freeze and thaw cycles were performed using the freeze/thaw testing machine shown in Fig. 2. The tests were performed according to ASTM C-666 procedure-A, “resistance of concrete to rapid freezing and thawing in water”. The dynamic modulus of elasticity, dynamic modulus of rigidity, poisson’s ratio, flexural strength and durability factors were determined after each number of cycles. The dynamic moduli for the concrete specimens were determined according to ASTM C215-02 (2002) procedures, while flexural strength tests were performed according to ASTM C78 -09 using third point loading conditions. A 400,000 pound capacity universal testing machine was used to carry out the flexural test. The calculations in these tests require very accurate measurements. The average dimensions of seven cross sections and three longitudinal sections as well as the weight of each specimen were measured before the freeze/thaw cycles (designated as 0 cycle) and recorded in Table 1. Similar average measurements

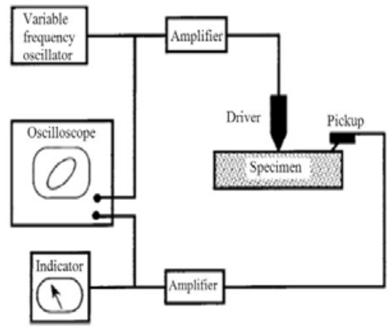



Fig. 3: Forced resonance method (ASTM C215-02)

(a)

(b)

(c)

Fig. 4: Transverse, Longitudinal and Torsional resonant frequencies (a) Transverse mode setup (b) Longitudinal mode setup (c) Torsional mode setup

were made at 40, 70 and 100 cycles. It should be noted that, there are two different methods of determining the fundamental resonant frequencies; the forced resonance method (Fig. 3) and the impact resonance method. The first method was adopted in this study, using C-2010 Geotest Sonometer with Oscilloscope (Fig. 4). The concept of the forced resonance method is to excite the supported specimen to vibrate by an electro-mechanical driving unit and record the response by a lightweight pickup unit. The driving frequency is varied until the response reaches the maximum amplitude. The value of frequency at this maximum amplitude was recorded as the resonant frequency of the specimen.

Table 1: Average dimensions and weights at 0 cycle

| SPECIMEN | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
|---|---|---|---|---|---|---|---|
| Thickness, t (inch) | 2.980 | 2.970 | 3.020 | 2.950 | 3.010 | 3.010 | 2.980 |
| Width, b (inch) | 4.000 | 4.010 | 4.010 | 4.010 | 4.010 | 4.010 | 4.010 |
| Length, L (inch) | 15.983 | 16.007 | 15.989 | 15.996 | 15.999 | 15.987 | 16.021 |
| Weight (lb) | 16.200 | 16.300 | 16.300 | 16.500 | 16.300 | 16.200 | 16.300 |
| SPECIMEN | 8.000 | 9.000 | 10.000 | 11.000 | 12.000 | 13.000 | 14.000 |
| Thickness, t (inch) | 3.050 | 3.040 | 2.990 | 2.990 | 2.980 | 2.980 | 2.990 |
| Width, b (inch) | 4.010 | 4.010 | 4.000 | 4.000 | 4.010 | 4.010 | 4.010 |
| Length, L (inch) | 16.023 | 16.008 | 15.998 | 16.018 | 16.015 | 16.001 | 16.008 |
| Weight (lb) | 16.600 | 16.700 | 16.300 | 16.300 | 16.200 | 16.200 | 16.400 |
| SPECIMEN | 15.000 | 16.000 | 17.000 | 18.000 | 19.000 | 20.000 | 21.000 |
| Thickness, t (inch) | 3.040 | 2.830 | 3.030 | 3.010 | 3.020 | 2.990 | 2.990 |
| Width, b (inch) | 4.010 | 4.010 | 4.000 | 4.000 | 4.000 | 4.000 | 4.000 |
| Length, L (inch) | 16.008 | 16.008 | 15.995 | 15.997 | 16.006 | 15.998 | 16.018 |
| Weight (lb) | 16.60 | 15.400 | 16.600 | 16.400 | 16.500 | 16.300 | 16.300 |

Determination of the concrete dynamic moduli (ASTM C215-02, 2002) includes three different testing modes: transverse, longitudinal and torsional resonant frequencies. Different modes were achieved by changing the location of the driver, pick up and the supports of the specimens. In case of the transverse mode (Fig. 4a), the specimen's supports were at 0.224 L from the edge of the specimen; the driver at the middle of the width "b" and the pickup at the middle of the thickness "t" at the specimen edge. The vibration was gradually increased until the maximum value was reached, which is the resonance transverse frequency for the specimen. The resonance occurs when the driving frequency is a fraction of the fundamental frequency. But, the oscilloscope pattern will only have the ellipse shape when the specimen reaches its fundamental resonant frequency. For the longitudinal mode (Fig. 4b), the supports were at the middle of the specimen; driver at the center of the end cross section and the pickup at the specimen's top sensing in the direction of vibrations. Again, the vibration was gradually increased until the maximum value was reached. The value of this vibration is recorded as the resonance longitudinal frequency for this specimen. The torsional mode (Fig. 4c) was achieved by placing the supports in the middle; the driver at 0.13 of the specimen's length and at height of t/6 and the pickup at 0.224 L from the edge of the specimen

## RESULTS

**Dynamic moduli:** Twenty-one specimens of Very High Strength Concrete (VHSC) were evaluated for dynamic moduli before freeze/thaw cycles (0 cycles). Results of the dynamic modulus of elasticity (Ed) for both transverse mode and longitudinal mode and modulus of rigidity (Gd) are tabulated in Table 2 and shown in Fig. 5. Table 2 also shows the Poisson's ratio (μ) of the material. Three specimens were tested for flexural strength (presented at the end of this section).

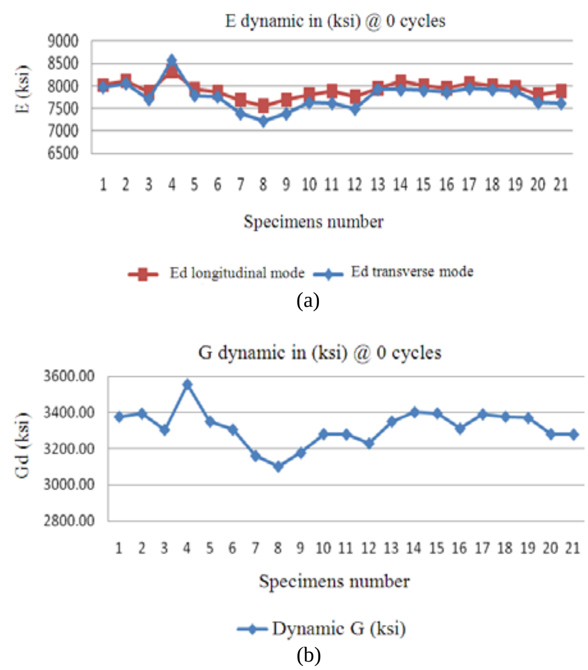



Fig. 5: Dynamic Moduli at 0 cycles (ksi) (a Dynamic Modulus of Elasticity (Ed) (b) Dynamic Modulus of Rigidity (Gd)

The remaining Eighteen specimens were subjected to rapid freeze/thaw cycles for 40 cycles following ASTM C-666 procedure-A. After 40 cycles of rapid freeze/thaw, the dynamic moduli were evaluated using ASTM C215-02 method. Results of the dynamic modulus of elasticity (transverse and longitudinal); dynamic modulus of rigidity and poisson's ratio are tabulated in Table 3 and shown in Fig. 6. Random specimens were then selected for the flexural test to evaluate the effect of 40 rapid freeze/thaw cycles on the flexural strength of VHSC material. The remaining specimens were returned to the freeze/thaw machine for an additional 30 cycles.

Table 2: Dynamic Modulus of Elasticity (Ed), Dynamic Modulus of rigidity (Gd) and Poisson's Ratio (μ) at 0 cycles

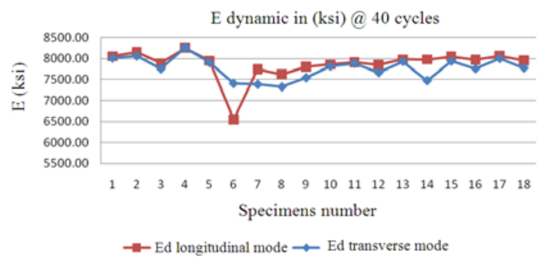
| | Ed/Transverse | | Ed/Longitudinal | | Gd/Torsional | | |
|---|---|---|---|---|---|---|---|
| Specimen | ksi | Mpa | ksi | Mpa | ksi | Mpa | (μ) |
| 1 | 7975 | 55003 | 8021 | 55316 | 3377 | 23288 | 0.1877 |
| 2 | 8059 | 55578 | 8107 | 55912 | 3394 | 23408 | 0.1943 |
| 3 | 7703 | 53123 | 7870 | 54273 | 3305 | 22790 | 0.1907 |
| 4 | 8578 | 59157 | 8340 | 57518 | 3555 | 24518 | 0.1730 |
| 5 | 7791 | 53734 | 7921 | 54627 | 3350 | 23106 | 0.1821 |
| 6 | 7762 | 53528 | 7859 | 54199 | 3305 | 22796 | 0.1888 |
| 7 | 7391 | 50970 | 7685 | 53003 | 3161 | 21800 | 0.2156 |
| 8 | 7224 | 49822 | 7551 | 52079 | 3103 | 21399 | 0.2169 |
| 9 | 7387 | 50942 | 7692 | 53046 | 3178 | 21916 | 0.2102 |
| 10 | 7630 | 52621 | 7798 | 53782 | 3282 | 22632 | 0.1882 |
| 11 | 7619 | 52546 | 7888 | 54403 | 3279 | 22617 | 0.2027 |
| 12 | 7491 | 51663 | 7767 | 53566 | 3230 | 22275 | 0.2024 |
| 13 | 7929 | 54681 | 7948 | 54812 | 3350 | 23106 | 0.1861 |
| 14 | 7917 | 54600 | 8103 | 55880 | 3402 | 23460 | 0.1910 |
| 15 | 7900 | 54482 | 8016 | 55284 | 3395 | 23416 | 0.1805 |
| 16 | 7856 | 54180 | 7944 | 54785 | 3311 | 22833 | 0.1997 |
| 17 | 7948 | 54815 | 8060 | 55583 | 3390 | 23382 | 0.1886 |
| 18 | 7918 | 54605 | 8018 | 55295 | 3370 | 23241 | 0.1871 |
| 19 | 7879 | 54335 | 7980 | 55033 | 3370 | 23241 | 0.1840 |
| 20 | 7630 | 52621 | 7798 | 53782 | 3282 | 22632 | 0.1882 |
| 21 | 7619 | 52546 | 7888 | 54403 | 3279 | 22617 | 0.2027 |

Table 3: Dynamic Modulus of Elasticity (Ed), Dynamic Modulus of rigidity (Gd) and Poisson's Ratio (μ) at 40 cycles

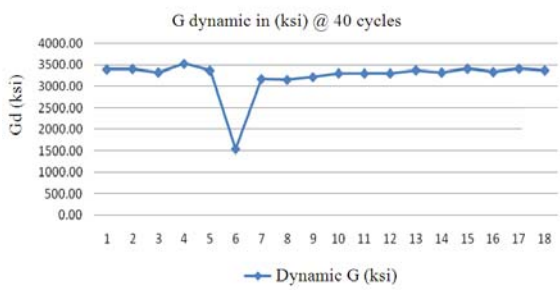
| | Ed/Transverse | | Ed/Longitudinal | | Gd/Torsional | | |
|---|---|---|---|---|---|---|---|
| Specimen | ksi | Mpa | ksi | Mpa | ksi | Mpa | (μ) |
| 1 | 8015 | 55275 | 8060 | 55589 | 3399 | 23447 | 0.1854 |
| 2 | 8063 | 55605 | 8153 | 56226 | 3413 | 23536 | 0.1945 |
| 3 | 7752 | 53464 | 7893 | 54435 | 3327 | 22947 | 0.1861 |
| 4 | 8265 | 57000 | 8257 | 56948 | 3529 | 24336 | 0.1700 |
| 5 | 7908 | 54540 | 7955 | 54859 | 3371 | 23247 | 0.1799 |
| 6 | 7408 | 51092 | 6549 | 45169 | 1541 | 10627 | 1.1252 |
| 7 | 7388 | 50949 | 7749 | 53439 | 3177 | 21913 | 0.2193 |
| 8 | 7328 | 50538 | 7627 | 52597 | 3158 | 21777 | 0.2076 |
| 9 | 7544 | 52025 | 7807 | 53843 | 3223 | 22226 | 0.2113 |
| 10 | 7820 | 53929 | 7860 | 54210 | 3308 | 22812 | 0.1882 |
| 11 | 7887 | 54391 | 7910 | 54549 | 3305 | 22796 | 0.1964 |
| 12 | 7665 | 52859 | 7853 | 54160 | 3306 | 22798 | 0.1878 |
| 13 | 7933 | 54713 | 7985 | 55069 | 3379 | 23306 | 0.1814 |
| 14 | 7994 | 55132 | 7974 | 54991 | 3441 | 23729 | 0.1998 |
| 15 | 7943 | 54776 | 8049 | 55509 | 3418 | 23574 | 0.1773 |
| 16 | 7897 | 54463 | 7971 | 54975 | 3336 | 23006 | 0.1948 |
| 17 | 8005 | 55207 | 8074 | 55681 | 3418 | 23574 | 0.1810 |
| 18 | 7943 | 54780 | 7958 | 54882 | 3376 | 23283 | 0.1786 |

Table 4: Dynamic Modulus of Elasticity (Ed), Dynamic Modulus of rigidity (Gd) and Poisson's Ratio (μ) at 70 cycles

| | Ed/Transverse | | Ed/Longitudinal | | Gd/Torsional | | |
|---|---|---|---|---|---|---|---|
| Specimen | ksi | Mpa | ksi | Mpa | ksi | Mpa | (μ) |
| 1 | 7754 | 53476 | 7862 | 54219 | 3308 | 22815 | 0.1882 |
| 3 | 8090 | 55790 | 7912 | 54568 | 3395 | 23411 | 0.1654 |
| 5 | 7690 | 53037 | 7790 | 53726 | 3307 | 22805 | 0.1780 |
| 7 | 7154 | 49340 | 7538 | 51989 | 3085 | 21279 | 0.2216 |
| 9 | 7201 | 49659 | 7540 | 52003 | 3106 | 21423 | 0.2137 |
| 10 | 7439 | 51305 | 7671 | 52905 | 3237 | 22324 | 0.1849 |
| 14 | 7792 | 53739 | 7992 | 55120 | 3389 | 23369 | 0.1793 |
| 15 | 7662 | 52841 | 7871 | 54282 | 3348 | 23088 | 0.1755 |
| 16 | 7585 | 52310 | 7720 | 53242 | 3212 | 22151 | 0.2018 |
| 17 | 7676 | 52937 | 7890 | 54412 | 3323 | 22920 | 0.1870 |
| 18 | 7466 | 51493 | 7771 | 53595 | 3307 | 22810 | 0.1748 |

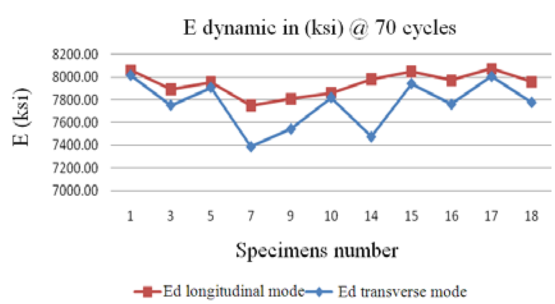



(a)

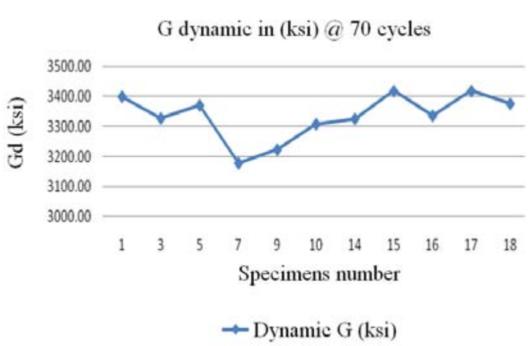



(b)

Fig. 6: Dynamic Moduli after 40 cycles (ksi) (a) Dynamic Modulus of Elasticity (Ed) (b) Dynamic Modulus of Rigidity (Gd)

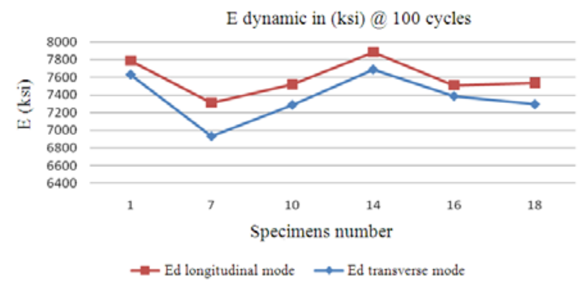



(a)

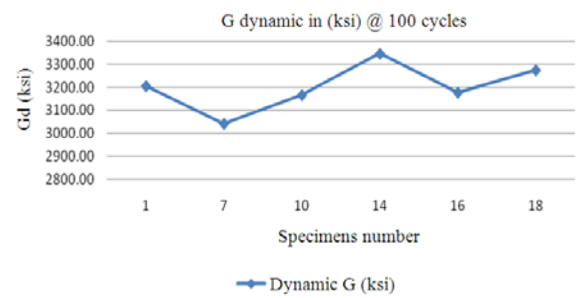



(b)

Fig. 7: Dynamic Moduli after 70 cycles (ksi) (a) Dynamic Modulus of Elasticity (Ed) (b) Dynamic Modulus of Elasticity (Ed)




(a)




(b)

Fig. 8: Dynamic Moduli after 100 cycles (ksi) (Dynamic Modulus of Elasticity (Ed) (b) Dynamic Modulus of Rigidity (Gd)

After a total of 70 rapid freeze/thaw cycles, the dynamic moduli and poisson's ratio were evaluated and recorded in Table 4 and shown in Fig. 7. Again, some of the specimens were tested for flexural, while the remaining was returned to the freeze/thaw machine for an additional 30 cycles. Results after 100 cycles are shown in Table 5 and Fig. 8. Specimens (number 1, 7, 10, 14, 16 and 18) were exposed to the entire hundred freeze and thaw cycles. Thus, results of dynamic moduli of these specimens were compared at different cycles in order to investigate the effect of freeze/thaw cycles on the properties of VHSC. Table 6 shows the percent change in dynamic moduli at different cycles, while Fig. 9 shows the effect of freeze/thaw cycles on these moduli.

**Weight change:** Deterioration of VHSC due to freeze and thaw were investigated at the end of each cycle by averaging the change in weight of specimens after the exposure to the freeze and thaw cycles. Table 7 shows the relative weight (% of the original weight) and the percent change in weight due to rapid freeze/thaw cycles.

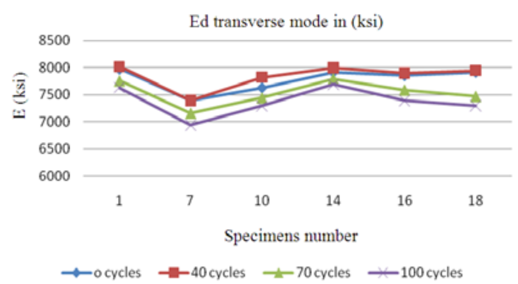
**Durability factor:** Effect of freeze/thaw cycles on the durability of VHSC was measured by the Durability Factor (DF) which is the ratio of the dynamic modulus (Ed) at N of cycles to the dynamic modulus at 0 cycles.

Table 5: Dynamic Modulus of Elasticity (Ed), Dynamic Modulus of Rigidity (Gd) and Poisson's Ratio (μ) at 100 cycles

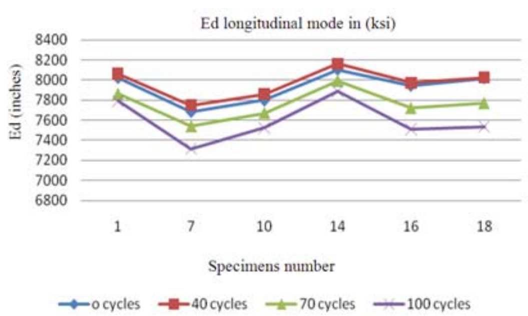
| | Ed/Transverse | | Ed/Longitudinal | | Gd/Torsional | | |
|---|---|---|---|---|---|---|---|
| Specimen | ksi | Mpa | ksi | Mpa | ksi | Mpa | (μ) |
| 1 | 7630 | 52621 | 7790 | 53722 | 3206 | 22108 | 0.2150 |
| 7 | 6936 | 47831 | 7315 | 50451 | 3041 | 20973 | 0.2028 |
| 10 | 7290 | 50274 | 7523 | 51881 | 3166 | 21836 | 0.1880 |
| 14 | 7688 | 53017 | 7887 | 54396 | 3347 | 23080 | 0.1785 |
| 16 | 7388 | 50951 | 7511 | 51797 | 3177 | 21913 | 0.1819 |
| 18 | 7296 | 50320 | 7537 | 51979 | 3274 | 22582 | 0.1509 |

Table 6: Percent change in dynamic moduli due to freeze/thaw cycles

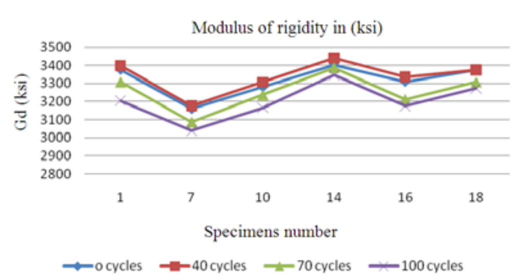
| | 40 cycles | | | 70 cycles | | | 100 cycles | | |
|---|---|---|---|---|---|---|---|---|---|
| Specimen | Ed (Trans.) | Ed (Long.) | Gd | Ed (Trans.) | Ed (Long.) | Gd | Ed (Trans.) | Ed (Long.) | Gd |
| 1 | 0.03 | 0.04 | 1.1 | -3.2 | -2.2 | -2.1 | -4.3 | -3.1 | -5.2 |
| 7 | 0.04 | 1.1 | 1.3 | -3.3 | -2.3 | -2.2 | -6.1 | -5.1 | -4.3 |
| 10 | 2.1 | 1.3 | 1.3 | -3.3 | -2.1 | -1.3 | -4.2 | -4.3 | -4.1 |
| 14 | 1.3 | 1.2 | 1.4 | -2.4 | -1.3 | 0.06 | -3.2 | -3.1 | -2.2 |
| 16 | 0.98 | 0.06 | 1.2 | -3.2 | -3.3 | -3.3 | -6.1 | -5.3 | -4.2 |
| 18 | 0 | 0.04 | 0 | -6.1 | -3.2 | -2.1 | -8.3 | -6.1 | - |




(a)




(b)




(c)

Fig. 9: Effect of freeze/thaw cycles on dynamic moduli of VHSC (a) Dynamic Modulus of Elasticity (Ed-Trasverse) (b) Dynamic Modulus of Elasticity (Ed-Longitudinal) (c) Dynamic Modulus of Rigidity (Gd)

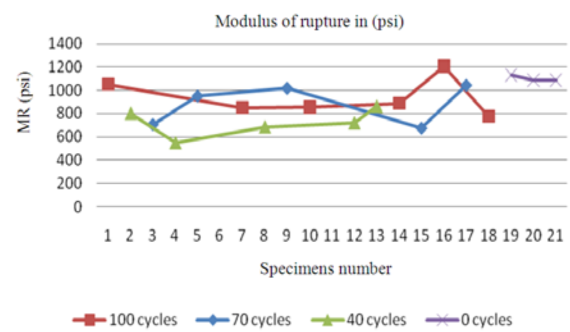



Fig. 10: Effect of freeze/thaw on flexural strength

Table 7: Rapid freeze thaw durability

| No. of Cycles | Relative Weight (% of original weight) | Relative Durability Factor (% of Ed @ 0) |
|---|---|---|
| 40 | 99.61 (-0.39% change) | 101.2 |
| 70 | 99.55 (-0.45% change) | 97.8 |
| 100 | 99.52 (-0.48% change) | 94.7 |

Table 7 shows the relative durability factor as a percentage of the original dynamic modulus.

**Flexural strength:** Pre-test and post-test flexural strength (Modulus of Rupture) were carried out using third point loading method according to ASTM C78-09. Three beams (specimens 19, 20 and 21) were tested at 56 days with no freeze/thaw cycling (referred as pre-test) and set of other beams were tested for flexural after each N of freeze/thaw cycles (post-test). The post-test retained flexural strength ratio is expressed as percent retained flexural strength. The averages (3-5 beams) at each N-cycle are reported in Table 8. Effect of rapid freeze/thaw cycling on the flexural strength of VHSC beams is shown in Fig. 10.

Table 8: Retained Flexural Strength - Modulus of Rupture (MR)

| 0 cycles | | 40 cycles | | | 70 cycles | | | 100 cycles | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Load (P) lb | MR (initial) psi | Load (P) lb | MR psi | Retained flexural strength (%) | Load (P) lb | MR psi | Retained flexural strength (%) | Load (P) lb | MR psi | Retained flexural strength (%) |
| 3547.7 | 1102.7 | 2692.8 | 842.0 | 76.4 | 2491.7 | 777.6 | 70.6 | 2457.5 | 767.3 | 69.6 |

## DISCUSSION

**Dynamic moduli:** The experimental study started with twenty one specimens. Three specimens were destructively tested for flexural strength at the initial state before any freeze/thaw cycles. The remaining specimens were subjected to freeze and thaw test for forty (40) cycles. After forty cycles, five specimens were tested for retained flexural strength. Then, the remaining specimens were returned to the freeze/thaw machine for an additional 30 cycles. Five specimens were tested for flexural and the remaining returned for the final 100 freeze/thaw cycling before final flexural strength test. At the end of each N-cycle, dynamic moduli of VHSC specimens were evaluated and compared as shown in Table 6 and Fig. 9. Two methods were used to evaluate the dynamic modulus of elasticity, namely transverse and longitudinal modes. The observed difference in the results may be related to the fact that the dynamic modulus in transverse mode was calculated based on an estimation of what called a “T” value (according to ASTM C215-02). Any small change in the value of “T” causes a significant change in the value of the dynamic modulus. On the other hand, no estimations were made in the calculation of the dynamic modulus in longitudinal mode. It is believed that the values obtained by the second mode were more accurate, thus the dynamic modulus of elasticity values obtained from the longitudinal mode were used to calculate Poisson’s Ratio ($\mu$). As seen from Tables 2-5, freeze/thaw cycling did not significantly affect the poisson’s ratios. An average value in the range of 0.17-0.21 was obtained which is in agreement of the normal range of poisson’s ratios.

**Dimensional and weight changes:** The experimental test results reveal that there was no significant effect of freeze and thaw cycling on the dimensions of cross section and length. The reason for this finding is that VHSC uses dense particle packing technology which maximizes the solid materials and minimizes the voids. Moreover, the small decrease in weight, of VHSC specimens, suggests that there is little or no deterioration has occur, which leads to the conclusion that Very high strength concrete material is good for freeze-thaw cycling. VHSC minimizes the amount of freezable water, thus less susceptible to Freeze-thaw damage.

**Durability factor:** Table 7 quantifies freeze-thaw durability by the term Durability Factor. The equation used to calculate the durability factor is expressed as: $DF = (E\times N)/M$. Where: DF = Durability factor; E = Relative dynamic modulus of elasticity at N of cycles (by %); N= the number of cycles at which E reaches 60% of $E_0$ or the number of cycles at which the test is to be terminated, whichever is less; $E_0$ = Original dynamic modulus and M = The specified number of cycles at which exposure is terminated. In this study, the test was terminated at 100 cycles before any modulus of elasticity reaches 60% of the original value. Thus, the durability factor was in fact the relative dynamic modulus of elasticity (N = M = 100 cycles). From Table 7, very high strength concrete showed good Freeze-Thaw resistance (durability factor>85%).

**Flexural strength:** The Freeze-Thaw specimens were useful for beam size for flexural strength determination. But, the retained flexural strength was not useful for prediction of Durability Factor (DF). Based on findings from this study, it may be concluded that freeze-thaw cycling of 40-100 cycles caused 24-30% change in the flexural strength (Table 8). It should be noted that all beams’ fractures took place in the middle third of the span length during flexural test.

## CONCLUSION

The main purpose of this investigation is to study the effect of rapid freeze and thaw cycles on VHSC properties and to evaluate the Dynamic Modulus of Elasticity, Dynamic Modulus of Rigidity, Poisson’s Ratio, ductility factor and Modulus of Rupture. The following observations and conclusions can be drawn:

- In cold climates, cyclic freezing and thawing can lead to concrete deterioration. However, Very High Strength Concrete (VHSC) is produced using the particle packing theory which maximizes the solid material and limits the number and size of void spaces. These very fine voids greatly lower the freezing point of any trapped water, thus making VHSC less susceptible to Freeze-Thaw damage
- Freeze and thaw cycles did not significantly affect VHSC specimens’ cross sectional dimensions, length, or Poisson’s Ratio

- There was a decrease in the specimens' weight with the increase in number of freeze/thaw cycles. However, the decrease was very little indicating little or no deterioration has occur due to freeze/thaw damage
- Both the Dynamic Modulus of Elasticity (longitudinal and transverse) and the Dynamic Modulus of Rigidity increase at forty cycles then gradually decrease at seventy and one hundred cycles
- The Modulus of Rupture decreases as freeze/thaw cycles increases. Moreover, flexural fractures occur in the middle third of the all tested specimens
- The test results indicated that VHSC is good freeze-thaw resistance (durability factor>85%) and can avoid freeze/thaw cycling
- The use of silica fume in VHSC reduces pore size and thus makes water unable to freeze at ambient temperatures

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