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Evaluating Freeze-Thaw Deterioration with Tensile Strength

A J K Komar\(^1\) and A J Boyd\(^1\)
\(^1\)Department of Civil Engineering, McGill University, Montreal, QC, H3A 0C3, Canada

Email: andrew.komar@mail.mcgill.ca; andrew.boyd@mcgill.ca;

Abstract. Freeze-thaw damage is one of the leading contributors to infrastructure deterioration in temperate northern climates. Deterioration caused by freeze-thaw cycling is primarily induced by hydraulic pressures within the hydrated cement paste matrix that cause tensile cracking. Such damage should, therefore, be more effectively detected with tensile testing. This work presents the detection and evaluation of ongoing freeze-thaw (F/T) damage in plain concrete cylinders using the pressure tensile strength test, as it compares to compressive strength evaluation. Pressure tension test results exhibited significantly higher levels of deterioration compared to compression testing, with the samples losing up to 90% of their undamaged tensile capacity. Moreover, it was shown that tensile strength testing is far more sensitive to freeze-thaw deterioration, evidenced by a significant drop in the tensile to compressive strength ratio to below 5%.

1. Background
Portland cement concrete is among the most commonly used construction materials in the world, and is incorporated into many different kinds of structures and pavements. It is subject to inclement weather conditions that may adversely affect material strength. In particular, temperate northern climates go through months where the mean temperature hovers around the freezing point of the pore solution, thus resulting in repetitive cycles of freezing and thawing. Movement of water through the concrete microstructure under pressure, due to differential freezing, can induce very large hydrostatic pressures. These stresses can cause internal damage on the microstructural level such as cracking, spalling, delamination, aggregate pop outs and other such flaws that can lead to dramatically increased porosity [1].

By far the most common method for evaluating the strength concrete subject to deterioration is compressive strength testing. Compressive strength typically overestimates the true material resistance to crack propagation since the direction of loading will act to close active cracks. Other destructive test methods are more sensitive to the expansive damage associated with F/T cycles, such as the Pressure Tension (PT) test. This method applies compressed air over the curved surface of a cylinder, while the flat ends are left exposed to regular atmospheric pressure [2]. The pore water contained within the sample comes to a hydrostatic equilibrium with the applied gas pressure [3]. Since the applied gas pressure is a applied only along the curved surface a net tensile stress field develops parallel to the axis of the cylinder [4]. This indirect tensile effect will act to apply tension at every point within the cylinder at a magnitude equal to the applied stress, resulting in a tension failure crack that propagates across the specimen as the specimen is pushed apart from the inside.

The PT method, because its mode of action applies stress from within the sample as opposed to an external application (Fig 1), will be more sensitive to expansive damage such as the kind associated with F/T damage [4-8]. Any microstructural cracks that are present in a test specimen will be ‘pushed apart’ at the stress that is required to propagate them. Thus, this test will indicate deterioration as a loss of tensile strength which would not otherwise be detectable using more common methods [9].
2. Materials and Methods

Two OPC mixtures were prepared with different water to cement ratios (W/C), 0.45 and 0.65, in order to ascertain the effect of different porosities. The purpose of this study was to demonstrate the effectiveness of the pressure tension test method in detecting ongoing F/T damage, so air entrainment was not used in order to ensure adequate damage within a reasonable time frame. Each mix produced one batch of thirty 100 mm diameter x 200 mm cylinders. Each concrete cylinder was placed into an individual container conforming to the dimensional specifications laid out in ASTM C 666, specifically the maximum clearance between the edge of the container and the sample being less than 3 mm. The containers were filled with tap water to a depth of 3 mm above the specimen. The water was replaced during the thawing portion of each cycle. For the freezing phase of the cycle the containers with the samples within were placed in commercially available freezers with a minimum operating temperature of -25 °C ± 3 °C. Thermocouples were embedded in two samples and indicated that a uniform temperature of -25°C was reached at the centre of the specimens after approximately 18 hours of exposure in the freezer. For the thawing portion of the cycle, the samples were transferred from the freezers into a large water bath equipped with a heating element and a circulating pump, ensuring that no thermal gradient could develop within the heat transfer medium of the water bath. From their frozen condition, it took on average four hours for the temperature of the water bath and the samples to reach a minimum temperature of 15 °C. An entire freeze-thaw cycle with this large temperature range could thus be performed in 24 hours. The extremes of the temperature range were beyond the standards as prescribed in ASTM C 666 but this was selected as a more severe environment to be more representative of extreme conditions which may occur in the field.

A baseline for strength comparison was established by testing samples at the conclusion of the curing period, prior to the initiation of freeze-thaw cycling. Subsequent testing intervals were established in order to track ongoing changes to the material strength as detected by the destructive testing methods. Destructive tests were performed after 1, 5, 10, 20 and 30 F/T cycles. Standard compressive strength tests as prescribed in ASTM C 39 were performed on all specimens selected for compressive strength testing. At every testing interval, two samples were tested in this manner. Pressure tension tests were also conducted at every testing interval on two samples, with the pressurizing rate set at 2.00 MPa/min.

3. Results and Discussion

At the conclusion of the testing, visual physical damage was observed on both the 0.45 and 0.65 samples. The extent of the deterioration was much more severe for the samples that had undergone more F/T cycles. As expected, the extent of surface scaling and deterioration was much more severe on the higher w/c specimens. The paste was particularly weakened, with some mass loss being observed through simple handling of the specimens, especially around the aggregates. In the case of the 0.65 w/c mixture, the extent of the surface deterioration led to some difficulties producing a solid seal during pressure tension testing, since 100% of the specimen exhibited surface scaling.

![Pressure tension mechanism](image)

**Figure 1.** Pressure tension mechanism.
Compression tests failed in the usual manner (i.e. conical failure planes with paste crumbling). Pressure tension failure specimens showed a more disparate pattern across the levels of deterioration. Samples tested few cycles showed a break perpendicular to the tensile stress, with the fracture surface passing through the aggregates (Fig 2a). As damage levels increased, a greater area of the fracture surface was found to have passed around the surface of the aggregates (Fig 2b). This apparent failure through the interfacial transition zone (ITZ) was found to be more prominent in the higher porosity w/c mix, as well as specimens exposed to more F/T cycles.

**Figure 2a** (left) and **2b** (right): Failure planes from pressure tension testing.

The results of the compression testing can be found in Figure 3. The compressive strength decreased as a function of cyclic deterioration for both of the mixtures, with the 0.45 w/c dropping from 48 MPa to 35 MPa over 30 cycles, and the 0.65 w/c dropping from 25 MPa down to 15 MPa over the same period. This represents a compressive strength loss of 27% and 40%, respectively. Statistically, the decrease in compressive strength results reached significance after the 20th cycle for the 0.45 w/c, and the 10th cycle for the 0.65 w/c.

**Figure 3.** Compressive strength deterioration.

The results of the pressure tension testing can be found in Figure 4. For both mixes, deterioration in the tensile capacity was observed, with the 0.45 w/c dropping from 6.4 MPa to 1.4 MPa, and the 0.65 w/c dropping from 4.2 MPa to 0.4 MPa. This represents a tensile strength loss of 78% and 90%.

**Figure 4.** Pressure tensile strength deterioration.
respectively. Of particular note was the dramatic reduction in tensile capacity for both mixes. After a single F/T cycle, the 0.65 w/c concrete lost 49% of its original strength. This falloff was statistically significant. The decrease reached significance for the 0.45 w/c by the 10th cycle, by which it had lost 42% of its original tensile capacity.

In both cases, the resulting tensile capacity resembled a negative exponential curve, with the damage converging on some minimal number for both mixtures (Fig. 5). It is important to note that the assumption of tensile capacity of concrete being roughly 10-15% of the compressive strength does not hold true for this study. As Figure 5 shows, the undamaged concrete at cycle zero reflected this assumption, though if the assumption remained valid then the figure would be a constant value for both mixes. However, by Cycle 20 for both mixes the ratio had dropped below 5%, where it bottomed out at 4% for the 0.45 w/c and 3% for the 0.65 w/c mix.

![Figure 5. Tensile to compressive strength ratio.](image)

This data demonstrates that the tensile capacity of concrete is more severely affected by F/T deterioration than the compressive strength, which is understandable given that the mode of damage tends to be cracks in the concrete paste. Only a tensile mode of loading will open these existing cracks, thus resulting in failure at a lower applied stress when compared to compression. A further observation was that the PT test detected a significant deterioration signal much earlier (i.e. at much fewer F/T cycles) than the compressive strength test.

4. Conclusions

It is clear that pressure tension testing detected F/T damage much earlier than compression testing. This result was particularly true for the higher porosity mix, where a significant loss in material strength was detected after a single F/T cycle. Considering that cracking has such a strong effect on tensile capacity, more research into this significant drop-off in tensile strength as a function of deterioration is clearly in order. The basic engineering assumption of a constant ratio between tension and compression was shown to be invalid in this case due to the greater effect of cracking on tensile capacity, which could lead to an overestimation in the residual material capacity with other modes of loading such as compression.

In addition, the fracture surfaces associated with the pressure tension failure specimens showed a systematic change in the material behavior due to the ongoing F/T cycles. The fracture surfaces first showed a cohesive bond between the aggregates and the surrounding paste in the undamaged state resulting in aggregate failure. Samples from increased F/T cycles, however, exhibited more intact aggregate particles while the paste appeared to fail around them within the ITZ. Since the ITZ is a zone of higher porosity, it follows that more severe damage from expansive processes would occur there, yet ‘aggregate pullout’ phenomenon was not observed on the compressive strength failure
specimens which also displayed a less significant deterioration trend. This aggregate pullout was only detected using the pressure tension method. This is expected, since that is the only method that will act to open existing cracks as opposed to compressing the existing fracture surfaces together. Considering that many structural loading modalities such as flexure incorporate tension, it is of integral importance to understand the true material behavior.

5. References


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