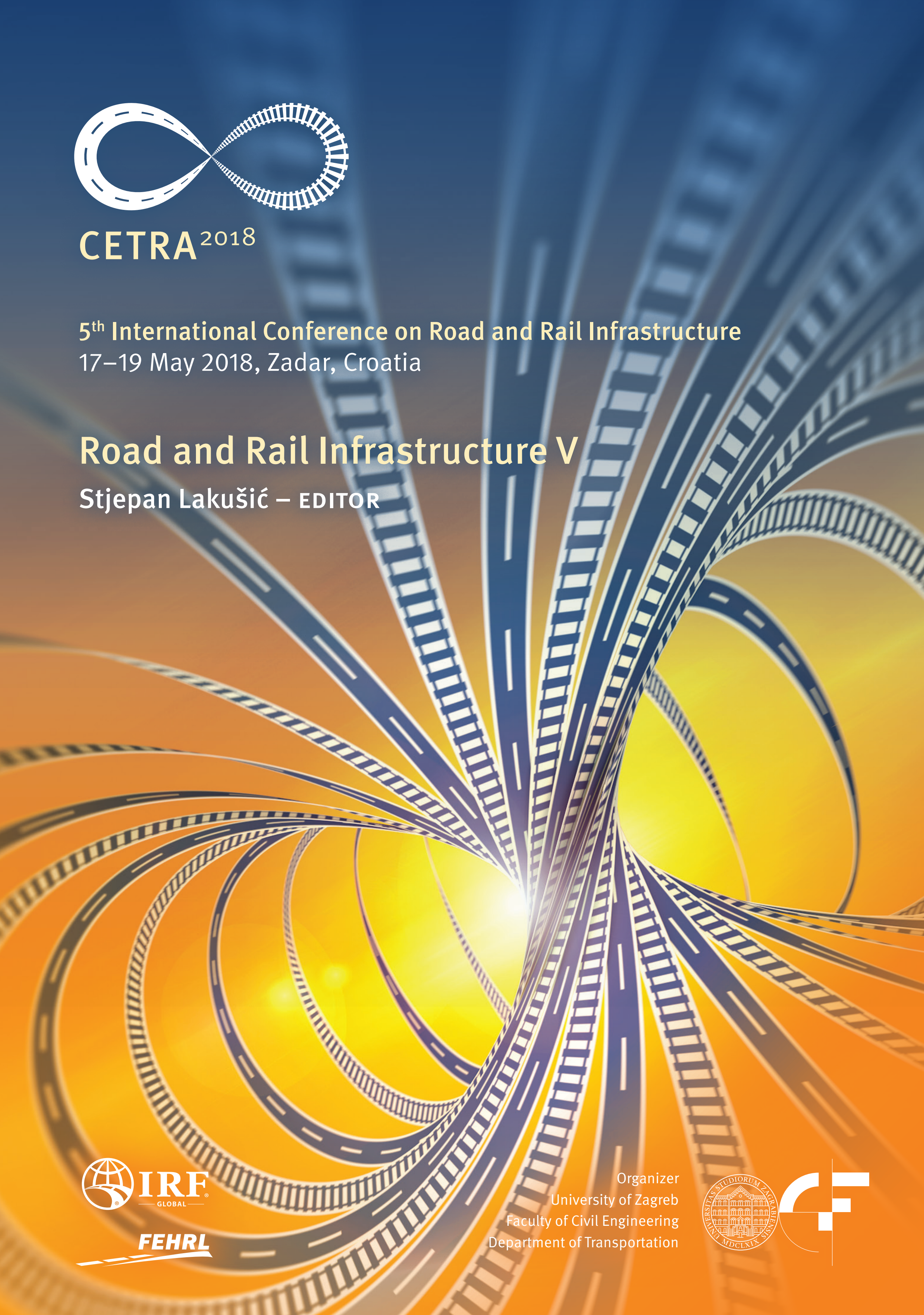

CETRA 2018

5th International Conference on Road and Rail Infrastructure
17–19 May 2018, Zadar, Croatia

Road and Rail Infrastructure V

Stjepan Lakušić – EDITOR

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TENSILE STRENGTH FOR EVALUATING DETERIORATION IN CONCRETE

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Abstract

The vast majority of deterioration mechanisms in concrete revolve around the development of some form of internal expansive stress that causes cracking within the hydrated cement paste. Whether this expansive stress is due to the expansion of water during freezing, the expansion of alkali-silicate gel during an alkali silica reaction, or the formation of ettringite during sulfate attack, the mechanical effect is the same. Even the corrosion of reinforcing steel results in a volume increase of the steel that induces tensile stress in the surrounding concrete. Cracking in a brittle material like concrete is a tensile phenomenon, and thus the evaluation of mechanical properties induced by such deterioration should intuitively rely on tensile strength evaluation. However, measuring the tensile strength of a brittle material, particularly concrete, is not easy. Gripping specimens without inducing additional stresses and localized failure at the contact points is difficult. This paper describes the development of an alternative technique that induces an internal pore pressure using a non-contact gas pressure loading approach. This test is capable of generating a true tensile failure from the inside, using the diphase concept of load application. Though the fundamental form of this method for static tensile strength determination has been used for quite some time, recent developments to the apparatus have now expanded its capabilities to include long-term sustained loading (creep), cyclic loading, or any combination of loading/unloading the researcher requires. Results from testing various forms of deterioration have shown that the pressure tension test is capable of detecting damage at much lower levels, or at significantly earlier stages, than other destructive testing techniques currently in use.

Keywords: concrete, tensile strength, durability, deterioration, cracking

1 Introduction

When investigating the deterioration of concrete under adverse exposure conditions, it is vital to properly characterize the impairment in mechanical properties of the concrete. The most commonly employed test method for evaluating mechanical performance of such concrete is compressive strength testing of drilled cores (ASTM C39). Occasionally, the splitting tensile strength test (ASTM C496) is also used. Both of these procedures apply a compressive load to the concrete that induces tensile failure in an indirect manner [1].

Unfortunately, these loading mechanisms lack sensitivity to the type of damage induced by most concrete deterioration mechanisms – tensile cracking of the hydrated cement paste. Application of a compressive stress to such a material will act to close those cracks not closely aligned with the direction of loading, and thus resist or arrest crack propagation. Alternatively, a tensile stress would induce crack propagation [2]. Thus, a concrete strength would be obta-

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ined that is more representative to the amount of internal damage. This concept is depicted schematically in Figure 1. This phenomenon is exacerbated in the case of chemical deterioration (e.g. sulfate attack) by the fact that in situ deterioration first requires an external source of sulfate to penetrate into the concrete, which creates a sulfate concentration gradient along the path of ingress. The damage due to the subsequent expansive stresses results in cracking that tends to be parallel to the surface of ingress. Thus, a core taken inward from the exposure surface will be prone to a cracking configuration as depicted in Figure 1.

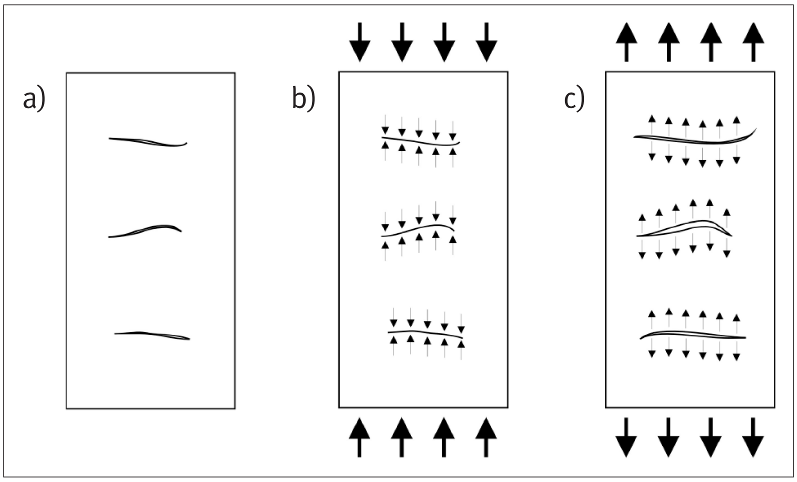

Figure 1 Schematic representation of cracked concrete under a) no stress, b) compressive stress, and c) tensile stress [2]

Tensile testing of concrete can be an arduous task due to the difficulties inherent in gripping a brittle material without inducing stress concentrations and failure at the gripping locations. This paper describes the development of an alternative technique that induces an internal pore pressure using a non-contact gas pressure loading approach. Called the pressure tension test (PT), it is both more sensitive to internal microcracking and immune to the gripping problems associated with more traditional methods of determining tensile strength of concrete.

2 Pressure tension test apparatus

In essence, the pressure tension test applies the 'load' to a cylindrical specimen (cast cylinder or core) by means of a gas pressure applied to the curved surface of the specimen, but not the ends. This configuration is achieved by placing the cylinder within a pressure sleeve with the ends projecting outside the pressurized area, as shown in Figure 2.

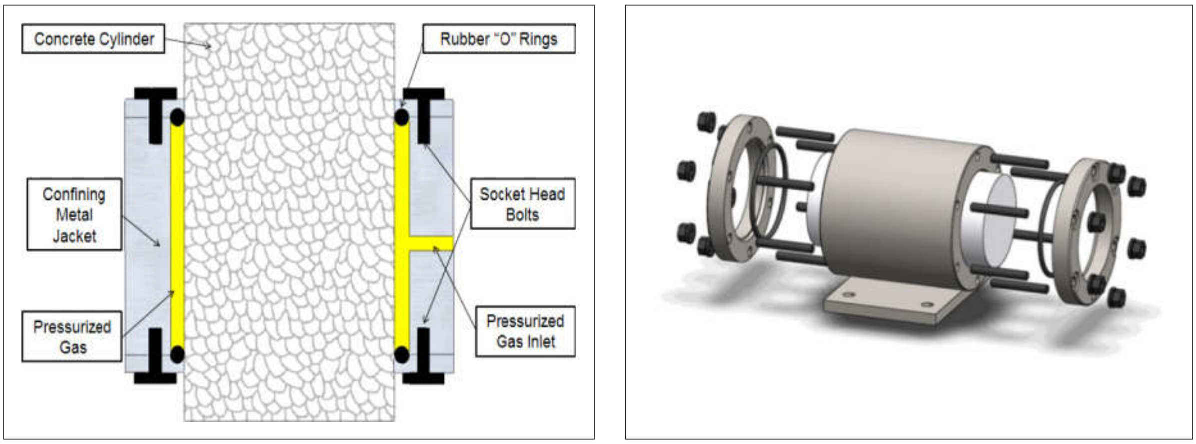

Figure 2 Pressure tension apparatus: (left) schematic representation and (right) exploded view [3]

O-ring seals near the ends of the specimen prevent leakage of the applied gas and allow the applied pressure to be increased at will. The pore water contained within the sample comes to a hydrostatic equilibrium with the applied gas pressure [4]. However, since pore pressure acts in all directions and the applied pressure acts only on the curved surface, a net tensile stress field (equal to the applied stress) develops parallel to the axis of the cylinder [5]. This phenomenon is depicted schematically in Figure 3. Once the applied pressure reaches the tensile strength of the material, a tensile failure crack propagates across the specimen and pushes the specimen apart from the inside.

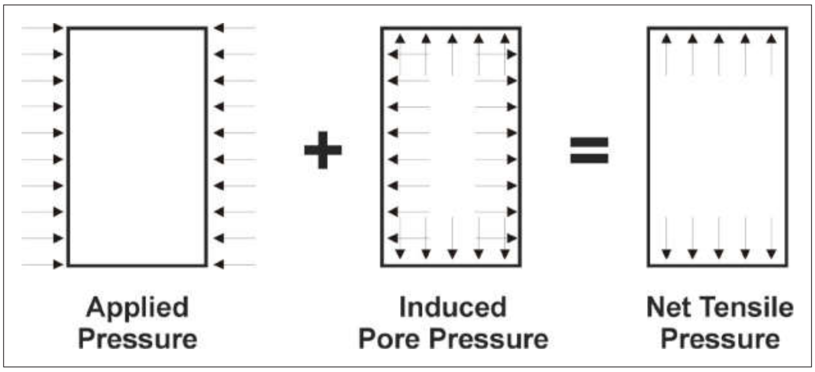

Figure 3 Schematic depiction of the diphase concept [6]

Early versions of the apparatus used bottled nitrogen as the applied gas source, but newer modifications have switched to air. By incorporating an air compressor into the system that is capable of recharging the air reservoir during testing, much longer term tests are now feasible. A pressure transducer is used to monitor the applied pressure at all times and to record the peak pressure reached at failure, taken as the tensile strength of the specimen. Pressurizing of the chamber is controlled through a servo-valve, which allows very fine adjustments to the applied pressure. A second servo-valve attached to the gas outlet allows a controlled reduction in pressure as well. Combined, the two servo-valves permit the user to implement any loading or unloading rate desired, or any combination of the two. This means that long-term stable pressures can be maintained (e.g. creep loading) and even complete pressure rate reversal is possible (e.g. cyclic loading).

3 Applications to concrete deterioration

Since the pore pressure induced by the pressure tension test is uniform throughout the cylinder, the specimen is essentially allowed to fail at its weakest point, unlike the splitting tension test that forces a failure plain down the center of the cylinder. In the case of concrete subject to deterioration, this should represent the region of greatest damage, making the test very sensitive to even low levels of deterioration, which means that durability related degradation can be detected at much earlier ages than with conventional testing methods.

3.1 Alkali-silica reaction

Alkali-silica reaction is a severe deterioration mechanism in which alkalis from the cement react with specific forms of silica found in some aggregates to form an alkali-silicate gel that then expands as it imbibes water. This expansion, of course, is highly detrimental to the concrete as it produces internal tensile stresses that induce severe cracking. During a study to examine the effect of alkali silica reaction on mechanical properties, it was found that the development in mechanical strength under an accelerated exposure regime exhibited some telling trends (Figure 4).

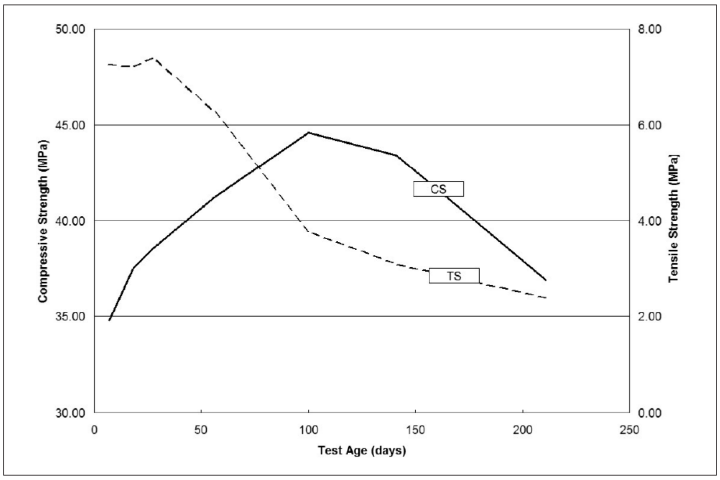

Figure 4 Strength development in ASR specimens [7]

In this study [7], concrete cylinders with a W/C of 0.44 containing highly reactive course aggregates were exposed to a high temperature (38°C) moist curing regime designed to accelerate ASR. The compressive strength continued to increase for the first 100 days before finally showing effects of the ASR damage. On the other hand, the tensile strength began to drop much earlier, at the 28 day mark, clearly illustrating its higher sensitivity to early age damage.

3.2 Sulfate attack

a similar study involving sulphate attack on concrete produced comparable results [8]. Sulphate attack is another deterioration mechanism involving expansive reaction products. In this case, external sulfates into the concrete and react with the hydrated cement paste to produce gypsum, which further reacts to produce at her night. Both reaction stages are expansive, but they also induce a paste softening mechanism that degrades mechanical properties, which may not be captured through the standard expansion measurements used in current standards.

In this case, a high W/C concrete (0.65) containing a sulphate resistant cement was used in order to evaluate very early age deterioration. The high W/C was intentionally chosen to represent field concrete used in some residential concrete that had been investigated in the field. The results, shown in Figure 5, illustrate that once again the pressure tension test was able to detect the deterioration much earlier than the compressive strength test or the splitting tension test.

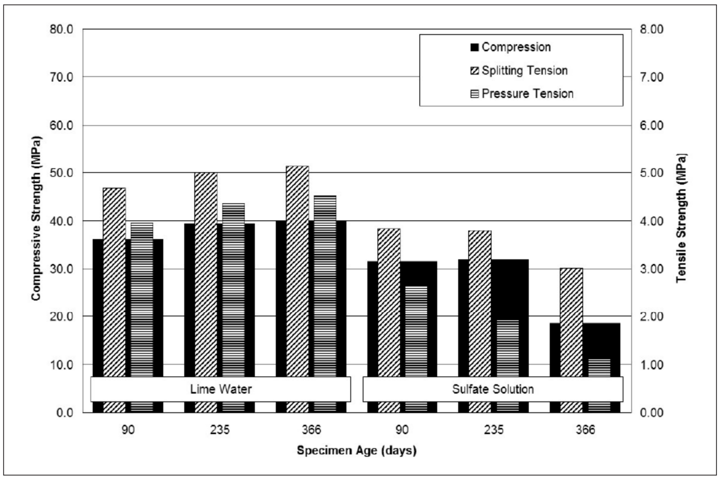

Figure 5 Strength development in sulfate exposed specimens [7]

For the specimens exposed to a 5 % sodium sulphate solution, the compressive strength and splitting tensile strength remained unaffected for 8 months, while the pressure tension results were exhibiting deterioration by 90 days. This again illustrated the capabilities of the pressure tension test with respect to early age damage detection in deteriorating concrete.

3.3 Freeze-thaw cycling

more recently, the pressure tension test was implemented in the evaluation of deterioration induced by freeze-thaw cycling. Since this was part of a feasibility study to determine whether or not the test method would be capable of picking up freeze-thaw deterioration, only non-air entrained concretes were implemented at this stage so that significant damage could be achieved at very early ages, thus shortening the time required to produce results [9,10]. Two different W/C were used, 0.45 and 0.65, and the results produced very similar trends. The best way to illustrate the superior ability of the pressure tension test to detect damage, when compared to compressive strength testing, is the plot the ratio of the two properties (as shown in Figure 6).

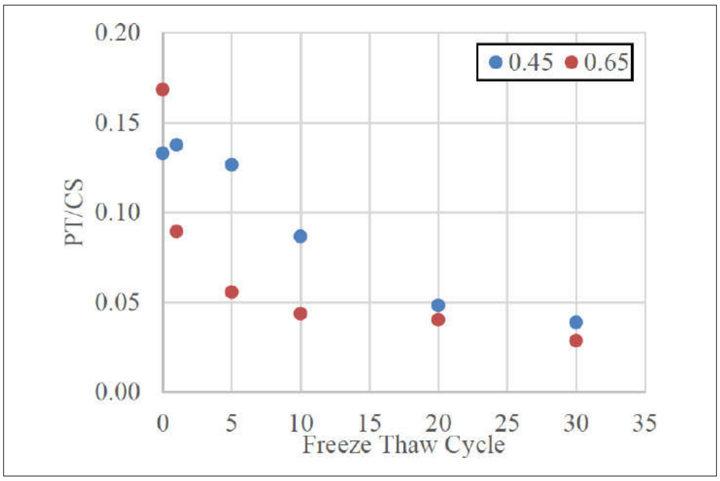

Figure 6 Ratio of tensile to compressive strength in freeze-thaw cycling [9]

Since the tensile strength is more severely affected by the freeze thaw cycling, it drops off much quicker than the compressive strength, thus resulting in a decreasing ratio at early stages. Not only does this illustrate the higher effectiveness of the tensile testing, it also indicates that the traditional method of assuming tensile strength to be a set proportion of compressive strength is highly erroneous once any form of deterioration initiates.

After first demonstrating that the pressure tension test could be used to induce cyclic loading in concrete [11], a further study was designed to take advantage of the newly introduced cyclic loading capabilities, which will be called fatigue loading in order to differentiate the loading cycling from the freeze-thaw cycling. In this study, specimens from a 0.45 W/C air entrained mixture were subjected to freeze-thaw cycling for up to 50 cycles, with three sample sets removed after 0, 25, and 50 cycles. One set was used to determine the tensile strength at that point while the other two were subjected to fatigue loading. Fatigue loading was carried out at two different stress levels, one corresponding to 60 % of the ultimate tensile strength and the second corresponding to 80 %. Fatigue performance was measured by the number of cycles to failure at the given stress level.

Though the tensile strength, in this case, was unaffected by the freeze-thaw cycling due to the entrained air, the fatigue performance exhibited a very different trend, as shown in Figure 7. Even though no measurable reduction in tensile strength could be detected even after 50 freeze-thaw cycles, the subsequent resistance of the concrete to repeated loading cycles degraded dramatically. This effect was, of course, amplified at the higher stress level (80 %), where a reduction in performance of nearly 90 % was recorded after only 50 cycles of freeze-thaw. This was an unexpected result, especially at such a low number of freezing cycles and further studies are now underway in order to develop a better understanding of this phenomenon.

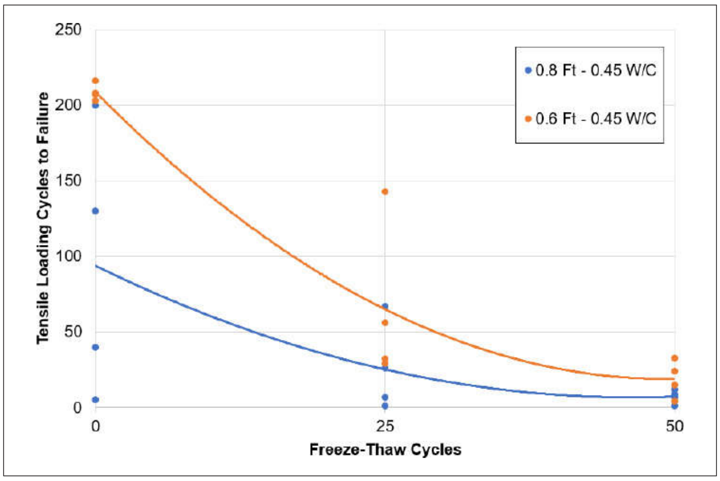

Figure 7 Fatigue behaviour of concrete after exposure to freeze-thaw cycling

3.4 Creep loading

With the ability to adjust the applied pressure in either direction, the pressure tension test can now be used to maintain a specified pressure for an indefinite period. Though not traditionally considered to be a true durability mechanism, long term sustained loading can indeed cause damage in concrete at a high enough level of stress. An initial study designed to evaluate the effects of creep loading on residual strength using 0.45 W/C specimens loaded to 70 % of their ultimate tensile strength for extended periods clearly illustrated this effect, as shown in Figure 8.

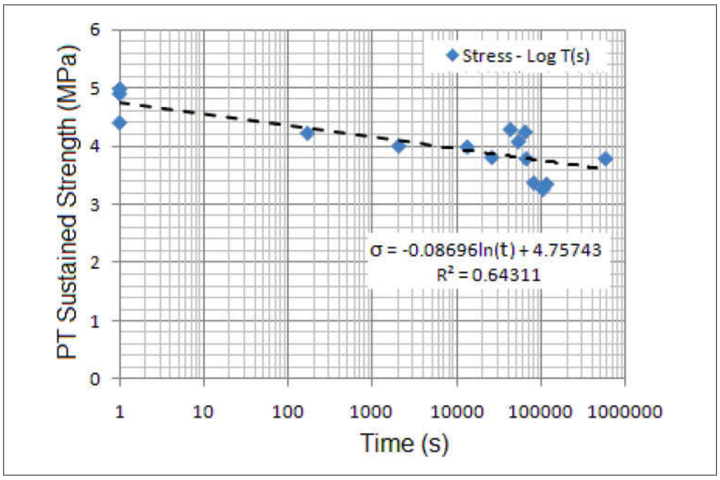

Figure 8 Residual strength of concrete exposed to sustained (creep) loading

This phenomenon is exacerbated Even exposes a short as 12 days resulting in a reduction in tensile strength of 20 %. The results for a 0.65 W/C mixture were even more severe, with a strength reduction of well over 50 %. As with the fatigue testing, this phenomenon is currently being investigated in more detail but clearly indicates some of the important capabilities and contributions that the pressure tension test can provide.

4 Conclusions

The pressure tension test has been shown to be an applicable and effective method for evaluating durability related deterioration in concrete. Its high sensitivity to microcracking permits the detection of concrete damage at much lower levels than conventional techniques such as compressive strength or splitting tension. When the microcracking is a result of an ongoing deterioration mechanism, such as alkali silica reaction, sulphate attack, or freeze-thaw cycling, this translates into the ability to detect damage at much earlier ages, which has significant implications toward preventive maintenance strategies.

Additionally, the ability to quantify the effect of such deterioration on mechanical properties has the potential to contribute toward more effective design of concretes for deleterious exposure conditions, something not possible with indirect measures of deterioration such as volumetric expansion. The simplicity of the pressure tension test apparatus, operation and data accumulation makes this test attractive as a forensic tool in the evaluation of damaged or deteriorating concrete.

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