# Evaluating the effects of combined freezing and thawing and flexural fatigue loading cycles on the fracture properties of FRC

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## Abstract

In cold climate regions, the life span of concrete structures can be significantly reduced if the mechanical properties of critical components of a structure are affected by the deterioration caused by simultaneous fatigue loading and freezing and thawing cycles. This makes the residual mechanical properties of the constitutive concrete material an important design consideration, after years of exposure in such a climate.

The objective of the research program was to evaluate the residual mechanical properties of plain and Fiber Reinforced Concrete (FRC) (hooked-end steel, corrugated steel, and polyolefin fibers) exposed to several combinations of freezing and thawing cycles and flexural fatigue loading cycles. The residual mechanical properties (flexural strength, flexural stiffness, and flexural toughness) and the flexural fatigue resistance of the conditioned plain and FRC specimens were compared to the properties of unconditioned companion specimens to quantify the level of damage caused by each conditioning combination and to determine whether the addition of fibers could reduce the level of damage caused by conditioning.

In general, the results indicated that the flexural strength, stiffness, and toughness of plain concrete and both steel and polyolefin fiber reinforced concrete, after exposure to a combination of 300 freezing and thawing cycles followed by 2 million cycles of flexural fatigue loading, 10-40% or 10-45% of the 90-day flexural strength, is greater than or approximately equal to the lowest residual flexural strength, stiffness, and toughness of specimens exposed to 300 freezing and thawing cycles or 2 million flexural fatigue loading cycles (between the same stress range).

Interestingly, for all specimens, the residual flexural strength, after flexural fatigue loading at a stress range between 10-45% of the 90-day flexural strength value, was higher than specimens exposed to a stress range between 10-40% of the 90-day flexural strength. The applications of freezing and thawing cycles on all specimens (plain concrete and FRC) prior to flexural fatigue loading cycles resulted in higher flexural fatigue endurance limit than unconditioned specimens.

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# 1 Introduction

In cold climate regions, many concrete structures are subjected simultaneously to freezing and thawing cycles and flexural fatigue loading cycles.

The premature deterioration of many structures before the end of their design service life and the lack of knowledge on the expected reduction in performance of concrete exposed to simultaneous environmental and physical loading has motivated this investigation into the interaction of freezing and thawing cycles and flexural fatigue loading cycles and their effect on the performance of plain and Fiber Reinforced Concrete (FRC).

To simulate the interaction of freezing and thawing cycles and flexural fatigue loading cycles, a test program was conducted where the current single variable accelerated tests were performed, in series, on a single test specimen and the residual flexural performance, after conditioning, was evaluated and compared to the performance measured on unconditioned companion specimens.

In a previous paper by the authors [1], the effects of 2 million cycles of flexural fatigue loading between 10% and 40% of the flexural strength, followed by 300 cycles of freezing and thawing cycles, on the flexural properties of plain and FRC were discussed. The results of the previous study indicated that all types of concrete (plain and FRC) evaluated suffered a loss in flexural strength and stiffness when subjected to flexural fatigue loading and freezing and thawing cycles separately or when combined. The results also indicated that the use of steel fibers had a positive impact on the flexural strength and stiffness of the specimens subjected to freezing and thawing cycles alone or when previously fatigued samples were subjected to freezing and thawing cycles.

The present study is a continuation of this work and will evaluate the effect of reversing the order of the conditioning; that is, performing the flexural fatigue loading on beams that have been previously subjected to 300 cycles of freezing and thawing.

# 2 Test program

To evaluate the residual mechanical properties of plain concrete and several types of FRC's exposed to combined freezing and thawing cycles and flexural fatigue loading, and to determine the effects of freezing and thawing cycles on the flexural fatigue performance of plain concrete and FRC, the test program, as outlined below, was conducted.

A total of one plain concrete mixture, two steel fibers and one synthetic fiber reinforced concrete mixtures were investigated. An illustration of each fiber, their physical characteristic, and identification (F1-F3), is shown in Figure 1.

The steel macro fibers, F1 and F2, were added at a manufacturers suggested dosage rate of 40kg/$m^3$ (0.5% by volume), while the polyolefin macro fiber, F3, was added at a dosage rate of 15kg/$m^3$ (1.67% by volume). A plain control mixture was also prepared and tested under identical conditions.

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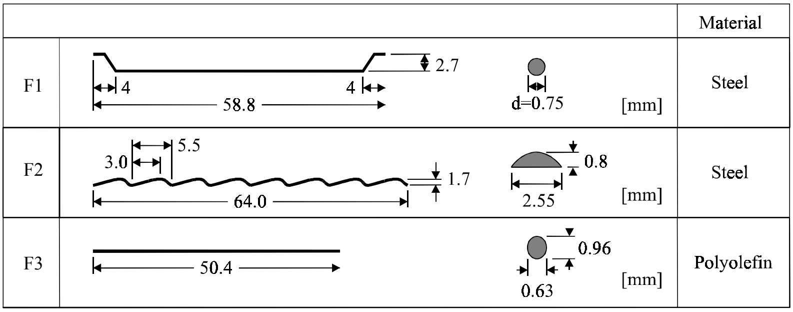


Figure 1: Fibers investigated.

The concrete used for all mixtures was a 32 MPa compressive strength air entrained concrete designed for exterior slab on grade applications subjected to severe freezing and thawing in the presence of deicing chemicals. The concrete mixture composition is shown in Table 1.

Table 1: Mixture composition (kg/m$^3$).

| Cement Type 10 | Fine Aggregate | Coarse Aggregate | Water | WRA$^A$ | SP$^B$ | AEA$^C$ |
|---|---|---|---|---|---|---|
| 373 | 800 | 975 | 168 | 746 ml | 1305ml | 93ml |

A. Water reducing agent **Euclid DX,** B. Superplasticizer **Euclid Ch**
C. Air- entrainment agent, Master Builder **Micro-Air,**

To simulate field conditions, all 6m$^3$ batches were produced and delivered by a local ready-mix company, using conventional 8m$^3$ ready-mix trucks. Additional information on aggregate gradation, properties of the fresh concrete before and after fiber addition, hardened concrete air-void characteristics, and freezing and thawing resistance can be found in a previous publication [2].

The fibers were added to the concrete mixture and mixed for five minutes at full mixing speed to ensure uniform fiber dispersion. From each of the FRC and control mixture, the following specimens were taken: 12 – 150 x 300mm cylinders for compression tests at 7, 28, and 90 days, 12 – 100 x 100 x 350mm beams for flexural tests at 7, 28, and 90 days. The results of all compressive and flexural tests can also be found in a previous publication [2]. An additional 55 – 100 x 100 x 350mm beams taken and exposed to the following conditions:

- specimens that have been cured for 90-days
- specimens that have been subjected to 2 million cycles of flexural fatigue between 10%-40% of their original 90-day flexural strength
- specimens that have been subjected to 2 million cycles of flexural fatigue between 10%-45% of their original 90-day flexural strength
- specimens that have been subjected to 300 cycles of freezing and thawing, followed by 2 million cycles of flexural fatigue between 10% and 40% of their original 90-day flexural strength

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- specimens that have been subjected to 300 cycles of freezing and thawing, followed by 2 million cycles of flexural fatigue between 10% and 45% of their original 90-day flexural strength.

After conditioning the residual flexural performance was evaluated and compared to the performance measured on unconditioned companion specimens.

Figure 2 shows the flexural testing equipment and a beam specimen with a yoke device surrounding the specimen to measure the center point deflection of the specimen. The same setup was used to perform the flexural fatigue loading cycles.

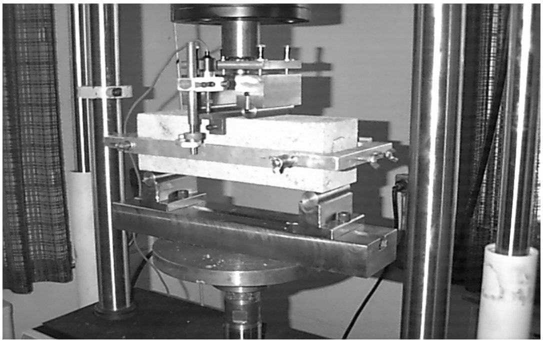

Figure 2: ASTM C 1018 Test in progress.

# 3 Test results

## 3.1 Flexural fatigue endurance limit

The flexural fatigue endurance limit was determined for unconditioned specimens and for conditioned beam specimens that were previously subjected to 300 cycles of freezing and thawing. All percentages used are based on the 90-day flexural strength of unconditioned beam specimens. The unconditioned strength was kept as a reference throughout the flexural fatigue endurance testing despite the fact that the flexural strength of specimens subjected to 300 cycles of freezing and thawing was 30% lower for plain concrete and 15% lower for FRC [1].

For the purpose of this report, the flexural fatigue endurance limit was defined as the maximum stress range, expressed as a percentage of the 90-day flexural strength, that can be sustained by a specimen for a total of 2 million cycles of non-reversing sinusoidal flexural fatigue loading. The lower value of stress applied during flexural fatigue cycling was kept at 10% of the 90-day flexural strength.

Table 2 shows that the flexural fatigue endurance limit of plain concrete is 49% of the 90-day flexural strength, which is within the range noted in previous investigations [3,4]. Similar to previous investigations [5,6], the addition of steel

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fibers in mixture F1 (MF1) and mixture F2 (MF2), at a volume fraction of 0.5%, and the polyolefin fibers in mixture F3 (MF3), at a volume fraction of 1.7%, did not increase the endurance limit of unconditioned concrete specimens. This is a clear indication that the presence of fibers, either steel or polyolefin, at the dosages evaluated in this study, did not have a significant impact on the micro-cracking process (micro-crack initiation and growth) that resulted from fatigue cyclic loading of unconditioned specimens.

Table 2: Flexural fatigue endurance limit (% of 90-day strength).

| Mixture | Static Flexural Strength at 90 days (MPa) | Flexural Fatigue Endurance Limit of Unconditioned Specimens (% of 90-day Strength) | Flexural Fatigue Endurance Limit of Freeze-thaw Specimens (% of 90-day Strength) |
|---|---|---|---|
| M0(Plain) | 6.60 | 49% | 64% |
| MF1 | 7.09 | 48% | 68% |
| MF2 | 6.66 | 49% | 68% |
| MF3 | 6.55 | 49% | 70% |

Despite the 30% reduction in flexural strength that plain concrete specimens subjected to freezing and thawing cycles experienced, when subsequently exposed to flexural fatigue loading, the plain concrete specimens could sustain a much higher flexural stress range of 10-64% of their 90-day unconditioned flexural strength. For all FRC evaluated a 15% reduction in flexural strength after freezing and thawing was experienced, compared to a 30% reduction for plain concrete, their residual flexural fatigue endurance limit was only marginally higher. It appears that the addition of fibers, at the dosage used in this study, does not significantly increase the endurance limit for the steel fibers or synthetic fibers.

For both the plain and FRC specimens that were subjected to freezing and thawing, the increase in fatigue endurance limit can be attributed to the presence of microcracks at the surface of the concrete specimens that resulted from the freezing and thawing process. The application of fatigue loading cycles results in further microcracking on the tension face of the specimen. With every load cycle near the endurance limit of the concrete, existing microcracks will propagate in a stable manner and new microcracks will form. The presence of freeze-thaw induced microcracks surrounding the advancing crack tips, which have been linked to increases in fracture energy [7], allows for the redistribution of stresses within the cement matrix resulting in larger critical crack length at failure and therefore an increase in fracture surface. The additional energy required to form the new crack surfaces and the frictional energy dissipated within the specimen due to the opening and closing of the crack surfaces during flexural fatigue loading cycles is responsible for the increase in fatigue endurance limit.

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Although the data presented supports the above postulation, a greater number of freezing and thawing cycles or freezing and thawing cycles performed on less durable specimens may result in significantly more microcracking damage within the specimen. It is believed that each concrete type has a microcracking damage threshold, beyond which, the matrix has been weakened to the point where the benefits of having microcracking are outweighed by the negative effects the tendency of a large number of microcracks to coalesce into a larger more critical crack upon loading.

### 3.2 Flexural toughness of plain concrete: original 90-day values, after flexural fatigue loading, after combined freezing and thawing and flexural fatigue loading

In this section, the results of the flexural toughness tests performed on plain concrete beam specimens, subjected to several combinations of flexural fatigue loading and freezing and thawing cycles .

The results of the flexural toughness testing of plain specimens are presented in Table 3. The average stress versus deflection graphs for the plain concrete specimens are presented in Figure 3.

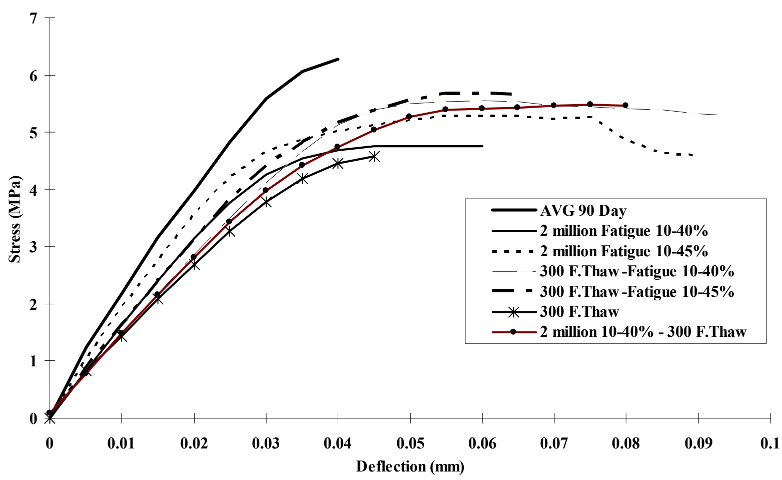


Figure 3: Average flexural curves for plain concrete M0 for all test conditions.

Figure 3 also includes two additional reference curves, from a previous publication [1], of the same plain concrete mixture that has been subjected to 2 million cycles of flexural fatigue between 10% and 40% of their original 90-day flexural strength, followed by 300 cycles of freezing and thawing, and subjected to 300 cycles of freezing and thawing cycles only.

All flexural toughness graphs have been normalized and presented as stress versus center point deflection.

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Table 3: Flexural strength, flexural stiffness and cracking deflection.

| Mixture | Condition | Flexural Strength (MPa) | Initial Flexural Stiffness (MPa/mm) | Cracking Deflection (mm) | Flexural Toughness (kN.mm) |
|---|---|---|---|---|---|
| M0 | 90-day | 6.60 | 173.8 | 0.041 | 0.529 |
| | F.Thaw | 4.65* | 117.9* | 0.043* | 0.431 |
| | Fatigue(10-40) | 4.78 | 137.6 | 0.060 | 0.733 |
| | Fatigue(10-45) | 5.34 | 157.5 | 0.089 | 1.410 |
| | F.Thaw + Fatigue(10-40) | 5.55 | 134.2 | 0.092 | 1.787 |
| | F.Thaw + Fatigue(10-45) | 5.75 | 146.2 | 0.064 | 0.825 |
| | Fatigue(10-40) + F.Thaw | 5.25* | 127.6* | 0.080* | 1.171 |

* values from a previous publication [1]

When comparing the 90-day original curve to that of all other conditioned specimens, it is clear that all test conditions had a negative effect on the flexural strength and stiffness of the plain concrete beam specimens.

The average stress-deflection curve of the plain concrete specimens that have been fatigued between a range of 10-40% of their 90-day flexural strength shows the presence of a significant plateau that extends up to a deflection of 0.06mm. This represents a 50% increase over that of the original 90-day specimens. An increase in stress range to 10-45% of the 90-day flexural strength, representing approximately 90% of the endurance limit listed in Table 2, showed an even longer plateau up to a cracking deflection of 0.089mm. Such an increase in cracking deflection was not found with specimens that have been subjected to only freezing and thawing cycles.

It is possible that a further increase in the stress range, closer to the endurance limit of 49%, will lead to a greater residual flexural strength than the initial 90-day flexural strength, as observed by Ramakrishnan *et al.* [4]. Interestingly, the specimens subjected to freezing and thawing followed by fatigue loading between a stress range of 10-40% of the 90 day flexural strength, experienced a slight increase in residual flexural strength and stiffness and a large increase in flexural toughness (fracture energy) of 144%, when compared to the specimens subjected to only fatigue loading at the same stress range.

When the order of conditioning was reversed, the increase in flexural toughness was only 60% greater than that of specimens subjected to fatigue loading at the same stress range. Therefore, the level of damage associated with combined flexural fatigue loading and freezing and thawing cycles is not cumulative and is dependent on the samples load history (physical and environmental).

The relationship between the level of microcracking damage and the increase in fracture energy and the critical crack length is unknown, but the results of this test program seem to indicate that low levels of damage cause an increase in critical crack length and fracture energy, but a decrease in the matrix strength. Higher levels of damage (combination of load and environment conditions) resulted in even greater critical crack length and fracture energy, and the flexural strength approached that of the unconditioned sample.

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### 3.3 Flexural toughness of fiber reinforced concrete: original 90-day values, after fatigue loading, after combined freezing and thawing and flexural fatigue loading

In this section, the results of the flexural toughness tests performed on FRC concrete beam specimens, subjected to several combinations of flexural fatigue loading and freezing and thawing cycles .

The results of the flexural toughness testing of FRC specimens are presented in Table 4. The average stress versus deflection graphs for MF1 are presented in Figure 4.

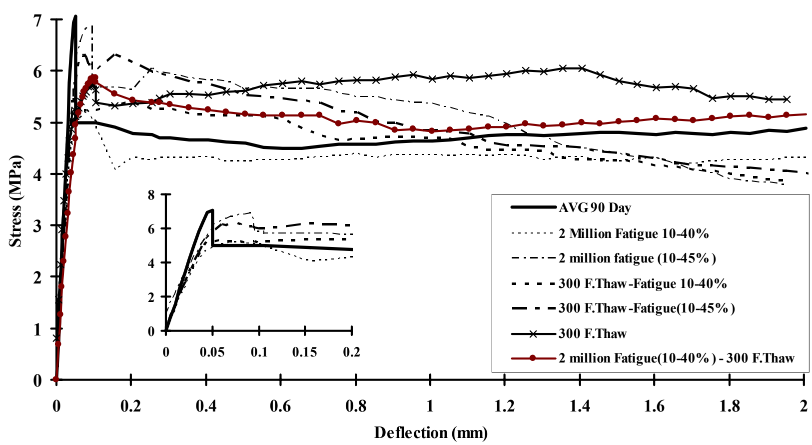


Figure 4: Average stress-deflection curves for MF1 under all test conditions.

Figure 4 also includes two additional reference curves, from a previous publication [1], of the same MF1 mixture that has been subjected to 2 million cycles of flexural fatigue between 10% and 40% of their original 90-day flexural strength, followed by 300 cycles of freezing and thawing, and subjected to 300 cycles of freezing and thawing cycles only.

Within Figure 4, a close-up view of the initial portion of the stress-deflection curves is also shown. The significant non-linearity of the conditioned specimens makes the determination of the first-crack deflection, required for ASTM C 1018 toughness analysis, impossible, and therefore will not be presented here. Instead, the Japanese Society of Civil Engineers toughness index (JSCE SF-4) was used to provide a comparison of the post-crack flexural performance.

In general, the 2 million cycles of flexural fatigue loading, between the range of 10-40% of the specimen's original 90-day flexural strength, caused a 25% reduction in the flexural strength of FRC specimens tested, while the plain concrete flexural strength was reduced by 27.5%. Based on these results, it is concluded that the reduction in modulus of rupture of concrete subjected to flexural fatigue loading, between 10 and 40% of the 90-day flexural strength, is

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only slightly improved by the addition of fibers. However, when the stress range is increased to 10-45%, the flexural strength of the fatigued steel FRC specimens is almost equal to that of the unconditioned specimens.

The results get even more interesting when freezing and thawing cycles are performed prior to flexural fatigue loading at a stress range between 10-40% where freezing and thawing cycles had a positive effect on the flexural strength, stiffness, and toughness of all FRC specimens; however, when the stress range is increased to 10-45%, the freezing and thawing cycles reduce the flexural strength compared to the specimens that are only fatigued. Once again, it seems that the microcracking damage caused by combining freezing and thawing cycles with 2 million cycles of flexural fatigue, between 10-45% of the 90-day flexural strength, is above the threshold of beneficial microcracking damage.

Table 4: Flexural strength and stiffness, Japanese toughness.

| Mixture | Condition | Flexural Strength (MPa) | Initial Flexural Stiffness (MPa/mm) | Japanese Toughness (JSCE SF-4) (MPa) |
|---|---|---|---|---|
| MF1 | 90-day | 7.09 | 160.0 | 4.67 |
| | F.Thaw | 6.11* | 123.0* | 5.66* |
| | Fatigue(10-40) | 5.34 | 117.9 | 4.02 |
| | Fatigue(10-45) | 7.06 | 117.0 | 5.19 |
| | F.Thaw + Fatigue(10-40) | 5.73 | 127.9 | 4.59 |
| | F.Thaw + Fatigue(10-45) | 4.93 | 133.2 | 4.93 |
| | Fatigue(10-40) + F.Thaw | 6.00* | 99.0* | 5.10* |
| MF2 | 90-day | 6.66 | 152 | 3.92 |
| | F.Thaw | 5.59* | 126.3* | 4.18* |
| | Fatigue(10-40) | 5.10 | 109.3 | 3.29 |
| | Fatigue(10-45) | 6.53 | 103 | 3.88 |
| | F.Thaw + Fatigue(10-40) | 6.30 | 122.9 | 3.92 |
| | F.Thaw + Fatigue(10-45) | 6.00 | 138.9 | 3.98 |
| | Fatigue(10-40) + F.Thaw | 5.51* | 110* | 4.16* |
| MF3 | 90-day | 6.55 | 149.8 | 4.32 |
| | F.Thaw | 5.51* | 129.2* | 3.59* |
| | Fatigue(10-40) | 4.76 | 108.9 | 3.52 |
| | Fatigue(10-45) | N/A | N/A | N/A |
| | F.Thaw + Fatigue(10-40) | 6.43 | 123.4 | 3.95 |
| | F.Thaw + Fatigue(10-45) | 6.21 | 135.2 | 4.01 |
| | Fatigue(10-40) + F.Thaw | 5.35* | 116.4* | 3.89* |

*Values from a previous study [1]

The toughness results in Table 4 show that higher levels of damage (combination of load and environment conditions) of mixtures MF1 and MF2, resulted in higher post-conditioning flexural toughness than the unconditioned samples. Although, an increasing trend with the level of damage was observed with MF3, the flexural toughness of these conditioned specimens never reached that of the unconditioned specimens. The difference in trend between the flexural toughness of steel fibers and the polyolefin fiber can possibly be explained by concluding that the freezing and thawing cycles have affected the quality of the fiber-matrix transition zone; this has a significant impact on the

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pull-out resistance of the straight, smooth, polyolefin fibers, which are generated entirely through frictional forces.

## 4 Conclusions

Although the testing program presented here was not intended to perfectly simulate loading and exposure conditions that are representative of those applied to concrete structures in cold climates, the test results do give insight into the interaction of the deterioration caused by freezing and thawing cycles and flexural fatigue loading cycles and how they may affect the mechanical properties of plain and fiber reinforced concrete exposed to such conditions.

In general, the flexural strength, stiffness, and toughness of plain concrete and both steel and polyolefin fiber reinforced concrete, after exposure to a combination of 300 freezing and thawing cycles followed by 2 million cycles of flexural fatigue loading, 10-40% or 10-45% of the 90-day flexural strength, is greater than or equal to the lowest residual flexural strength, stiffness, and toughness of specimens exposed to 300 freezing and thawing cycles or 2 million flexural fatigue loading (between the same stress range).

Flexural fatigue endurance limit testing of previously freeze-thawed, plain concrete and FRC (steel, polyolefin) resulted in an increase in endurance limit, from 49% of the 90 day flexural strength, for all unconditioned mixtures, to an endurance limit of 64% for M0, 68% for both MF1 and MF2, and 70% for MF3 after freezing and thawing. The increases in fatigue endurance limit of freeze-thaw, plain concrete and FRC has been attributed to the formation of a fine network microcracking within the concrete matrix. This network of fine microcracks has the effect of redistributing stresses and increasing the fracture energy and critical crack length of the cement matrix. The added energy required to form the additional crack surfaces and the frictional energy dissipated, during the fatigue induced opening and closing of these new crack surfaces, may explain the increase in flexural fatigue endurance limit of previously freeze-thawed concrete specimens.

Comparing the results of this study to the results presented in a previous publication [1] where the order of conditioning was reversed, it is concluded that the level of damage associated with combined flexural fatigue loading and freezing and thawing is not cumulative and is dependent on the sample load history (physical and environmental).

In general, the results from single variable accelerated testing (flexural fatigue loading cycles, freezing and thawing cycles) can be used to predict the residual mechanical properties of specimens exposed to combined freezing and thawing cycles and flexural fatigue loading cycles performed in series. Although the results look promising, further study under more realistic, simultaneous flexural fatigue loading and freezing and thawing cycles, is required to confirm these observations.

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## References

[1] Trottier, J.-F., & Forgeron, D., Cumulative Effects of Flexural Fatigue Loading and Freezing and Thawing Cycles on the Flexural Toughness of Fiber Reinforced Concrete, *Third International Conference on Concrete Under Severe Conditions: Environment and Loading*, Vancouver, Canada, June 18-20, 2001.

[2] Trottier, J.-F., Morgan, D.R., & Forgeron, D., Fiber Reinforced Concrete for Exterior Slab on Grade Applications. Influence of Fiber Geometry and Type on Mechanical Properties and Durability, Part I, *American Concrete Institute, Concrete International*, pp. 35-39, June 1997.

[3] Ramakrishnan, V., & Bjorn, J.L., Fatigue Strength and Endurance Limit of Plain and Fiber Reinforced Concretes - A critical Review, *International Symposium on Fatigue and Fracture in Steel and Concrete Structures*, 1991.

[4] Ramakrishnan, V., Oberling, G., & Tatnall, P., Flexural Fatigue Strength of Steel Fiber Reinforced Concrete, *Fiber Reinforced Concrete Properties and Applications*. SP 105-13, American Concrete Institute, Detroit, Michigan, pp. 225-245, 1987.

[5] Mailhot, T., Bissonnette, B., Sausier, F., & Pigeon, M., Flexural Fatigue Behavior of Steel Fiber Reinforced Concrete After Cracking, *Material and Structures*, Vol. 34, July, pp. 351-359, 2001.

[6] Ramakrishnan, V., & Sivakumar, C., Performance of Polyolefin Fiber Reinforced Concrete under Cyclic Loading, *Proceedings, Second CANMET/ACI International Conference*, SP 186-10, Gramado, RS, Brazil, pp. 161-18, 1999

[7] Shum, D.K., & Hutchinson, J.W., On Toughening of Microcracks, *Mechanics of Materials 9*, Elsevier, 1990.

High Performance Structures and Materials II, C.A. Brebbia & W.P. De Wilde (Editors)