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AUTC Project (410029)

Accelerated Degradation and Durability of Concrete in Cold Climates

***- Progress Report Meeting* (Aug. 12, 2011)**

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Background

- Degradation of aggregate in concrete can be caused by erosion or fracture, and both cementitious materials and aggregate age over time.

- The specification requirements for the degradation of aggregates have been established for hot mix asphalt and for most aggregate products (WSDOT Standard Specifications, 2006); however, **degradation specifications for concrete aggregate** have not been established.

- There is a need to characterize the **long term performance of concrete** considering the aggregate degradation process as good quality gravel sources are increasingly becoming exhausted.

Objectives

- To conduct a combined accelerated freeze/thaw (F/T) conditioning and test the condition samples to reveal the intergranular and intragranular decay and failure in concrete (Task A) (in progress)
- To evaluate damage accumulation and failure mechanism of concrete in the low temperature and F/T cycling using statistical and phenomenological-based damage mechanics models (Task B) (in progress)
- In collaboration with the AKDOT&PF and WSDOT, to correlate and validate the prediction models with the field data and establish the baseline criteria for long term performance (Task C) (ongoing)
- To develop recommendations for test methods on long term performance characterization of concrete in cold regions, specifications on performance criteria and service life predictions, and guidelines for DOTs to evaluate concrete performance and safety in the cold regions (Task D) (in progress)

Research Focus

- To evaluate the **long term performance of concrete**, using a combined mechanical (dynamics and fracture) and accelerated environmental conditioning testing protocol
  - Accelerated environmental conditioning
  - Dynamic modulus test
  - Vickers indentation test
  - Develop damage evolution and service life prediction models
  - Better understanding and potential development of specification recommendations
- Two types of aggregate sources in concrete are evaluated:
  - Concrete with low degradation aggregate (**LD-WSDOT**)
  - Concrete with normal aggregate (**NA-WSDOT**)

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Materials and Test Samples

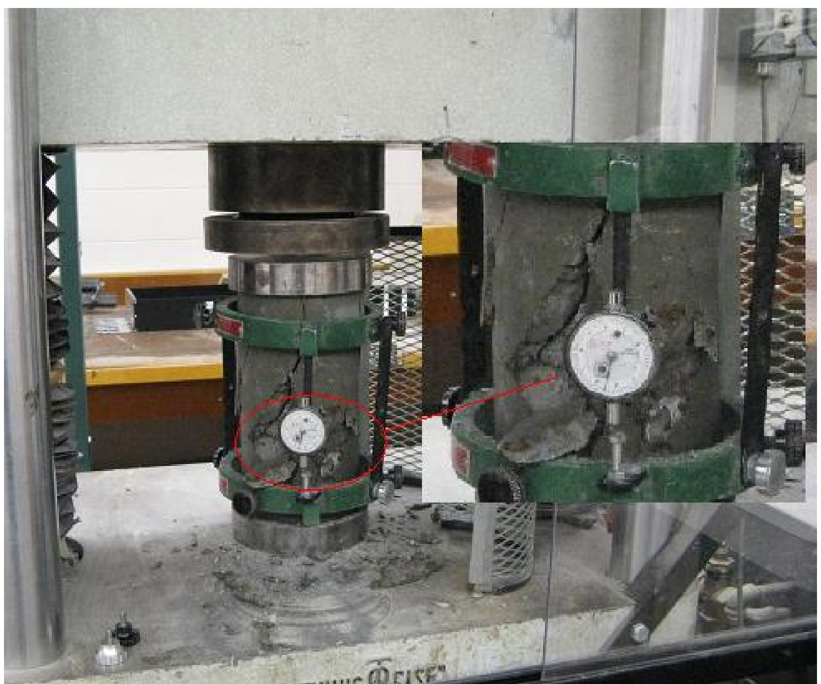
- Mix design for beam specimens (prisms) with dimensions of 3 x 4 x 16 in. with two identified aggregate sources (one low degradation aggregate (LD) and the other normal aggregate (NA))
- Degradation Factor (WSDOT TM 113):
  - Aggregate degradation factor for LD: 31
  - Aggregate degradation factor for NA: 59
  - 35 is considered as low degradation per WSDOT TM 113

Mixtures	Cement (lb/yd^3)	3/4" Aggregate (lb/yd^3)	Sand (lb/yd^3)	w/cm	**Slump (in.)**	**Air Content (%)**
LD-WSDOT	564	1830	1270	0.48	4	4.8
NA-WSDOT	564	1830	1270	0.48	2.5	3.0

Materials and Test Samples

- Mechanical properties of hardened concrete (28 days)

Mixtures	Compressive strength (psi)	Young's Modulus ($X10^6$ psi)	Flexural Strength (psi)	Dynamic Modulus ($X10^6$ psi)
LD-WSDOT	4432.0	3.4	748.0	5.2
NA-WSDOT	4844.1	3.3	691.6	5.5



Test Methods Considered

1. Rapid freezing and thawing (F/T) test (ASTM C666)
2. Dynamic modulus test (ASTM C215)
3. Fracture energy test (RILEM 50-FMC)
4. Vickers Indentation (ASTM E384)

Test Methods

- **Rapid F/T test (ASTM C666)**

F/T conditioning machine (17 samples plus one control sample)

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Test Methods

- **Rapid F/T Test (ASTM C666):**
  - ✓ Being used to condition the concrete prism samples
  - ✓ The temperature range: 0 to 40^0F
  - ✓ The normal temperature range: from 0 to 40^0F with error of $1\sim2^0$F
  - ✓ The cycle frequency is 6~9 cycles per day (or 2.6~4 hrs/cycle)
  - ✓ The time required for the temperature exchange (from freezing 37 to 3^oF or thawing 3 to 37^oF): 70% of cooling or heating period (meets ASTM C666 of not less than 50%).
  - ✓ 1,500 cycles of F/T corresponding to 25 years of service (60 cycles per year) (Wisconsin DOT's study).

Test Methods

- **Dynamic Modulus Test (ASTM C215):**

  ✓ Being used to evaluate the dynamic modulus of concrete prism samples under different F/T conditioning cycles

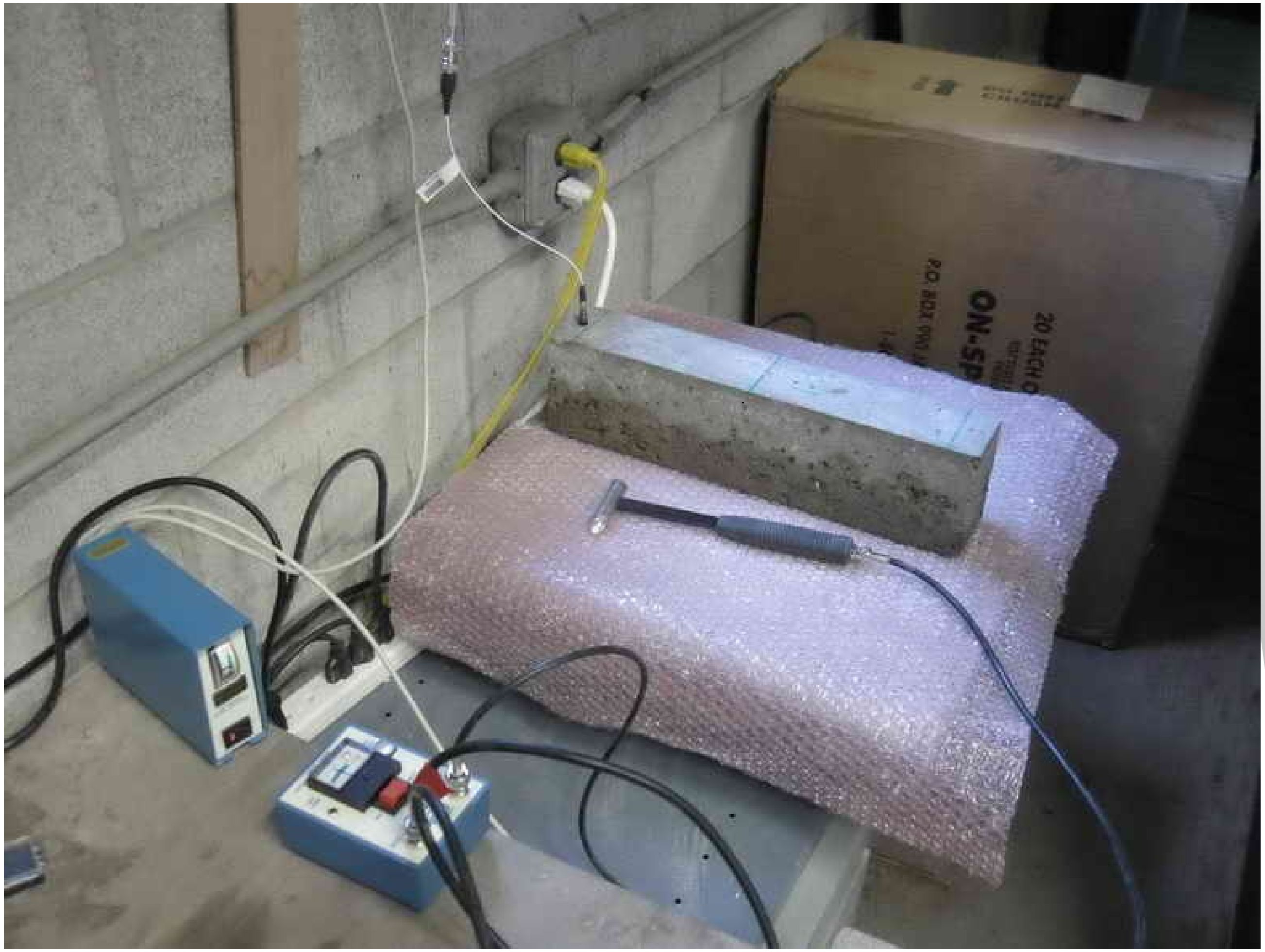
  ✓ The impact test method is used to measure the transverse frequency, and an accelerometer (output signal) is attached to one end of the beam

  ✓ The test sample is supported by a thick pad and impacted by the hammer at the middle span.

  ✓ The time domain response data are recorded by dSPACE and then transferred to the frequency domain using MatLab.

Test Methods

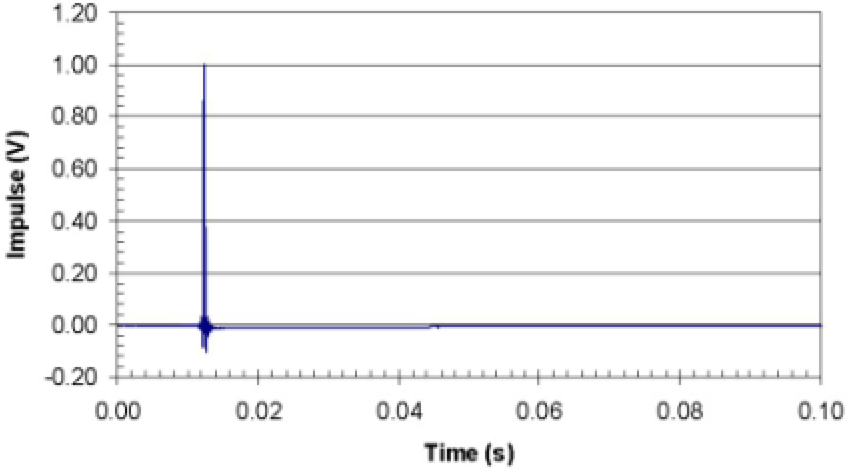
- **Dynamic Modulus Test (ASTM C215):**



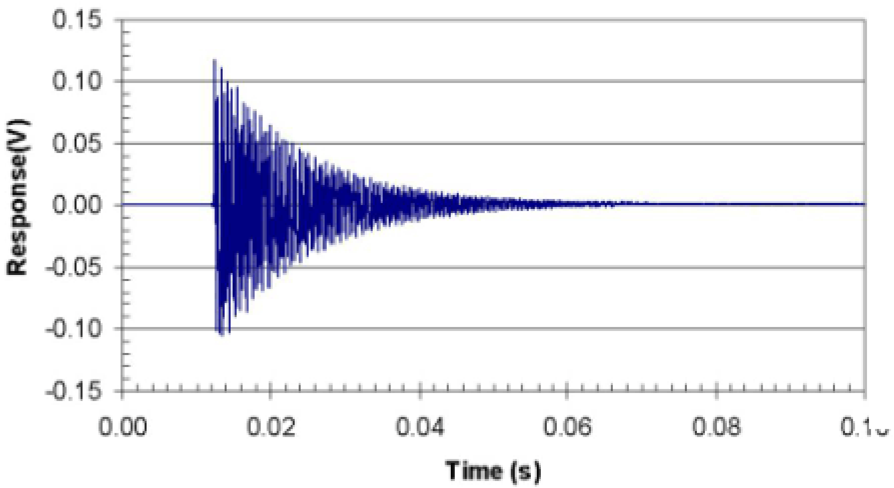
Dynamic modulus test setup

Test Methods

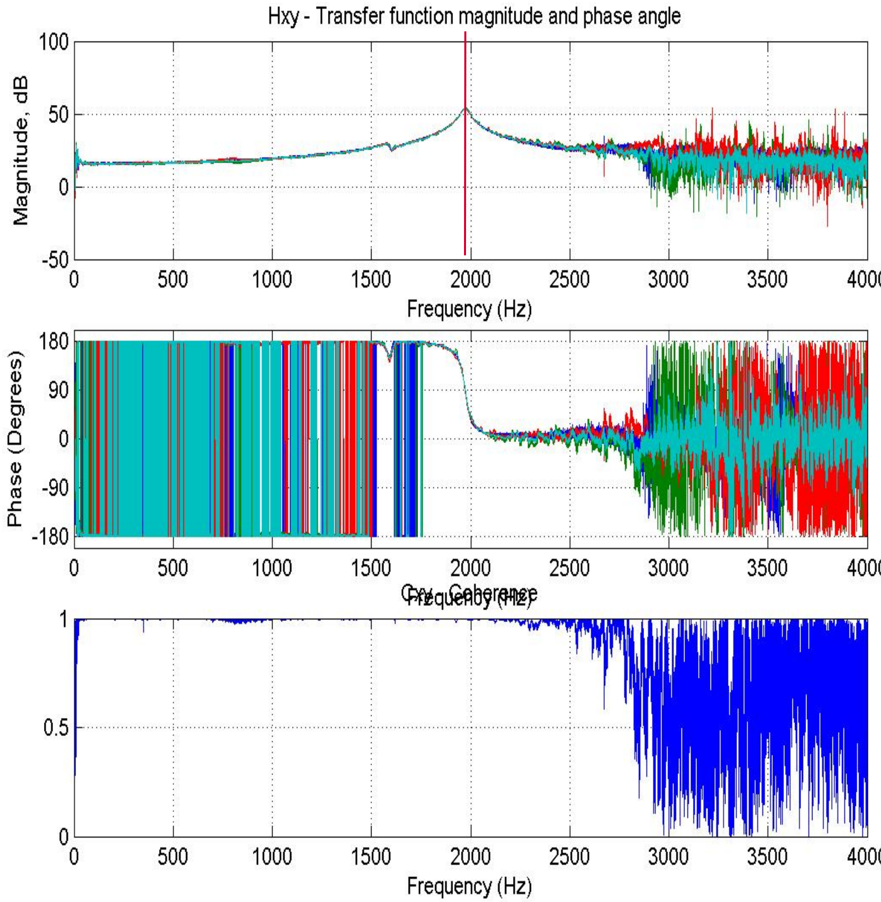
- **Dynamic Modulus Test (ASTM C215):**



Time domain impulse data



Time domain response data



Frequency domain response data

Test Methods

- **Dynamic Modulus Test (ASTM C215):**

  - Data reduction procedures:
    - The dynamic modulus of elasticity, E (Pa), can be determined from the fundamental transverse frequency (n), mass (M), and dimensions (C) of the test sample:

$$E = CMn^2$$

    - According to ASTM (C215), for a prism:

$$C = 0.9464 \frac{TL^3}{bt^3}$$

where, *L*, *t* and *b*: the length, thickness and width of the sample;

T: the correction factor that depends on the ratio of the radius of gyration to the length of the specimen and on the Poisson's ration (*T* = 1.41 in this study)

Test Methods

- **Dynamic Modulus Test (ASTM C215):**

Relative dynamic modulus of elasticity (P_c) after *c* F/T cycles:

$$P_c = \left(n_1^2 / n^2\right) * 100$$

n – the fundamental transverse frequency at 0 cycles
n_1 – the fundamental transverse frequency after *c* F/T cycles

❖ According to ASTM C666, it is not recommended that samples be continued in the test after their relative dynamic modulus of elasticity has fallen below 50%.

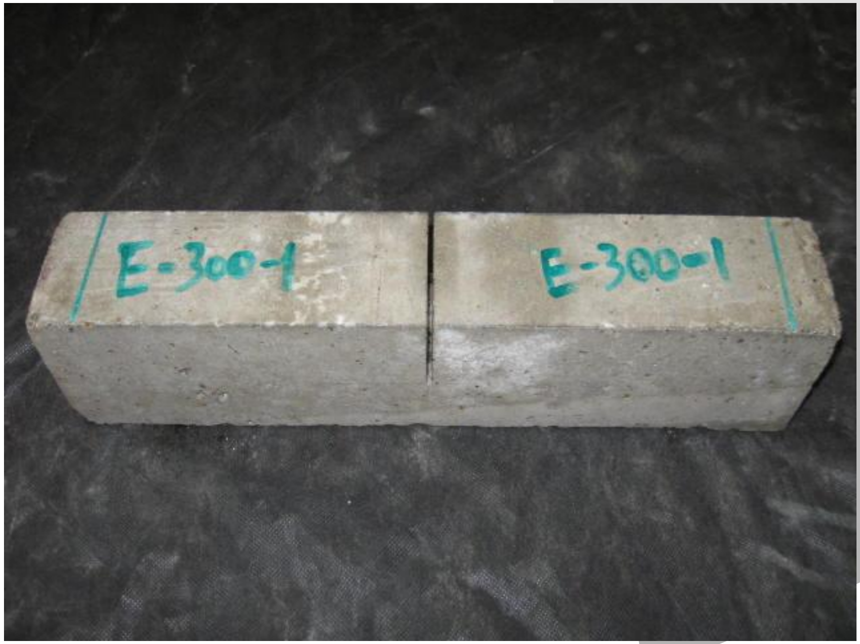
Test Methods

- **Fracture Energy Test (RILEM 50-FMC)**
  - **Sample preparation**

✓ Before fracture test, the samples are cut with notches at the mid-span of the sample by a diamond saw with high accuracy.

✓ In order to keep the maximum bending moment as lower as possible, a rather deep notch is recommended by the RILEM 50-FMC (1985). Thus, the depth of the notch is cut as the half of the depth of the sample.

Notch-cutting by diamond saw

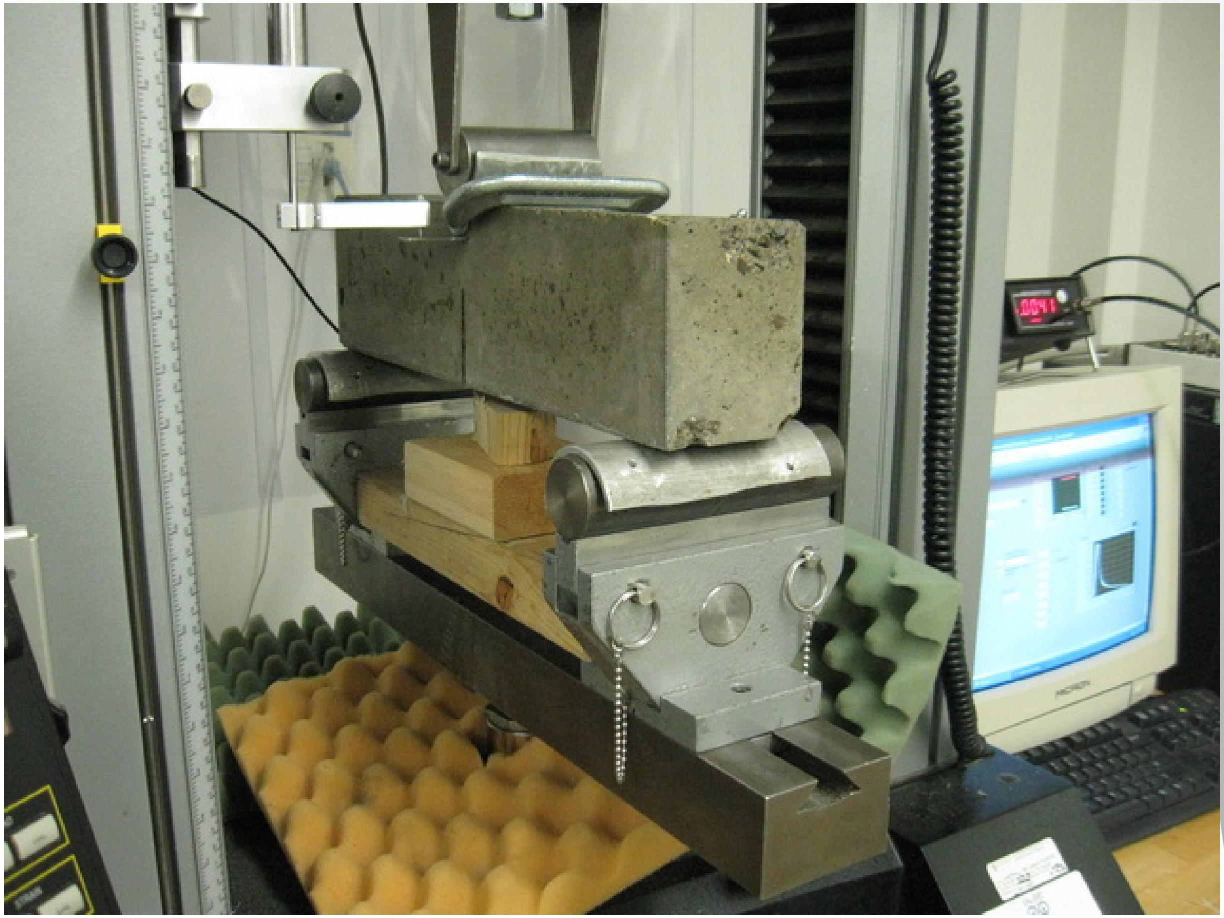


Notched sample for fracture test

Test Methods

- **Fracture Energy Test (RILEM 50-FMC)**
  - Test setup: All the fracture tests are performed on an MTS servo hydraulic testing machine by the three-point beam bend (3PBB) method as recommended by RILEM 50-FMC (1985).

Fracture Test setup



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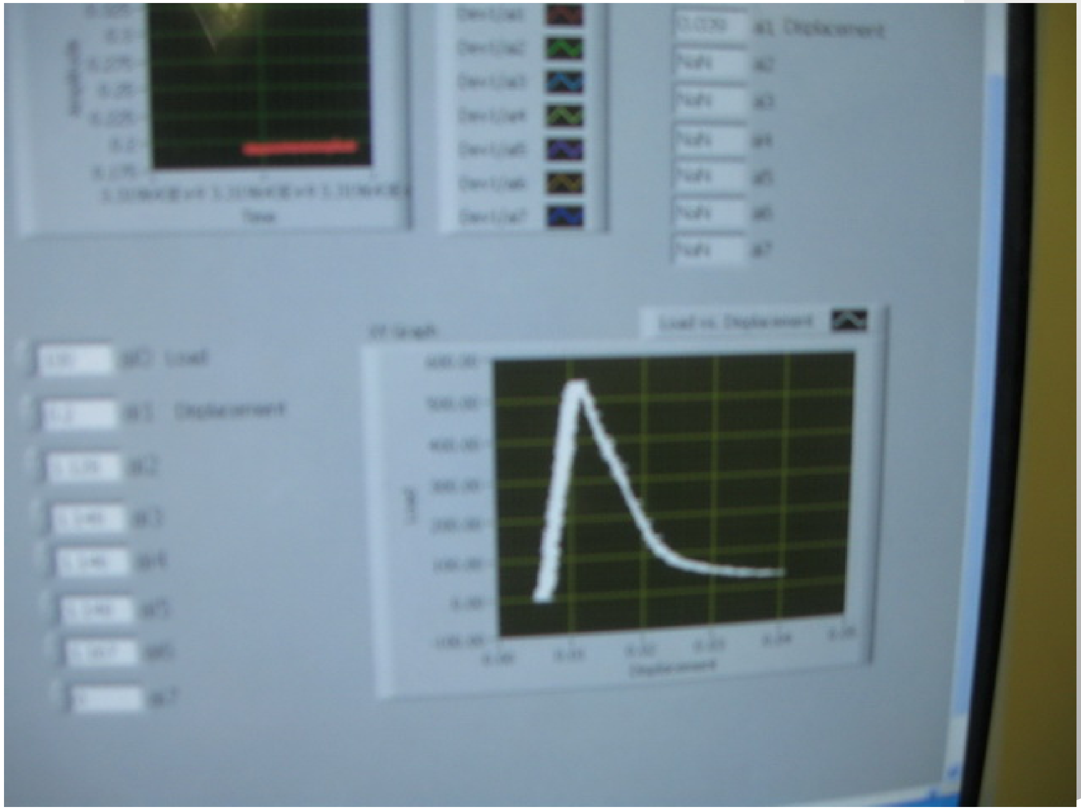
Test Methods

- **Fracture Energy Test (RILEM 50-FMC)**
  - All the experiments are conducted under displacement-controlled mode with a loading rate of 0.0236 in./min. (0.6 mm/min. = 0.01 mm/sec.)
  - The measurements of applied load and mid-span displacement (MSD) are automatically and continuously recorded by the “Labview” software.

Load-MSD diagrams using Labview



Test Methods

- **Fracture Energy Test (RILEM 50-FMC)**

Fractured surfaces

Test Methods

- **Fracture Energy Test (RILEM 50-FMC)**
  - **Data reduction procedures:**

✓ Fracture energy is determined following the procedure as recommended by RILEM 50-FMC (1985)

✓ The idea of this test is to measure the amount of energy of the notched sample which is absorbed when the sample is broken into two halves.

✓ This energy is divided by the fracture area (projected on a plane perpendicular to the tensile stress direction), whose resulting value is assumed to be **the fracture energy G_F**. which is assumed to be **a material property** that may be as important as the normal strength properties.

Test Methods

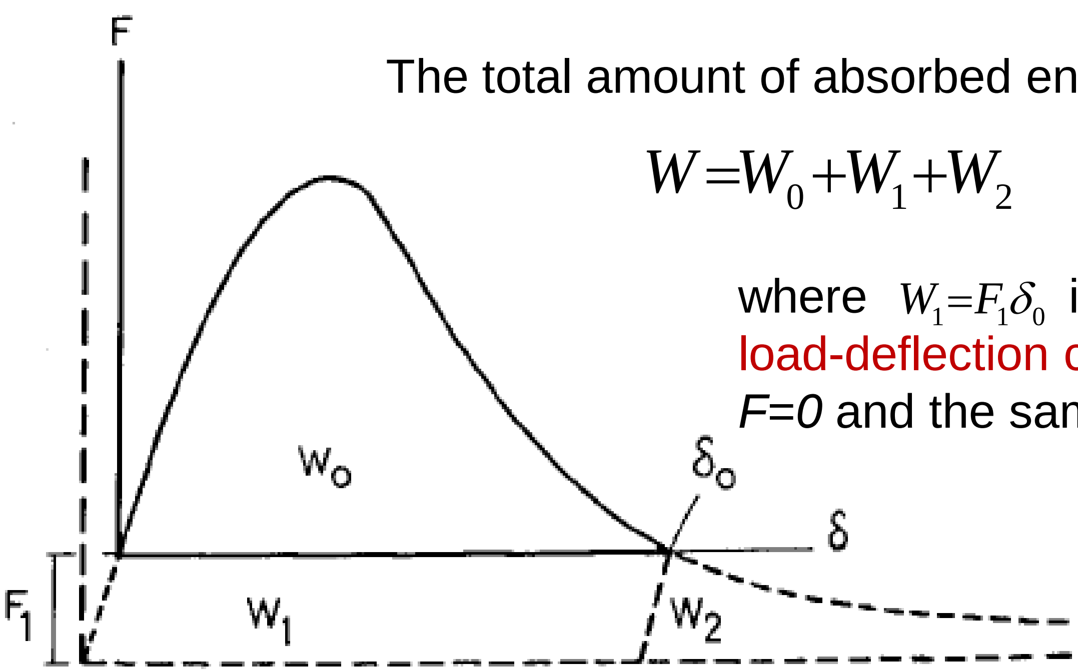
- **Fracture Energy Test (RILEM 50-FMC)**
  - **Data reduction procedures (cont.):**

✓ The remaining parts of the hypothetical complete load-deflection curve are shown in dashed lines (wehre *F1* – the self-weight of the sample and is not included in the measured load *F*).

The total amount of absorbed energy *W* is:

$$W = W_0 + W_1 + W_2$$

where $W_1 = F_1 \delta_0$ is the area below the measured load-deflection curve; δ_0 is the deflection when *F=0* and the sample breaks.



Typical measured load-deflection curve

Test Methods

- **Fracture Energy Test (RILEM 50-FMC)**

  - **Data reduction procedures (cont.):**

    ✓ It was demonstrated that W_2 is approximately equal to W_1. Therefore, the fracture energy can be determined by:

$$G_F = \frac{W_0 + 2F_1\delta_0}{A_{lig}}$$

where A_{lig} is the fractured area of the sample.

$$A_{lig} = b(t - a_0)$$

where b is the width of the sample; t is the thickness of the sample; a_0 is the depth of the notch.

Test Methods

- **Vickers Indentation Test (ASTM E384):**

  ✓ Being used to evaluate micro-indentation hardness of intragrannular (aggregate and paste) and intergrannular (aggregate-paste interface) portions of concrete;

  ✓ The test sample is grinded with silicon carbide sanding paper and then polished up to 0.3 *μm* with diamond suspension;

  ✓ Vickers Indenter, made from diamond of 136° pyramidal geometry, is pressed into the test specimen surface under an 1000 gf applied force.

  ✓ The applied force is maintained for 10 seconds, after which the indenter is removed, leaving a pyramid shape indent in the test sample.

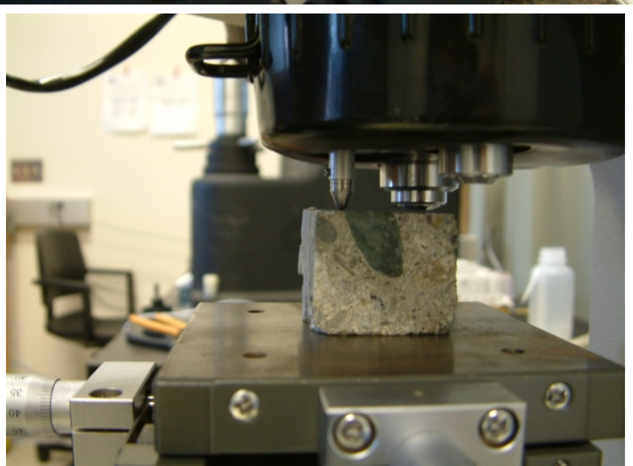
  ✓ The Vickers hardness, kgf/mm^2 is determined as:

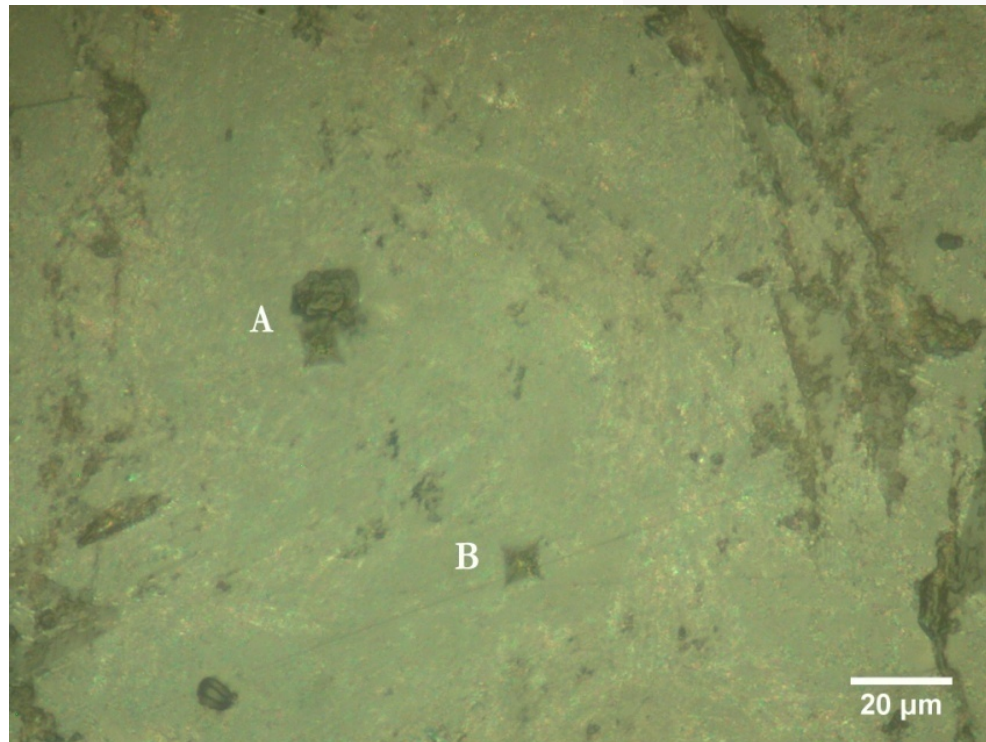
$$HV = 1.8544 \times P / d^2$$

where P is the applied force (kgf) and d is the mean diagonal length of the indentations (mm)

Test Methods

- **Vickers Indentation Test (ASTM E384):**





(A) Non-usable indentation due to rupture of surrounding area; and (B) Acceptable indentation with linear cracks.

Probabilistic Damage Modeling

- Based on 1-D continuum damage mechanics (CDM), the damage parameter (*D*) of concrete due to freezing and thawing effect can be defined as (E_t – dynamic modulus of aged sample, and E_0 – dynamic modulus of virgin sample)

$$D = 1 - \frac{E_t}{E_0}$$

- The kinetic law for measuring F/T damage in concrete is described as the cumulative density function through a three-parameter Weibull distribution. The probability density function for Weibull distribution is:

$$f(N) = \frac{\beta}{\eta}\left(\frac{N-\gamma}{\eta}\right)^{\beta-1} \exp\left[-\left(\frac{N-\gamma}{\eta}\right)^{\beta}\right]$$

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Probabilistic Damage Modeling

- The cumulative density function is regarded as the probability of failure and represents the cumulative damage parameter (*D*) due to accelerated aging of F/T:

$$P_f(N) = \int_0^N f(s)ds = 1 - \exp[-(\frac{N-\gamma}{\eta})^\beta]$$

- The probability of reliability:

$$P_r(N) = \int_N^{+\infty} f(s)ds = 1 - P_f(N) = \exp\left\{-\left(\frac{N-\gamma}{\alpha}\right)^\beta\right\}$$

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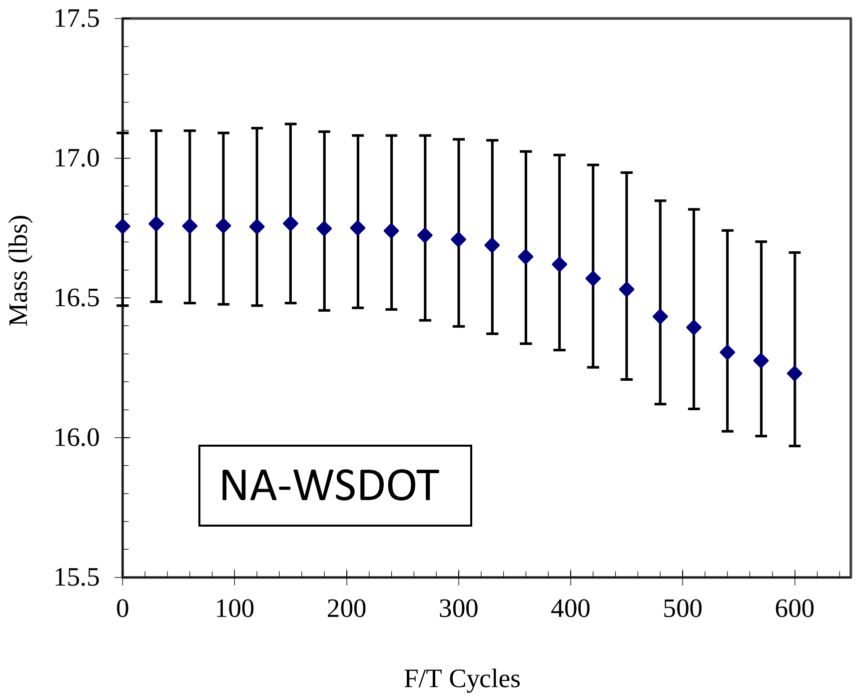
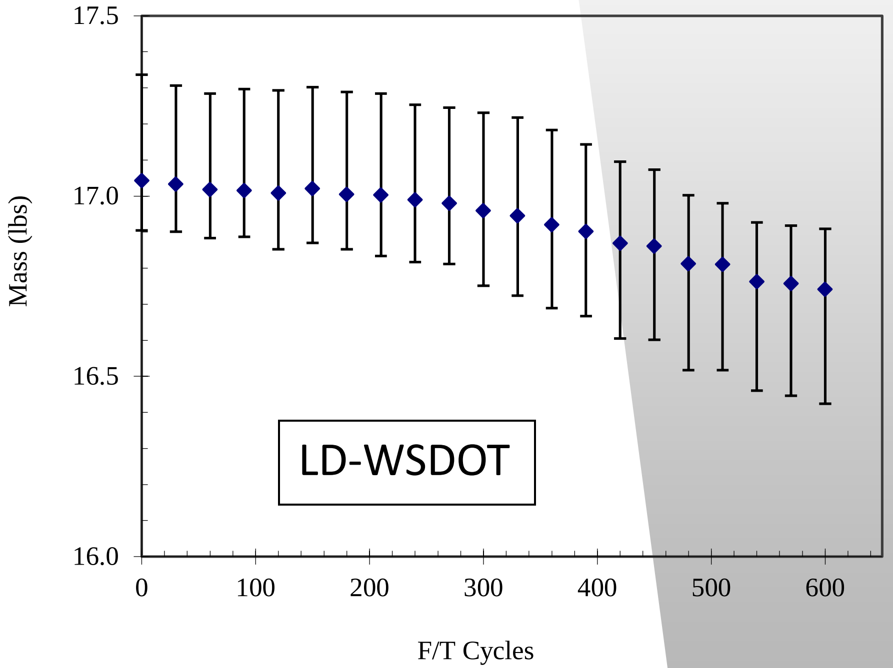
Results and Discussions

- **Dynamic Modulus Test (ASTM C215):**
  - ✓ Comparison of Weight deduction for NA-WSDOT and LD-WSDOT with the F/T cycles, primarily due to scaling of concrete:

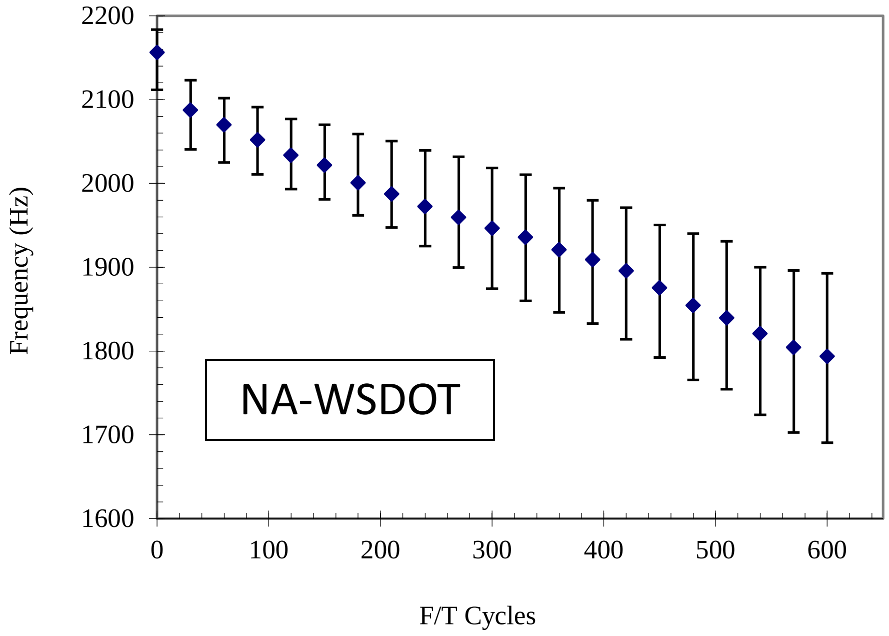


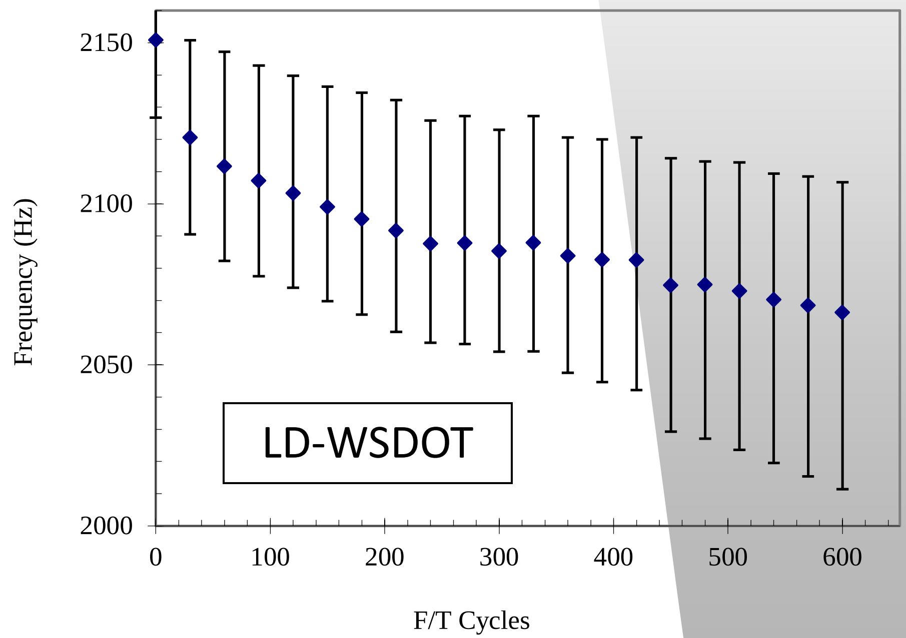


Results and Discussions

- **Dynamic Modulus Test (ASTM C215):**

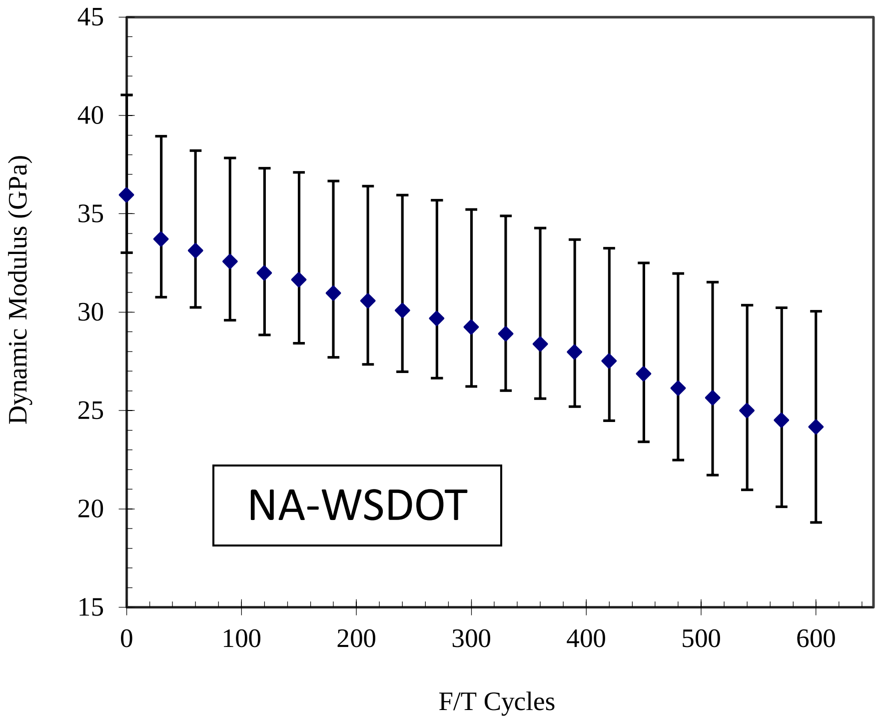
✓ Comparison of fundamental transverse frequency for NA-WSDOT and LD-WSDOT with the F/T cycles

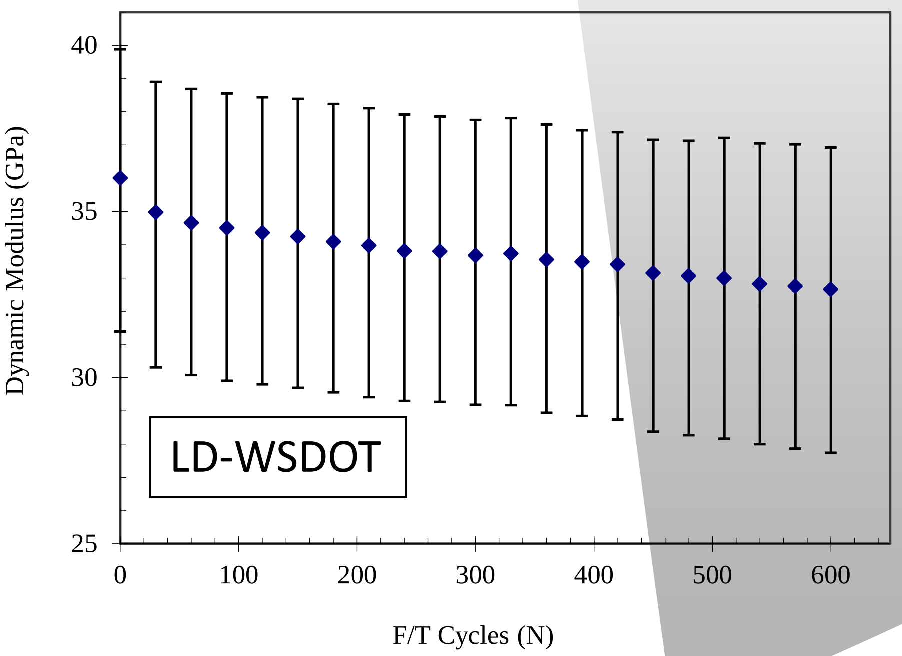




Results and Discussions

- **Dynamic Modulus Test (ASTM C215):**
  - ✓ Comparison of Dynamic modulus for NA-WSDOT and LD-WSDOT with the F/T cycles

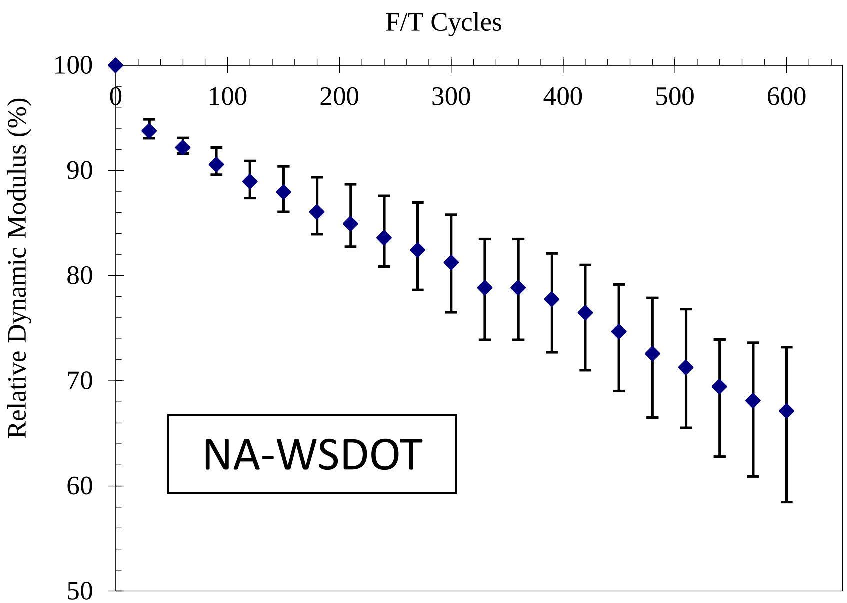


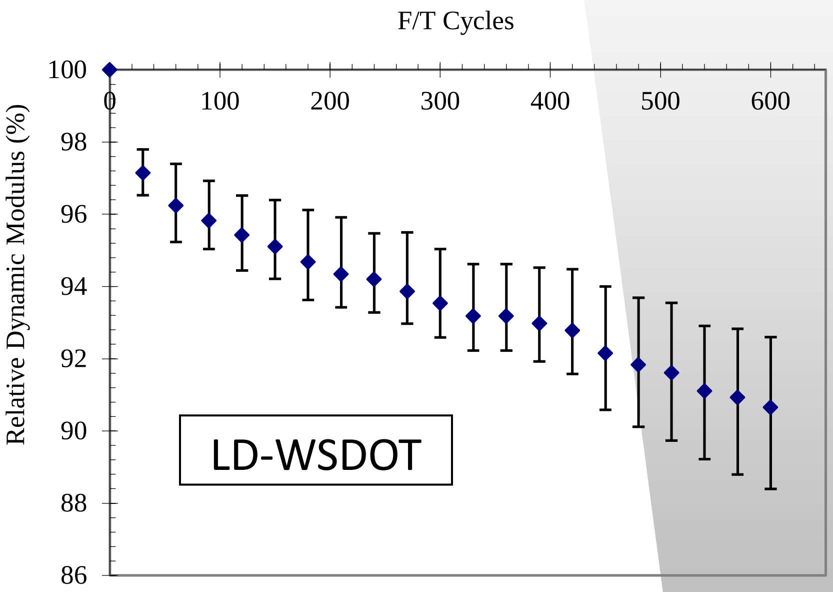


Results and Discussions

- **Dynamic Modulus Test (ASTM C215):**

✓ Comparison of Relative dynamic modulus for NA-WSDOT and LD-WSDOT with the F/T cycles



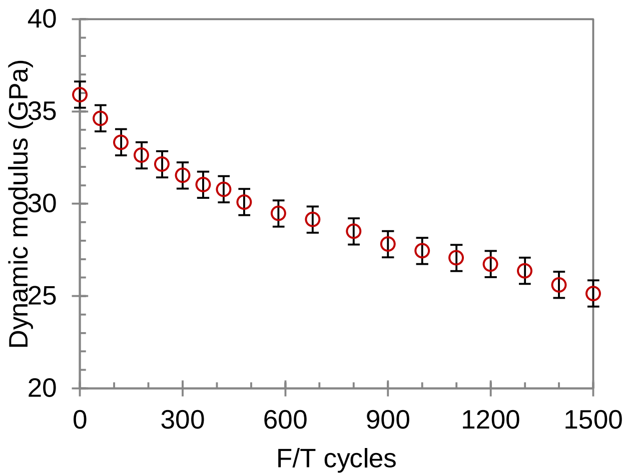


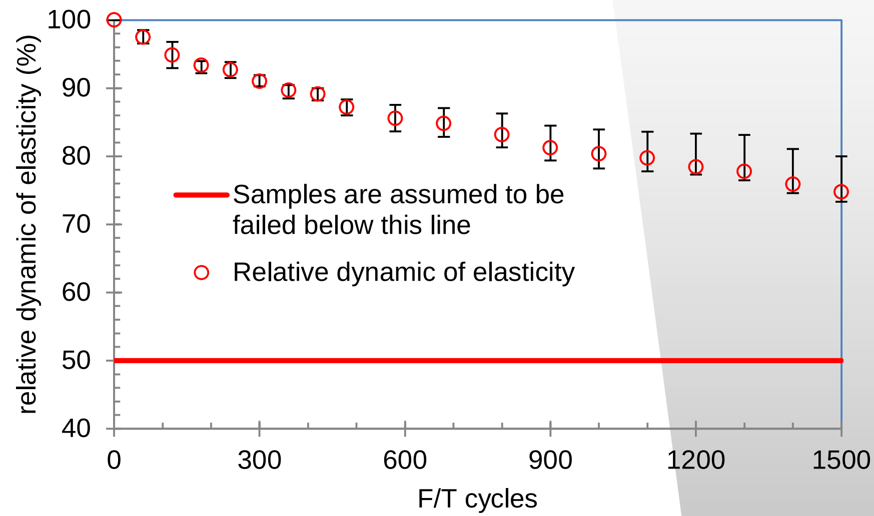
❖ The relative dynamic modulus of elasticity after certain F/T cycles. ASTM C215: < 50% indicating failure.

Results and Discussions

• Dynamic Modulus Test (ASTM C215):

✓ Dynamic modulus (LD-WSDOT: **previous study** with the samples being conditioned up to 1500 F/T cycles)





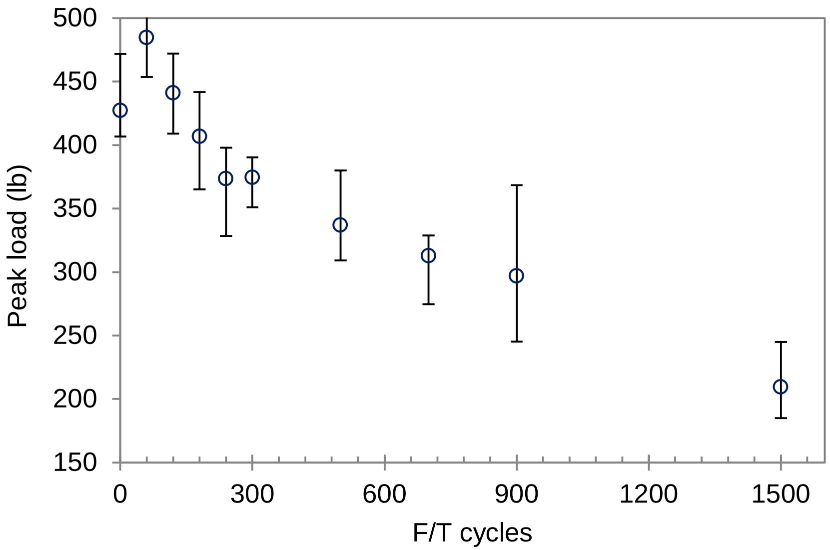
✓ The relative dynamic modulus of elasticity after certain F/T cycles. ASTM C215: < 50% as failed.

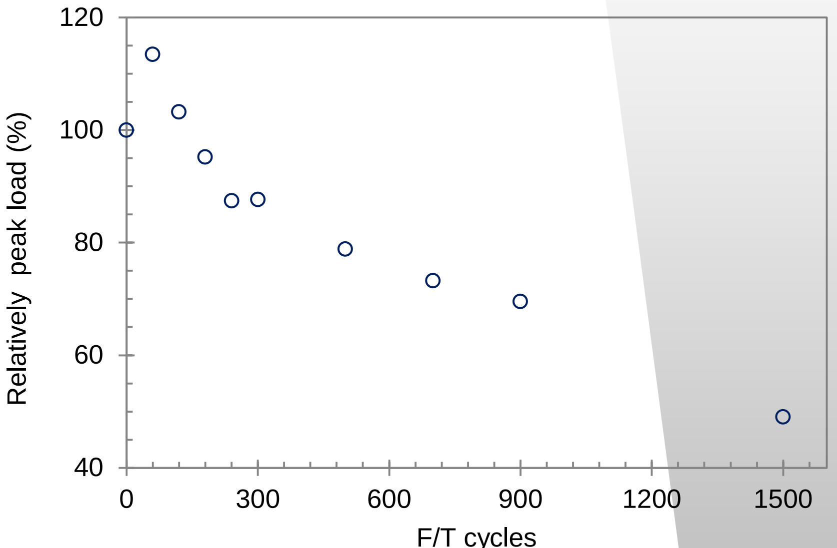
✓ At the 1,500 F/T cycle, the relative dynamic modulus of elasticity of LD-WSDOT is about 74.7%, which is still larger than the benchmark 50% as defined by ASTM C666.

Results and Discussions

- **Fracture Energy Test (RILEM 50-FMC)**

✓ Peak fracture load (LD-WSDOT: **previous study** with the samples being conditioned up to 1500 F/T cycles)





• The relative value is calculated by dividing the value at certain cycles with respect to that at 0 cycle

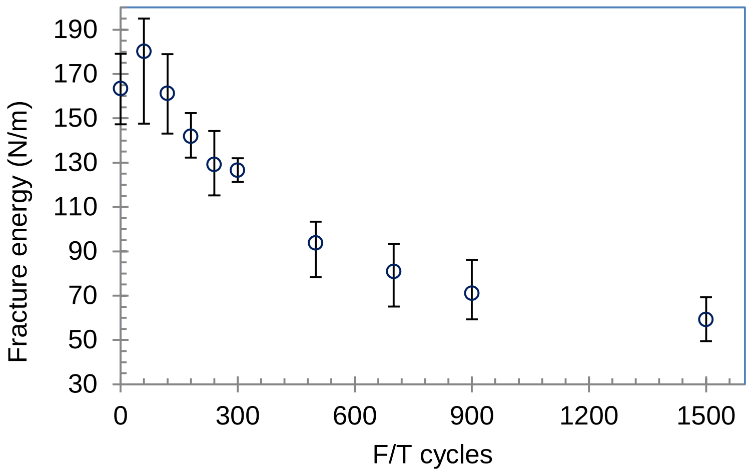
❖ Increased peak load and fracture energy at 60 cycles are due to toughened effect of ingress moisture

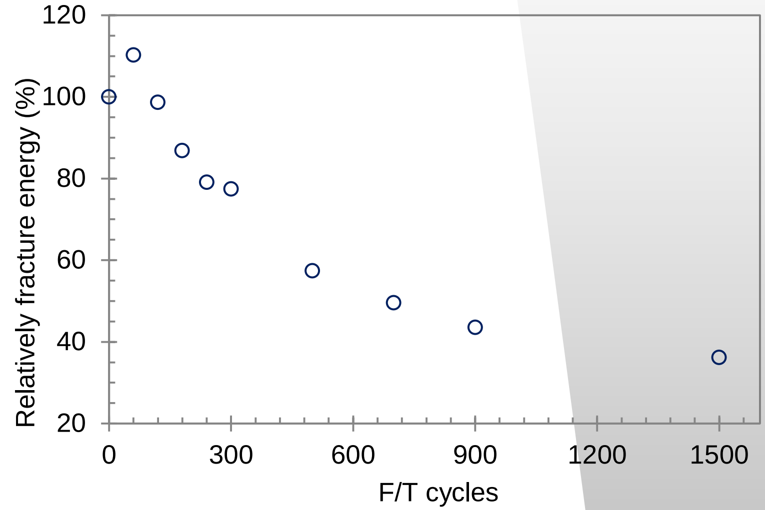
❖ After 60 cycles, the concrete begins to degrade due to F/T conditioning

❖ At the 1500 F/T cycles, the fracture peak load reduces about 50.9% (while the dynamic modulus reduces about 25.4%).

Results and Discussions

- **Fracture Energy Test**
  - ✓ Fracture energy (LD-WSDOT)

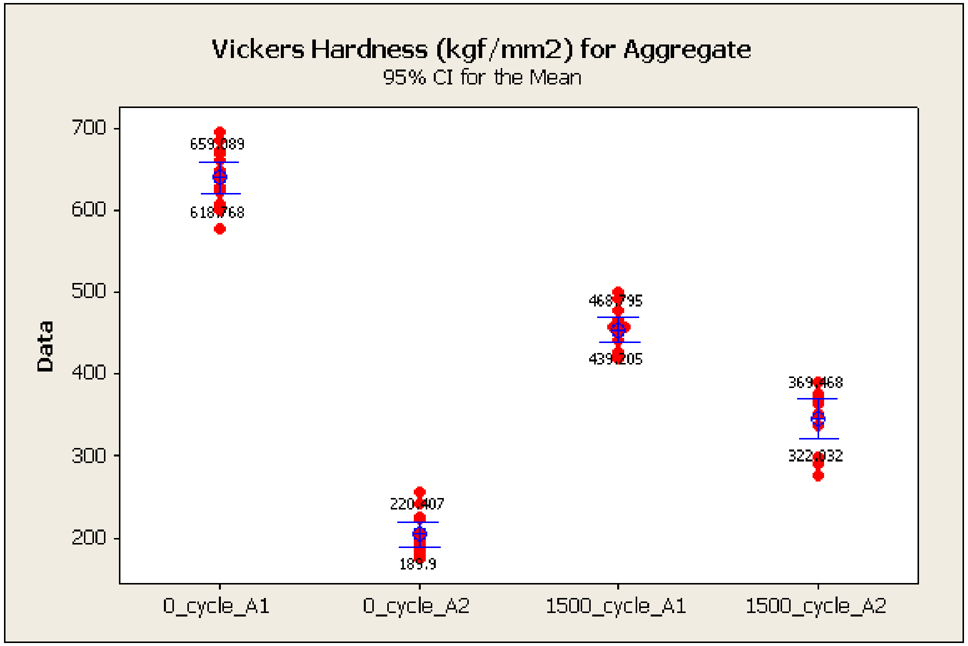




- ❖ **More than 63.8% of fracture energy reduction** after 1500 F/T cycles, which is significant
- ❖ More sensitive to screen degradation caused by the F/T conditioning
- ❖ Degradation of aggregate can be manifested by the fracture test (fracture through aggregate)

Results and Discussions

- **Vickers Indentation Test (ASTM E384):**
  - ✓ Vickers Hardness for Aggregate (LD-WSDOT)

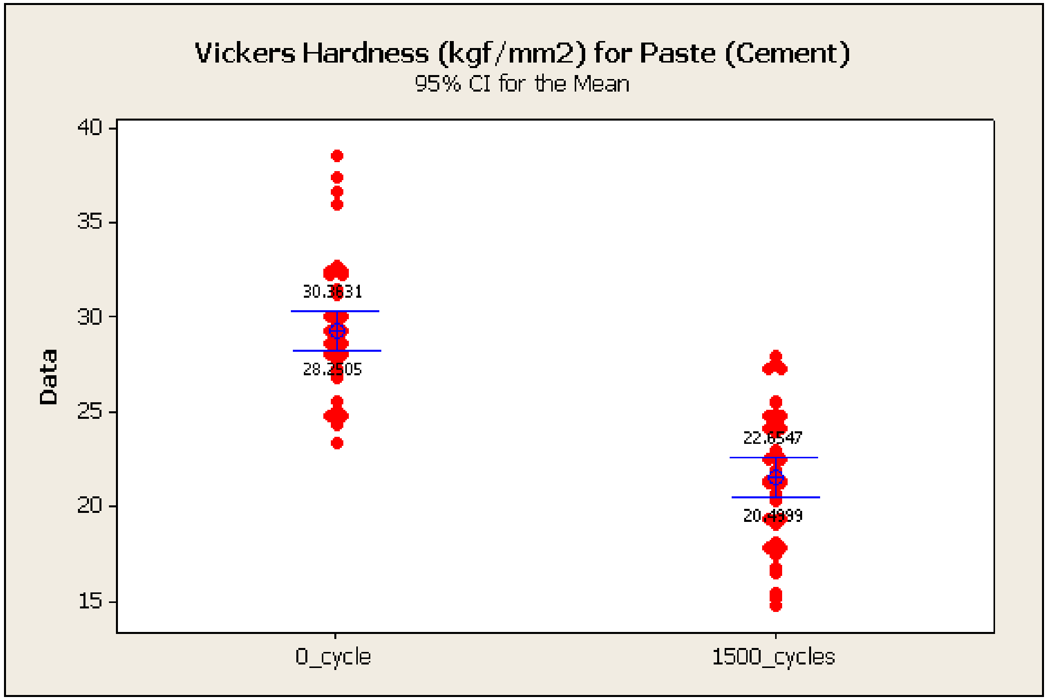


❖ Large discrepancies of the measured hardness exist for different aggregates even in the same sample;

❖ Measuring the Vickers hardness for a given aggregate in concrete under different F/T cycles can provide consistent data to indicate the accumulated damage and degradation in aggregate.

Results and Discussions

- **Vicker's Indentation Test (ASTM E384):**
  - ✓ Vickers Hardness for Paste (Cement) (LD-WSDOT)



❖ The Vickers hardness of cement paste shows the reduced values for the 1500 cycles.

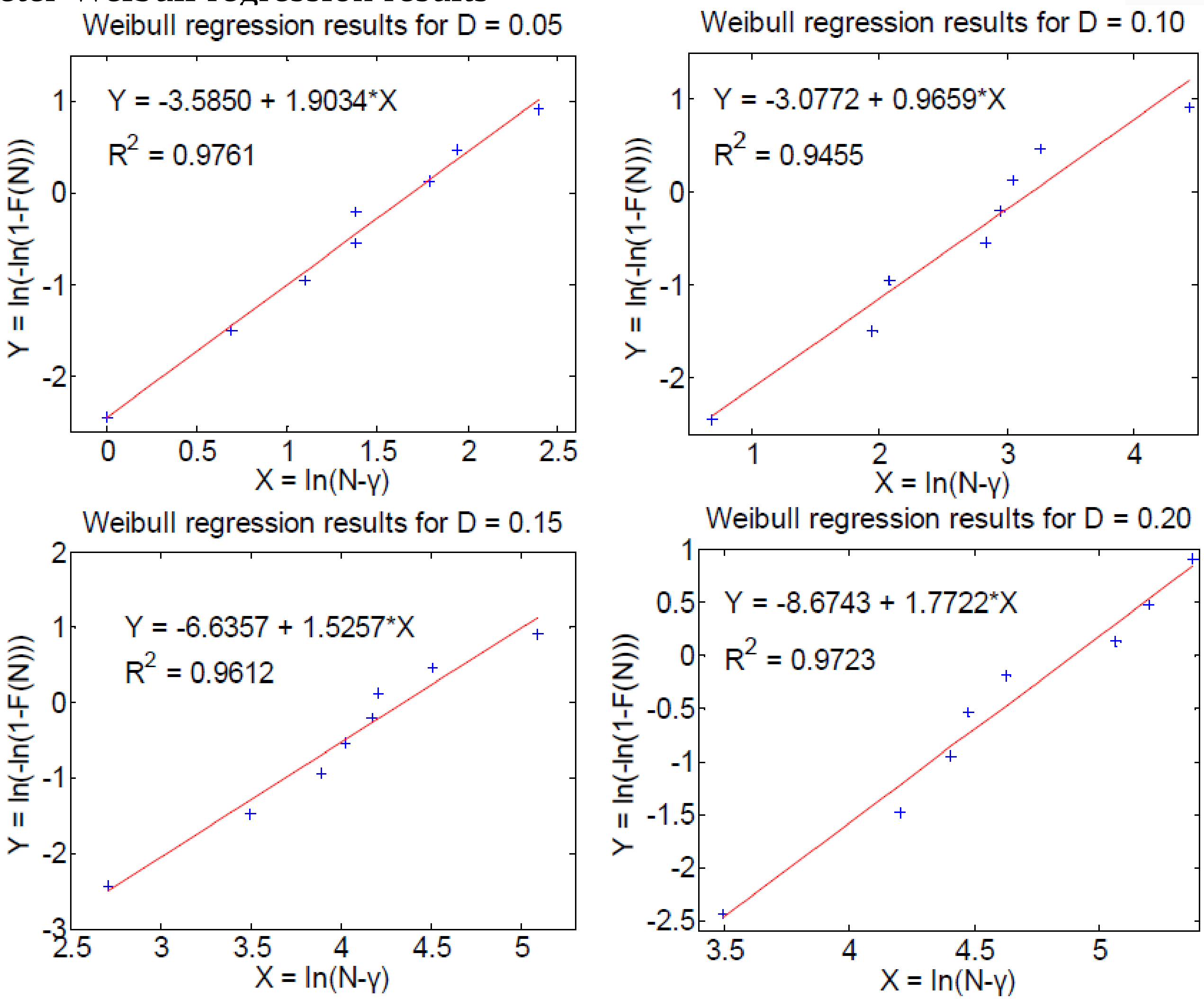
Results and Discussions

- **Probabilistic modeling results:**
  - ❖ Distribution parameters in different damage and limit cycles in various reliability probabilities

Damage (*D*)		0.05	0.10	0.15	0.20
Least life parameter γ		24	74	151	219
Characteristic life parameter α		6.5763	24.1900	77.4283	133.5695
Weibull shape parameter β		1.9034	0.9659	1.5257	1.7722
Correlation Coefficient R		0.9880	0.9724	0.9804	0.9860
Cycles in different liability probabilities	95%	25.3813	75.1173	162.0620	244.0080
	50%	29.4244	90.5517	211.8934	327.6146
	5%	35.7037	149.3223	309.9288	467.0314

Results and Discussions

- **Probabilistic modeling results:**
  - ❖ 3-parameter Weibull regression results

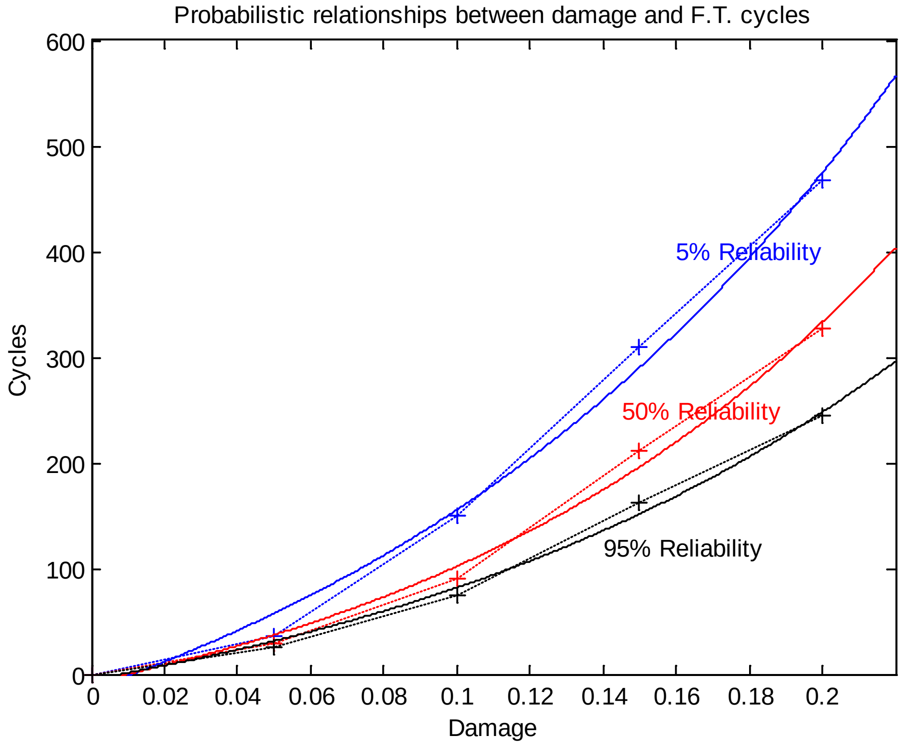


Results and Discussions

- **Probabilistic modeling results:**

❖ Relationship between the life freeze-thaw cycles and damage parameter at different reliabilities for samples with normal aggregates:

$$\begin{cases} N = 44.75816\exp(6.4767D) - 5.2008; & \text{at 95\% Reliability and } R^2 = 0.99605; \\ N = 47.57737 \times \exp(7.4789D) - 7.6253; & \text{at 50\% Reliability and } R^2 = 0.99997; \\ N = 82.70756 \times \exp(6.3335D) - 14.3904; & \text{at 5\% Reliability and } R^2 = 0.98366. \end{cases}$$

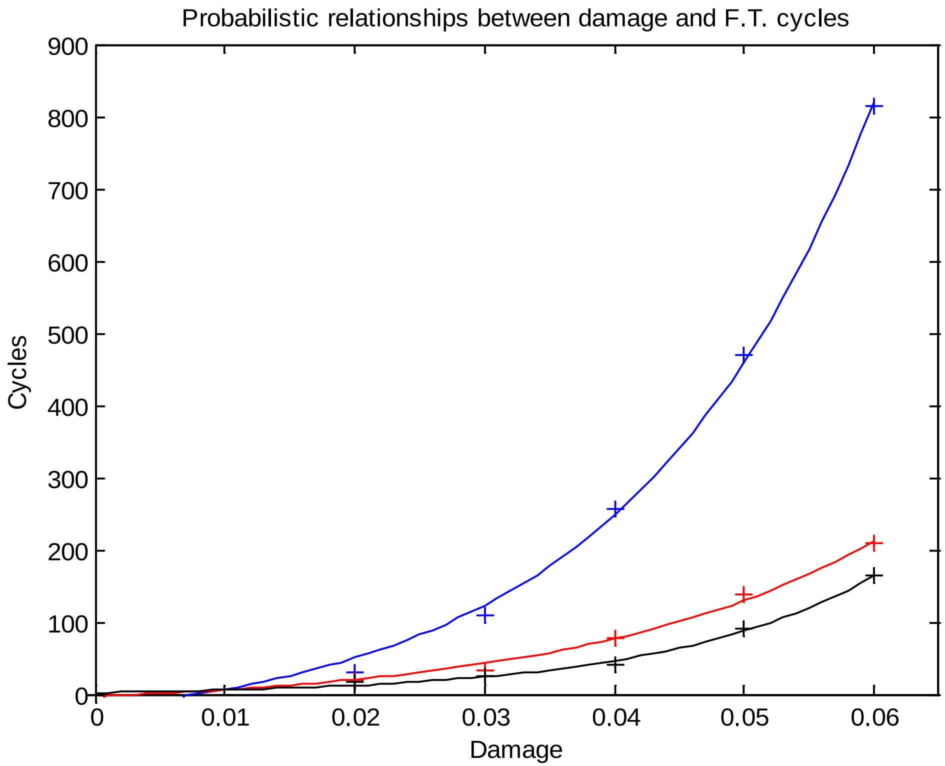


Results and Discussions

- **Probabilistic modeling results:**

❖ Relationship between the life freeze-thaw cycles and damage parameter at different reliabilities for samples with low degradation aggregates:

$$\begin{cases} N = 4.402\exp(61.87D)-1.699; & \text{at 95\% Reliability and } R^2 = 0.99652; \\ N = 16.52\exp(44.04D)-19.61; & \text{at 50\% Reliability and } R^2 = 0.99192; \\ N = 36.42\exp(52.99D)-55.00; & \text{at 5\% Reliability and } R^2 = 0.91566. \end{cases}$$



Summary and Preliminary Results

- The data for evaluation plan (tests) up to 1,500 F/T cycles of ASTM C666 (dynamic modulus) and fracture for one source of aggregate (LD-WSDOT with WSDOT degradation factor of 31) are available.
- Damage and degradation in the concrete samples can be effectively accumulated (accelerated) by using the F/T conditioning protocol (ASTM C666).
- Both the dynamic modulus of elasticity and fracture energy tests are capable of probing the material degradation by the F/T cycles.
- **Fracture energy test method is more sensitive to screen material degradation and better associated with degradation of aggregate**, since the degraded aggregate is prone to fracture. After 1500 F/T cycles, the material already shows more than **63.8% of fracture energy reduction**; while there is only about 25.3% of dynamic modulus reduction after 1500 F/T cycles.
- The Vickers indentation test can be an effective test method to discern the degradation rate of intragrannular (like aggregate and cement paste) and intergrannular (e.g., aggregate-paste interface) materials, and it can better reveal the role of aggregate degradation in concrete.

Ongoing Study

- Tests for the third round of the concrete samples with both the normal aggregate (NA-WSDOT) and low deg. aggregate (LD-WSDOT) are still in process (the samples now being conditioned up to 640 F/T cycles for the dynamic modulus test)
- Continuing development of accumulated damage prediction model(s)
- Comparison of lab data with some field data
- Recommendations of test methods and damage prediction model
- Some recommendations and conclusions as well as research direction will be provided, based on the tests of concrete with both the normal and low deg. sources of aggregates.
  - Comparisons of LD-WSDOT vs. NA-WSDOT
  - WSDOT (TM 113) degradation factor vs. F/T cycles
  - Dynamic modulus vs. fracture energy
  - Vickers indentation tests

Some recommendations

- Based on the performance benchmarks established in this project, the recommended tests (Dynamic modulus, fracture energy and Vickers hardness) should be conducted to screen degradation for concrete with different sources of normal or low degradation aggregates.

- Correlation of material properties of concrete (dynamic modulus, fracture energy, and Vickers hardness) with WSDOT TM 113 Aggregate Degradation Factor data should be empirically established with collaboration of WSDOT Mat Lab.

- Test methods, specifications and recommendations for concrete with low degradation aggregate screening should be developed.

- Accumulated damage and degradation in aggregate, cement paste and their interface can be established by consistently comparing the same aggregate, paste and interface locations in the same samples with F/T cycles through Vickers indentation test, and the Vickers hardness can reveal different rates of degradation of the constituent materials in concrete.