U.S. Department of Transportation

Federal Railroad Administration

Office of Research, Development and Technology
Washington, DC 20590

Performance-Based Specifications for Concrete Railroad Tie Freeze-Thaw Durability

DOT/FRA/ORD-24/17

Final Report | May 2024

REPORT DOCUMENTATION PAGE	*Form Approved* *OMB No. 0704-0188*

1. REPORT DATE *(DD-MM-YYYY)*	**2. REPORT TYPE**	**3. DATES COVERED** *(From - To)*
05/03/2024	Technical Report	February 9, 2017 to May 31, 2018

4. TITLE AND SUBTITLE

Performance-Based Specifications for Concrete Railroad Tie Freeze-Thaw Durability

5a. CONTRACT NUMBER
DTFR53-17-C-00006

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)

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5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
University of Florida
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8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
U.S. Department of Transportation
Federal Railroad Administration
Office of Railroad Policy and Development
Office of Research, Development, and Technology
Washington, DC 20590

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)
DOT/FRA/ORD-24/17

12. DISTRIBUTION/AVAILABILITY STATEMENT
This document is available to the public through the FRA website.

13. SUPPLEMENTARY NOTES
COR: Cameron D. Stuart

14. ABSTRACT

The University of Florida and the University of Illinois at Urbana-Champaign, in partnership with the Austrian firm voestalpine Railway Systems Nortrak, developed a performance-based manufacturing control process for ensuring the freeze-thaw durability of concrete railroad ties. Air entrainment of concrete is known to provide freeze-thaw durability, but there remains concern about how vibration and the handling of fresh concrete might degrade the size and spacing of air bubbles. Therefore, concrete railroad tie freeze-thaw durability has traditionally been measured by saw-cutting hardened concrete samples from product for freeze-thaw testing. Because damage can occur during the saw-cutting process, false negative results can occur. The relationship between concrete fresh air content and the hardened air void system after consolidation is mixture- and process-dependent. The research team developed and tested a method to determine the minimum fresh air content required to ensure durability. This project demonstrated a performance-based approach to determine the fresh concrete minimum air content required to provide sufficient air voids for durability after consolidation. Recommendations for changes to current AREMA concrete railroad tie specifications are given to ensure freeze-thaw durability in track.

15. SUBJECT TERMS
Concrete railroad ties, freeze-thaw durability, manufacturing process control

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
a. REPORT **Unclassified**	**b. ABSTRACT** **Unclassified**	**c. THIS PAGE** **Unclassified**		50	**19b. TELEPHONE NUMBER** *(Include area code)*

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. 239-18
298-102

METRIC/ENGLISH CONVERSION FACTORS

ENGLISH TO METRIC

LENGTH (APPROXIMATE)

1 inch (in)	=	2.5 centimeters (cm)
1 foot (ft)	=	30 centimeters (cm)
1 yard (yd)	=	0.9 meter (m)
1 mile (mi)	=	1.6 kilometers (km)

AREA (APPROXIMATE)

1 square inch (sq in, in^2)	=	6.5 square centimeters (cm^2)
1 square foot (sq ft, ft^2)	=	0.09 square meter (m^2)
1 square yard (sq yd, yd^2)	=	0.8 square meter (m^2)
1 square mile (sq mi, mi^2)	=	2.6 square kilometers (km^2)
1 acre = 0.4 hectare (he)	=	4,000 square meters (m^2)

MASS - WEIGHT (APPROXIMATE)

1 ounce (oz)	=	28 grams (gm)
1 pound (lb)	=	0.45 kilogram (kg)
1 short ton = 2,000 pounds (lb)	=	0.9 tonne (t)

VOLUME (APPROXIMATE)

1 teaspoon (tsp)	=	5 milliliters (ml)
1 tablespoon (tbsp)	=	15 milliliters (ml)
1 fluid ounce (fl oz)	=	30 milliliters (ml)
1 cup (c)	=	0.24 liter (l)
1 pint (pt)	=	0.47 liter (l)
1 quart (qt)	=	0.96 liter (l)
1 gallon (gal)	=	3.8 liters (l)
1 cubic foot (cu ft, ft^3)	=	0.03 cubic meter (m^3)
1 cubic yard (cu yd, yd^3)	=	0.76 cubic meter (m^3)

TEMPERATURE (EXACT)

[(x-32)(5/9)] °F = y °C

METRIC TO ENGLISH

LENGTH (APPROXIMATE)

1 millimeter (mm)	=	0.04 inch (in)
1 centimeter (cm)	=	0.4 inch (in)
1 meter (m)	=	3.3 feet (ft)
1 meter (m)	=	1.1 yards (yd)
1 kilometer (km)	=	0.6 mile (mi)

AREA (APPROXIMATE)

1 square centimeter (cm^2)	=	0.16 square inch (sq in, in^2)
1 square meter (m^2)	=	1.2 square yards (sq yd, yd^2)
1 square kilometer (km^2)	=	0.4 square mile (sq mi, mi^2)
10,000 square meters (m^2)	=	1 hectare (ha) = 2.5 acres

MASS - WEIGHT (APPROXIMATE)

1 gram (gm)	=	0.036 ounce (oz)
1 kilogram (kg)	=	2.2 pounds (lb)
1 tonne (t)	=	1,000 kilograms (kg)
	=	1.1 short tons

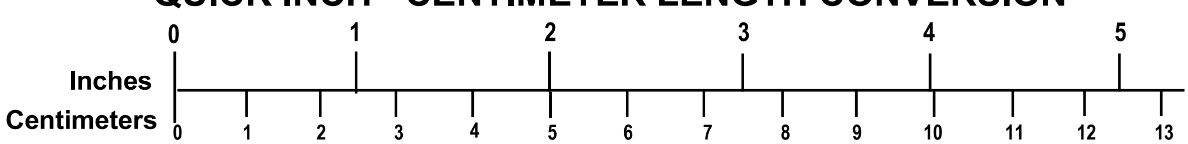
VOLUME (APPROXIMATE)

1 milliliter (ml)	=	0.03 fluid ounce (fl oz)
1 liter (l)	=	2.1 pints (pt)
1 liter (l)	=	1.06 quarts (qt)
1 liter (l)	=	0.26 gallon (gal)
1 cubic meter (m^3)	=	36 cubic feet (cu ft, ft^3)
1 cubic meter (m^3)	=	1.3 cubic yards (cu yd, yd^3)

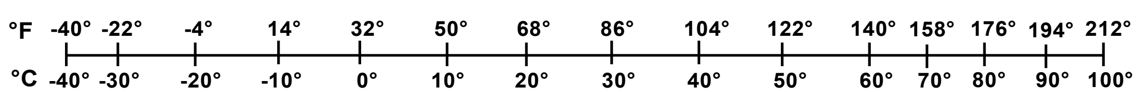
TEMPERATURE (EXACT)

[(9/5) y + 32] °C = x °F

QUICK INCH - CENTIMETER LENGTH CONVERSION



QUICK FAHRENHEIT - CELSIUS TEMPERATURE CONVERSIO



For more exact and or other conversion factors, see NIST Miscellaneous Publication 286, Units of Weights and Measures. Price $2.50 SD Catalog No. C13 10286

Updated 6/17/98

Acknowledgments

This project was performed with the cooperation of industry partner voestalpine Railway Systems Nortrak. The assistance of Steve Mattson is gratefully acknowledged.

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Executive Summary

Researchers from the University of Florida and the University of Illinois at Urbana-Champaign, in partnership with voestalpine Railway Systems Nortrak, developed a performance-based manufacturing control process for ensuring the freeze-thaw durability of concrete railroad ties. The research team recommended changes to the American Railway Engineering and Maintenance-of-Way Association (AREMA) concrete railroad tie material and fabrication specifications to ensure their durability. This research was conducted under a Federal Railroad Administration contract between February 9, 2017 and May 31, 2018.

Air entrainment of concrete is known to provide freeze-thaw durability, but concerns remain over how vibration and the handling of fresh concrete might degrade the size and spacing of air bubbles. Therefore, concrete railroad tie freeze-thaw durability has traditionally been measured by saw-cutting hardened concrete samples from product for freeze-thaw testing. Because damage can occur during the saw-cutting process, false negatives can occur. The research team developed and validated a match vibration process to make concrete samples for freeze-thaw quality control testing. In this process, the team measured the vibration energy imparted on concrete railroad ties during consolidation using submersible accelerometers. Samples for testing were then made and consolidated on a vibrating table using the same vibration energy measured during tie manufacture. The research team validated this process by making concrete ties and match-vibrated samples from the same concrete batches. Hardened air void analysis of both sample sets showed the validity of this approach.

The relationship between concrete fresh air content and the hardened air void system after consolidation is mixture- and process-dependent. Researchers developed and tested a method to determine the minimum fresh air content required to ensure durability for a particular mixture and plant. They measured the fresh air content and hardened air void system of product for five different fresh air contents. They then used the fresh air content-hardened concrete air relationship to determine the minimum fresh air content required to provide a hardened air system required for durability.

Researchers examined current specifications for concrete railroad tie materials and manufacturing in light of project results and current concrete materials industry best practices and guidelines. They developed and validated recommendations for changes to the material and testing requirements to ensure freeze-thaw durability to include the performance-based approach. They also made recommendations to prevent delayed ettringite formation (DEF), an expansive form of concrete cracking and deterioration. The concrete temperature should be maintained below 158°F (70°C) to prevent DEF. As long as this curing temperature is not exceeded, no other preventive measures or tests, such as the Duggan concrete expansion test, are required. To prevent alkali-aggregate reaction in concrete, the team recommends specifications refer to the new ASTM C1778, Standard Guide for Reducing the Risk of Deleterious Alkali-Aggregate Reaction in Concrete. This specification will be maintained by the concrete industry, reducing the need for continued updates of AREMA specifications to incorporate new knowledge.

1. Introduction

Researchers at the University of Florida and the University of Illinois at Urbana-Champaign, in partnership with voestalpine Railway Systems Nortrak, studied the relationship between concrete air content and the freeze-thaw durability of concrete railroad ties. This research was conducted under a Federal Railroad Administration contract between February 9, 2017 and May 31, 2018.

1.1 Background

Concrete is an excellent material for producing high-quality, serviceable, and durable railway crossties. However, concrete can be vulnerable to freeze-thaw cycles that are common in most of North America. Freezing can cause internal pressure and damage when water expands. Properly entraining air bubbles into a fresh concrete mixture is known to alleviate this issue, as tiny air bubbles provide space for pressure relaxation [1] [2]. Too much air in a fresh mixture, however, often leads to an unacceptable reduction in concrete strength [3]. Thus, evaluating the size distribution and quantity of the air entrainment is a key factor for predicting the durability of concrete crossties.

In crosstie production, testing concrete freeze-thaw durability is critical for quality control. Although testing the fresh air content in concrete using an air meter is fast, it requires correlation to materials and plant processes to be predictive of freeze-thaw performance, as shown in Figure 1 [4] [5] [6]. Therefore, testing the air content and the spacing factor of hardened concrete, as specified by ASTM C457, is commonly preferred and specified in the industry [7]. This approach has drawbacks, including the expense and the delayed feedback of commercial testing services. In addition, samples are often extracted directly from production crossties, and the extraction is time-consuming and wasteful.

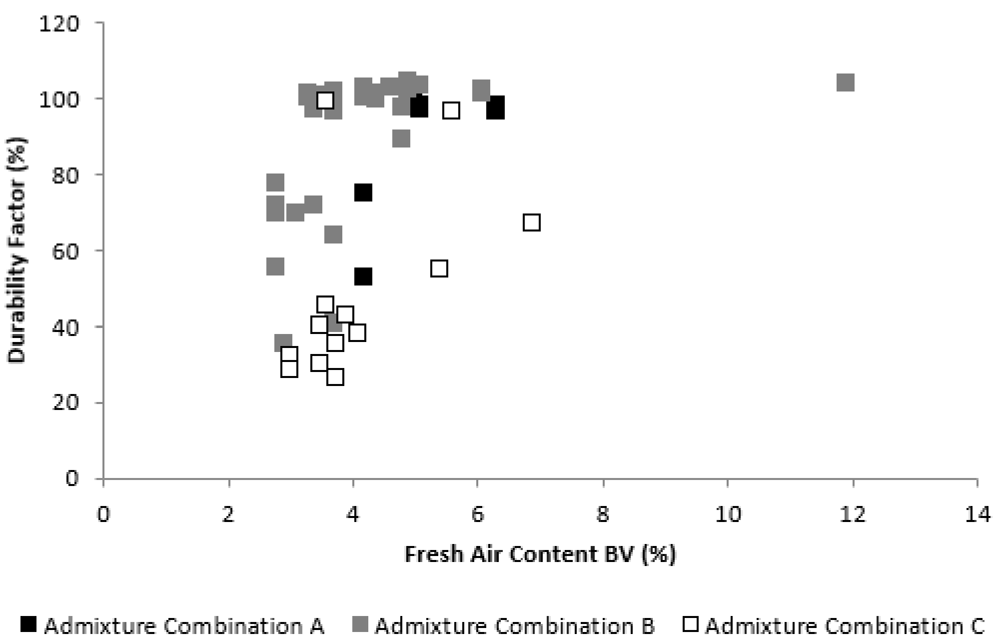

Figure 1. Relationship of fresh air content and durability factor

1.2 Objectives

To solve the issues stated on concrete railroad tie quality control, the objectives of this project were to develop and validate a new performance-based testing approach for concrete freeze-thaw quality control. A new concept of using match-vibration to measure the concrete air void system properties after placement and consolidation was introduced to accomplish this objective.

1.3 Overall approach

The approach used in this project can be summarized as follows:

- Validate the concept of match-vibration for concrete manufacturing process quality control.
- Introduce industry to performance-based concrete freeze-thaw durability specifications.
- Demonstrate use of performance-based concrete freeze-thaw quality control procedures in a plant environment.

The research team validated this approach through air void experiments performed at a precast concrete railroad tie manufacturing plant. The team made fresh and hardened air void measurements on five fresh concrete mixtures with different amounts of air entrainment. In addition to preparing the normal crosstie samples, the fresh mixtures were cast into cylinder molds and then consolidated on a specially designed vibration table to match the vibration intensity of the rod vibrator used for consolidating the crosstie samples. To validate this approach, the vibration intensity of the fresh mixtures in the two types of molds was measured using accelerometers, and an automated hardened air void analysis was carried out on those samples. Mixtures were also made with increasing air content to demonstrate how to determine the minimum air content required for concrete freeze-thaw durability. This information was used to develop a performance-based specification for concrete railroad tie freeze-thaw durability.

1.4 Scope

Researchers studied the concrete air void system in concrete railroad ties and samples that were match-vibrated at a precast concrete railroad tie manufacturing plant. Based on this work, they recommended changes to AREMA 30 concrete crosstie material specifications.

1.5 Organization of Report

This report contains the following sections:

Section 2: Materials and Mix Designs

Section 3: Apparatus and Procedure

Section 4: Results and Discussion

Section 5: Ballots for the Performance Specification

Section 6: Conclusion

Appendix A: Tie and Cylinder Acceleration Data

2. Materials and Mix Designs

The research team used a conventional concrete mix design in commercial use for casting concrete crossties. Six mixtures were designed, and their only variable was the dosage of the air-entraining admixtures in each mix. Table 1 shows the air content measured per ASTM C231 [8]. A schematic of the air mixture content is shown in Figure 2.

Table 1. Air content by air meter for mix designs

Mix ID	Air Content (%)
A	5.8
B	4.6
C	0.8
D	6.1
F	9

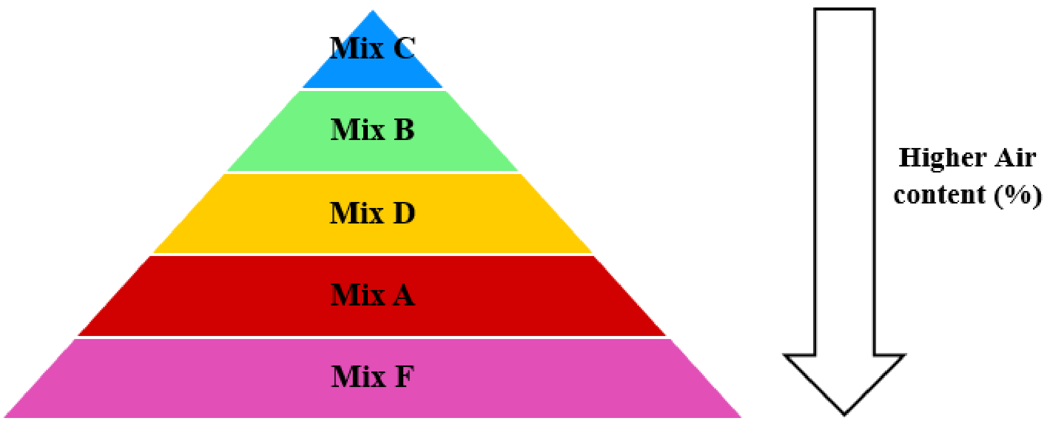

Figure 2. Air content by mix design

The fresh concrete was cast into the 4-inch by 8-inch cylinders and commercial crosstie molds. Different levels of vibration were applied to the cylinders and crossties. A typical rod vibrator for vibrating concrete was used for consolidation, and the vibrator was inserted inside the concrete at eight different locations with equal spacing, as shown in Figure 3. Accordingly, two accelerometers were put inside the concrete: sensor 1 at the center of the tie and sensor 2 at one end of the tie. The immersion vibrator was inserted into the concrete starting from point 1 to point 8.

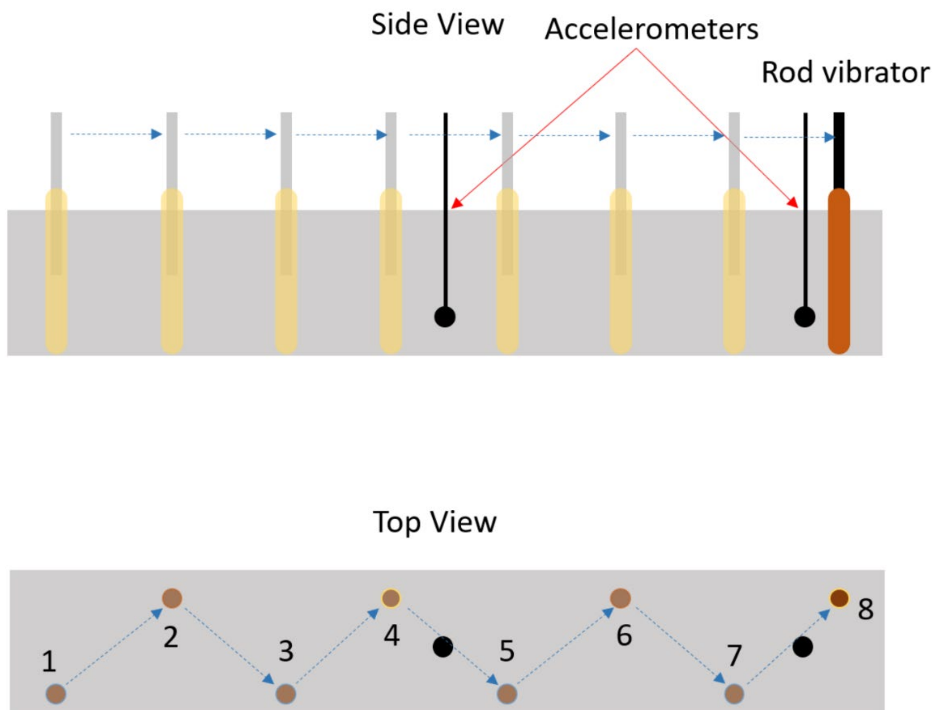

Figure 3. Schematic of the vibrating locations and sensor placement in the concrete tie

Table 2 shows the vibration period for each test on both cylinders and concrete ties; 15 concrete ties and 15 cylinders were tested.

Table 2. Vibration period for each test

Test Number	Vibration Level	Vibration Period (seconds)
1	No vibration	0
2	Typical vibration	6
3	Excessive vibration	12

For simplicity, the samples were named in a way such that they represented, in sequence, the mixture name (along with air entrainment), mold type, and length of vibration. Figure 4 shows the labeling method; for example, D(TA)_T_6 represents Mixture D with the target air that was cast in the crosstie mold and vibrated for 6 seconds.

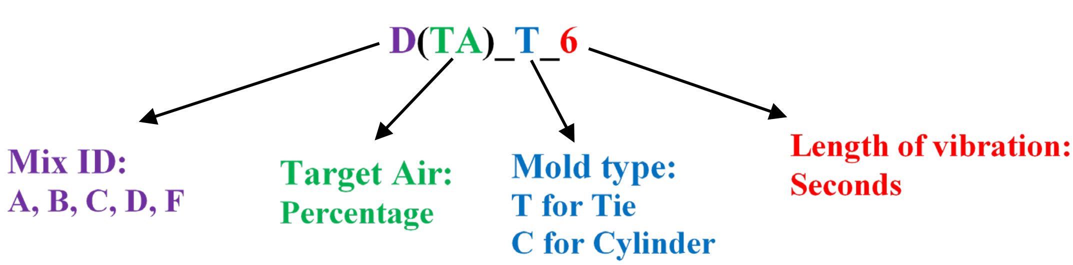

Figure 4. Labeling scheme for the samples and tests

3. Apparatus and Procedure

The research team measured concrete fresh air content according to ASTM C231 [8] using current plant sampling procedures after mixing. The team performed hardened concrete air void analysis on match-vibrated samples and samples extracted from concrete railroad ties using an image-analysis procedure compliant with ASTM C457 [7].

3.1 Measuring Vibration Intensity

The intensities of the vibration experienced by the fresh concrete in both the crosstie molds and the cylinder molds during the consolidation were measured using accelerometers immersed in the fresh concrete. The vibration testing setup is shown in Figure 5. The acceleration measurement was conducted with two PCB 3-axis accelerometers (model W356A12), connected to a data logger for real-time data acquisition and interpretation. The raw data were further processed to calculate the acceleration in each of the three directions and the magnitude of the overall acceleration experienced by each sensor, presented as g-force. The sampling frequency of the accelerometers was set as 2,500 Hz, more than 10 times the vibration frequency of the vibrator used in the factory (235 Hz). This practice ensured a desirable resolution for capturing details of the vibration [9]. After each test, results were stored in a computer for post-processing.

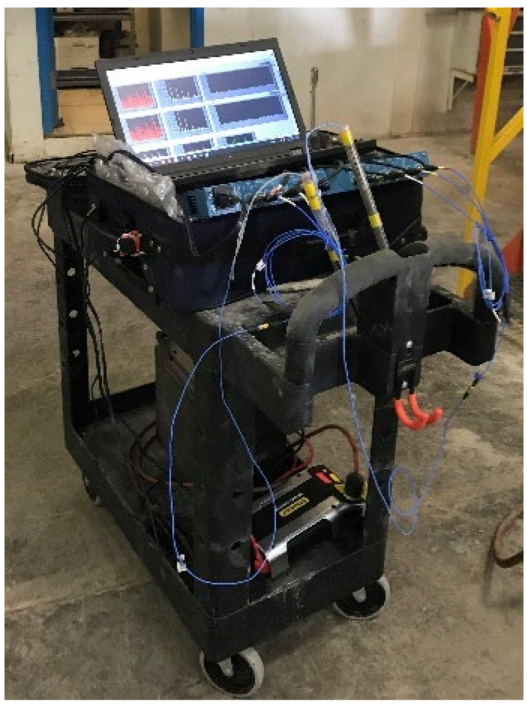

Figure 5. Acceleration measurement equipment cart

The vibration measurement from the crosstie is illustrated in Figure 3-2. The accelerometers were injected into the fresh concrete immediately after casting at two locations: the mid-point and near one end of the crosstie mold. The injection was conducted with a guiding tube to ensure precise sensor placements, at 1 inch from the bottom. After the injection, the guiding tube was lifted by 1/2 inch to let it fully detach with the sensor, eliminating any potential interference from the tube. During testing, a worker consolidated the fresh concrete with eight evenly spaced insertions of a rod vibrator across the entire length of the mold. The duration of each insertion was controlled: 0 seconds (no vibration), 6 seconds (moderate vibration), and 12 seconds (excessive vibration). After vibration measurements were collected, the crosstie samples were cured in place for 24 hours until demolding. After curing, a hardened concrete sample of each mixture was extracted vertically from the top-center of the crosstie, as shown in Figure 6.

Figure 6. Measuring the acceleration in the vibrated fresh concrete in the concrete crosstie mold

Figure 7. Sample extraction from a concrete crosstie

Vibration intensity was also measured in the cylinder samples, as shown in Figure 7, using only one sensor positioned in the center of each cylinder sample. For each group of samples, fresh concrete from the same batch was cast into 4-inch by 8-inch standard cylinders for the match study. A table vibrator driven by compressive air was prepared for this test, as shown in Figure 8. A steel bracket held the cylinder mold tight to the table to ensure the vibration energy was effectively transferred to the samples. The vibrator was designed to have the same vibration frequency as the rod vibrator used for the crossties. By tuning the air valve, air flow could be regulated to adjust vibration intensity. Vibration time was also controlled at 0 seconds (no vibration), 6 seconds (typical vibration), and 12 seconds (excessive vibration). After testing, the samples were cured in the cylinder molds and then prepared for hardened air void analysis.

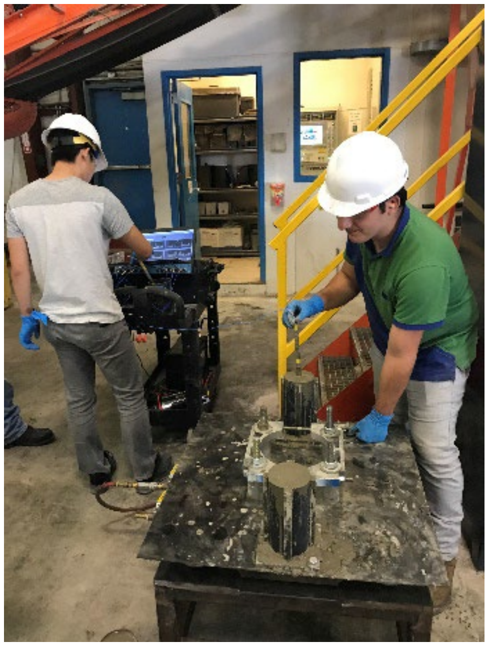

Figure 8. Measuring the acceleration in the vibrated fresh concrete in the cylinder mold

Figure 9. Air-driven table vibrator

3.2 Automated Hardened Air Void Analysis

Researchers saw-cut the cylinder samples in halves for air-void analysis. The cross-section size was 4 inches by 8 inches. They then saw-cut the tie samples to an approximate area of 5 inches by 4 inches and polished them in accordance with ASTM C457 [7]. The methods of sample preparation, image acquisition, and image processing followed in this study were like those described in Song, et al. [10].

The polished surfaces, after cleaning and drying, were treated with 5 percent phenolphthalein in an ethanol solution to distinguish the cement paste from the air voids and aggregate phases. Shortly after drying, an orange, fluorescent chalk powder filled the air voids exposed on the sample surface. After all the air voids were filled, a sharp razor blade was slowly run across the surface at a very low angle to strike off the excess powder. To obtain a high-resolution colored scan of each prepared sample, the polished surface was then placed on a flatbed scanner with a resolution of 4,800 dpi. The edge length of each pixel was 5.3 µm. Three scans of 2 inches by 2 inches were obtained from each sample, rendering a total scanning area of 12 in^2 that satisfied the minimum requirements in ASTM C457 [7]. Figure 10 (a) shows an example of the surface after polishing but before treatments, (b) the sample after phenolphthalein treatment, and (c) the sample after the orange (crush chalk) powder was pressed into the voids [8].

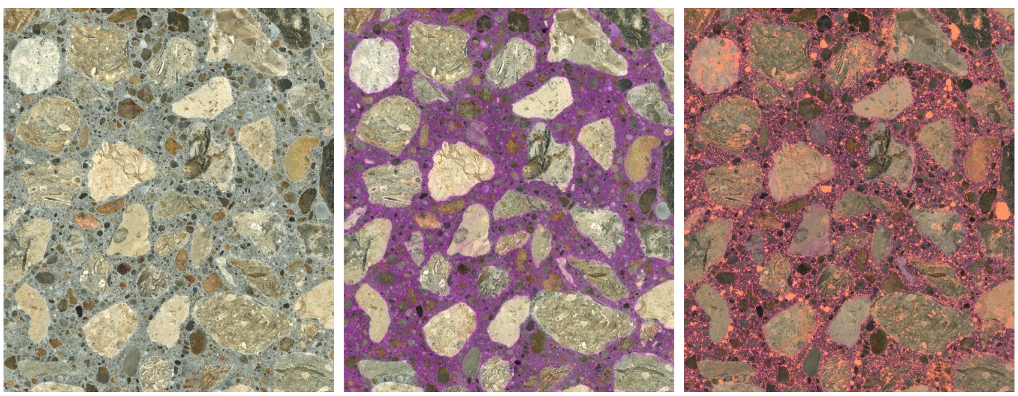

Figure 10. Sample preparation for air void analysis, left to right: (a), (b), (c)

After acquiring the scans, researchers processed the images using a series of computer programs. Multispec, a free image-segmentation software package, was used to recognize the three phases in the scans (air void, paste, and aggregate) [11]. This was done in a semi-automatic manner by manually sampling the two colored regions (fluorescent orange for the air voids, pink for the cement paste), and then using Multispec to segment the RGB scans into the three corresponding phases (air voids, paste, aggregates [no color]). Automated image segmentation was achieved using an image analysis algorithm in Multispec, the ECHO Classifier (Extraction and Classification of Homogeneous Objects), in which spectral-spatial features of the categorized selections were used for the recognition. For example, the spectral characteristics could be the color contrast created by the fluorescent chalk powder representing air voids, and spatial characteristics involved with the change in color from an air void to adjacent, pink-colored paste causing discontinuity of homogeneity at the phase boundary. For the final processing work, researchers used ImageJ, developed by the National Institutes of Health [12]. During the processing, air voids smaller than 20 µm, aggregates smaller than 100 µm, and voids in the aggregate were filtered out as a noise-reduction step to get a ternary image. Finally, a MATLAB script calculated the ASTM C457 parameters from the ternary image.

4. Results and Discussion

Researchers used concrete tie acceleration measurements during vibration to determine vibration energy required for match vibration. They then used fresh and hardened air void measurements of concrete tie and companion samples to validate the concept of match vibration for freeze-thaw testing.

4.1 Vibration Effects on the Fresh Concrete Mixtures

For the crosstie samples, the fresh mixtures of Groups A, B, C, D, and F were tested for vibration effects. The three samples in each group experienced 0-, 6-, and 12-second consolidation for each injection of the rod vibrator (8 injections in total; see Figure 3). Appendix A contains the acceleration data for each tie and cylinder measured. The results of the samples in Group A are discussed below as an example. The recorded vibration history collected by the two sensors in sample A(HA)_T_6 is given in Figure 11. Sensor 1 detected the vibration in the middle of the crosstie mold, while sensor 2 was placed at the one end of the mold.

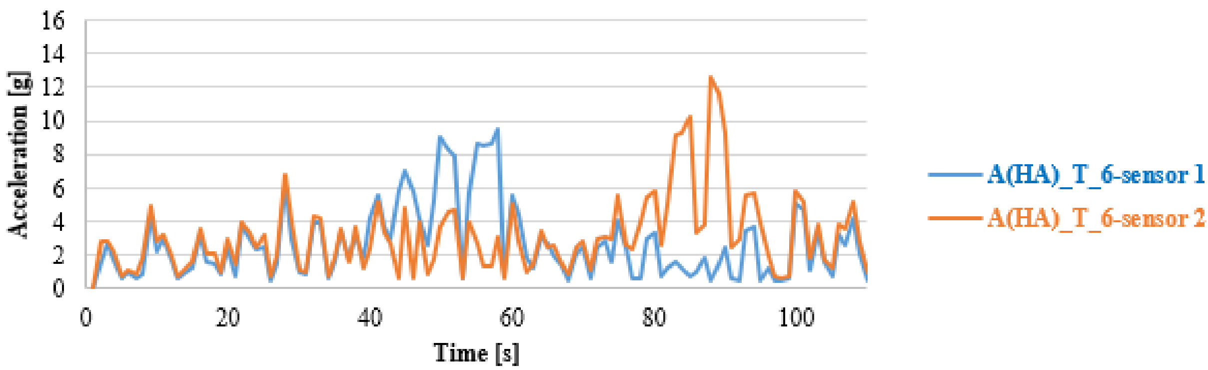

Figure 11. Vibration history of the two sensors embedded in sample A(HA)_T_6

The regions where the two sensor signals were roughly identical (0–40 seconds, 60–75 seconds, and after 95 seconds) represent the background vibrations in the plant and other environmental noise. The regions where the signals differed (40–60 seconds, 75–95 seconds) represent the times when the rod vibrator was in use.

To support the comparison between the mix types, vibration time periods, and the hardened air void analysis, the researchers decided to isolate the peak acceleration levels of each time history. Given the relative insensitivity of each sensor to vibrations near the other sensor, calculating the difference between the two sensors removed the background vibrations from the data and isolated the peak vibration periods that correspond to the immersion rod vibration times. This calculated, relative acceleration is shown in Figure 12.

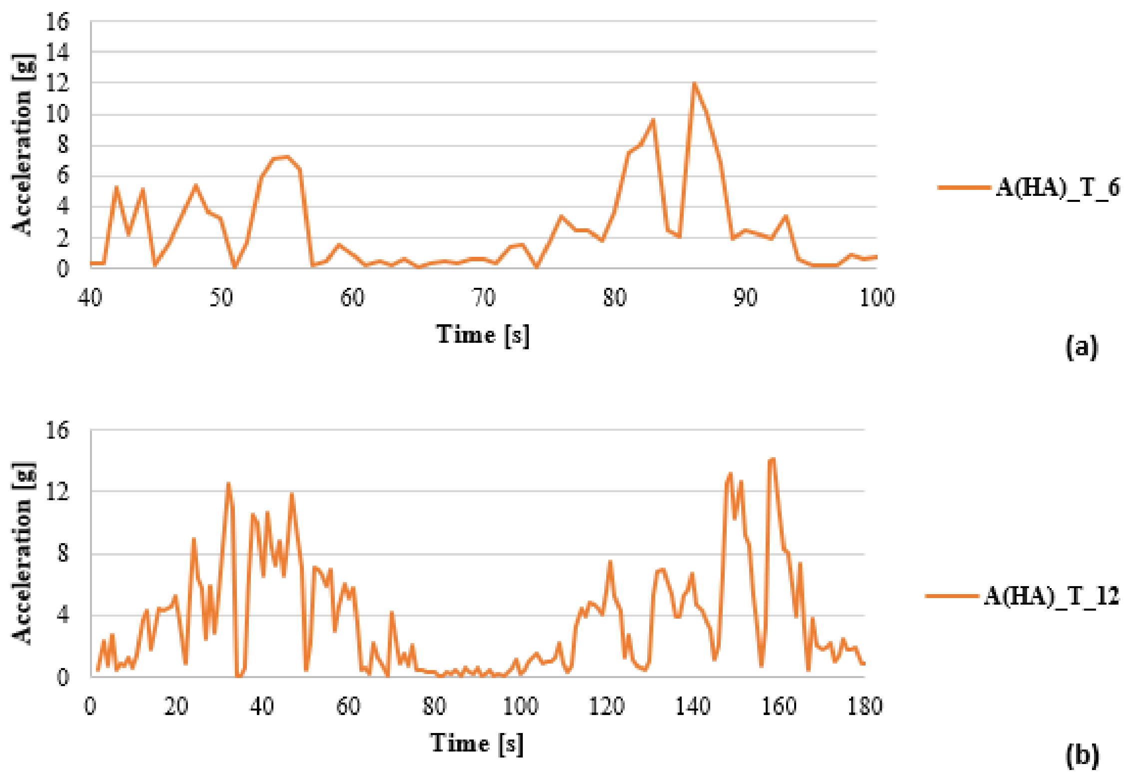

Figure 12. Vibration history with background plant vibration removed: (a) sample A(HA)_T_6 (moderate vibration) and (b) sample A(HA)_T_12 (excessive vibration)

Researchers calculated the vibration profile of sample A(HA)_T_12 in the same manner, as shown in Figure 12 (b). The excessive vibration profile of sample A(HA)_T_12 was almost double of the peak values of sample A(HA)_T_6, and the peak durations were longer. Therefore, one could expect a 12-second vibration to make a substantial difference in the consolidation of the concrete, which should be reflected in the results of the hardened air void analysis.

The results of the vibration tests are summarized in Figure 13 for the concrete tie and cylinder experiments. The charts plot the maximum calculated acceleration of each mixture subjected to 6- and 12-second vibration times. For each of the five mixtures, the 12-second vibration resulted in a higher vibration intensity than the 6-second data. The vibration intensity tended to be lower as the dosage of the air entrainment was reduced. The maximum vibration recorded from the cylinder samples are given in Figure 13 (b), for comparison to the tie samples. The results indicated small increases in peak acceleration when the vibration was extended from 6 to 12 seconds. The vibration levels in all the cylinder samples ranged from 12 to 20g, and the peak accelerations of the cylinder samples were higher than those measured from the tie samples. This difference was likely due the steel cylinders tightly constraining the concrete. In addition, the cylinder samples were expected to be consolidated more uniformly, as the total volume of the cylinder sample was much smaller than the tie sample. Overall, the potential of simulating the real vibration scenario in the fresh concrete in the crosstie mold by conducting the match-vibration on the cylinder samples showed promise; however, it may be difficult for plants to control precisely.

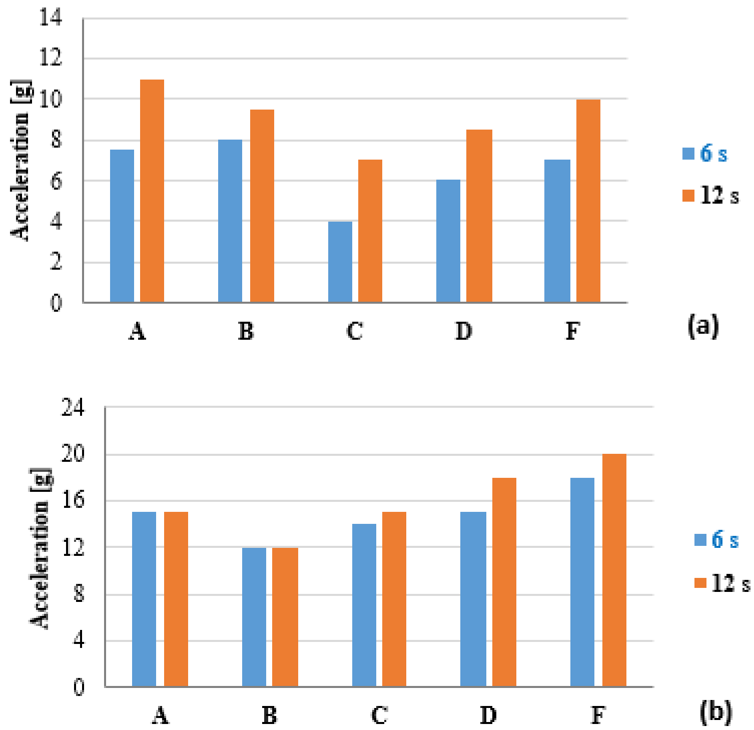

Figure 13. Maximum calculated accelerations for each mix type: (a) in the crosstie molds (middle sensor) and (b) in the cylinder molds

Figure 14 shows the original scan and its ternary image after processing for sample C(NA)_T_6 to represent the quality of the image processing work. Mixtures A, B, C, D, and F had fresh air content values of 5.8 percent, 4.6 percent, 0.8 percent, 6.1 percent, and 9.0 percent, respectively, as measured with an air meter (Table 1). Based on the processed ternary images, the ASTM C457 parameters were also obtained for each sample. The parameters of air content, paste content, and spacing factor for the tie and the cylinder samples are given in Table 3 and Table 4, respectively.

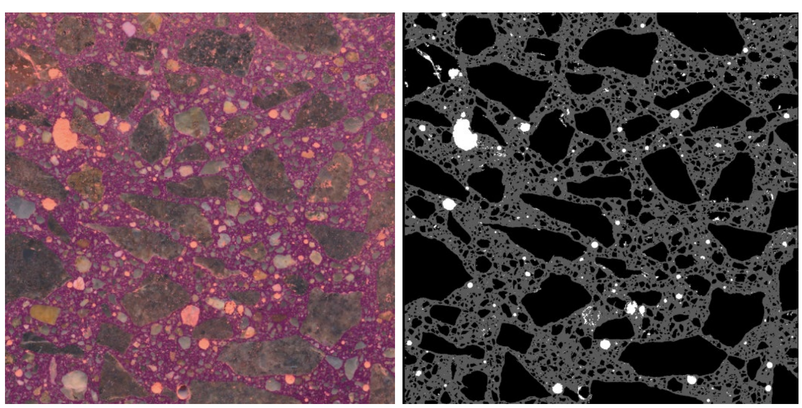

Figure 14. Original scan and its ternary image after processing of sample C(NA)_T_6

Table 3. Air void parameters of the tie samples

Sample	Air [%]	Paste [%]	Spacing factor [mm]
A(HA)_T_0	8.88	49.24	0.217
A(HA)_T_6	7.85	45.25	0.261
A(HA)_T_12	7.10	47.20	0.179
B(LA)_T_0	4.93	51.37	0.193
B(LA)_T_6	6.10	46.75	0.237
B(LA)_T_12	5.88	42.32	0.158
C(NA)_T_0	1.31	40.18	0.513
C(NA)_T_6	1.57	47.04	0.802
C(NA)_T_12	1.38	43.32	0.755
D(NA)_T_0	6.64	42.94	0.248
D(TA)_T_6	6.35	43.73	0.221
D(TA)_T_12	3.88	48.85	0.202
F(EA)_T_0	8.35	56.31	0.166
F(EA)_T_6	11.09	46.23	0.192
F(EA)_T_12	6.46	43.70	0.216

Table 4. Air void parameters of the cylinder samples

Sample	Air [%]	Paste [%]	Spacing factor [mm]
A(HA)_C_0	6.95	46.67	0.174
A(HA)_C_6	6.93	53.00	0.177
A(HA)_C_12	6.33	39.83	0.148
B(LA)_C_0	7.02	48.88	0.158
B(LA)_C_6	6.07	44.81	0.174
B(LA)_C_12	6.94	44.05	0.153
C(NA)_C_0	2.75	41.13	0.361
C(NA)_C_6	1.87	38.60	0.636
C(NA)_C_12	1.84	47.24	0.653
D(TA)_C_0	6.06	44.78	0.128
D(TA)_C_6	9.61	40.18	0.116
D(TA)_C_12	6.60	45.61	0.154
F(EA)_C_0	8.92	44.76	0.193
F(EA)_C_6	7.35	46.91	0.197
F(EA)_C_12	10.45	48.33	0.140

The effect of vibration on air contents for the various mixtures for the tie and the cylinder samples are shown in Figure 15. The air content values for both ties and cylinders with 0 seconds vibration were reasonably close to their fresh air content values (air meter), considering the variability of air content measurements. This result supports the utility and expediency of the automated hardened air void method used in this research.

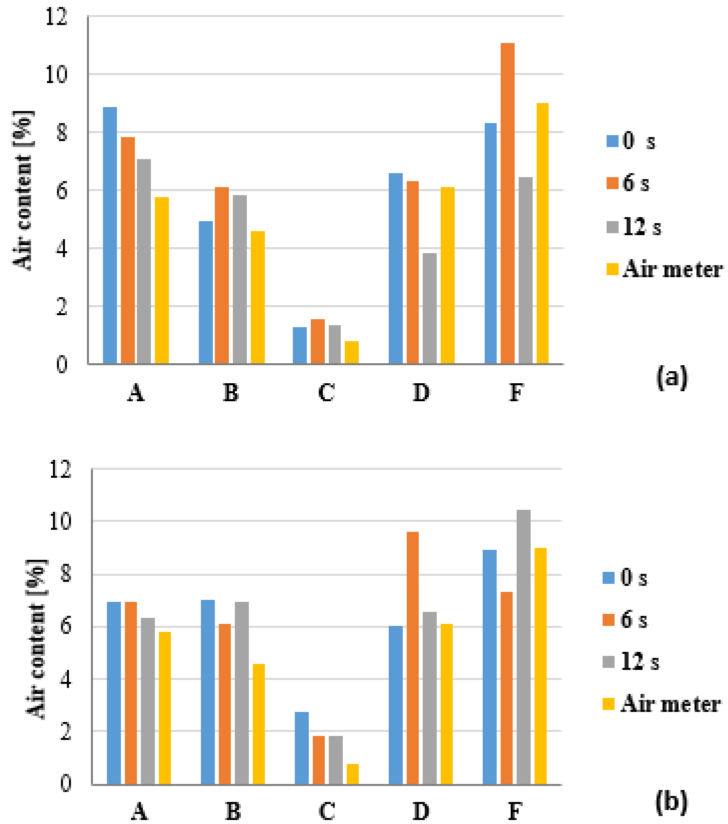

Figure 15. Effect of vibration on air content for (a) tie samples and (b) cylinder samples

The effect of vibration on the spacing factor for the two types of samples are compared in Figure 16 (a) and (b), respectively. The spacing factor was expected to increase with vibration. However, this rule was only confirmed by the response of Mixture C – but not for Mixtures A, B, D, and F that were air-entrained. The results showed that the air void systems in these mixtures were robust, as their spacing factors were little changed by long vibration periods. For the exceptional case of Mixture C, that had no air entrainment and a very limited population of small air bubbles (0.8 percent fresh air content), the spacing factors became higher after the vibration. This behavior was very likely related to the size of the air bubbles. The entrapped air voids were larger than the entrained air voids and were prone to exit the concrete during vibration, resulting in a larger spacing factor after vibration. The small voids in the air-entrained mixtures were more stable and did not leave the concrete during vibration; therefore, they maintained similar void spacing after the extended vibration.

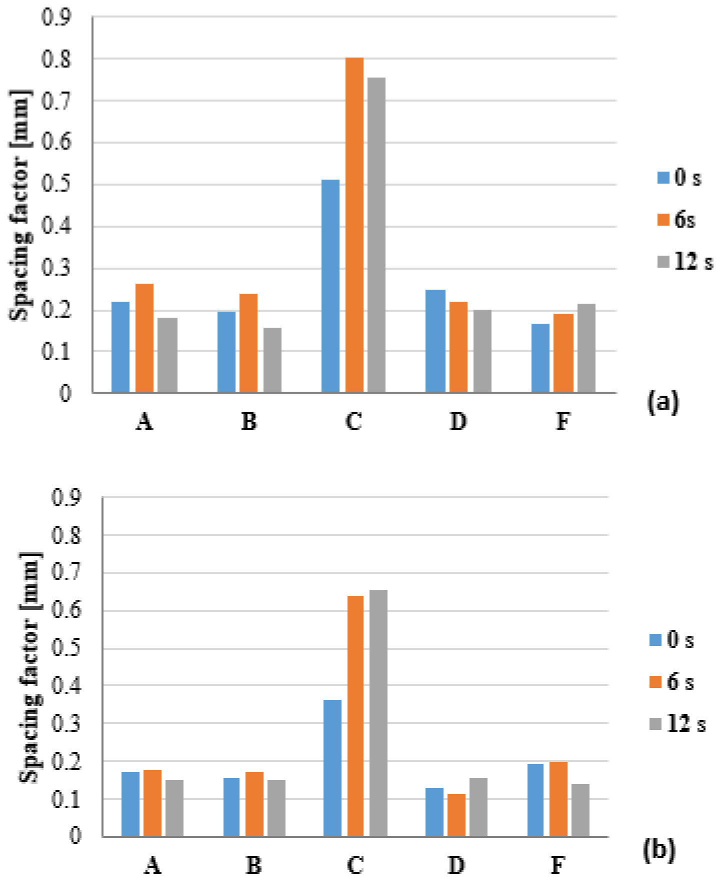

Figure 16. Effect of vibration on the spacing factor for (a) tie samples and (b) cylinder samples

A comparison of the air content and the spacing factor values for the two types of samples are given in Figure 17 (a) and (b). Figure 17 (a) shows that as the air content value increased, the data points were distributed within a wider range around the line of equality. In the spacing factor comparison shown in Figure 17 (b), all the samples except for Sample C had spacing close to 0.2 mm, indicating that desirable freeze-thaw durability could be anticipated for those samples. Comparing the spacing factor results between the two types of molds, values obtained from the tie samples were very similar to their counterparts, as most of the data points in Figure 17 (b) lie very close to the line of equality. While the total air content between the two sample vibration methods had low correlation, researchers found good agreement (Coefficient of Determination R^2=0.94) between the two methods for spacing factor. The good correlation seen with spacing factor indicates that match vibration could be used to determine freeze-thaw durability.

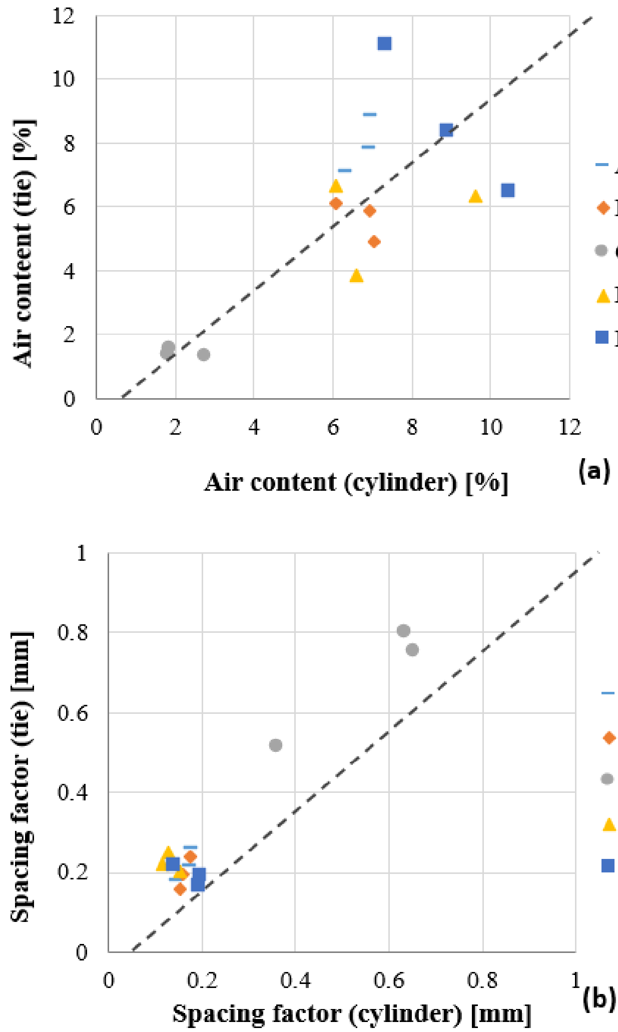

Figure 17. Comparisons of (a) air content and (b) spacing factor between the tie and cylinder samples

The Federal Railroad Administration report [Concrete Material and Manufacturing Requirements for Freeze-Thaw Durable Concrete Railroad Ties] [6] and the experiments described in Sections 2–4 of this report describe a performance-based approach for concrete railroad tie material and process qualification and quality control requirements to protect against freeze-thaw deterioration. Project researchers developed suggestions to further improve the AREMA Chapter 30 specifications for concrete material durability. They also examined concrete material requirements found in the AREMA Chapter 30 specifications not related to freeze-thaw durability and proposed changes to harmonize these specifications with the recommendations found in American Concrete Institute (ACI) 201.2R-16, Guide to Durable Concrete [13]. Since the goal of these efforts was to gain adoption in the AREMA Chapter 30 specifications, recommendations for implementation of a performance-based approach were developed around existing AREMA Chapter 30 specifications and are presented in this report as ballots for the AREMA committee to consider.

4.2 Freeze-Thaw Durability Specifications

Aggregates comprise 60 to 80 percent of concrete by volume. Some coarse aggregates of sedimentary origin can be inherently non-freeze-thaw durable when used in concrete. In cold climates, concrete pavement made with these aggregates can develop cracks near the joints, often referred to as D-cracking [13]. This is primarily because the aggregate pore system is of a small-to-intermediate size range [14]. Reduction of an aggregate's nominal maximum size can increase concrete service life in wet, cold conditions; however, damage could eventually still occur. Coarse aggregates of sedimentary origin should be tested to verify that they are freeze-thaw durable before use in concrete railroad ties. To verify, concrete samples made with coarse aggregate should be made and cured according to ASTM C1646 [15] and tested in freezing and thawing according to ASTM C666, Procedure A [16].

An air-entraining agent should be used in the concrete to ensure freeze-thaw durability of the paste portion of the concrete. The concrete mixing, handling, placing, and consolidation process affects the concrete air void system and should be considered when proportioning the mixture, mixing sequence, and manufacturing process. Producers should ensure that the hardened air-void spacing factor of product, or match-vibrated samples, is less than 0.009 inch (0.23 mm), or less than 0.010 inch (0.25 mm) if the w/cm is lower than 0.36. As shown in Figure 18, if the concrete air void system meets these spacing factor requirements, the concrete railroad ties have a high probably of freeze-thaw durability, negating the need for freeze-thaw testing [6]. Data are displayed with ACI and CSA Group (Canadian standards) limits indicated.

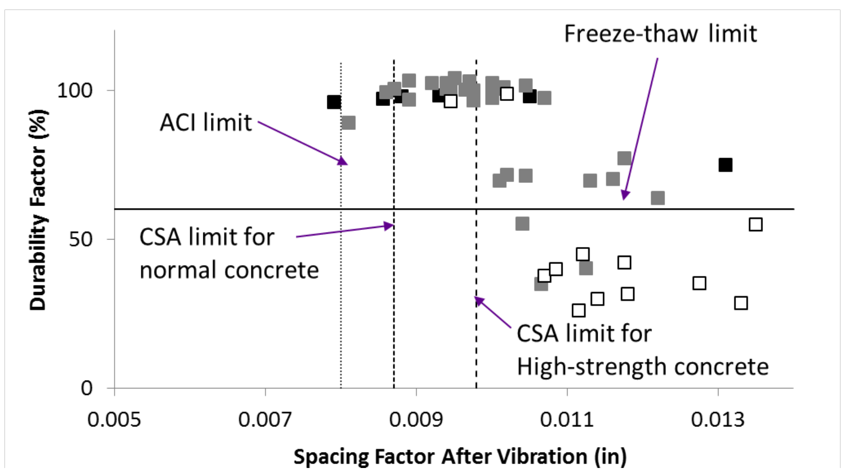

Figure 18. Hardened air void spacing factor requirements for vibrated concrete to ensure freeze-thaw durability [6]

The minimum air content required for freeze-thaw durability varies because different air-entraining admixtures and mixture designs produce different air void size distributions. Large bubbles will be removed quickly from the mixture during vibration, whereas small air bubbles will remain and provide freeze-thaw protection. The fresh air content required to meet the hardened air void requirements in product is material- and plant-process-specific. Testing is required to determine the minimum air content needed to maintain quality standards. To determine the hardened air void content required for daily quality control testing, mixtures should be made with different levels of total air content. A comparison of the fresh air content with the air content of hardened concrete can be used to determine the minimum air content required to achieve freeze-thaw durability for the materials and methods used. Figure 19 shows an example of this procedure for the concrete mixtures described in Table 2-1. In this example, the minimum fresh air content required for freeze-thaw durability was 4 percent. To ensure the concrete fresh air content does not fall below 4 percent, the producer would likely choose a value slightly higher than 4 percent as a margin against testing, material, and process variability. The correlation between fresh air content and hardened air content should be verified whenever the process or materials change.

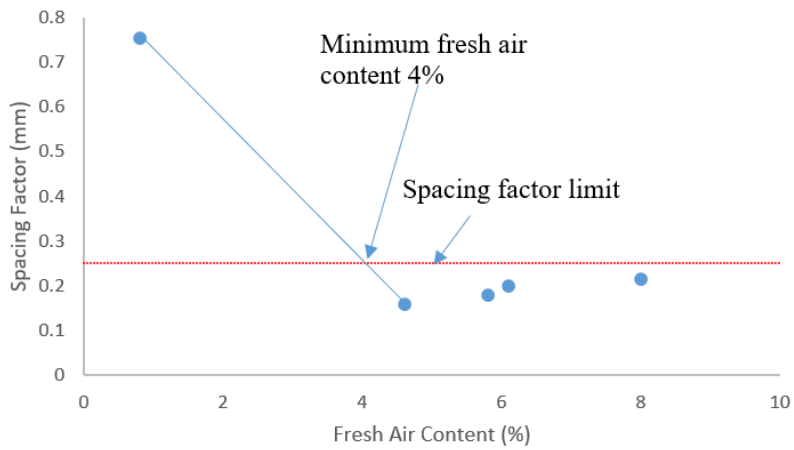

Figure 19. Hardened air void spacing factor requirements for vibrated concrete to ensure freeze-thaw durability

4.2.1 Proposed Specification Changes

The research team propose changes to the AREMA Chapter 30 specifications to ensure the freeze-thaw durability of concrete railroad ties based on experimental results. Table 5-1 contains the proposed specification changes and the accepted changes reflected in the 2020 edition of the manual.

Table 5. Proposed AREMA Chapter 30[1] freeze-thaw specification changes

Section	Specification Text (2020 AREMA Chapter 30 contents. Strikethrough = deletion, italicized = addition)
4.2.2.2 Aggregates, section d	*Suppliers should qualify each new coarse aggregate material for freeze-thaw durability. Samples to measure the aggregate freeze-thaw durability should be made and cured according to ASTM C1646. After curing, samples should then be tested according to ASTM C666 Procedure A. Samples should have a durability factor greater than 90 percent after 300 cycles of freezing and thawing.* Suppliers should qualify each new coarse aggregate material for freeze-thaw durability. Concrete should be tested according to ASTM C666 Procedure A. Samples should have a durability factor greater than 90 percent after 300 cycles of freezing and thawing.

[1] American Railway Engineering and Maintenance Right-of-Way Association. (2020). *Manual For Railway Engineering.* Chapter 30 – Ties. Lanham, MD.

Section	Specification Text (2020 AREMA Chapter 30 contents. Strikethrough = deletion, italicized = addition)
4.2.2.4 Admixtures	Chemical admixtures for concrete shall conform with ASTM C 494. Additives containing chlorides shall not be used. Where ties will be exposed to freeze-thaw conditions, an air entraining agent according to ASTM C 260 shall be used. ~~As a guide, freeze-thaw durability can generally be obtained with 4.5 percent minimum air in the wet concrete, 3.5 percent minimum air-void-content in the hardened concrete, and an air-void spacing factor not exceeding 0.008 inch (0.20 mm).~~ *Minimum fresh air content should be determined as the minimum amount required to meet the hardened air spacing factor requirements in product or match vibrated concrete.* Chemical admixtures for concrete shall conform with ASTM C 494. Additives containing chlorides shall not be used. Where ties will be exposed to freeze-thaw conditions, an air entraining agent according to ASTM C 260 shall be used. As a guide, freeze-thaw durability can generally be obtained with 4.5 percent minimum air in the wet concrete, 3.5 percent minimum air-void-content in the hardened concrete, and an air-void spacing factor not exceeding 0.008 inch (0.20 mm). Minimum fresh air content should be determined as the minimum amount required to meet the hardened air spacing factor requirements detailed in Article 4.2.2.6, Durability of CuredConcrete.
4.2.2.6 Durability of Cured Concrete	The second area of concern is concrete that fails due to environmental effects. Freeze thaw damage and reinforcement corrosion are two common results. Freeze thaw damage is caused by the formation of ice within the cement matrix, resulting in expansion damage to the concrete. Whether or not this formation of ice becomes a problem depends upon a combination of the permeability, water-to-cement ratio, air void spacing and size, total entrained air, and the extent of microcracking. ~~The best indicator of concrete's ability to avoid freeze thaw damage is successful completion of ASTM C666, Method A to 90 percent at 300 cycles. It is recommended that ASTM C666 testing be conducted at six-month intervals.~~ *Freeze-thaw resistance of the paste portion of the concrete should be assured by use of air entraining admixtures. To assure the quality of the air void system, the concrete air void spacing factor determined by ASTM C457 should be determined at 6-month intervals. The hardened concrete spacing factor should be less than 0.009 in. (0.23 mm), or less than 0.010 in. (0.25 mm) if the w/cm is lower than 0.36. The hardened concrete spacing factor can be determined from product samples or match-vibrated concrete samples. The intensity of the vibration in product can be measured using an accelerometer, being sensitive to the variation in vibration intensity throughout the volume of the concrete product. The vibration intensity profile used for match-vibrated specimens should equal or exceed that measured in the concrete product.* Freeze thaw damage is caused by the formation of ice within the cement matrix, resulting in expansion damage to the concrete. Whether or not this formation of ice becomes a problem depends upon a combination of the permeability, water-to-cement ratio, air void spacing and size, total entrained air, and the extent of microcracking. An indicator of concrete's ability to avoid freeze thaw damage is successful completion of ASTM C666, Method A to 90% at 300 cycles. It is recommended that ASTM C666 testing be conducted at six-monthintervals.

4.3 Delayed Ettringite Formation Specifications

During normal cement hydration, sulfate ions from gypsum react with tricalcium aluminate and water to form ettringite. During the early stages of concrete curing, the porosity is high enough to accommodate ettringite crystal growth without causing deterioration. If the concrete temperature during curing is high – above 158°F (70°C) – the formation of ettringite is delayed. When delayed, ettringite can form in small pores in the hardened concrete, creating large stresses on the pore walls and expansion [13]. This delayed ettringite formation (DEF) has been shown to cause significant expansion and cracking of concrete structures in service [17].

Industry research has concluded that temperature control is sufficient to prevent DEF from occurring. The ACI 201.2R-16, Guide to Durable Concrete [13] recognizes this:

> To minimize the risk of poor durability due to deleterious DEF reactions associated with exposure to elevated temperatures at early ages, the maximum internal temperature of concrete should be controlled such that it does not exceed 158°F (70°C) at any time.

The requirement to keep the concrete temperature below 158°F (70°C) is sufficient to control DEF. This control negates the value of conducting the Duggan (concrete expansion) test. The temperature limit specifications in AREMA Chapter 30 can also be increased to 158°F (70°C) without a significant increase in DEF risk.

4.3.1 Proposed Specification Changes

Section 4.2.3 of AREMA Chapter 30 contains the requirements for the Duggan test. Since this test method does not provide a reduction in risk compared to adherence to the maximum temperature limits, this test should not be required, and the section should be deleted from the chapter. Other recommended changes to sections on curing and the durability of cured concrete are shown in Table 7, along with the accepted changes reflected in the 2020 edition of the manual.

Table 6. Proposed AREMA Chapter 30 delayed ettringite formation specification changes

Section	Specification Text (2020 AREMA Chapter 30 contents. Strikethrough = deletion, italicized = addition)
4.2.2.5 Curing	It is recommended that the concrete be cured by a method or procedure such as set forth in the PCI Manual for Quality Control (MNLI 16, latest edition), modified as follows: After placing and consolidating the concrete, the exposed surface shall be covered with impermeable sheeting. Concrete shall not be placed in forms whose temperatures are less than 40 degrees F and the concrete temperature shall not be allowed to fall below 50 degrees F between casting and transfer of prestress. During the preset period, the concrete temperature shall not exceed 90 degrees F (32 degrees C) during the first 3 hours and 105 degrees F (40 degrees C) during the first 4 hours. With accelerated heat curing, the heating rate shall not exceed 35 degrees F (19.4 degrees C) per hour. ~~and the curing temperature within the concrete shall not exceed 140 degrees F (60 degrees C), unless the supplier can demonstrate that the materials used would be satisfactory for long-term durability, in which case temperatures up to 158 degrees F (70 degrees C) may be used.~~ *The curing temperature within the concrete shall not exceed 158 degrees F (70 degrees C).*

Section	Specification Text (2020 AREMA Chapter 30 contents. Strikethrough = deletion, italicized = addition)
	During the preset period, the concrete temperature shall not exceed 90 degrees F (32 degrees C) during the first 3 hours and 105 degrees F (40 degrees C) during the first 4 hours. With accelerated heat curing, the heating rate shall not exceed 35 degrees F (19.4 degrees C) per hour. The curing temperature within the concrete should not exceed 158 degrees F (70 degrees C).
4.2.2.6 Durability of Cured Concrete	Delayed Ettringite Formation (DEF) is commonly used to refer to the reformation of ettringite after the initial curing of the concrete, resulting in expansive failure. ~~Two potential causes are excessive sulfate content in the cement or excessive temperatures during the concrete curing process. To test for either situation, the Duggan Test (4.2.3 Duggan Concrete Expansion Test (1993)) is currently the only known method.~~ *DEF can occur when temperatures in the concrete if the temperature reaches above 158 degrees F (70 degrees C).* DEF is commonly used to refer to the reformation of ettringite after the initialcuring of the concrete, resulting in expansive failure. DEF can occur when concrete experiences excessive temperatures or excessive temperature rise during the curing process. The Duggan Concrete Expansion Test(1993) is not a standardized test recommended for concrete durability determination. Test method ASTM C856 can be used to detect the presence of DEF in hardened concrete. The best current guidance to avoid DEF is touse the recommendations in Article 4.2.2.5 Curing.

4.4 Alkali-Aggregate Reaction

Significant advances have been made in understanding alkali-aggregate reaction (AAR) mechanisms in concrete, test methods, and mitigation measures. This knowledge has been standardized as ASTM C1778 [18], Standard Guide for Reducing the Risk of Deleterious Alkali-Aggregate Reaction in Concrete, and provides the latest accepted guidance for alkali-aggregate reaction risk reduction in concrete. The ASTM standard will be maintained by experts, ensuring the concrete railroad tie industry maintains best practices. This standard contains all the tests described in the old specification language, with more detailed and updated guidance and requirements. Prescriptive and performance options are given within ASTM C1778 to address local options to control alkali-aggregate reaction. ASTM C1778, introduced in 2014 and updated in 2016, contains the most recent guidance to mitigate the risk of alkali-aggregate reaction. The standard has a flow chart that provides guidance on the test methods and mitigation required.

The prescriptive requirements contained in ASTM C1778 for AAR mitigation require the selection of a structural risk classification. For example, the consequences of AAR in a nuclear containment facility are greater than in a sidewalk. Concrete railroad ties match the description provided for SC3 classification, and fit the example given in the standard of “Precast elements in which economic costs of replacement are severe, Service life normally 40-74 years.” [18]

4.4.1 Proposed Specification Changes

Changes should be made to the durability of cured concrete section of AREMA Chapter 30 to refer to AAR requirements contained in ASTM C1778. Table 8 shows the proposed changes along with the accepted changes reflected in the 2020 edition of the manual.

Table 7. Proposed AREMA Chapter 30 alkali-aggregate reaction specification changes

Section	Specification Text (2020 AREMA Chapter 30 contents. Strikethrough = deletion, italicized = addition)
4.2.2.6 Durability of Cured Concrete	Alkali reactivity relates to chemical compatibility between cement and aggregates. Alkali reactivity is a combination of the total mix alkali content and aggregate reactivity. The appropriate test depends on the type of aggregate. ~~Petrographic analysis of the aggregates proposed for concrete usage per ASTM C295 and petrographic analysis of the hardened concrete per ASTM C856 combined with the following tests can be useful in determining the potential for alkali aggregate reactivity Silica based aggregate reactivity (ASR) can be tested by ASTM C 1260 (2 week test) and/or ASTM C 1293 (1-2 year test). Potentially reactive aggregates may still be acceptable when combined with supplementary cementitious materials and/or with cements with total alkalis less than 0.6% as needed to pass ASTM Cl 567 and/or ASTM C 1293 modified with materials to match the job mix. Carbonate based alkali aggregate reactivity (ACR) can be determined by ASTM Cl 105. Six-month intervals are recommended for durability tests to ensure ongoing aggregate suitability, or for any new aggregate source.~~ *Material testing and mitigation methods required to reduce the risk of alkali-silica and alkali-carbonate reaction should follow ASTM C1778, using a structure class of SC3. Durability testing should be conducted upon the introduction of new materials or sources. Six-month intervals are recommended for durability tests to ensure ongoing materials performance.* Alkali reactivity relates to chemical compatibility between cement and aggregate. Alkali reactivity is a combination of the total mix alkali content and aggregate reactivity. The appropriate test depends on the type of aggregate. Material testing and mitigation methods required to reduce the risk of alkali-silica and alkali-carbonate reaction should follow either the performance-based or prescriptive approach within ASTM C1778. When using the prescriptive mitigation methods, the structure class SC3 is recommended. Durability testing should be conducted upon the introduction of new materials or sources. Six-month intervalsare recommended for durability tests to ensure ongoing materials performance.

5. Conclusion

This study presents a new performance-based approach to evaluate concrete freeze-thaw durability in concrete crossties. A research team conducted experimental work to determine the validity of a match-vibration concept for freeze-thaw sample preparation and to demonstrate qualification and quality-control testing requirements in a prestressed concrete railroad tie manufacturing plant.

The team cast fresh concrete mixtures with different air entrainment in both crosstie and cylinder molds. The tie samples were consolidated using a rod vibrator as used in actual plant production. The cylinder samples were consolidated by a table vibrator intended to match the intensity of the rod vibrator used for the tie samples. The consolidating effect of the two types of samples was characterized based on the acceleration measured in the fresh mixtures during the vibration. After hardening, the air void parameters of the two groups of samples were compared using an automated flatbed scanner method for the C457 air void analysis.

Researchers found that the air void systems of the air entrained mixtures were robust, as their spacing factors were generally unchanged by long exposure to vibration. This robust performance was encouraging for the specific mixture and vibration protocols used in this study. The results suggested that freeze-thaw durability of the considered concrete ties would be insensitive to changes in vibration duration.

The results also showed some scatter in the relationship between air contents measured on the tie and cylinder samples. Although a strong air content correlation was not found for the samples, the much more important spacing factors were highly correlated, validating this study's performance-based testing approach. This proposed approach has the potential to help the rail industry better qualify concrete mixtures in a shorter time – which can improve crosstie production quality control.

The team critically examined AREMA Chapter 30 specifications for concrete material durability and recommended changes to ensure the concrete durability against premature deterioration from freeze-thaw, delayed ettringite, and alkali-aggregate reaction.

6. References

[1] Powers, T.C., and Willis, T. (1950). The Air Requirement of Frost Resistant Concrete. *Highway Research Board Proceedings, 29,* 184–211.

[2] Scherer, G.W., and Valenza, J.J. (2005). Mechanisms of Frost Damage. In J. Skalny and F. Young (Eds.), J. Skalny and F. Young (Eds.), *Materials Science of Concrete*, vol. VII. Westerville, OH: American Ceramic Society, 209–246.

[3] Popovics, S. (1985). New Formulas for the Prediction of the Effect of Porosity on Concrete Strength. *ACI Journal, 82*(2), 136–146.

[4] Hover, K.C. (1989). Some Recent Problems with Air-Entrained Concrete. *Cement, Concrete and Aggregates,* 11(1), 67–72.

[5] Hanson, T. and Hart, J. (2001). Plastic Air Content versus Hardened Air Content by High Pressure Air Meter. Ames, IA: Iowa Department of Transportation.

[6] Federal Railroad Administration (2018). Concrete Material and Manufacturing Requirements for Freeze-Thaw Durable Concrete Railroad Ties: Volume II. Washington, DC: U.S. Department of Transportation.

[7] ASTM International. (2016). ASTM C457, Standard Test Method for Microscopical Determination of Parameters of the Air-Void System in Hardened Concrete. West Conshohocken, PA.

[8] ASTM International. (2017). ASTM C231, Standard Test Method for Air Content of Freshly Mixed Concrete by the Pressure Method. West Conshohocken, PA.

[9] Banfill, P.F., Teixeira, M., and Craik, R.J. (2011). Rheology and Vibration of Fresh Concrete: Predicting the Radius of Action of Poker Vibrators from Wave Propagation. *Cement and Concrete Research, 41,* 932–941.

[10] Song, Y., Zou, R., Castaneda, D., Riding, K.A., and Lange, D. (2017). Advances in Measuring Air-Void Parameters in Hardened Concrete Using a Flatbed Scanner. *Journal of Testing and Evaluation, 45,* 1713–1725.

[11] Landgrebe, D.A. (1980). The development of a spectral-spatial classifier for earth observational data. *Pattern Recognition, 12,* 165–175.

[12] Rasband, W.I. (2012). *Imagej.* Bethesda, MD: U.S. National Institutes of Health.

[13] ACI International. (2016). ACI 201.2R-16, Guide to Durable Concrete. Farmington Hills, MI.

[14] Marks, V.J. and Dubberke, W. (1982). Durability of Concrete and the Iowa Pore Index Test. *Transportation Research Record, 853,* 25–30.

[15] ASTM International. (2016). ASTM C1646, Standard Practice for Making and Curing Test Specimens for Evaluating Resistance of Coarse Aggregate to Freezing and Thawing in Air-Entrained Concrete. West Conshohocken, PA.

[16] ASTM International. (2015). ASTM C666, Standard Test Method for Resistance of Concrete to Rapid Freezing and Thawing. West Conshohocken, PA.

[17] M. Thomas, M., K. Folliard, K., T. Drimalas, T., and T. Ramlochan, T. (2008). Diagnosing delayed ettringite formation in concrete structures. *Cement and Concrete Research, 38,* (6), 841–847.

[18] ASTM International. (2016). ASTM C1778, Standard Guide for Reducing the Risk of Deleterious Alkali-Aggregate Reaction in Concrete. West Conshohocken, PA.

Appendix A – Tie and Cylinder Acceleration Data

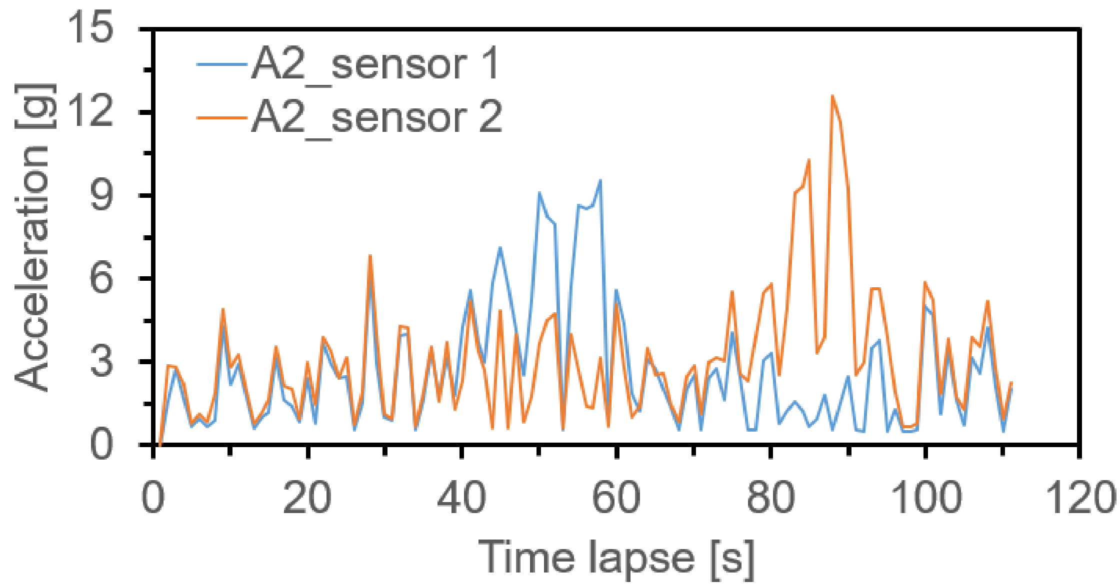

Figure 20. Raw acceleration readings in tie A2

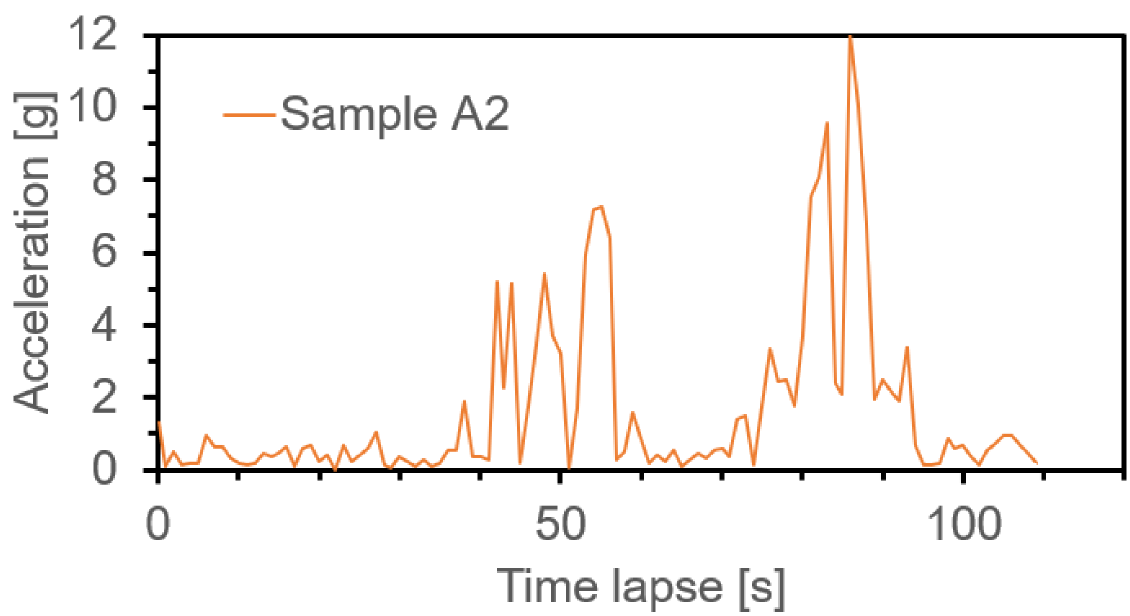

Figure 21. Acceleration readings after subtracting environmental vibration for tie A2

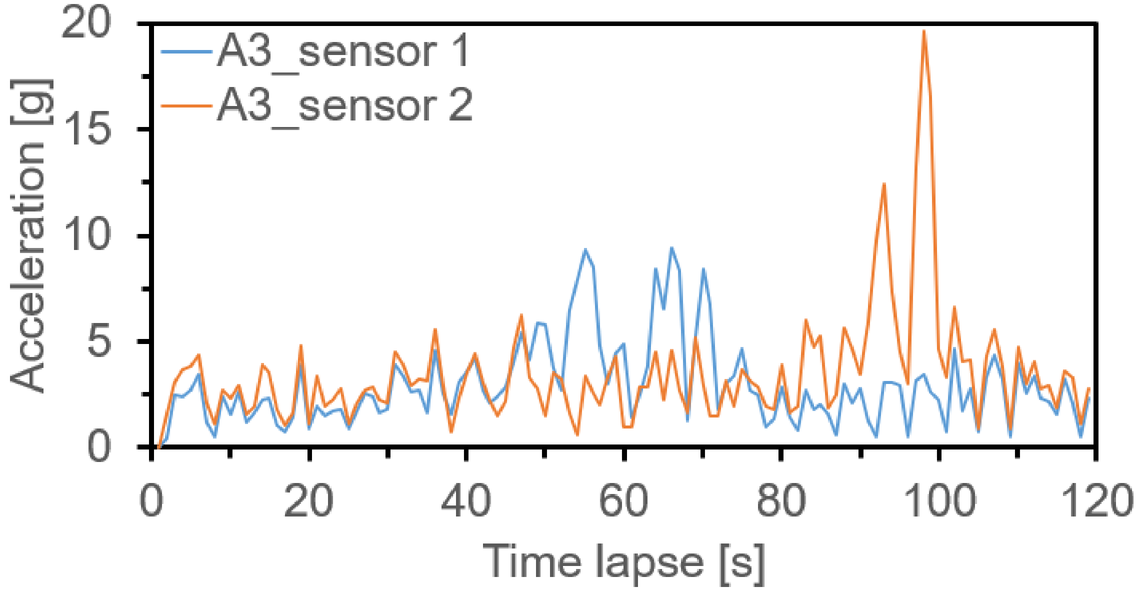

Figure 22. Raw acceleration readings in tie A3

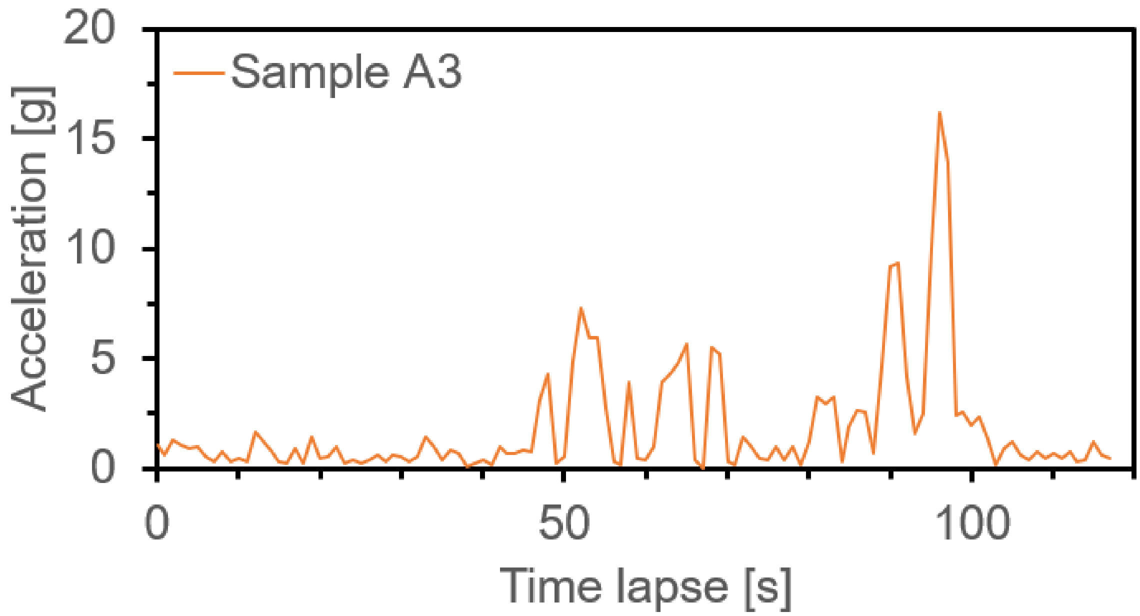

Figure 23. Acceleration readings after subtracting environmental vibration for tie A3

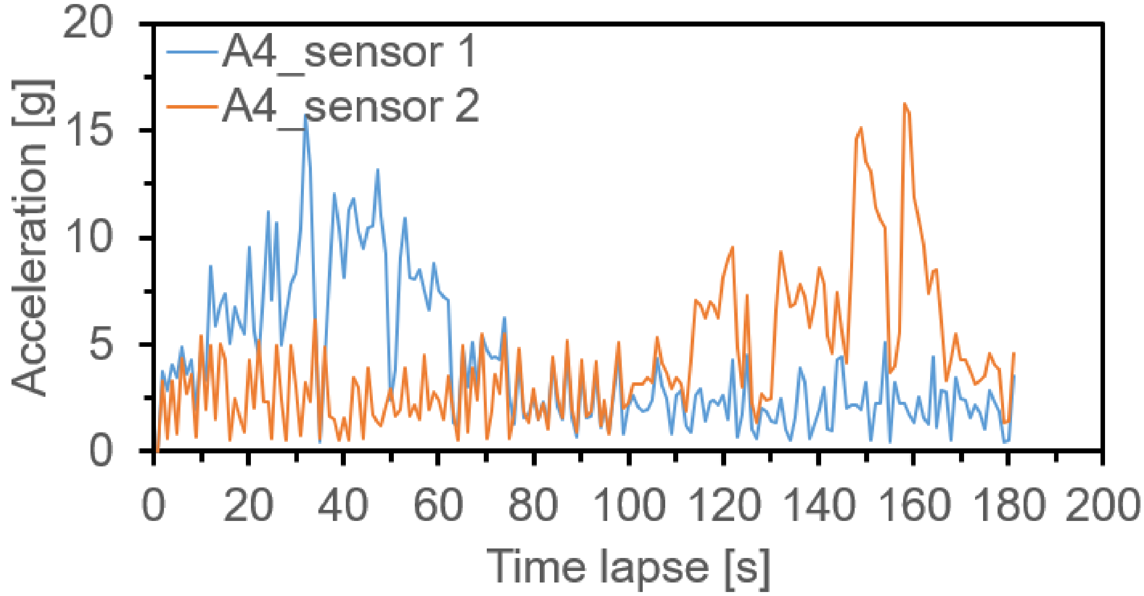

Figure 24. Raw acceleration readings in tie A4

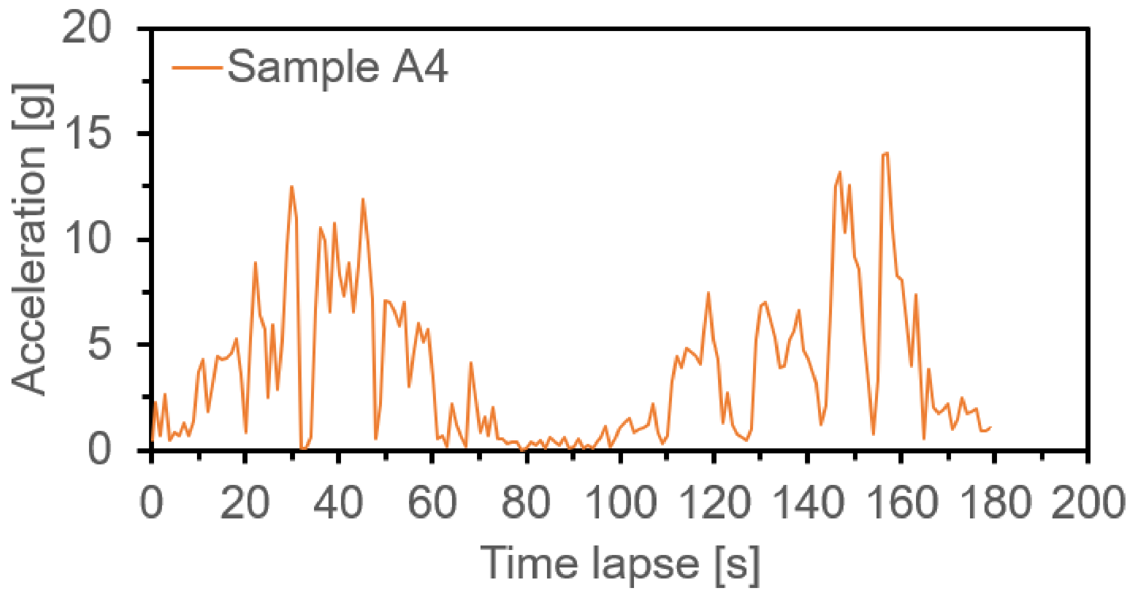

Figure 25. Acceleration readings after subtracting environmental vibration for tie A4

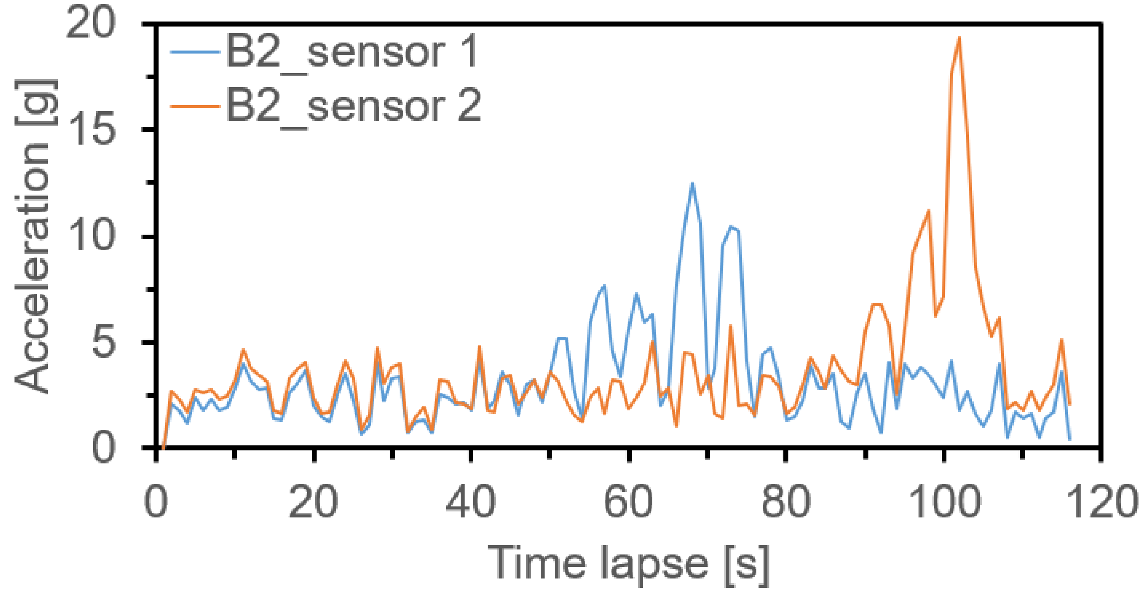

Figure 26. Raw acceleration readings in tie B2

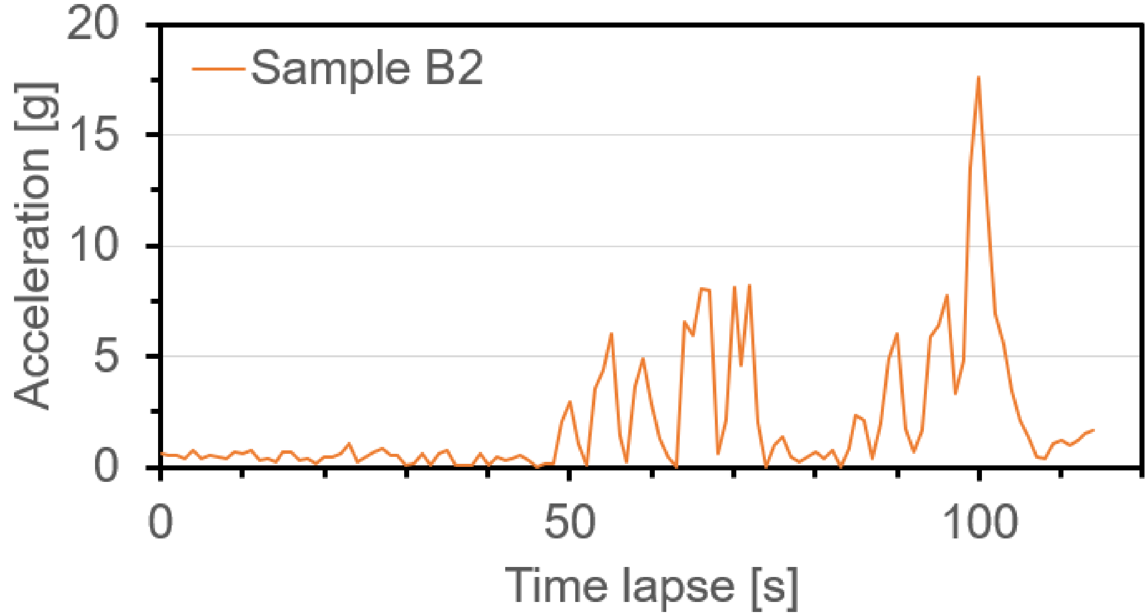

Figure 27. Acceleration readings after subtracting environmental vibration for tie B2

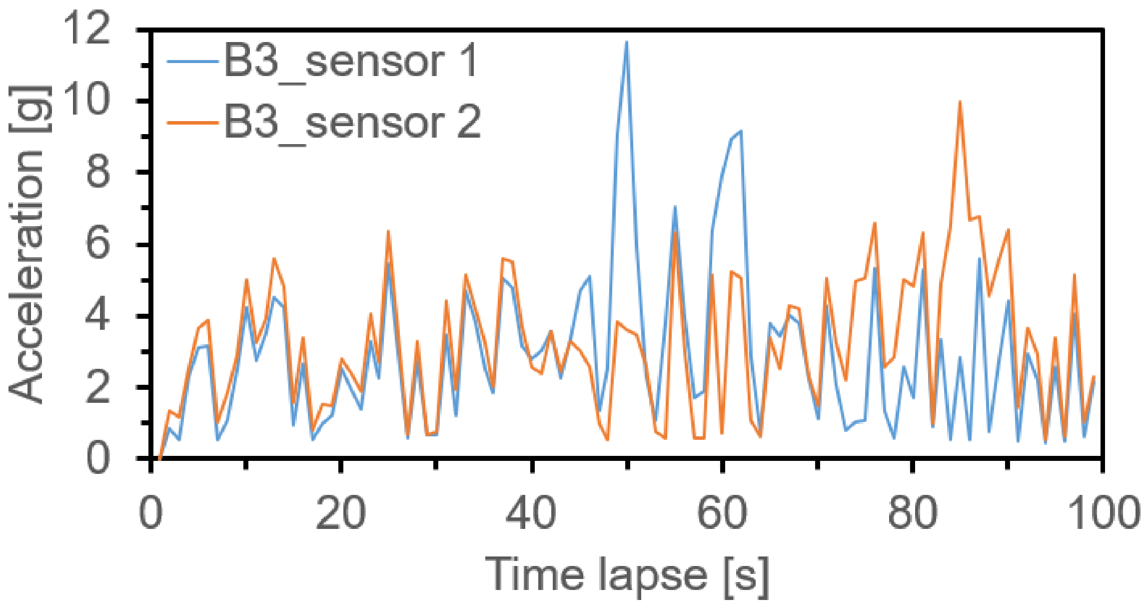

Figure 28. Raw acceleration readings in tie B3

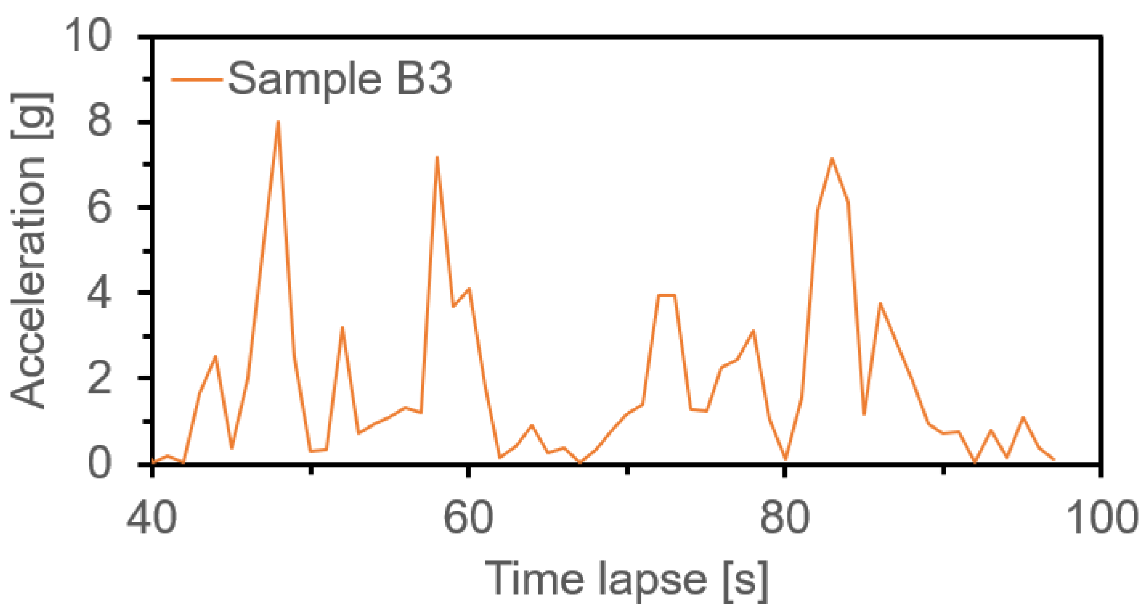

Figure 29. Acceleration readings after subtracting environmental vibration for tie B3

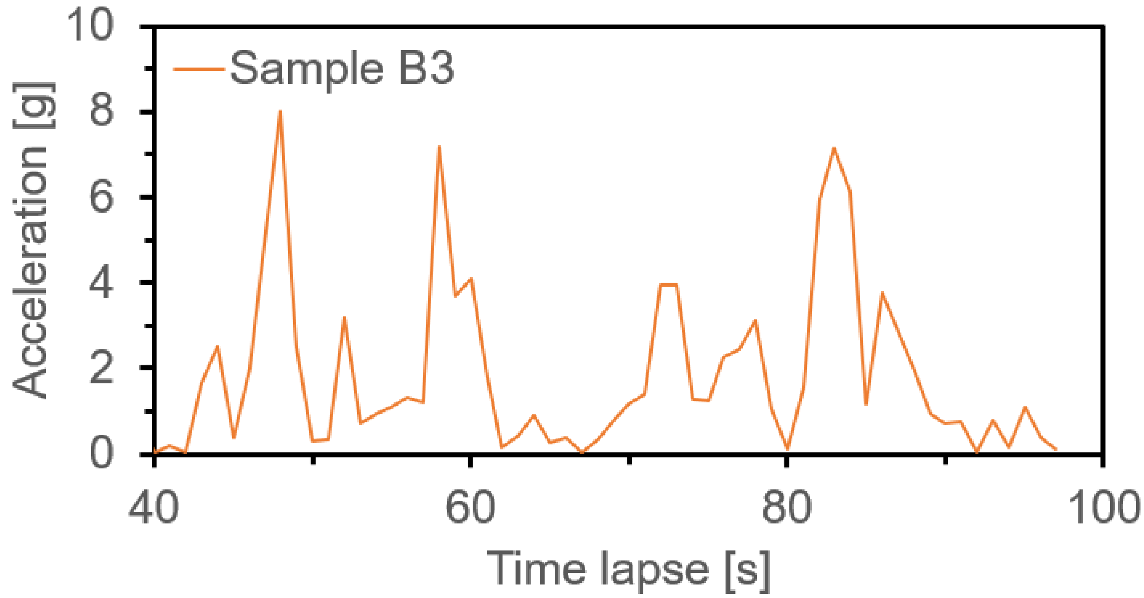

Figure 30. Acceleration readings after subtracting environmental vibration for tie B3

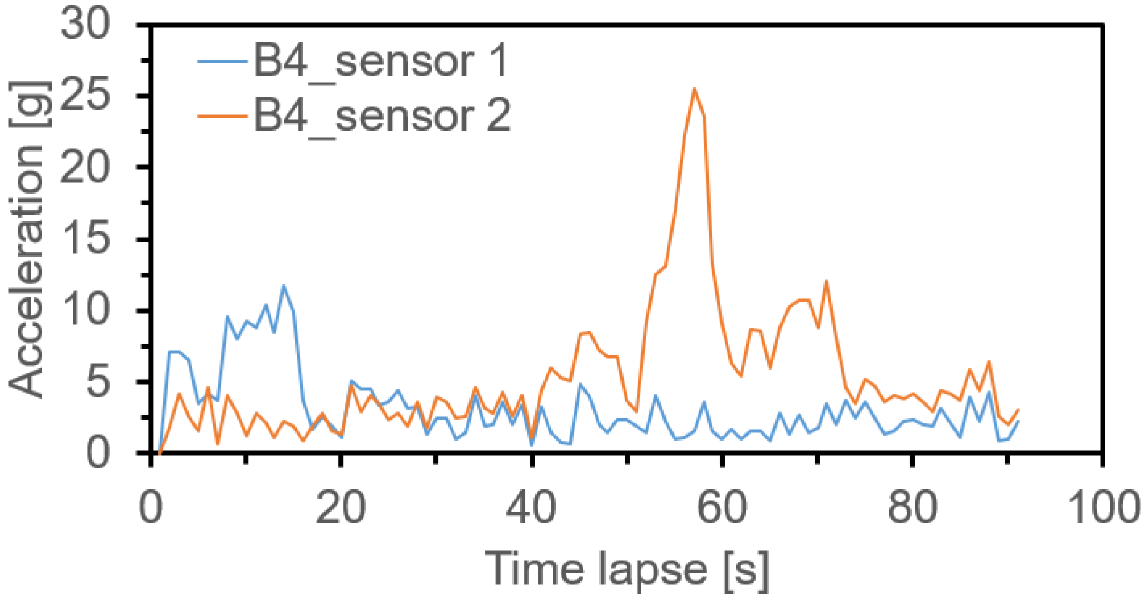

Figure 31. Raw acceleration in tie B4

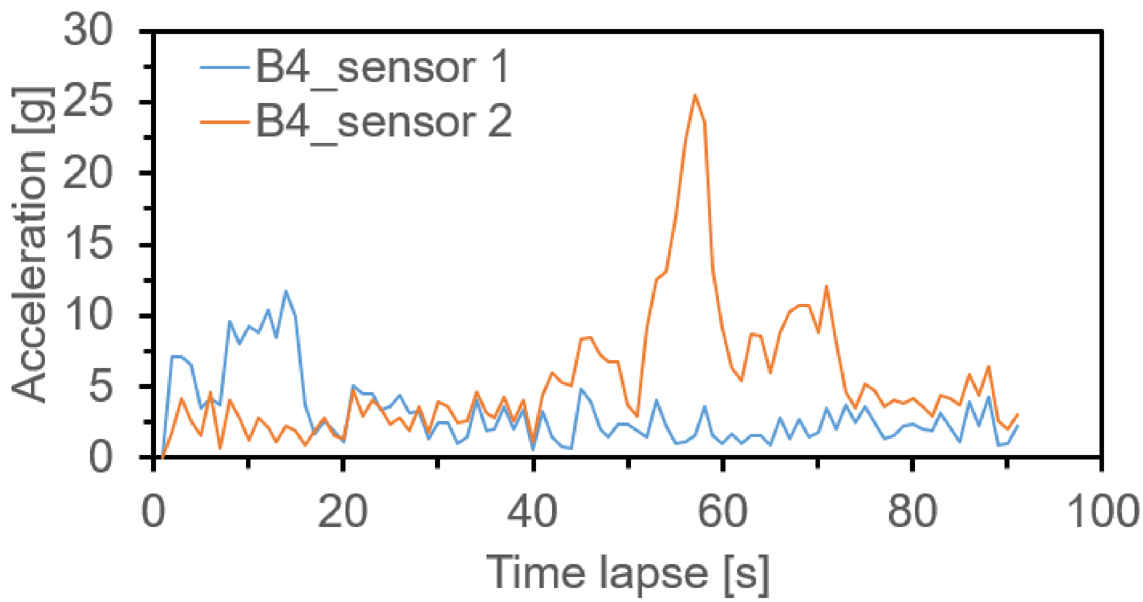

Figure 32. Raw acceleration in tie B4

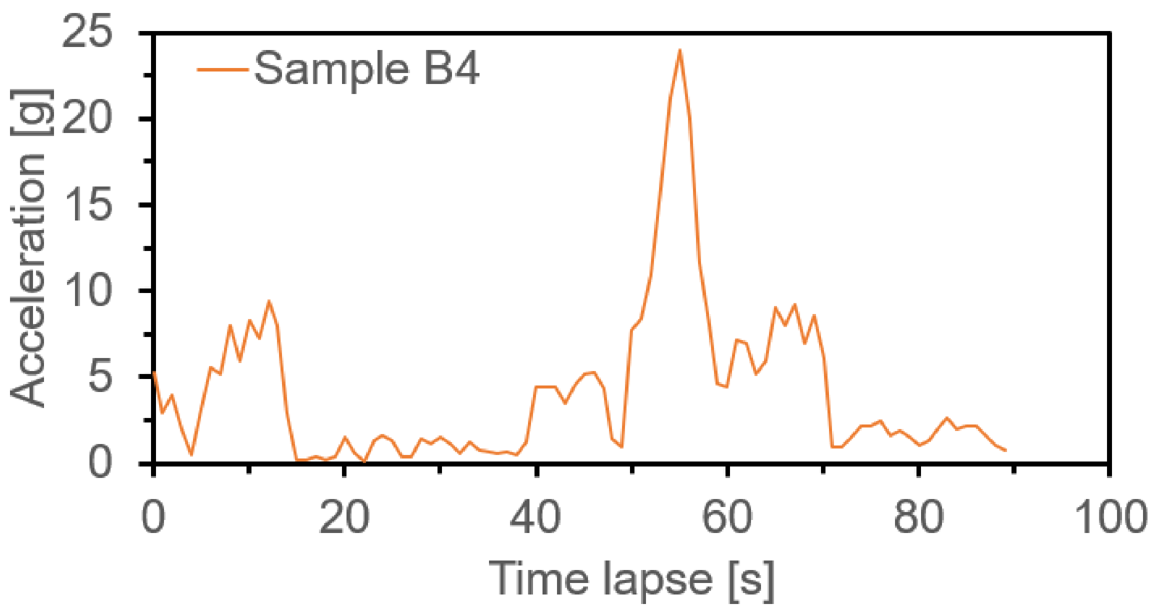

Figure 33. Acceleration readings after subtracting environmental vibration for tie B4

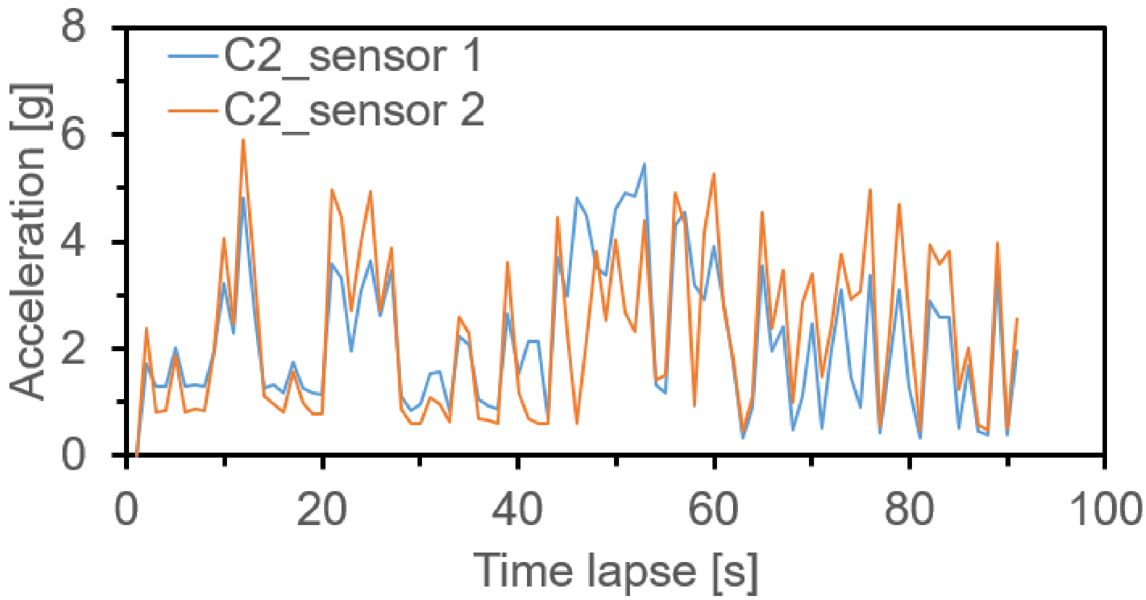

Figure 34. Raw acceleration in tie C2

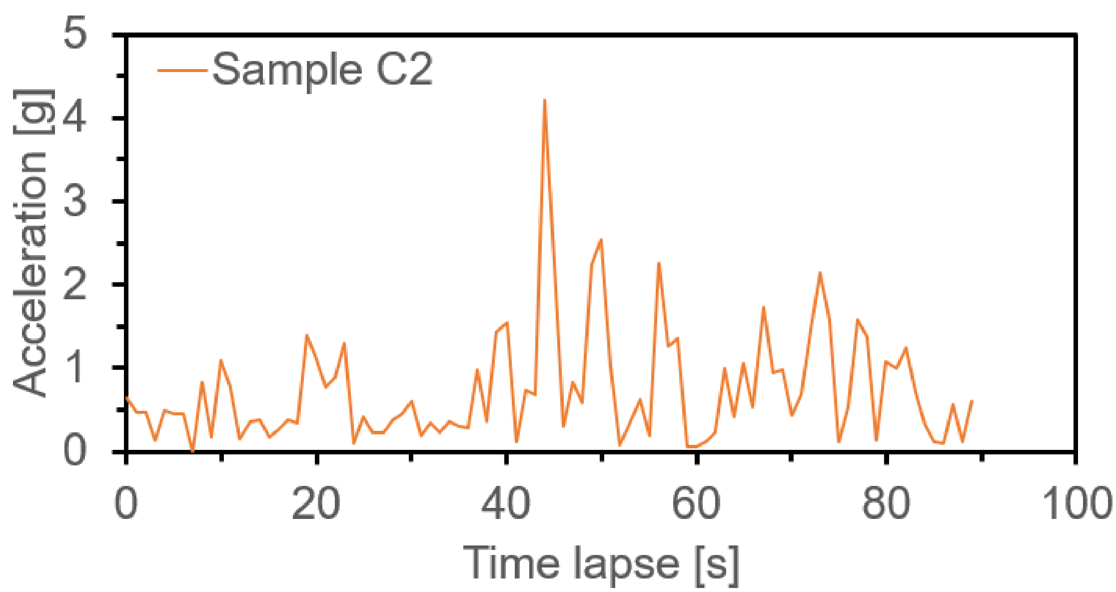

Figure 35. Acceleration readings after subtracting environmental vibration for tie C2

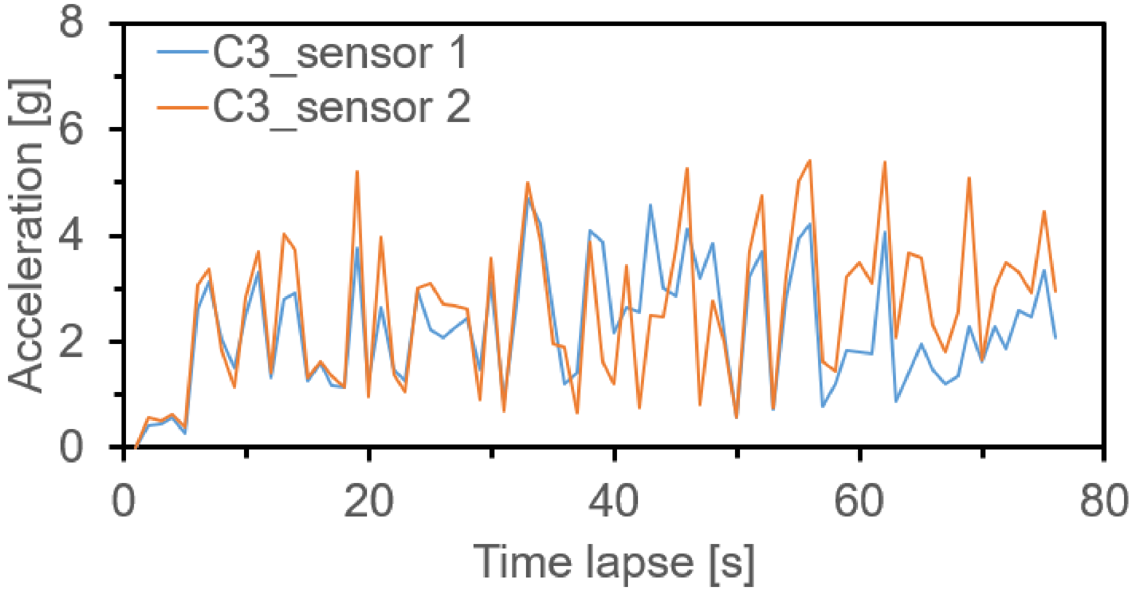

Figure 36. Raw acceleration readings in tie C3

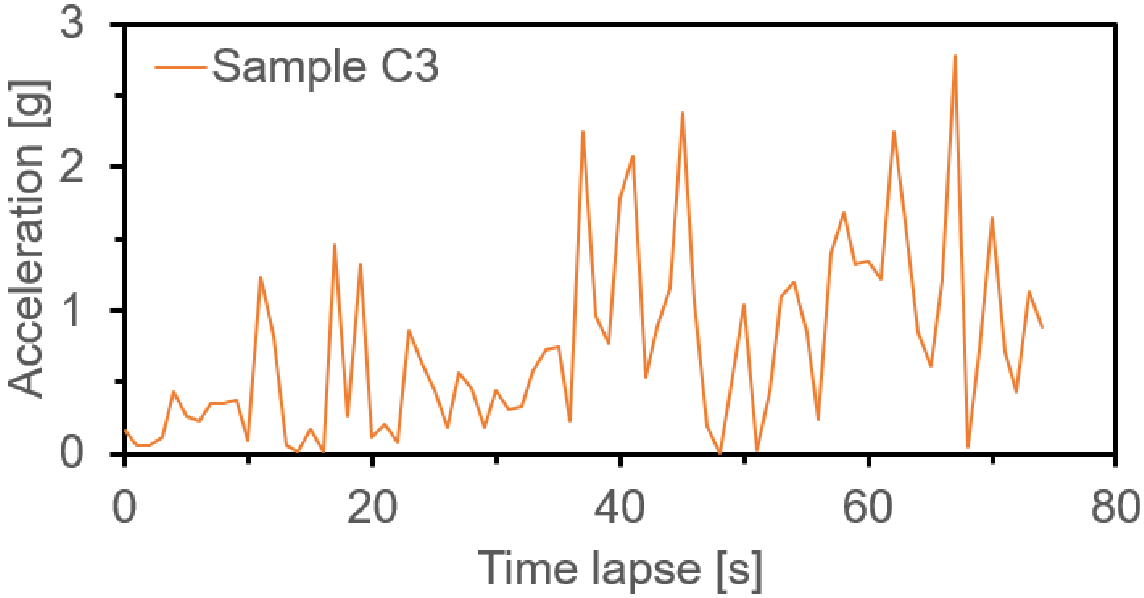

Figure 37. Acceleration readings after subtracting environmental vibration for tie C3

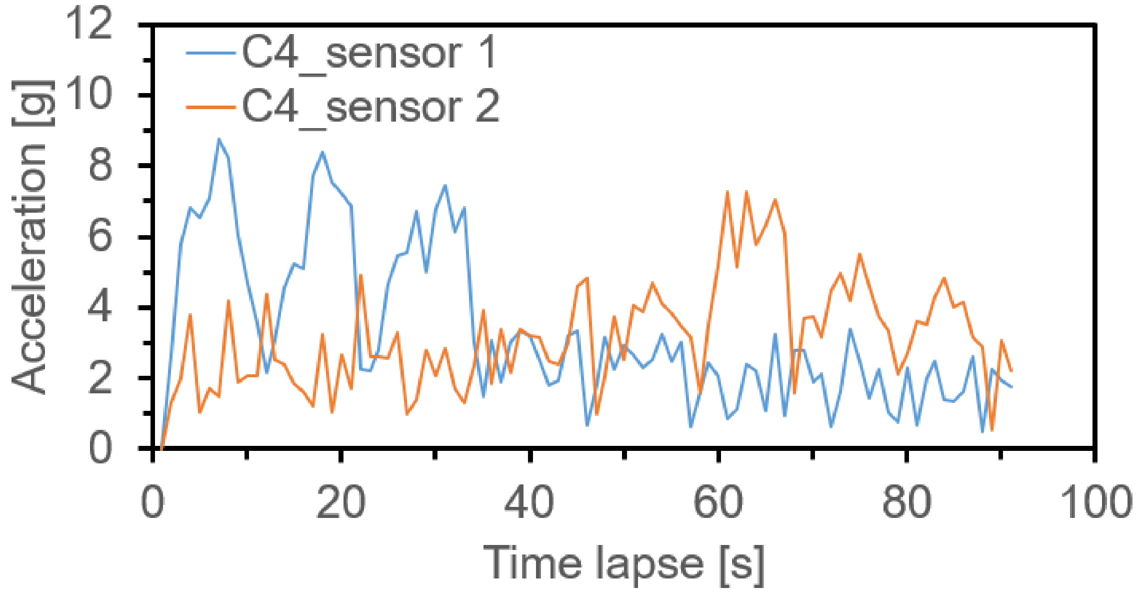

Figure 38. Raw acceleration readings in tie C4

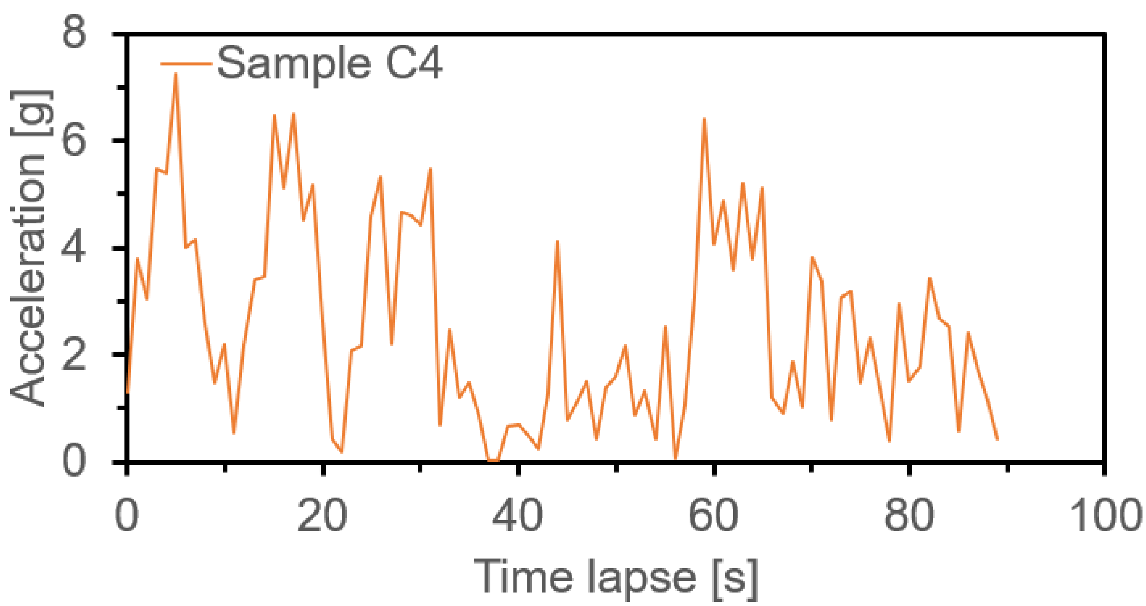

Figure 39. Acceleration readings after subtracting environmental vibration for tie C4

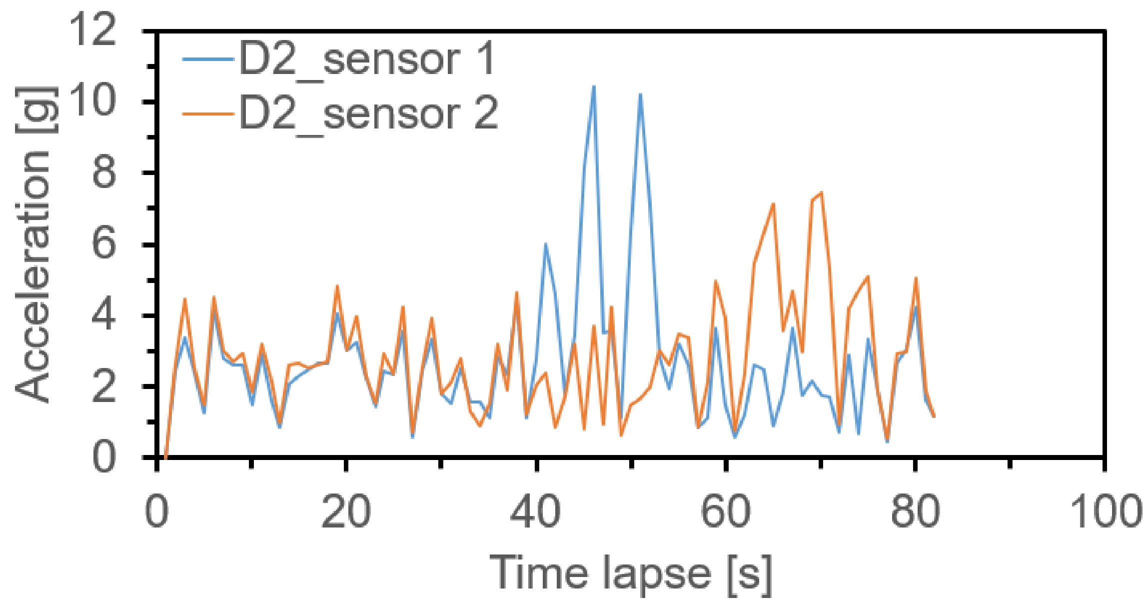

Figure 40. Raw acceleration readings in tie D2

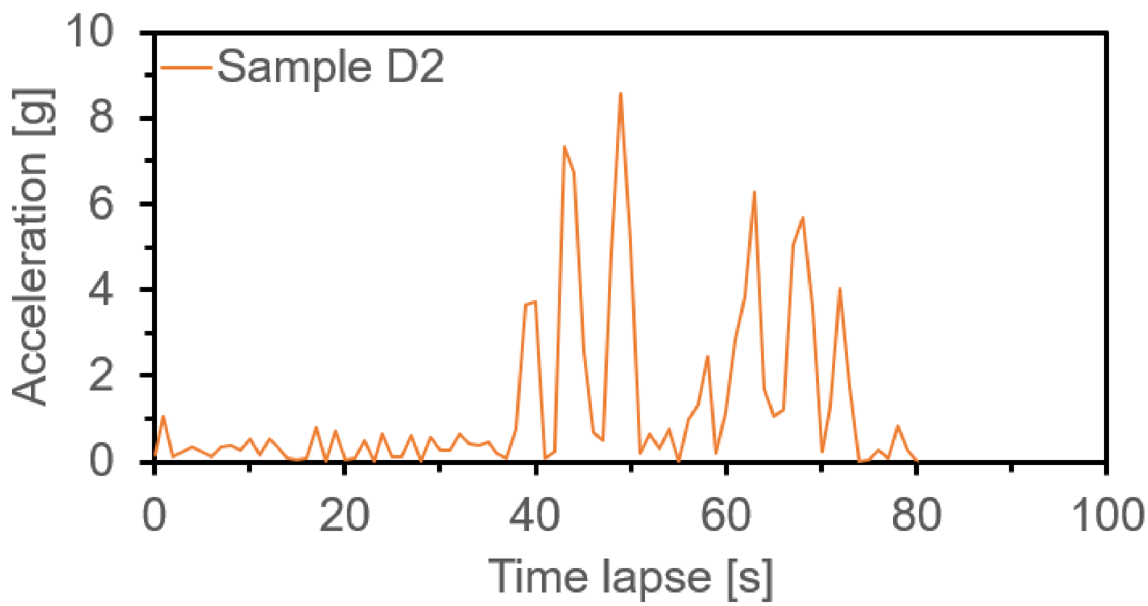

Figure 41. Acceleration readings after subtracting environmental vibration for tie D2

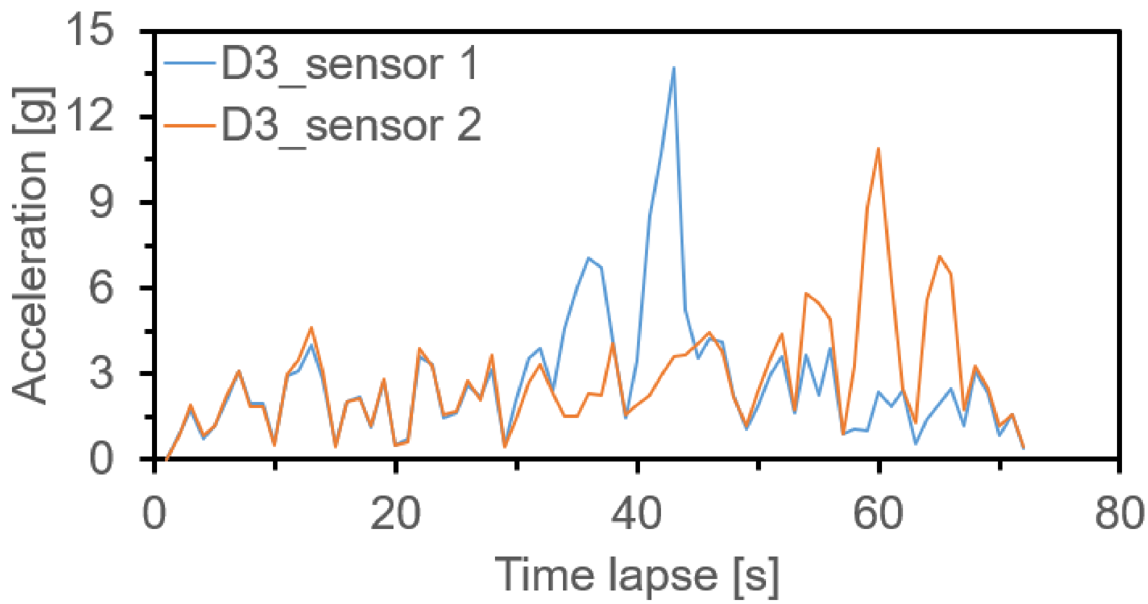

Figure 42. Raw acceleration readings in tie D3

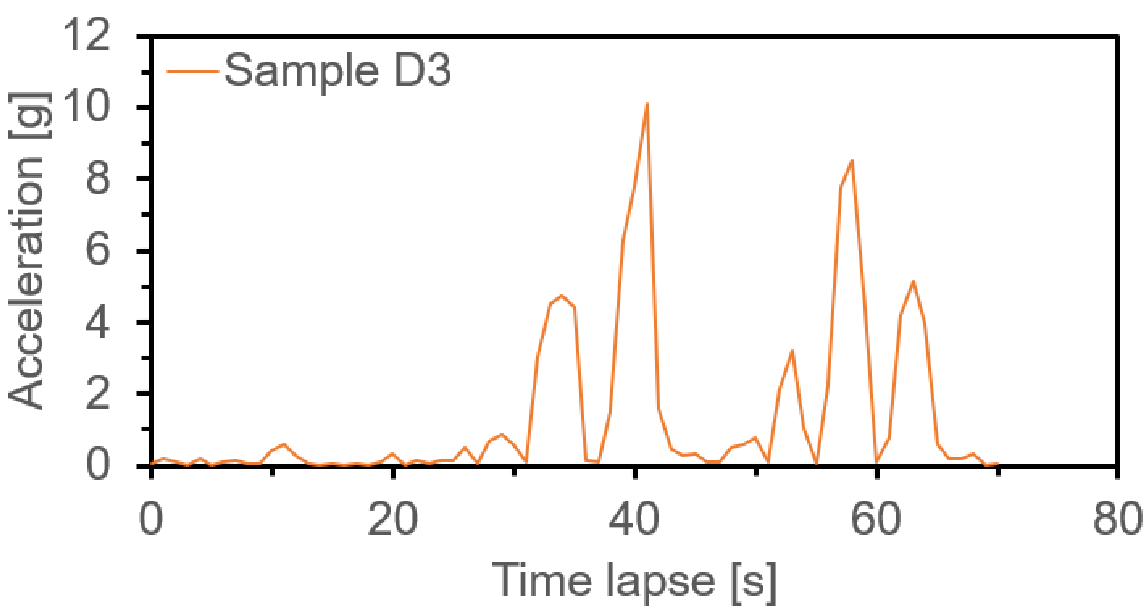

Figure 43. Acceleration readings after subtracting environmental vibration for tie D3

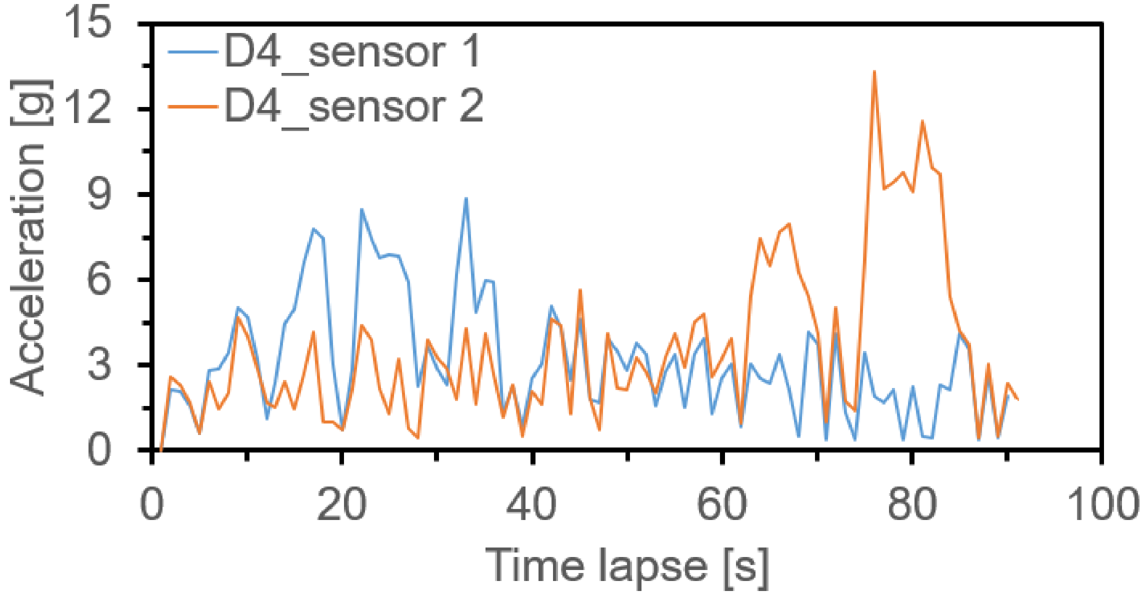

Figure 44. Raw acceleration readings in tie D4

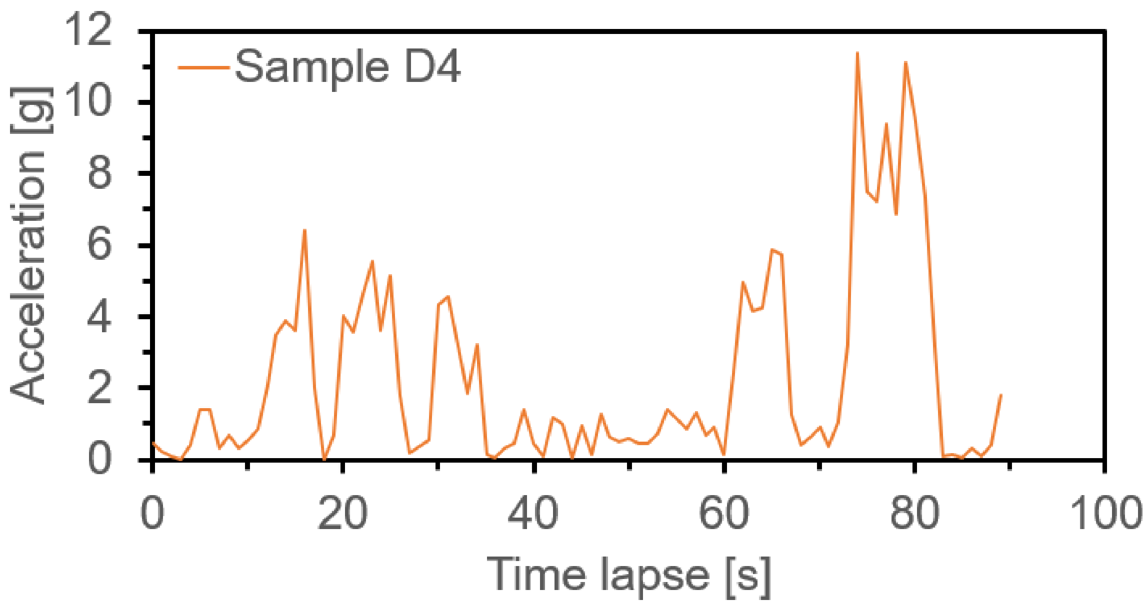

Figure 45. Acceleration readings after subtracting environmental vibration for tie D4

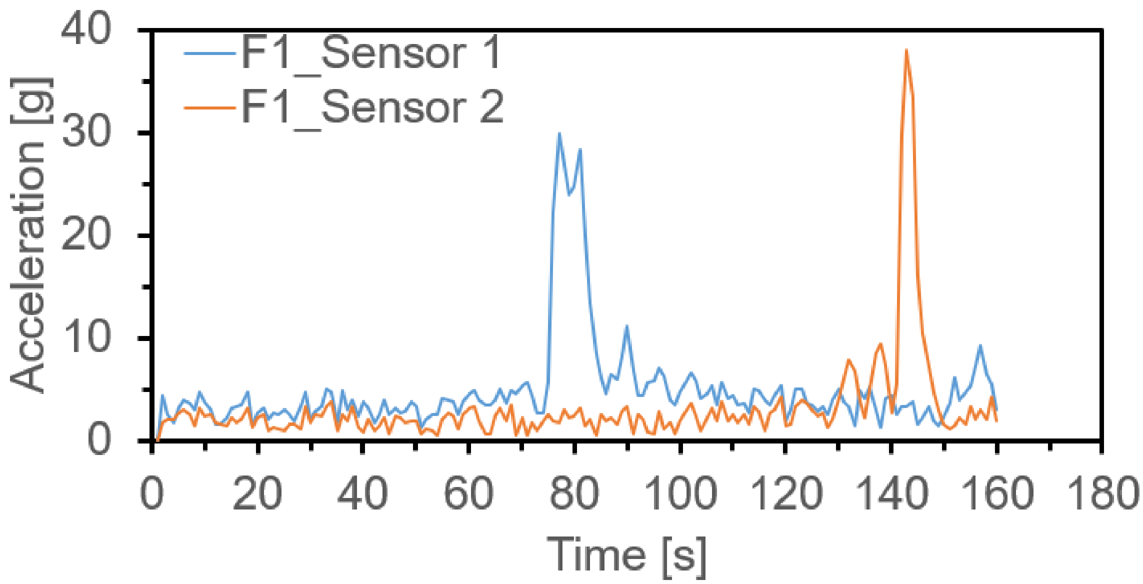

Figure 46. Raw acceleration readings in tie F1

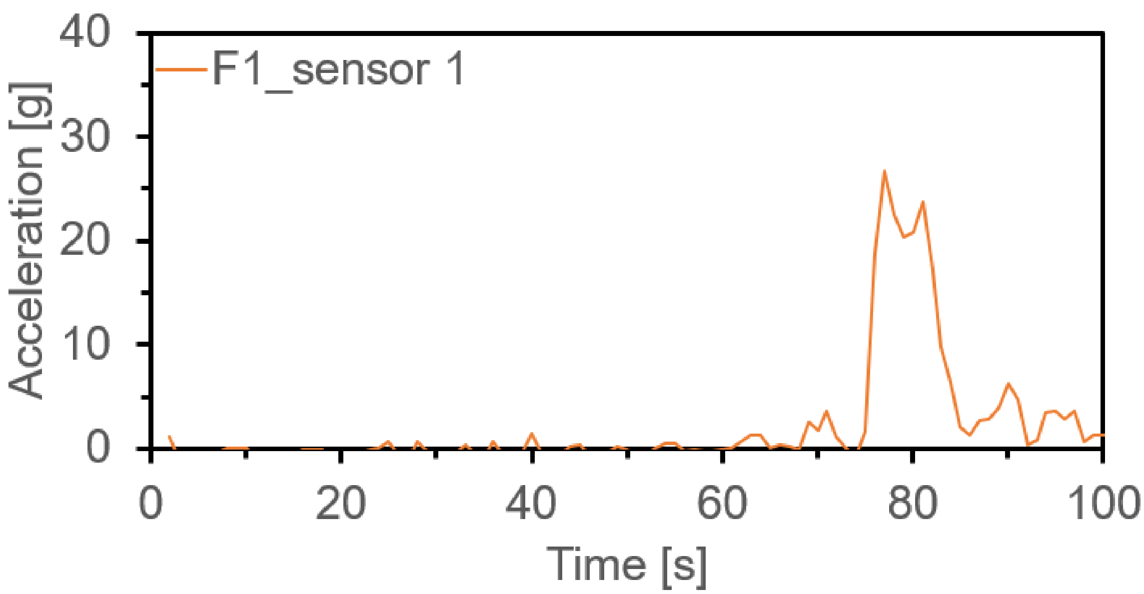

Figure 47. Acceleration readings after subtracting environmental vibration for tie F1

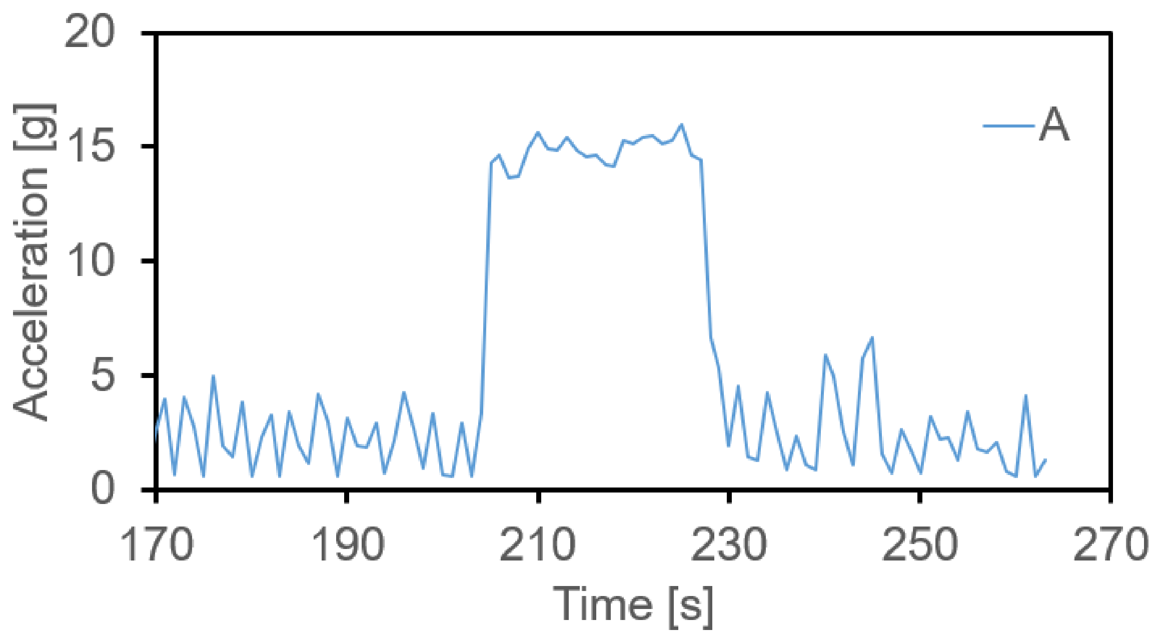

Figure 48. Acceleration measured for match-vibrated cylinders for mixture A

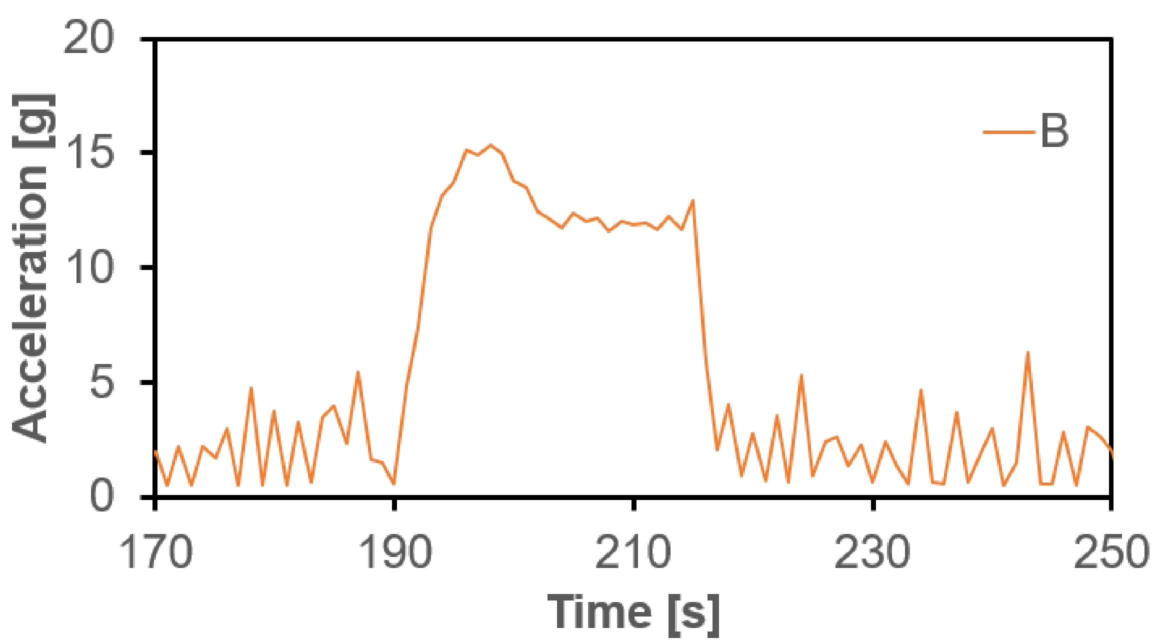

Figure 49. Acceleration measured for match-vibrated cylinders for mixture B

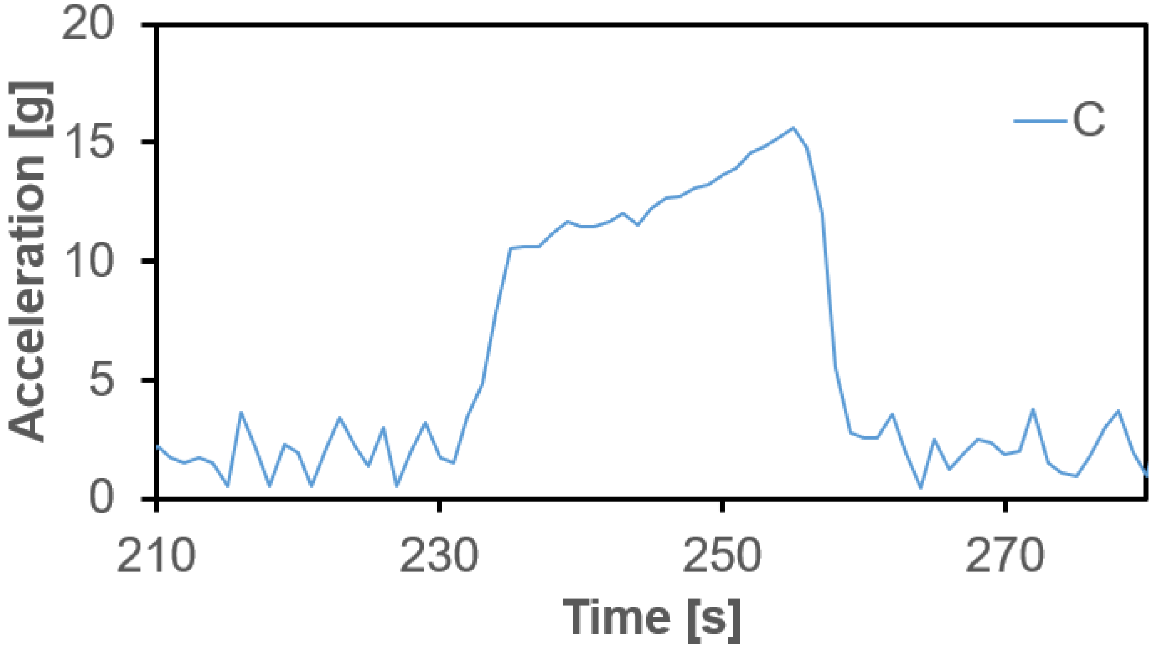

Figure 50. Acceleration measured for match-vibrated cylinders for mixture C

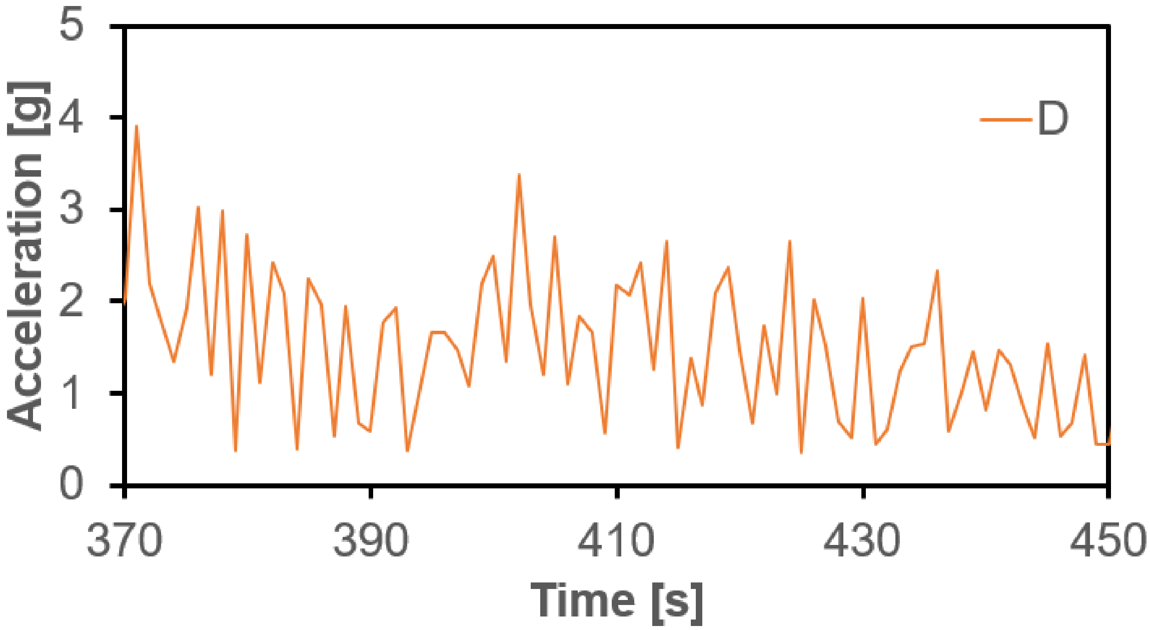

Figure 51. Acceleration measured for match-vibrated cylinders for mixture D

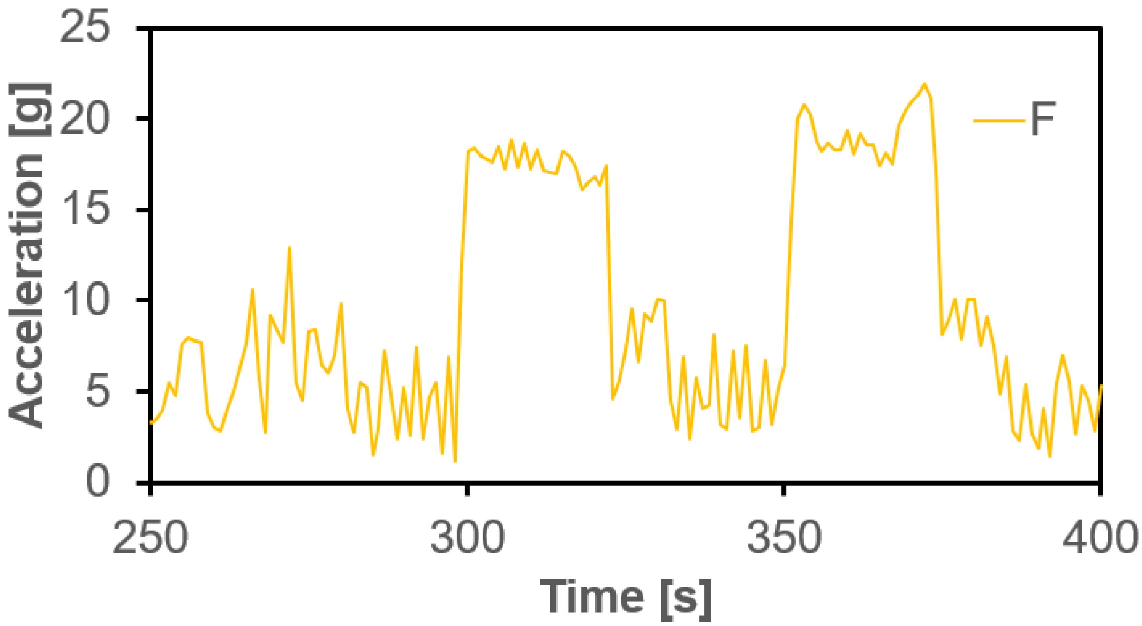

Figure 52. Acceleration measured for match-vibrated cylinders for mixture F

Abbreviations and Acronyms

ACRONYM	DEFINITION
AAR	Alkali-Aggregate Reaction
AREMA	American Railway Engineering and Maintenance-of-Way Association
DEF	Delayed Ettringite Formation
FRA	Federal Railroad Administration