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Ultrasonic characterization of damage induced by temperature variations in concrete medium treated with nanosilica

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Keywords: frequency band, concrete medium, ultrasonic wave velocity, wave attenuation

Abstract. Concrete is widely used as construction material in civil infrastructures. Generally, this type of material can deteriorate due to several reasons, such as temperature variations. It is essential to monitor the changes inside the concrete medium using a suitable technique. In this study, six concrete specimens (three prisms and three cylinders) with different nanosilica contents were made and tested using the ultrasonic pulse velocity (UPV) method. These specimens were evaluated under the effect of daily freeze-thaw (F-T) cycle (71 cycles) under controlled laboratory conditions. A new evaluation approach based on selected frequency bands is proposed to analyze the signal spectra to monitor the damage development inside the concrete medium under temperature variations and compared with other conventional procedures. The results obtained show that the proposed approach could capture the damage progress better than other procedures used to evaluate damage propagation in concrete medium. It is shown that the band with high frequencies (42–65 kHz) is more robust to capture damage in all concrete specimens tested in this study in comparison with the UPV methods. In conclusion, the findings of this study indicate that the proposed new approach can be applied to monitor damage propagation in concrete medium under laboratory and field conditions.

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1. Introduction

Non-destructive testing (NDT) methods are widely used to characterize and assess the internal condition of concrete structures, such as deep foundations, bridges, buildings, pavements, dams, and others [1, 2]. In many situations, the consequences of deterioration can include excessive repair, shortened service life, and collapse of the structure. It is essential to assess the condition of concrete members during construction and throughout their service life. NDT methods are generally used for quality control of structure members, for condition assessment of existing structures, for rehabilitation and maintenance, and for quality control of repairs. Ultrasonic pulse velocity (UPV) method is one of these NDT methods that are used widely to assess the condition of cement-based elements, both in laboratory and field conditions.

Recently, the method has been used in various fields, such as chemistry, medicine, biology, engineering, and physics [3–5]. Ultrasound is used in civil engineering for material characterization by NDT. In concrete, the ultrasonic velocity is less sensitive than the wave attenuation [6–14]. Therefore, wave attenuation may be considered as a key parameter that is required for material characterization. The importance of this parameter is due to the fact that any reduction in the wave attenuation (wave amplitude) indicates a loss of strength or degradation of the material's internal conditions [15, 16]. However, the use of wave attenuation has some limitations due to the difficulty of making reliable measurements at the testing site.

In cold climate areas, the freeze-thaw (F-T) cycle is considered to be the main parameter that causes deterioration in concrete structures [17]. P.J. Nixon [18] stated that V.M. Malhotra is a pioneer in using the UPV method (1976) to evaluate the F-T resistance of concrete containing recycled aggregates. The reduction in UPV was reported after certain F-T cycles, some of which were as high as 4 % after more than 600 cycles. Other researchers also used UPV as NDT procedure in F-T inspection [19, 20]. Other studies have discovered a few drawbacks of UPV under temperature variation [21, 22]. A. Erdélyi et al. [23] found that UPV measurements of heated dried specimens were significantly decreased after F-T cycles, but not on saturated specimens with NaCl. On the other hand, S.F. Selleck et al. [21] explained that the UPV sensitivity to detect changes of microcracking in concrete was not visible.

The literature review presented above highlighted the use of UPV as a suitable tool to assess the concrete conditions under temperature variation. However, the use of UPV alone cannot provide a reliable assessment to evaluate the crack propagation inside concrete medium due to the effect of temperature variations (F-T cycles). Using the wave attenuation under control conditions along with UPV can be considered as a reliable inspection technique to investigate the damages induced inside concrete medium subjected to F-T cycles. Based on that, a new approach is proposed in this study to assess the concrete conditions of specimens treated with nanosilica under F-T cycles.

The objective of this study is to investigate the ability of proposed new approach defining two frequency bands (low and high frequencies) to monitor the influence of temperature variations (F-T cycles) on the integrity of concrete specimens (prisms and cylinders) under controlled testing conditions. UPV and other conventional procedures are used for comparison with the proposed new procedure. Mixing concrete with nanosilica has received more attention due of its ability to enhance the main characteristics of concrete mixtures including compressive strength, durability, and decrease the effect of the F-T cycles [24, 25]. Therefore, the concrete specimens were mixed with different amounts of a nanosilica (0 %, 1 %, 3 %) to investigate the changes in P-wave characteristics that may occur under F-T cycles using UPV and two conventional procedures for comparison with the proposed new technique. The investigation includes proposing a damage index called damage reference (DR) based on wave velocity and signal amplitude to monitor internal damage in the concrete medium during different time periods. The results of the study show that suitability of the proposed new approach to identify the induced damage is better than the traditional measurements of UPV and other conventional procedures.

2. Materials and Methods

2.1. Concrete Specimens

Six concrete specimens (three prisms and three cylinders) with different nanosilica content were manufactured for this research. Cylinder and prism specimens contained three different percentages of nanosilica: one without nanosilica, one specimen with 1 % of nanosilica, and the last one with 3 % of nanosilica. Table 1 shows the properties of the concrete used in manufacturing the concrete specimens.

Table 1. Parameters of the concrete mixture.

Parameter name	Range value
Slump rate	75.0–100.0 mm
Air content percentage	5.0–8.0 %
Water/cement ratio	0.390
Concrete class	C-20
Nominal aggregate size	20.0 mm
Specified compressive strength (28 days)	32.50 MPa

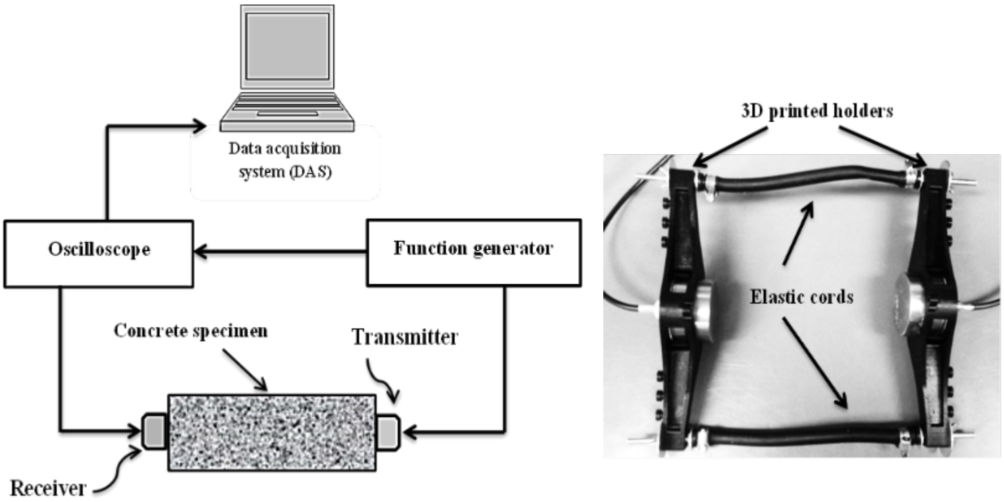
Each concrete specimen (prism and cylinder) was subjected to 71 days of F-T cycles using a special machine with the ability to control the temperature to mimic F-T conditions. Each accelerated F-T cycle represented a full day (24 hours) and was accompanied by a gradual temperature change set to a gradual increase from –25.0 to +25.0 °C with ±2.0 °C.

2.2. Instrumentation Setup

2.2.1. UPV setup

The UPV measurement equipment consisted of four components: 1) pair transducers; 2) a function-generator; 3) oscilloscope; and 4) laptop computer used as a data acquisition system (DAS) (Fig. 1a). A pair of 54 kHz transducers with a diameter of 50 mm was used for measurements, one transducer for transmitting the pulse, and the other for capturing the ultrasonic waves. To obtain consistent results, two 3D-printed transducer holders with elastic cords to control the pressure on both transducers were fabricated (Fig. 1b).

The function generator was used to generate square wave frequency of 60 kHz and amplitude 10.0 vpp. to excite each specimen. Coupling grease was used between specimens' surfaces and the transducers to minimize signal loss due to air voids. The input-output signal data were acquired using a laptop computer with Keysight-BenchVue® software, which was later used to calculate the UPVs and compute the areas below average spectra of signals.



a) **b)**

Figure 1. UPV testing configuration: a) testing setup, b) 3D-printed transducer holders.

2.2.2. Damage assessment

For the concrete cylinder specimens, the UPV testing was performed at defined periods of time (before the first F-T cycle, after two days, 15 days and each 7 days until 71 days were reached). To ensure the consistency of the results, each specimen was tested three times. As for the concrete prisms, they were tested to determine whether the UPV results reflect the change in the internal condition of the concrete in two axes (longitudinal and transverse) after 71 F-T cycles. In the transverse direction, four equally spaced points (edge and midpoints) were selected for ultrasonic testing. For that purpose, the average ultrasonic pulse velocities for each point from the three prism sets were determined before and after the F-T cycle tests following the same procedure used for testing the cylinder specimens. In addition, three procedures were used to evaluate the damage based on the signal energy, two of which were conventional and used by other researchers [1, 3, 9] and the last one is proposed in this research project. The first and second procedures take into account the damage inside the specimen based on the signal energy in the time and frequency domains, respectively, using index called the damage reference (DR), which can be estimated using the following equation:

$$DR = \frac{S_o - S_d}{S_o}(\%), \quad (1)$$

where S_o is the energy of signal in the time or frequency domain for intact specimen (no damage); S_d is the energy of signal in the time or frequency domain for specimen with damage. The larger the DR mains, the more damage exists inside the concrete specimen, and vice versa.

The third procedure is new and proposed in current research based on the definition of two frequency bands in the spectrum of each signal. Low frequency band (LFB ≈ 15–35 kHz) and high frequency band (HFB ≈ 42–65 kHz), which are shown more changes than other band frequencies. In addition, this procedure uses the DR by calculating the area under each band to evaluate the damage inside concrete specimen induced by temperature variations. All the results obtained by the traditional methods and the proposed method are compared to investigate the feasibility of the proposed third method for assessing the damage in concrete specimens under temperature variations.

3. Results and Discussion

3.1. Freeze-Thaw Effect on Concrete Prisms

3.1.1. Damage assessment using UPV

Fig. 2 shows the average P-wave velocities calculated from the longitudinal configuration test data compared to the F-T cycles for the three concrete prisms. The figure shows that in all cases (with and without nanosilica), the P-wave velocity of the specimens does not show any significant trend throughout the test period, which can be attributed to the selection procedure of the arrival time based on the UPV device readings.

In the initial periods (from 0 to 7 days), the velocity of the specimen with nanosilica shows a clear decrease and then increases to a value exceeding that of the specimen without nanosilica after 71 days. The difference between the calculated wave velocities of the specimens with and without nanosilica was obtained after two days, and it has a value of 2.6 %. A similar trend of the UPV results was obtained when testing the concrete prism in the transverse direction.

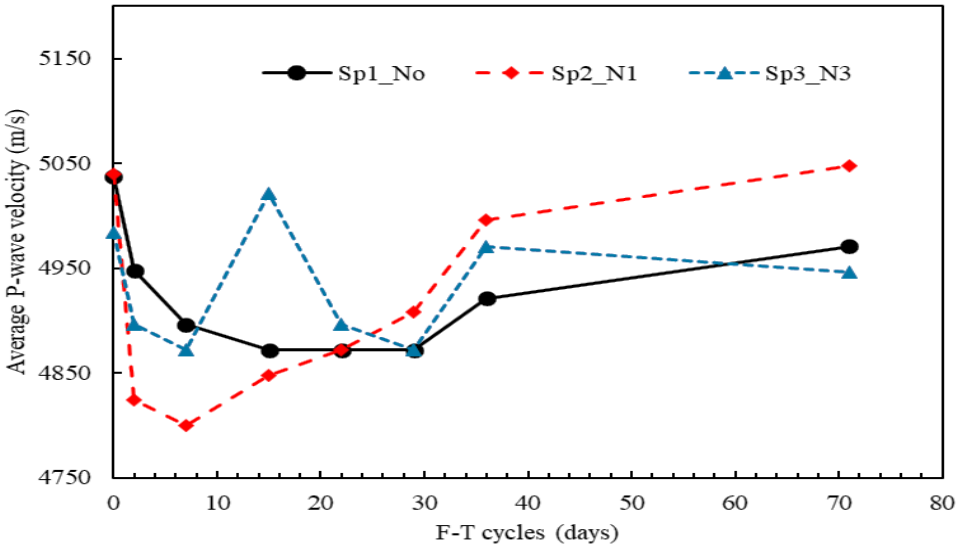


Figure 2. Average P-wave velocities of all prism specimens compared to the F-T cycles.

3.1.2. Damage assessment using signal information

Fig. 3 shows the time signals acquisition for two prisms, a prism with an intact case and a prism with 3 % nanosilica, tested before and after 71 days of F-T cycling. The time signals for the intact case show a significant decrease in the maximum amplitude (~ 28 %), while for the prism mixed with 3 % nanosilica the decrease is smaller than for the intact case (~ 19 %), which can be attributed to the effect of nanosilica that reduced the impact of temperature variations.

Moreover, the frequency spectra of the time signals obtained in Fig. 3 are shown in Fig. 4 with two identified frequency bands that are proposed as the third method for assessing the damage induced by temperature variations. In this figure, both spectra reveal a small difference in the peak frequencies, but the signal energy is significantly reduced for the intact case, while a smaller reduction is observed in the prism with 3 % of nanosilica. Similar results are obtained for the prism with 1 % of nanosilica.

Fig. 5 shows the comparison between the DR values for concrete prisms treated with 0 % and 3 % of nanosilica obtained by three procedures, the first and second depending on the peak amplitude of the signals over time and the total area under the frequency spectra. While the third procedure is proposed in this research and depends on areas under defined frequency bands that are most influenced by damage induced by temperature variations. Although the two conventional methods used to calculate DR for both cases are able to identify the damage progress better than the UPV method, the latter method, which depends on defined bands, shows better results. In particular, the higher frequency band is more robust than low frequency band in capturing the damage progress induced by F-T cycles.

Furthermore, the results in Fig. 5b show the ability of the added nanosilica to reduce the impact of F-T cycles on the internal condition of the prism. The analysis of the signals captured during the pulse velocity test provides an extra source of information that can assist in the examination of the condition of concrete members. This example shows that the proposed procedure was able to identify the damage to a greater extent than other conventional methods currently used in characterization of concrete medium.

On the other hand, the average time signals measured at four different points along the intact prism concrete and the prism treated with 3 % nanosilica before and after 71 F-T cycles are shown in Fig. 6.

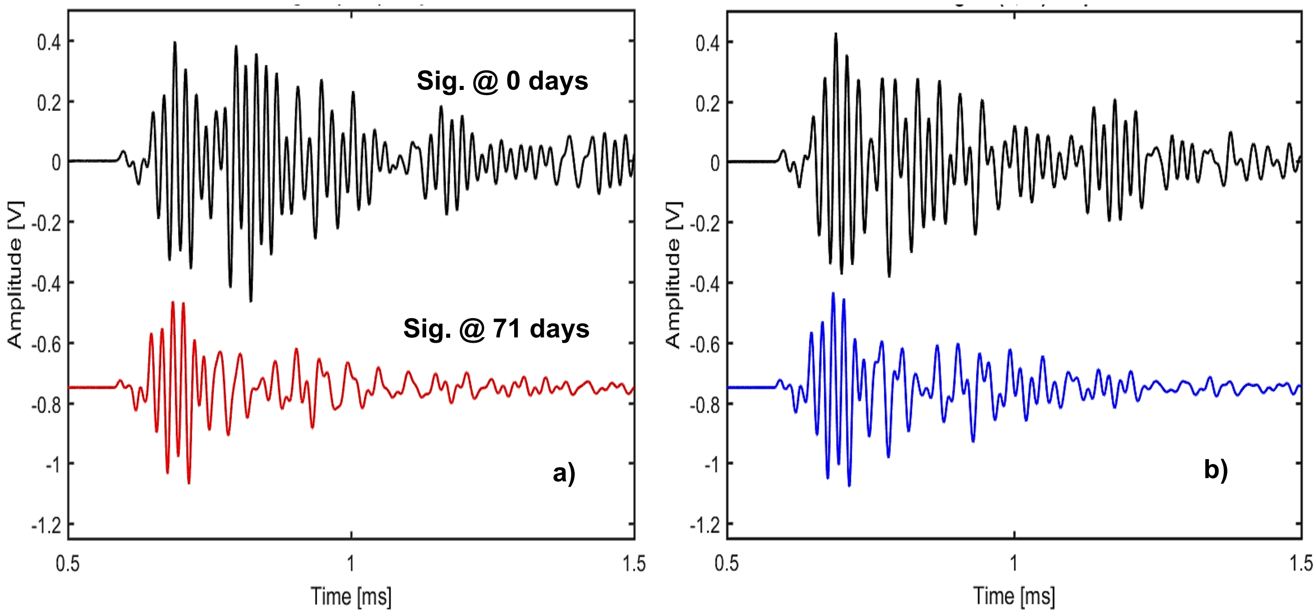


Figure 3. Typical time signals of the intact prism and the prism with 3 % nanosilica tested in the longitudinal direction at 0 and 71 days of F-T cycling: a) intact prism (0 %), b) prism with 3 % of nanosilica.

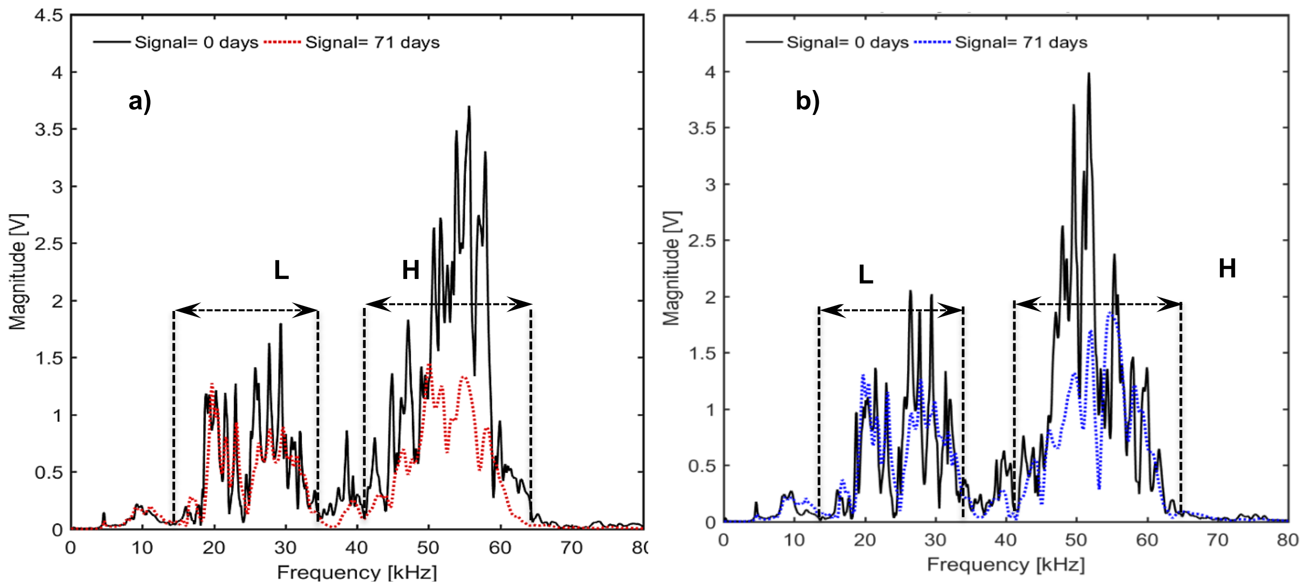


Figure 4. Typical spectra of the intact prism and the prism with 3 % of nanosilica signals at 0 and 71 days of F-T cycling: a) intact prism (0 %), b) prism with 3 % of nanosilica.

The figure also reveals that the time signals for the intact case show a clear decrease in the maximum amplitude (~ 23 %), while for the prism mixed with 3 % of nanosilica the decrease is smaller than that of the intact case (~ 14 %), which can be related to the addition of nanosilica that reduced the impact of F-T cycles. In addition, the frequency spectra of the time signals obtained in Fig. 6 are shown in Fig. 7 with two identified frequency bands that are proposed as the third method for assessing the damage induced by temperature variations.

In this figure, both spectra reveal a small difference in peak frequencies, but the signal energy is significantly reduced for the intact case, while in the prism treated with 3 % of nanosilica a smaller decrease is observed. Similar results are obtained for the prism with 1 % of nanosilica.

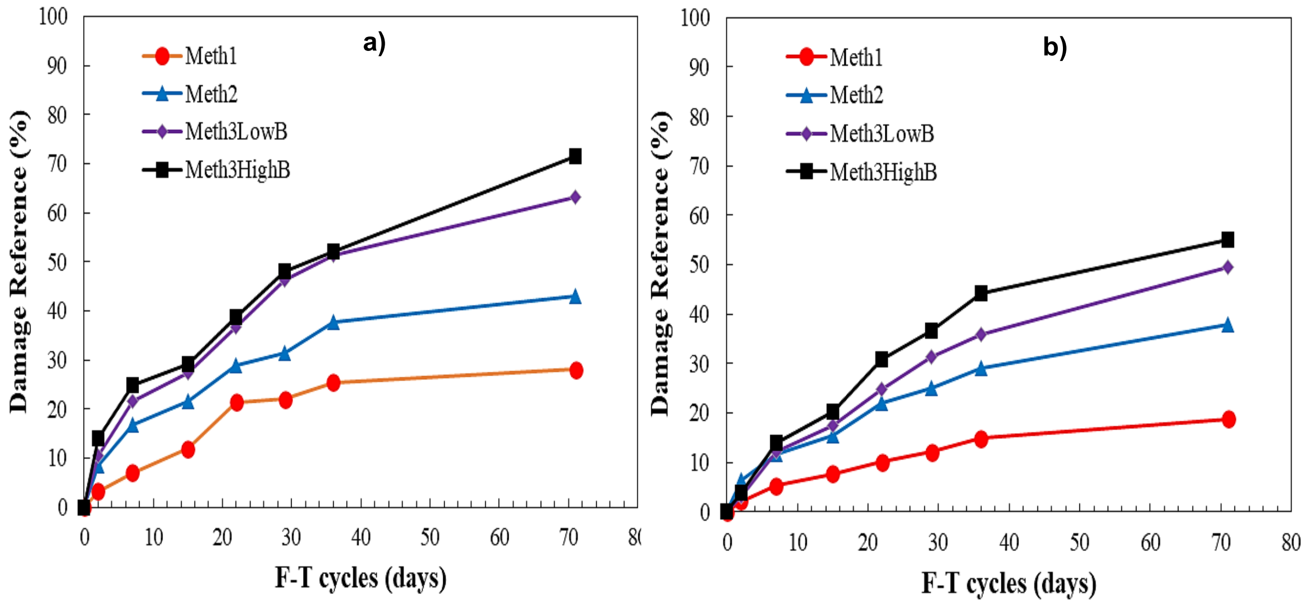


Figure 5. Comparison between DRs of the intact prism and the prism with 3 % of nanosilica signals under 71 days of F-T cycling: a) intact prism (0 %), b) prism with 3 % of nanosilica. Meth1 represents the 1st procedure based on the peak amplitude, Meth2 represents the 2nd procedure based on the total area under spectrum, Meth3LowB and Meth3HighB represent areas under low and high band spectra, respectively.

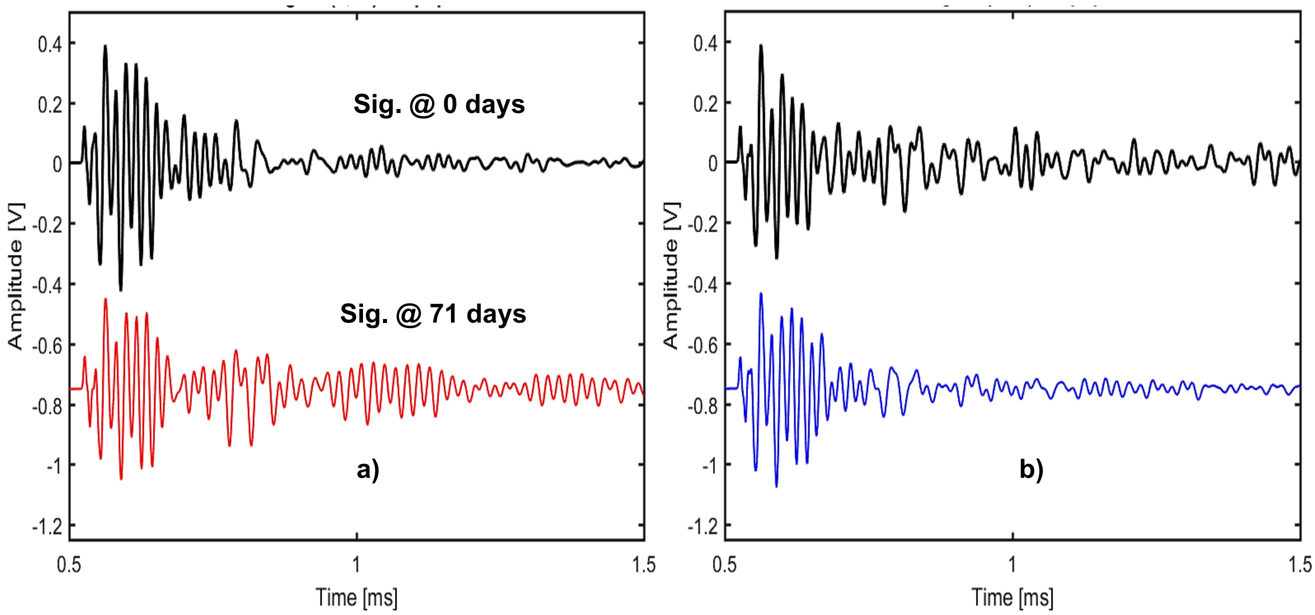


Figure 6. Average time signals of the intact prism and the prism with 3 % nanosilica tested in the transverse direction at 0 and 71 days of F-T cycling: a) intact prism (0 %), b) prism with 3 % of nanosilica.

Fig. 8 shows the DR values for concrete prisms with 0 % and 3 % of nanosilica, which are calculated using three procedures similar to the analysis of the testing result in the longitudinal direction. Although the two conventional methods used to calculate the DR for both cases are able to identify the damage progress better than the UPV method, the latter method, which depends on defined bands, shows better results. In particular, the higher frequency band is more robust than low frequency band in capturing the damage progress induced by F-T cycles.

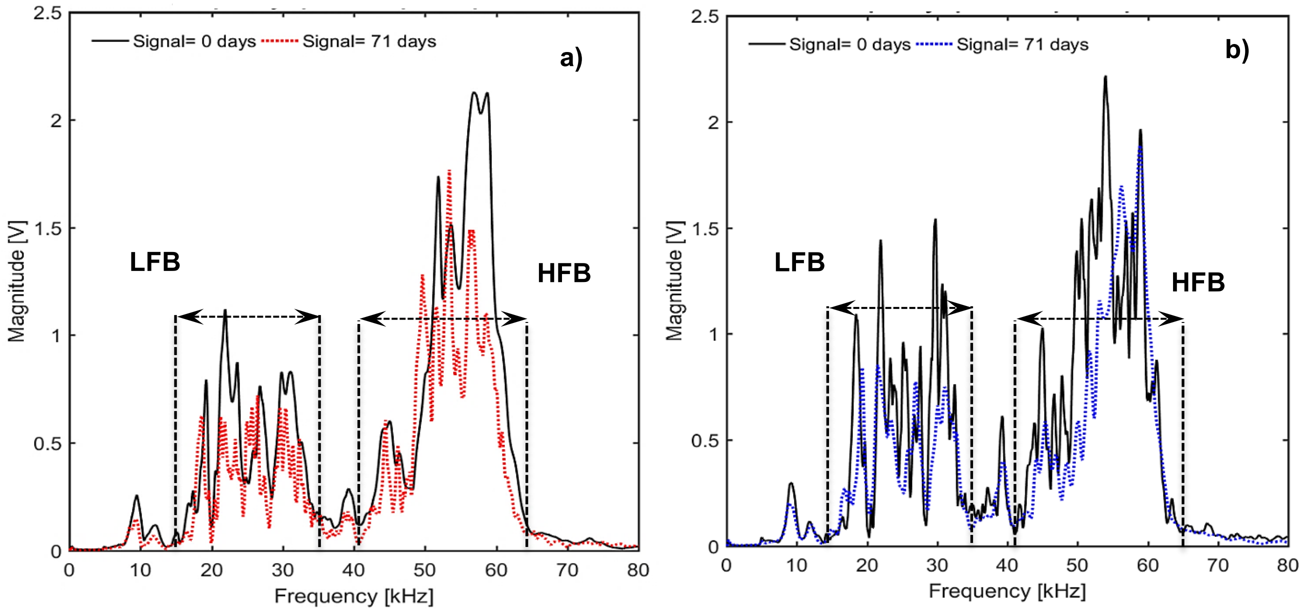


Figure 7. Typical spectra of the intact prism and the prism with 3 % of nanosilica signals tested in the transverse direction at 0 and 71 days of F-T cycling: a) intact prism (0 %), b) prism with 3 % of nanosilica.

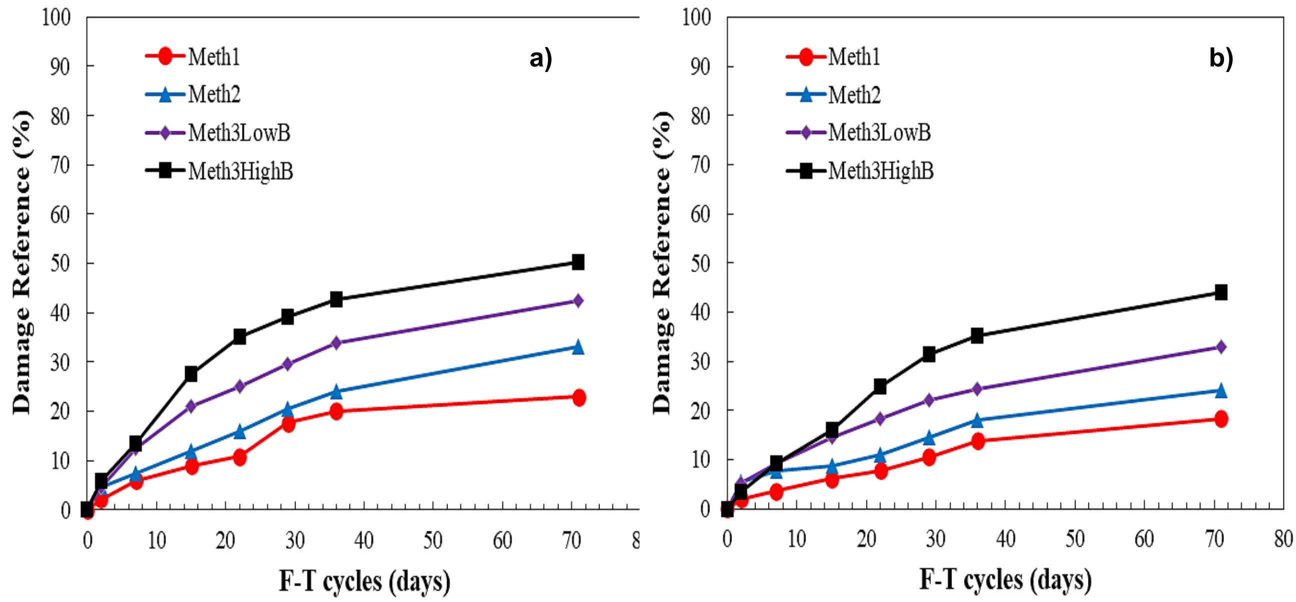


Figure 8. Comparison between DRs of the intact prism and the prism with 3 % of nanosilica signals tested in transverse direction after 71 days of F-T cycling: a) intact prism (0 %), b) prism with 3 % of nanosilica. Meth1 represents the 1st procedure based on the peak amplitude, Meth2 represents the 2nd procedure based on the total area under spectrum, Meth3LowB and Meth3HighB represent areas under low and high band spectra, respectively.

3.2. Freeze-Thaw effect on Cylinder Specimens

3.2.1. Damage assessment using UPV

Fig. 9 shows the average wave velocities plotted against the test periods for three specimens (0 %, 1 %, and 3 % of nanosilica). The average velocity of the specimen with 3 % of nanosilica showed a decreasing trend until it reached a steady-state level after 7 days. In contrast, the intact specimen (0 %) reveals an initial decrease in average velocity and after 7 days increases until it reaches a maximum value after
71 days. On the other hand, the UPV results did not show any consistent trend, which can be used to identify the damage induced by F-T cycles.

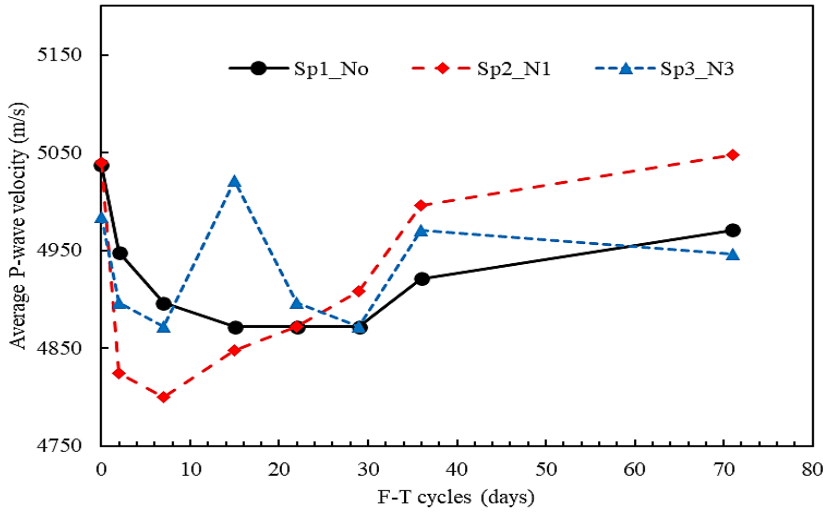


Figure 9. Typical average P-wave velocities of all cylinder concrete specimens (intact and with 1 % and 3 % of nanosilica).

3.2.2. Damage assessment using signal information

The time signals acquisition for two-cylinder specimens with the intact case and specimen with 3 % of nanosilica tested before and after 71 days of F-T cycling are shown in Fig. 10. The figure shows that the time signals for the intact case show a significant decrease in a maximum amplitude (~ 30 %), while for the cylinder mixed with 3 % of nanosilica, the decrease is smaller than that of the intact case (~ 12 %), which can be due to the effect of nanosilica that reduced the impact of F-T cycles.

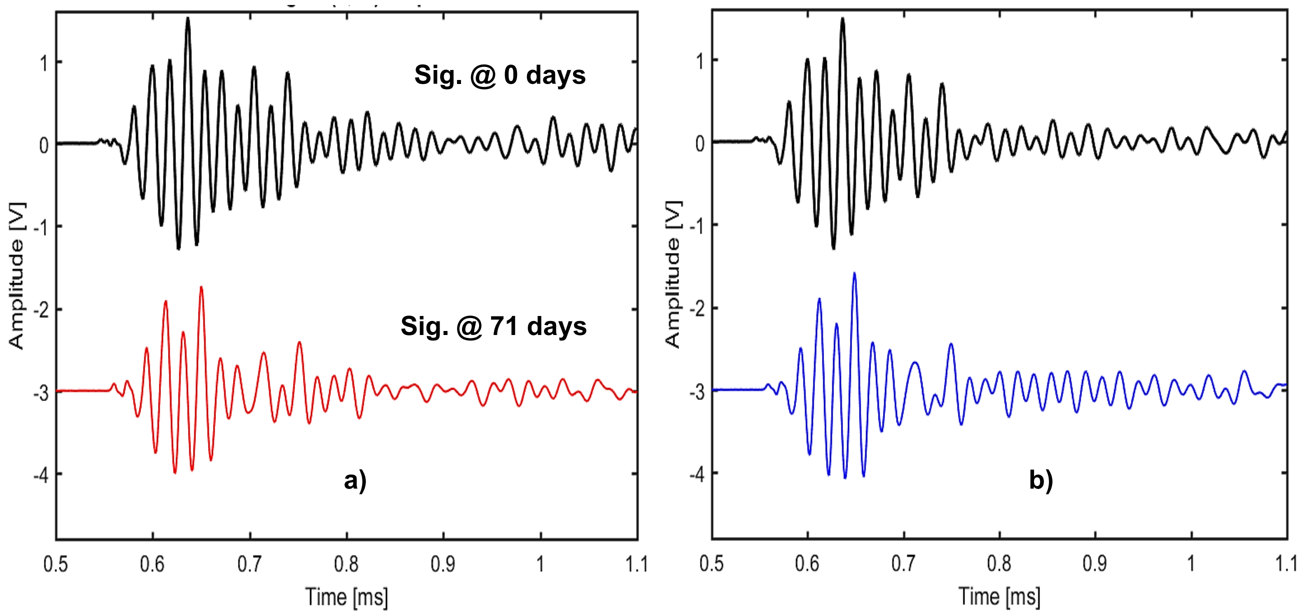


Figure 10. Average time signals of the intact concrete cylinders without and with 3 % of nanosilica tested at 0 and 71 days of F-T cycling: a) intact cylinder (0 %), b) cylinder with 3 % of nanosilica.

Furthermore, the frequency spectra of the time signals obtained in Fig. 10 are shown in Fig. 11 with two identified frequency bands that are proposed as the third method for assessing the damage induced by temperature variations. In this figure, both spectra appear to have a little change in the peak frequencies, but the signal energy is significantly reduced for the intact case, while in the cylinder with 3 % of nanosilica shows smaller decrease. Similar results are obtained for the cylinder with 1 % of nanosilica.

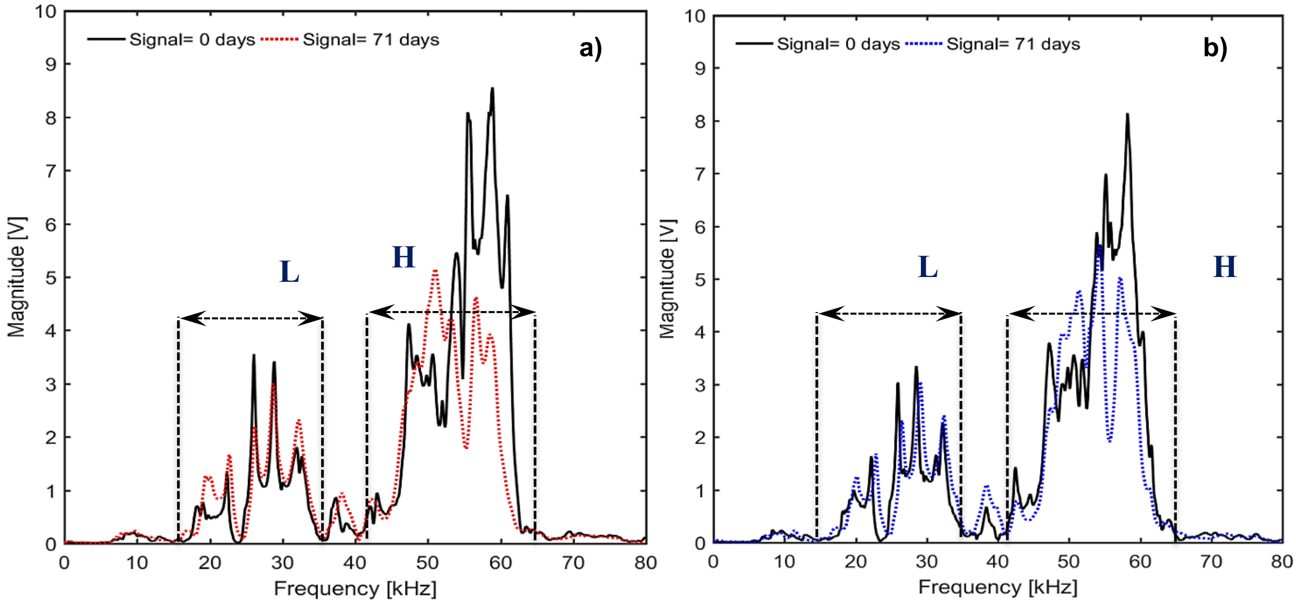


Figure 11. Typical spectra of the intact cylinders without and with 3 % of nanosilica signals at 0 and 71 days of F-T cycling: a) intact cylinder (0 %), b) cylinder with 3 % of nanosilica.

Fig. 12 shows the comparison between the DR values for concrete cylinders treated with 0 % and 3 % of nanosilica, which are calculated using three approaches, the first and second depending on the peak amplitude of the signals over time and the total area under the frequency spectra. While the third procedure is proposed in this research and depends on areas under defined frequency bands that are most influenced by damage induced by temperature variations. In addition, the two conventional methods used to calculate DR for both cases are able to identify the damage progress better than the UPV method, the latter procedure, which depends on defined bands, shows better results. In particular, the higher frequency band is more robust than low frequency band in capturing the damage progress induced by F-T cycles.

In addition to that, the observations in Fig. 12b confirm the ability of the added nanosilica to reduce the impact of F-T cycles on the internal condition of the cylinder, as was noticed with the prism specimens.

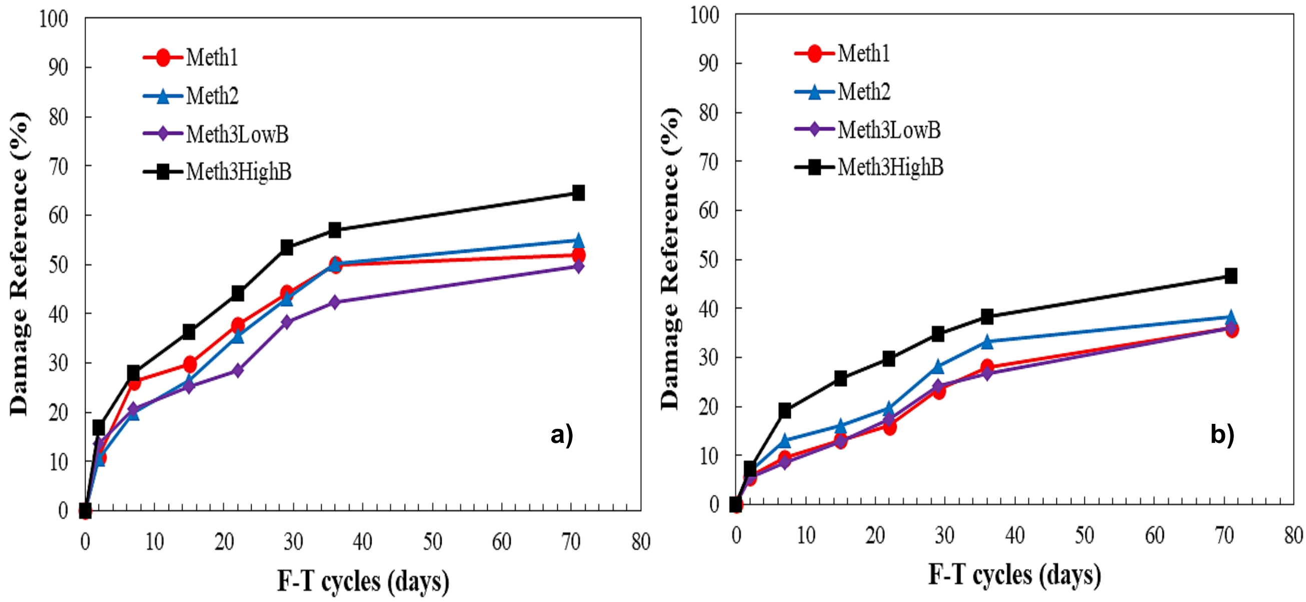


Figure 12. Comparison between DRs of the intact cylinders without and with 3 % of nanosilica signals tested after 71 days of F-T cycling: a) intact cylinder (0 %), b) cylinder with 3 % of nanosilica. Meth1 represents the 1st procedure based on the peak amplitude, Meth2 represents the 2nd procedure based on the total area under spectrum, Meth3LowB and Meth3HighB represent areas under low and high band spectra, respectively.

4. Conclusions

Different approaches based on the UPV testing including the proposed new approach are used to assess its potential to capture damage progress in two groups of concrete specimens (prism and cylinder) under the impact of 71 F-T cycles, each cycle lasting 24 hours. The UPV testing of all concrete specimens is conducted under controlled conditions to ensure the stability of the signals. The proposed technique depends on defining two frequency bands: low (15–35 kHz) and high (42–65 kHz) – on each signal spectrum obtained from testing of the concrete specimen. In addition, the DR is proposed to monitor the damage propagation inside concrete medium and to compare the conventional procedures with the proposed new technique. The following conclusions are drawn from the conducted study:

1. It was found that there is no significant variation was observed in the wave velocities measured by the conventional procedure during the study (less than 3 % changes) for all the specimens.
2. The results obtained from the time and frequency domains indicate a significant change in the specimens' condition under the impact of the F-T cycles.
3. The proposed new procedure with high frequency band was found to be more robust than other conventional procedures in assessing the damage induced in concrete specimens.
4. At the end of testing period, the DR values calculated based on three procedures for all tested prisms with nanosilica (0 % and 3 %) were in the range of 20–63 % and 14–55 %, respectively. While for the tested cylinders, the DR were 50–62 % for the intact case and 34–45 % for the case with 3 % of nanosilica. The lower values of DR are related to the 1st procedure, and the higher ones – to the 3rd procedure with high frequency band.
5. The results obtained in this research work indicated that a single pulse velocity measurement may not be sufficient to capture internal change in concrete medium.
6. Based on the results obtained in this study, exploring the suitability use of the proposed new procedure (HFB 42–65 kHz) to overcome the low sensitivity of the UPV measurements is a good choice for monitoring the integrity of concrete medium under temperature variations.

References

1. Bungey, J.H., Grantham, M.G. Testing of concrete in structures. 4th ed. CRC Press. London, 2006. 352 p. DOI: 10.1201/9781482264685
2. Carino, N.J., Chang, K.C.E. Nondestructive Testing of Concrete: History and Challenges. SP-144: Concrete Technology: Past, Present, and Future. American Concrete Institute. Farmington Hills, 1993.
3. Malhotra, V.M., Carino, N.J. Handbook on nondestructive testing of concrete. 2nd ed. CRC Press. Boca Raton, 2004. 384 p. DOI: 10.1201/9781420040050
4. Popovics, S. Effects of uneven moisture distribution on the strength of and wave velocity in concrete. Ultrasonics. 2005. 43(6). Pp. 429–434. DOI: 10.1016/j.ultras.2004.09.007
5. Krautkrämer, J., Krautkrämer, H. Ultrasonic Testing of Materials. 2nd ed. Springer. Berlin, Heidelberg, 2013. 373 p. DOI: 10.1007/978-3-662-02296-2
6. Ribeiro Filho, S.L.M., Thomas, C., Durão, L.M.P., Christoforo, A.L., Bowen, C., Scarpa, F., Panzera, T.H. Ultrasonic pulse velocity and physical properties of hybrid composites: A statistical approach. 2023. Hybrid Advances. 2. Article no. 100024. DOI: 10.1016/j.hybadv.2023.100024
7. Chai, H.K., Momoki, S., Kobayashi, Y., Aggelis, D.G., Shiotani, T. Tomographic reconstruction for concrete using attenuation of ultrasound. NDT & E International. 2011. 44(2). Pp. 206–215. DOI: 10.1016/j.ndteint.2010.11.003
8. Yim, H.J., Kwak, H.-G., Kim, J.H. Wave attenuation measurement technique for nondestructive evaluation of concrete. Nondestructive Testing and Evaluation. 2012. 27(1). Pp. 81–94. DOI: 10.1080/10589759.2011.606319
9. Fartosy, S., Gomez-Rodriguez, D., Cascante, G., Basu, D., Dusseault, M.B. Effects of a Fracture on Ultrasonic Wave Velocity and Attenuation in a Homogeneous Medium. Geotechnical Testing Journal. 2020. 43(2). Pp. 394–413. DOI: 10.1520/GTJ20180200
10. Fartosy, S., Abdalqadir, N.A., Al-Mussawy, H.A., Jafar, N.Q., Ghosh, S. A Combined Ultrasonic Procedure to Evaluate Damage in Concrete Beams Subjected to Static Load. Journal of Engineering and Sustainable Development. 2024. 28(2). Pp. 213–221. DOI: 10.21272/jeasd.28.2.5
11. Ramaniraka, M., Rakotonarivo, S., Payan, C., Garnier, V. Effect of Interfacial Transition Zone on diffuse ultrasound in thermally damaged concrete. Cement and Concrete Research. 2022. 152. Article no. 106680. DOI: 10.1016/j.cemconres.2021.106680
12. Komloš, K., Popovics, S., Nürnbergerová, T., Babál, B., Popovics, J.S. Ultrasonic pulse velocity test of concrete properties as specified in various standards. Cement and Concrete Composites. 1996. 18(5). Pp. 357–364. DOI: 10.1016/0958-9465(96)00026-1
13. Helal, J., Sofi, M., Mendis, P.A. Non-Destructive Testing of Concrete: A Review of Methods. Electronic Journal of Structural Engineering. 2015. 14(1). Pp. 97–105. DOI: 10.56748/ejse.141931
14. Drabkin S., Kim D. Failure monitoring of concrete specimen using frequency characteristics of ultrasonic waves. American Concrete Institute. Farmington Hills, 1994. 143(1). Pp. 257–274.
15. Ensminger, D., Bond, L.J. Ultrasonics: Fundamentals, Technologies, and Applications. 4th ed. CRC Press. Boca Raton, 2011. 904 p. DOI: 10.1201/9780429286964

16. Fartosy, S.H., Waleed, J.F., Abd, H.Z., Al, M.A.S.T. Evaluation bearing capacity of ring footings on reinforced loose sand. Journal of Applied Engineering Science. 2023. 21(1). Pp. 29–35. DOI: 10.5937/jaes0-37350
17. Shang, H.-S., Cao, W.-Q., Wang, B. Effect of Fast Freeze-Thaw Cycles on Mechanical Properties of Ordinary-Air-Entrained Concrete. The Scientific World Journal. 2014. Article no. 923032. DOI: 10.1155/2014/923032
18. Nixon, P.J. Recycled concrete as an aggregate for concrete – a review. Material and Structures. 1978. 11(5). Pp. 371–378. DOI: 10.1007/BF02473878
19. Richardson, A., Coventry, K., Dave, U., Pienaar, J. Freeze/Thaw Performance of Concrete Using Granulated Rubber Crumb. Journal of Green Building. 2011. 6(1). Pp. 83–92. DOI: 10.3992/jgb.6.1.83
20. Van Wesenbeeck, B.K., Wolters, G., Antolínez, J.A.A., Kalloe, S.A., Hofland, B., de Boer, W.P., Çete, C., Bouma, T.J. Wave attenuation through forests under extreme conditions. Scientific Reports. 2022. 12(1). Article no. 1884. DOI: 10.1038/s41598-022-05753-3
21. Selleck, S.F., Landis, E.N., Peterson, M.L., Shah, S.P., Achenbach, J.D. Ultrasonic investigation of concrete with distributed damage. ACI Materials Journal. 1998. 95(1). Pp. 27–36.
22. Molero, M., Aparicio, S., Al-Assadi, G., Casati, M.J., Hernández, M.G., Anaya, J.J. Evaluation of freeze–thaw damage in concrete by ultrasonic imaging. NDT & E International. 2012. 52. Pp. 86–94. DOI: 10.1016/j.ndteint.2012.05.004
23. Erdélyi, A., Csányi, E., Kopecskó, K., Borosnyói, A., Fenyvesi, O. Deterioration of steel fibre reinforced concrete by freeze-thaw and de-icing salts. Concrete Structures. 2008. 9. Pp. 33–44.
24. Pandiaraj, K.P., Sankararajan, V. Effect of nano silica on the properties of concrete and mortar – A state of art. International Review of Applied Sciences and Engineering. 2021. 13(1). Pp. 70–79. DOI: 10.1556/1848.2021.00309
25. Chekravarty, D.S.V.S.M.R.K., Mallika, A., Sravana, P., Rao, S. Effect of using nano silica on mechanical properties of normal strength concrete. Materials Today: Proceedings. 2022. 51(8). 2573–2578. DOI: 10.1016/j.matpr.2021.12.409

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