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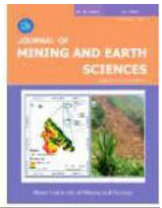

Evaluate the influence of steel fiber on the propagation time of ultrasonic waves in high-strength concrete

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ABSTRACT

In modern high-strength concrete, steel fibers are commonly added to the concrete mix to improve its mechanical properties and structure. The steel fibers typically have a specific length and are randomly distributed to increase the tensile and bonding strength of concrete structures. However, the presence of steel fibers can impact the propagation of ultrasonic waves in concrete, causing alterations in ultrasonic wave transmission characteristics and potentially affecting the ability to assess the quality and safety of construction projects. A successfully produced high-strength concrete (> 60 MPa) from cement, sand, silica fume, and superplasticizer. Using this concrete mix, the authors fabricated beam specimens with dimensions of 150 × 150 × 600 mm for both cases with and without steel fiber reinforcement. Based on the Time-of-Flight Diffraction (TOFD) ultrasonic testing method, the authors conducted a series of experiments on high-strength concrete beam specimens. The results of ultrasonic wave propagation experiments indicated that the presence of steel fibers at a 2% content increased the time of wave propagation. On the other hand, curing conditions, specimen maintenance time, and transmission path distance affected the ultrasonic wave propagation time in high-strength concrete. Understanding the influence of steel fiber content on the propagation time of ultrasonic waves in high-strength concrete can contribute to improving the inspection and quality assessment processes of construction projects. Additionally, it helps enhance the understanding of the properties of high-strength concrete reinforced with steel fibers.

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1. Introduction

Ordinary concrete typically exhibits low tensile strength, ductility, and tensile deformation capacity (Colyvas et al., 2020; Farhangi & Karakouzian, 2020; Sadeghian et al., 2021; Asgharzadeh et al., 2016). Throughout the usage of concrete components subjected to various loading stages, it is common to encounter tensile damage, which can impact the lifespan of the structure. In practice, for most load-bearing structures, enhancing tensile strength and ductility is achieved through the incorporation of reinforcing elements such as steel bars, or fibers including steel, glass, and polymer fibers. Unlike the reinforcement of steel bars, fibers mixed into a concrete mixture possess characteristics of short length, discontinuity, and random distribution throughout the concrete structure, resulting in better crack control capability (Prabhakaran et al., 2020; Aghayari & Moradi, 2016; Kazemi et al., 2020).

However, reinforcing with steel fiber alone cannot completely replace traditional reinforcement methods. Until now, there have been numerous studies on steel fiber reinforcement to improve the mechanical properties of concrete. Holschemacher et al (2010) have demonstrated that adding high-strength fibers increases the load-bearing capacity of concrete. Additionally, Rossi (1992) through experiments on concrete specimens and structural concrete members, has shown the effectiveness of steel fibers in reducing crack propagation. The ultrasonic pulse velocity (UPV) method is one of the most widely used non-destructive testing (NDT) methods to determine certain mechanical properties of concrete (Güçlüer, 2020; Bui et al., 2013). The majority of studies utilize wave propagation characteristics such as pulse velocity, travel time, wave amplitude, and pulse frequency in both indirect and direct modes to assess the mechanical properties of the surveyed materials (Nguyen, 2016; Pham & Khong, 2023).

Although the application of ultrasonic pulses for assessing the mechanical properties of construction materials has been employed for a long time, the results related to ultrasonic pulse propagation evaluation in high-strength concrete materials, especially high-strength concrete reinforced with steel fibers, are still limited. The main objective of this study is to evaluate the influence of steel fibers on the propagation time of ultrasonic pulses in high-strength concrete. In this experiment, high-strength concrete beam samples were made for both cases containing steel fibers and not containing steel fibers. Then use the Ultrasonic Pulse Analyzer to measure the ultrasonic pulse propagation time in these concrete beam samples. The pulse propagation time was recorded under the following conditions: before the sample was cured in moist heat after the sample was cured in moist heat for 3 days, and cured under normal conditions for 14 days, 28 days, and 120 days.

2. Experimental Program

2.1. Sample Fabrication Procedure

The mix design for manufacturing the concrete samples was partially based on the proportions of the main components from previously published research. It was adjusted during the experimental process to meet the requirement of a compressive strength of over 60 MPa for the concrete samples. The aggregates used in the production of high-strength concrete exceeding 60 MPa consist entirely of fine aggregates without coarse aggregates, with a water-to-cement ratio of 0.16 and, steel fiber content of 2%. Additionally, the experiments utilize active mineral additives such as silica fume and superplasticizer. The experimental program is shown in Figure 1.

To ensure accurate results and prevent command errors during the molding process, the procedure for casting a 50x50x50 mm cube mold is synchronized as follows:

- Dry mix cement with silica fume for a uniform mixture (for 2 minutes).
- Pour the mixed cement and silica fume into the mixer and turn on the mixer for even mixing (for 3 minutes).
- Pour water clockwise and counterclockwise around the mouth of the mixing bowl to ensure thorough mixing (for 3 minutes).
- Pour the superplasticizer around the mouth of the mixer bowl evenly and let the mixture rotate (for 5 minutes).

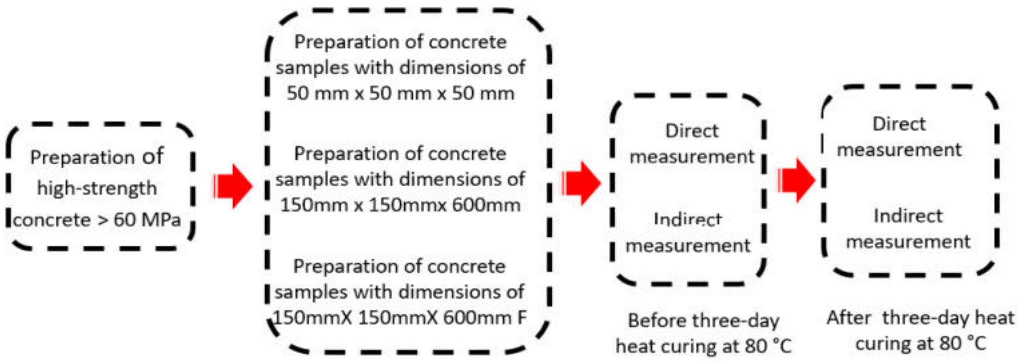

Figure 1. Experimental Program.

- Mix the steel fibers into the concrete mixture thoroughly (for 3 minutes).
- Proceed to pour the concrete into the prepared mold.

The concrete samples were removed from the mold after 2 days of maintenance under room conditions. After demolding, the concrete samples were maintained under experimental conditions: air, temperature, humidity, and water according to the experimental program.

2.2. Composition of high-strength concrete mix

2.2.1. Calculation of the mix composition of high-strength concrete using the absolute volume method

In Vietnam, some studies have proposed high material composition ratios for high-strength concrete (Van and Bui, 2019; Pham et al., 2020; Le, 2017) for both cases with and without steel rope. In these studies, the produced concrete met the requirements, with compressive strength at 28 days ranging from 120÷193 MPa.

According to the absolute volume method, the volume of 1 m³ of compacted concrete is considered as the total volume of water, aggregates, cement, mineral admixtures, superplasticizers, and the volume of entrapped air during the mixing process of the concrete mix. Therefore:

$$\frac{C}{\gamma_C} + \frac{SF90}{\gamma_{SF90}} + \frac{W}{\gamma_W} + \frac{S}{\gamma_S} + \frac{SR}{\gamma_{SR}} + ST + A = 1000 \quad (1)$$

Where: *C, SF90, S, W, SR* - The masses of cement, silica fume, sand, water, and superplasticizer; $\gamma_C; \gamma_{SF90}; \gamma_S; \gamma_W; \gamma_{SR500}$ - The densities of cement, silica fume, sand, water, and superplasticizer; *ST* - The volume of steel fibers in the concrete mix during mixing; *A* - the void volume due to air entrainment in the concrete mix during mixing.

The density of the materials used in this study has been determined and presented in Table 1.

Table 1. The density of materials.

Material	C	SF90	S	W	SR
The density of materials g/cm³	3.15	2.15	2.65	1.0	1.12

According to TCVN 10306:2014 standard, high-strength concrete is defined as concrete with a characteristic compressive strength of 55 MPa or greater at the age of 28 days tested on standard specimens. Based on this criterion, this study has investigated and calculated the mix design components of concrete with an average compressive strength at the age of 28 days exceeding 60 MPa, ensuring workability with a slump range of 150÷250 mm on the slump table.

2.2.2. Selection of material ratios

The material ratios chosen in this study are based on the findings of numerous research studies on high-strength concrete (without coarse aggregates) conducted in many countries around the world (Asgharzadeh et al., 2016; Prabhakaran et al., 2020) as well as in Vietnam (Van and Bui, 2019; Pham et al., 2020; Le, 2017).

The binder consists of 80% Pooc Lang PC40 But Son cement and 20% silica fume (B = C + SF90).

Based on the findings of multiple conducted studies the water/binder (W/B) ratio selected for this study is 0. 16 (Le, 2023).

In terms of aggregate content: based on the research findings of previous studies in this study, the sand/binder ratio ($\frac{S}{B}$) of 1.0 has been chosenv (Le, 2023; Aghayari & Moradi, 2016).

The amount of superplasticizer additive is taken at 7.84% of the total adhesive content (Le, 2023). In this study, a superplasticizer is used in a small amount to reduce water, aiming to adjust the flowability of the concrete mix on the slump table.

Steel fibers: The volume ratio of steel fibers is the percentage of the volume occupied by steel fibers in the concrete mix, typically ranging from 0.5÷2% of the absolute volume of concrete (Shi et al., 2020; Vo et al., 2020). The air content entrained in the concrete mix is 2% of the total volume of the concrete mix.

2.2.3. Establishing the composition table of high-strength concrete mixtures

Based on the aforementioned foundations combined with preliminary experimental survey results, this study has selected the base material ratio coefficients as shown in Table 2.

Where:

$$B = C + SF90$$

Calculated using the absolute volume method based on the selected material ratio values (in Table 2), the mixture composition of high-strength concrete as shown in Table 3 was obtained in Table 3.

Table 2. The material ratios used in the experiment.

Proportion	$\frac{S}{B}$	$\frac{W}{B}$	$\frac{C}{B}$	$\frac{SF90}{B}$	$\frac{SR}{B}$	ST, %	A, %
Non-fiber reinforced	1	0.16	0.8	0.2	0.078	-	2
Fiber reinforced	1	0.16	0.8	0.2	0.078	2	2

Table 3. The mix design of high-strength concrete.

Proportion	C (kg)	ST (kg)	SF90 (kg)	W (kg)	S (kg)	SR (kg)
Non-fiber reinforced	821.8	0.0	205.5	164.4	1.027.3	80.1
Fiber reinforced	805.0	20.0	201.3	161.0	1.006.3	78.5

The mixture proportions and manufacturing process of high-strength concrete beams reinforced with steel fibers are depicted in Figure 2 below.

2.3. The slump flow test

The test to measure the spreading flow of the concrete mix is conducted immediately after ceasing mixing and involves the following steps:

- Pour the mixed concrete into a flow cone.
- Use a tamping rod to compact the mix to be level with the top of the flow cone.
- Lift the cone vertically upwards with two hands.

Measure the spread flow of the concrete one minute after lifting the cone and record the result. The spread flow of the concrete mix achieves a range of 19.5÷21.5 cm, as shown in Figure 3.

2.4. Compressive strength

Using the ADVANTEST 9 automatic bending compression system (Controls - Italia) to determine the compressive strength of the sample. The loading rate in this case is 1000 N/s. The experimental samples have dimensions of 50x50x50 mm (following ASTM standards for testing fine aggregate concrete samples). The compressive strength of concrete samples containing steel fibers reaches 101 MPa, satisfying the requirement of >100 Mpa. For concrete samples without steel fibers, the compressive strength reaches 89.99 MPa. The compression test results and the sample's form upon failure are depicted in Figures 4 and 5.

From the compression test results, it is evident that the material mix design specified in Table 3 fully meets the requirements for producing high-strength concrete beam samples with dimensions of 150x150x600 mm for both cases: with and without steel fiber reinforcement. These beam samples are appropriately sized for conducting ultrasonic pulse tests to evaluate the impact of steel fibers on the ultrasonic pulse transmission time in high-strength concrete beams.

PC40 Cement

SongLo sand

Superplasticizer

Steel fiber

Silica fume

Mix a dry blend of cement and silica fume

Pour water into the mixed blend

Add superplasticizer into the cement + silica fume mixture

Add steel fibers into the mixed blend

Pour concrete into the mold

Wrap the freshly poured concrete sample

Remove the mold and curing

Figure 2. The manufacturing process of high-strength concrete beams.

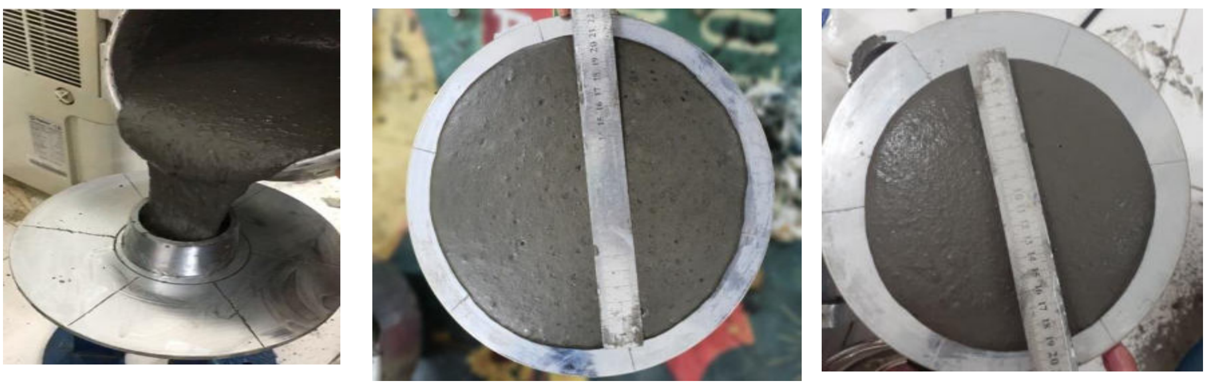

Figure 3. The Experiment measuring the spread flow of concrete.

Figure 4. Compression test to determine the compressive strength of concrete without steel fibers.

Figure 5. Compression test determining the compressive strength of steel fiber-reinforced concrete.

The procedure for fabricating 150x150x600 mm beam samples is the same as for casting 50x50x50 mm samples, with the fabrication steps illustrated in Figure 2

2.5. Time Of Flight Diffraction Technique (TOFD)

In the TOFD experiment, both indirect and direct measurements were conducted. Before measurements, TOFD tests were carried out on the standard bar as depicted in Figure 6a, with the pulse transmission time on the standard bar recorded as 55.9 µs. The arrangement of the two probes for both indirect and direct measurements is illustrated in Figures 6b and c.

3. Results and Discussion

3.1. Transmission time using the direct method

There are two ways to determine the pulse propagation time: one is by measuring the pulse propagation time, and the other is by observing the waveform displayed on the screen. In this experiment, with the equipment available at the Construction Engineering Laboratory of the Hanoi University of Mining and Geology, the pulse propagation time is recorded on the screen of the Ultrasonic Pulse Analyzer (Figure 7a). The Ultrasonic Pulse Analyzer has an integrated timer. Therefore, when the two probes of the ultrasonic device are positioned as shown in Figure 7b, the pulse propagation time is obtained using the direct method, as illustrated in Figure 7b

In the studies by Gebretsadik et al. (2021) and AL-Ridha et al. (2019), it was indicated that the steel fiber content affects the pulse propagation velocity. Additionally, the curing time also affects the pulse propagation velocity. Domestic research has shown that as the age of concrete increases, the ultrasonic pulse velocity tends to increase (Nguyen, 2017; Vuong, 2021; Pham & Khong, 2023). Regarding high-strength concrete reinforced with steel fibers, Vo et al. (2020) demonstrated that with the addition of 5% steel fiber content, both the concrete strength and UPV velocity significantly increased.

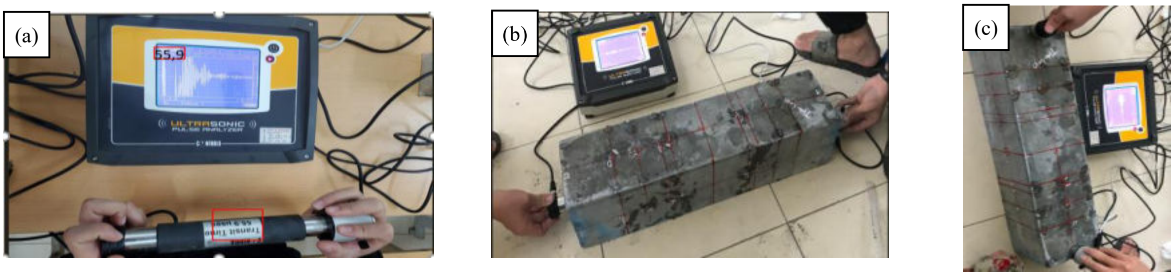

Figure 6. Ultrasonic pulse propagation time test using direct and indirect methods: (a) Test on standard bar, (b) Direct measurement, (c) Indirect measurement.

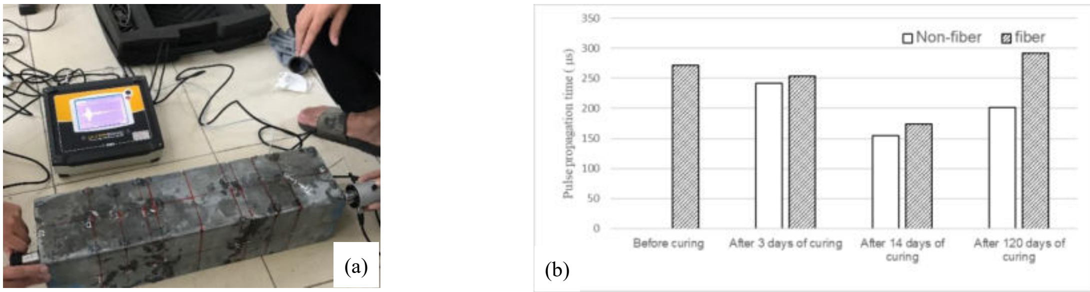

Figure 7. Transmission time using the direct method: (a) The two probes position, (b) Pulse transmission time.

The experimental results in Figure 8b exhibit some similarities with previous studies on non-fibre or fiber-reinforced concrete:

Firstly, after the sample underwent 3 days of thermal-humidity curing, the ultrasonic wave propagation time in both concrete samples, with and without fibers, decreased significantly. For the concrete sample with steel fibers, after removing the sample out of the mold, no pulse signal could be detected. This can be explained as follows: Before thermal-humidity curing, the concrete sample contained a relatively large amount of moisture, which affected the ultrasonic wave propagation process, resulting in an increased propagation time or even the receiving probe not detecting the pulse signal. Under the conditions of 80^{0}C thermal humidity, the hydration process of cement in the concrete sample is accelerated. The concrete sample's strength develops, and its structure becomes denser, thus the ultrasonic wave propagation time in the concrete becomes faster.

When 2% of steel fibers are added to the mixture, compared to the case without steel fibers, the ultrasound wave propagation time changes significantly. Specifically, with the direct wave transmission method, at the 120-day mark, the sample containing steel fibers showed a longer wave propagation time compared to the sample without fibers. However, at earlier time points, the difference in wave propagation time between these two types of samples was negligible.

Therefore, it can be concluded that the addition of steel fibers affects the wave propagation time when using the direct transmission method. However, to draw a definitive conclusion regarding whether the time increases or decreases, additional experiments with more sample combinations are needed to verify the results.

3.2. Results of Ultrasonic Pulse Measurement using the Indirect Method

For the indirect measurement method, the probe placement method is illustrated in Figure 8. Two probes are symmetrically placed across the center of the specimen, and their wings are spaced at distances of 8, 10, 15, 20 and 30 cm, corresponding to points A, B, C, D, and E, respectively. The distances between the probes are selected according to the recommendations of BS 1881 and TCVN: 9357-2012.

The pulse transmission time in concrete samples using the indirect method is shown in

Table 4. The results of pulse transmission time measurements are conducted at the same location on the surface of the concrete sample before and after curing time.

From the data in Table 4, several observations can be drawn:

- As the distance between the probes increases, the pulse transmission time also increases. The results indicate that the distance between the probes influences the pulse transmission time. Therefore, in practice, the selection of probe distances for measurements needs to be carefully considered, while also ensuring the minimum distance as recommended by BS 1981 (British Standards Institution, 1986) and TCVN 13537-2022 (Vietnamese standards, 2022).
- The results from the indirect pulse transmission method show that the presence of steel fibers alters the pulse wave propagation time. In the 120-day-old sample, adding steel fibers resulted in a faster pulse propagation time. However, in the samples at 0 days, 3 days, and 14 days old, the presence of steel fibers caused the pulse wave propagation time to increase.
- For concrete samples that have been subjected to moisture and heat curing for 3 days, there is a significant decrease in ultrasonic pulse transmission time. After the samples have been subjected to moisture and heat maintenance, continuing to keep the samples in normal air maintenance conditions at 14 days of age and 120 days of age, the ultrasonic pulse transmission time tends to decrease gradually with a relatively small decrease in amplitude.

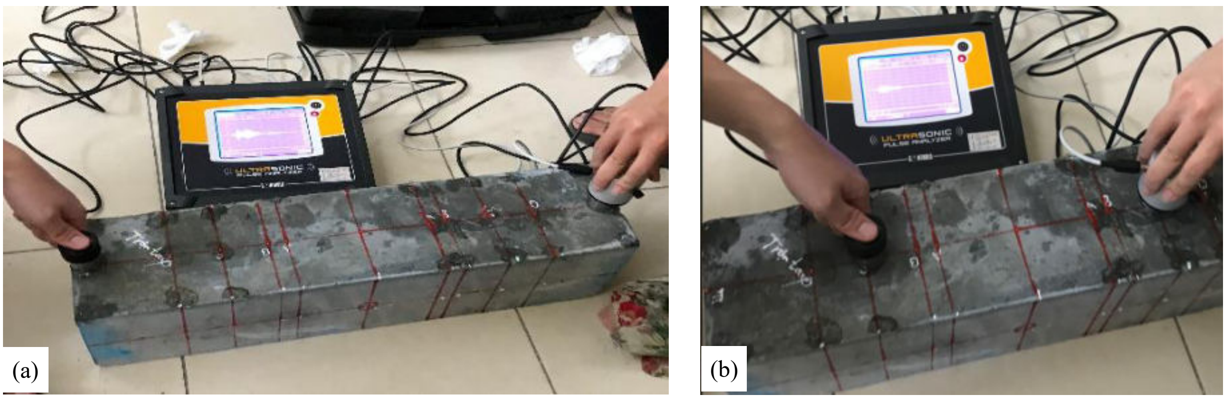

Figure 8. Ultrasonic pulse measurement using the indirect method with different distances, (a) 300 mm; (b) 150 mm.

Table 4. Pulse Transmission Time Before and After Thermal Maintenance.

Case study	A (μs)	B(μs)	C(μs)	D(μs)	E(μs)
None-fiber sample before curing time	55.3	70.4	90.2	130.3	194.1
Fiber sample before curing time	99.4	143.6	282	0	0
Non-fiber sample after 3 days of curing time	48.7	63.6	86.2	119.5	174.4
Fiber sample after 3 days of curing time	59.8	68.1	131.6	184.8	203.4
Non-fiber sample after 14 days of curing time	49.2	68	84.2	132.4	173.2
Fiber sample after 14 days of curing time	57.7	108.5	149	185.1	224.6
Non-fiber sample after 120 days of curing time	84.8	76.4	115.5	157.0	209.7
Fiber sample after 120 days of curing time	54	63.5	82.8	139.4	185.5

4. Conclusion

The paper presents some conclusions drawn from experiments determining the influence of steel fiber reinforcement in high-strength concrete (> 60 MPa) using the Time-of-Flight Diffraction (TOFD) method as follows:

- Successful fabrication of high-strength concrete beam samples with compressive strength exceeding 60 MPa, exhibiting a flow spread of 20÷22 cm, meeting the standards for high-strength concrete (> 55 MPa) to conduct ultrasonic pulse measurement experiments.
- Curing conditions significantly affect the pulse transmission time in concrete. For concrete samples containing 2% steel fibers at 0 days of age, direct pulse measurement showed no signal. After subjecting the concrete to moist heat curing at 80^0C for 3 days, the pulse transmission time decreased considerably.
- In both cases, with and without steel fiber reinforcement in concrete, the distance between the two probes also affects the pulse transmission time. As the distance between the probes increases, the pulse transmission time also increases.
- Experimental results indicate that the presence of steel fibers in concrete with a 2% content can alter the speed of ultrasonic pulses.

The research findings serve as a basis for future studies where the research group plans to expand the investigation on high-strength concrete reinforced with various percentages of steel fibers, considering different components such as steel fibers, steel slag, or the presence of cracks.

Contributions of authors

Nhan Thi Pham - conceptualization, funding acquisition, investigation, methodology, writing - original draft, supervision; Nghia Viet Nguyen - writing - original draft, review & editing.

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