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ORIGINAL STUDY

Picking of first arrival times on noisy ultrasonic S-wave signals for concrete and rock materials

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Abstract

Ultrasonic testing techniques are non-invasive and generally used in geosciences to obtain the longitudinal and shear wave velocities for either concrete or rock materials, which are essential to investigate the physical and mechanical properties of the materials. However, the accuracy and reliability of the material velocities depend on the precise reading of the first arrival time directly on the recorder. In ultrasonic testing, due to the heterogeneity of the samples and noise, it is often problematic especially to determine the S-wave first arrival time both directly on the recorder and from the recorded signal, and this process mainly depends on user experience. This study focuses on the semi-automatic picking of the first arrival time (FAT) of ultrasonic shear (S)-wave signals. For this, after an application of a band-pass filter (BP) to suppress the noise components, the cross-correlation (CC) technique using an operator signal estimated by Kolmogorov spectral factorization from the filtered signal is applied to determine the boundaries of the possible time interval of the FAT. An automatic search then reads the FAT which encounters the maximum amplitude value within the interval. The technique has been tested for synthetic and real data sets. The results show that the FAT can be picked within safe and acceptable limits within errors ± 2.0 µs and ensure that the velocities of materials such as rock and concrete will be obtained accurately. Therefore, this also provides the ability to calculate other related physical and mechanical parameters of the materials.

Article highlights

- A semi-automatic first arrival time picking procedure on ultrasonic shear-wave signals has been developed
- The proposed method consists of successive application of the bandpass filter and cross-correlation techniques
- It has been tested that the ultrasonic velocities of concrete and rock samples can be calculated more safely with the proposed procedure

Keywords Ultrasonic testing signals · First arrival time · Band-pass filter · Cross-correlation · Materials

Extended author information available on the last page of the article

1 Introduction

Ultrasonic waves, one of the non-destructive measurement techniques, are a branch of acoustics that uses high-frequency (>20 kHz) sound waves that the human ear cannot hear and has been used extensively for more than fifty years in the evaluation of engineering structures and materials (Mc Dowell et al. 2002). Ultrasonic testing has been widely used in many different fields, such as medicine (Qu et al. 2015), earth sciences (Hafez et al. 2010; Sabbağ and Uyanık 2017; Babacan et al. 2018), and civil and material engineering (Kaczmarek et al. 2017; Bau-Hamdan 2021; Bau-Hamdan and Abbas 2022; Moura et al. 2023). Especially in the earth sciences, the longitudinal (P) and shear (S) wave velocities of material samples such as rock, concrete, and wood in the laboratory and field are generally measured using ultrasonic frequencies varying between several kHz and MHz. Velocities are essential to determine the engineering properties such as strength, quality, and mechanical parameters of materials which play an important role in the design or restoration process of any engineering structure. In ultrasonic testing, the accuracy and reliability of network noise for both P- and S-wave velocities depend on either the direct reading of the recorder or the picking of the first arrival time of the recorded signals. Honarvar et al. (2004) noted that the signals of ultrasonic testing involve the effects of the measurement system and propagation paths taken by ultrasonic waves, and are distorted by noise originating from both the measurement system and structure of the core sample. When considering this explanation, while the first arrival time of the P wave is relatively easy to determine, it is difficult to read and pick the first arrival time of the S-wave on both devices and the recorded signal because of the signal attenuation, lower amplitude, high noise effect caused by mechanical and electrical circuits and heterogeneity of materials. However, although technological developments in ultrasonic testing devices have made it possible to read the S-wave first arrival time accurately and reliably, this problem still persists, especially for heterogeneous materials.

In geosciences and some other disciplines, it is essential to accurately determine the first arrival time of the signal on both acoustic and elastic waveforms from the transmitter to the receiver. In many cases, these first arrival times are picked manually. However, manually determining the first arrival times is time-consuming and can vary a lot depending on the human analyst, especially in low signal/noise ratio signals. Moreover, small changes in the selection of the first arrival time in ultrasonic measurements made on small-sized samples such as rocks and concrete can cause significant errors. On the other hand, semi-automatic or automatic determination of the first arrival times, especially on the noise signal form, will provide more accurate and stable results. In the common literature, there are studies on determining semi- or automatic first arrival times (Sarout et al. 2009; Zhou et al. 2020; Dong et al. 2023). As described by Sarout et al. 2009, there are several methods for determining first arrival times, including static thresholding, short-term averaging/long-term averaging (STA/LTA) (Allen 1982; Leonard and Kennett 1999), neural networks (Dai and MacBeth 2007), and another method is to model the signal as an autoregressive process and use statistical concepts to peak the start time (Leonard 2000). Among autoregressive methods, the AIC method (Akaike 1974; Kitagawa and Akaike 1978; Dong et al. 2023) has been used effectively in both fields (Zhang et al. 2003) and laboratory studies (Kurz et al. 2005) (Sarout et al. 2009). A detailed description of the Akaike method is given in the literature (Sarout et al. 2009; Zhou et al. 2020). These methods are more effective for determining the first arrival times of noise-free or weakly noisy signals. However, for acoustic signals with high noise, it becomes challenging to determine the time of first arrival accurately (Zhou et al. 2020).

To improve the readability of the first arrival time of ultrasonic S-wave signals, convenient data processing techniques can be applied to improve the signal-to-noise ratio (SNR) and time resolution of the signals. Some researchers have used techniques such as deconvolution, S-transform, wavelet analysis, Hilbert-Huang, Wiener filtering, and autoregressive spectral extrapolation to enhance the quality of the SNR of ultrasonic signals (Miyashita et al. 1985; Sin and Chen 1992; Honarvar et al. 2004; Sarout et al. 2009; Tiwari et al. 2017; Xu and Wei 2019; Benavente et al. 2020) and have generally obtained successful results. Although these techniques have their advantages and disadvantages, they are mostly time consuming in practice. Moreover, the general structure of the signal has been tried to be improved in most of these studies.

It is known that velocity measurements on rock samples (drilling cores) and reinforced concrete structures are carried out by ultrasonic tests in a laboratory environment. In these tests, the ultrasonic signal transmitted from one side of the core is recorded with a receiver probe on the other side of the core. The aim here is to measure the time required for the transmitted signal to reach the receiver, that is, the first arrival time. For these measurements, the first arrival time is read directly from the recorder in proportion to the possibilities offered by the equipment. However, given that the ultrasonic source wavelet has a minimum phase, this application is successful for signals with a high signal-to-noise ratio (where the noise level is very low), whereas reading the first arrival time may be inaccurate when the signal contains noise. This reading is user-controlled, and reading errors may differ between readers.

The old (Pundit Plus) and new (Pundit PL 200 with 40 kHz dry point contact (DCP) shear wave probe) (URL-1 2022) generation measurement systems are widely used in ultrasonic testing. In old systems, although the S-wave velocity can only be read numerically from the recorder screen, incorrect values are often obtained, or it is not sometimes possible to read a value. To solve this problem, the ultrasonic signal sent to the material is recorded using an oscilloscope (URL-1) added to the recorders. Thus, the velocity value can be obtained by dividing the first arrival time read on the recorded signals by the length of the material ($V=L/t$). However, since the ultrasonic signals recorded with the oscilloscope have a low SNR, it becomes difficult to read the correct first arrival time and is often impossible. However, the measurement capabilities and sensitivities of the new-generation ultrasonic systems are quite advanced, and the first arrival reading can be made more easily as the signals can be viewed directly in the recorder. However, with new generation measurement systems (Pundit PL 200), recordings with low SNR are encountered, especially in low-quality concrete.

Studies continue on techniques that will facilitate and provide accurate reading of the first arrival time on such low SNR ultrasonic signals. However, the literature has almost no application of the proposed holistic approach to evaluating ultrasonic signals from materials such as rock and concrete. Among these techniques, a semi-automatic technique was developed by Şenkaya and Karslı (2014) to analyze the seismic refraction data, to read the first arrival time more accurately, and to eliminate the differences between readers. In this technique, the contribution of the cross-correlation technique can be utilized, as in the seismic data analysis, to minimize the reading error and, therefore, to determine more accurate velocity values on the materials. If the signal recorded at the receiver and the source signal generating that signal are cross-correlated, maximum peaks occur where the correlation is high. In such a process, the maximum peak value within the time interval, including the first arrival time, is considered to be related to the value when the source signal first reaches the receiver.

The main aim of this study is to develop a practical procedure that provides accurate and reliable first arrival time picking when the S-wave ultrasonic signals are especially noisy. For this purpose, a workflow was implemented using a semi-automatic first arrival picking algorithm, which includes trend analysis, a band-pass filter to filter noises, an operator estimation, application cross-correlation between signal and operator, and automatic scanning of correlated signals to find the first arrival time position.

2 Data acquisition

This study used two different ultrasonic velocity measuring devices and transducers (transmitter and receiver) with piezoelectric properties. The first is the newer Pundit PL 200 (PPL200) (Fig. 1a, b) ultrasonic device and its transducer is used to measure the S-wave signals with a 40 kHz source pulse. The second is the relatively older Pundit Plus (PP) (Fig. 1c) with 1 MHz transducers. The signals from the system are recorded digitally using an oscilloscope. Moreover, a converter (the small box on the left of the device in Fig. 1c) is used in this system to generate S-wave signals.

The electrical signals produced by the piezoelectric transmitter are converted into mechanical vibrations and sent to rock or concrete samples. The piezoelectric receiver on the opposite side records the signal passing through the sample signal passing through the

Fig. 1 Ultrasonic testing devices. **a** and **b** respectively show the PPL200 device during the measurement of concrete column (left) and pouring concrete (right) with high heterogeneity, and **c** PP device for rock samples. S and R show source and receiver probes, respectively

sample. The ultrasonic pulse velocity is calculated from the transit time of the signal in the sample using the following formula Eq. (1);

$$V = \frac{L}{t} \tag{1}$$

Here, V, L and t stand for the ultrasonic velocity of the material, the length of the sample, and the first arrival time (or transmission duration of the pulse within the sample), respectively. An excellent acoustic coupling between the transducers and the sample is required during the ultrasonic measurements. Standard ultrasonic gels are used to ensure good acoustic coupling, but in measurements with 250 kHz S-wave, transducers require special gels, which are non-toxic and water-soluble organic substances of very high viscosity (URL-2; Corbett 2016). However, gel is unnecessary in the newly produced 40 kHz dry point contact transducers. The measurement is carried out under dry conditions. In practice, the position of transducers can be applied as direct, semi-direct, and indirect; and in each position, the velocities of the materials can be determined. Nevertheless, the direct transmission technique is the most favorable and desirable arrangement because the maximum energy of the pulse is transmitted and received (Popovics 2003). Therefore, this study used the direct transmission technique for data acquisition in ultrasonic signal measurements.

It has been stated that P- and S-wave velocity and/or time information can be easily read as explained in the user manual of the PP measurement set. However, in practice, P-wave velocity measurements can be read directly as numeric (time of first arrival or velocity), while the data of the S wave cannot be read numerically in many cases, and a lost signal warning occurs. To alleviate this, a digital oscilloscope is connected to the PP measurement set and the signal form of the S wave is recorded to be able to read the S-wave first arrival time and thus calculate the velocity. In addition, in this case, the complexity of the recorded S-wave signal form due to the instrument effect, network noise, and heterogeneous material properties makes it difficult to read the first arrival times. On the other hand, compared to the PP device, the PPL200 device has more advanced equipment, which includes lowering the frequency of the signal produced in the transducer used (from 1 MHz to 40 kHz), not using gels in the measurements (dry point) (Corbett 2016) and increasing the signal voltage level. This provides the signal with a high signal/noise ratio. However, there are two main types of noises: the noise caused by (1) electrical and measurement devices and (2) materials with low strength and high heterogeneity such as fractures, cracks, and voids. Therefore, noises decrease the SNR of the recorded signal.

Another problem with the automatic detection of the S wave first arrival time was that a weak amplitude P wave component always formed on the S wave signal. Therefore, a weak/small P-wave component can erroneously be detected by the auto-triggering. For this reason, the waveform analysis should be performed to read the correct first arrival time on the shear wave signal. Moreover, on small samples, the first arrival time of the P wave can be determined using S wave transducers (Pundit PL-200 Manual, 2013; Corbett 2016). S wave phases can be distinguished on the signal form due to the fact that the first arrival of the P wave seen on the signals recorded using the S wave receivers is both very low amplitude and almost twice the first arrival time in samples such as concrete. However, obtaining the S phase may not always be possible. Fortunately, the S-phase can be more easily distinguished by exploiting the polarizability of the shear waves. The S-wave signal increases or decreases depending on the alignment of the transducers. When they are aligned correctly, the signal is strongest, whereas when they are at 90° to each other, the signal almost disappears. By rotating one of the transducers, it is possible to observe the increase and decrease of the received S-wave and thus precisely determine its position (Corbett 2016). Moreover, Corbett (2016) showed that if the S-wave DPC transducers are used, P-wave arrivals are not observed on S-waveform.

3 Materials and methods

The proposed processing technique aims to obtain a correlation signal and determine the time interval to the peak at the first arrival. For processing, if the signal has a low signal-to-noise ratio, that is, it contains noise, first trend analysis and then an appropriate bandpass filter is applied to the signal. The trend removal is performed by subtracting the linear line (called DC component), a first-degree polynomial, from the signal to avoid discontinuity effects in subsequent steps. The correlation trace is produced from the cross-correlation of the signal with an operator (wavelet or source pulse) estimated from the filtered signal.

The first step in the proposed process is estimating the operator (also called source pulse or wavelet) signal from the recorded signal. In this step, initially, the signal is band-pass filtered to suppress the noise. In terms of practicality and effectiveness, the band-pass filter is arranged in a trapezoidal type in the spectral medium, with cut-off frequency values (f_1, f_2, f_3, f_4) conveniently to preserve the available the spectral band of the data domain. Then, the operator signal is estimated by the spectral factorization technique developed by Kolmogorov (1939). Kolmogorov spectral factorization is an efficient method for calculating the time-domain minimum phase function using the Fourier power spectrum of a signal (Robinson and Treitel 1980; Claerbout 1992). It is commonly applied to a wavelet to obtain its minimum phase equivalence. If this factorization is applied to a signal, the smoothed autocorrelation function of the signal is used. Then, the logarithmic Fourier amplitude spectrum is calculated, and the Hilbert transform is applied (while negative frequencies are zeroed, positive frequencies are doubled) to obtain the real component of the inverse Fourier transform of the exponentiated spectrum. Thus, a wavelet (or operator) with minimum phase is estimated from an input signal.

Cross-correlation is an important data processing technique that reveals the similarity characteristics of two signals and is used to precisely determine differences in signal arrivals. This technique is necessarily used in seismic signal analysis, calculation of Wiener deconvolution filter coefficients, and preprocessing of raw vibroseismic data. In particular, in vibroseismic studies, a sinusoidal signal called the sweep signal, which has a variable frequency (also known as the pilot signal) produced as the source signal, is cross-correlated with the recorded raw vibroseismic recording. Thus, the raw recording is converted into a signal containing zero-phase wavelet forms. The time value corresponding to the maximum amplitude of these wavelets is evaluated as the arrival time value at which the reflection is recorded for that reflection event. Therefore, the arrival time reading of the signal is more reliable and accurate than the minimum phase wavelet.

The cross-correlation technique between two signals is briefly explained by Buttkus (2000, P.161.) as follows. Let g(t) be a deterministic signal with the arrival time t_0 superimposed with random noise n(t),

$$f\left(t\right)=c\,g\left(t-t_{0}\right)+n\left(t\right),\quad -\infty<t<\infty \tag{2}$$

If the signal is known, the arrival time t_0 can be determined by cross-correlation of g(t) with f(t),

$$\begin{aligned}R_{fg}\left(\tau\right)&=\underset{T\to\infty}{Lim}\frac{1}{2T}\int_{-T}^{T}\left(cg\left(t-t_{0}\right)+n\left(t\right)\right)g\left(t+\tau\right)dt\\&=\underset{T\to\infty}{Lim}\frac{c}{2T}\int_{-T}^{T}g\left(\varepsilon\right)g\left(\varepsilon+\tau+t_{0}\right)d\varepsilon+R_{ng}\left(\tau\right)dt\\&=cR_{gg}\left(\tau+t_{0}\right)+R_{ng}\left(\tau\right)\end{aligned} \tag{3}$$

$R_{gg}(t+t_0)$ is the function autocovariance of g(t) shifted backwards in time by the arrival time t_0 and $R_{ng}(\tau)$ is the crosscorrelation between n(t) and g(t). If.

$$|R_{ng}(t)|<<|c\,R_{gg}\left(0\right)|, \tag{4}$$

Then.

$$R_{fg}(t)\gg c\,R_{gg}(t+t_{0}), \tag{5}$$

or near τ=-t_0.

$$R_{fg}\left(-t_{0}\right)\gg c\,R_{gg}\left(0\right). \tag{6}$$

In practice, instead of Eq. (3), $R_{fg}(t)=\int f\left(t\right)\ g(t+t_{0})\,dt$, the function $R'_{fg}(t)=\int f\left(t\right)\ g(t-t_{0})\,dt$ is used to map the signal arrivals at positive τ values. Now, $R'_{fg}(\tau)\approx cR_{gg}(-\tau+t_0)$ instead of Eq. (5), which means that the function $R'_{fg}(\tau)$ has its maximum at the arrival time $\tau=t_0$.

In the above equations, the parameters T, c and τ represent the signal period, scaling value, and time delay, respectively, between the two signals. If $R_{fg}(\tau)$ is high at a given time delay, these two signals are similar at that time delay. This is valid for both the positive and negative values of R_{fg}. On the other hand, a lower $R_{fg}(\tau)$ indicates that the signals differ at this delay value. Thus, according to the application procedure proposed in this study, f and g are the input signal and the operator respectively. Accordingly, the similarity of g in f is searched, and thus the maximum positive similarity (which is equivalent to the autocorrelation) in the first arrival part of the signal is determined. The workflow of the proposed procedure which is detailed above is shown in Fig. 2. An example of CC processing for a minimum phase wavelet is shown in Fig. 3 for noiseless and noisy cases. Having applied to CC technique to the wavelet (solid blue lines), the output (dashed red lines) is seen as a zero-phase wavelet. In this case, the maximum amplitude position of the result matches the first arrival time of the wavelet, as shown in Fig. 3 (green dashed lines). To test the reliability of the CC processing, noise (5% and 15%) was added to signals (Fig. 3b, c). Further details of this method can be found in Senkaya and Karslı (2014).

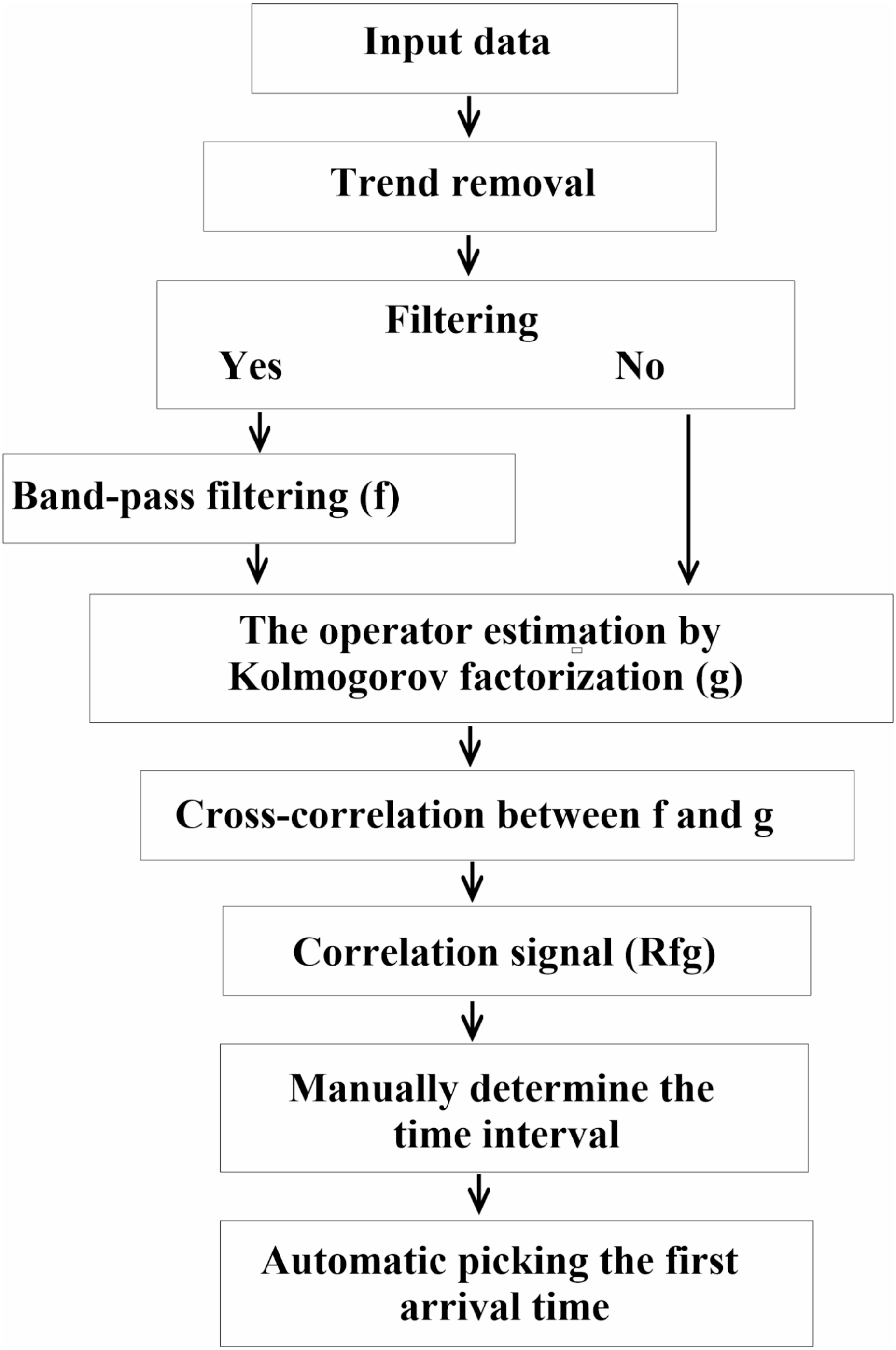

Fig. 2 The workflow of the proposed procedure

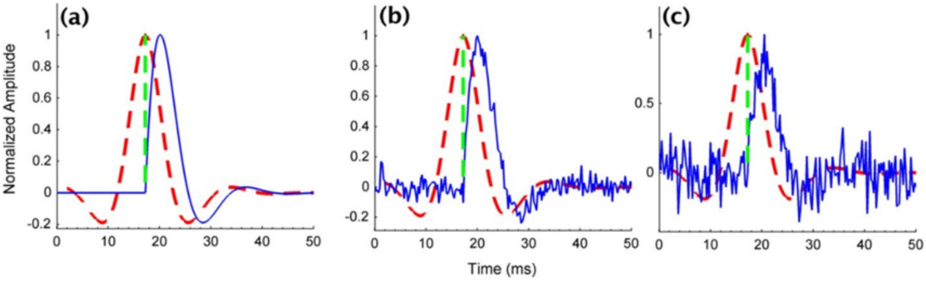

Fig. 3 Representation of the CC technique in effective picking first break times (modified by Senkaya and Karslı 2014). The application results are for noiseless **(a)**, 5% **(b)**, and **(c)** 15% random noises added. Blue, red and green lines show the input signals, correlated signals, and locations of the first arrival times, respectively

4 Applications

4.1 Tests on synthetic data

The technique intended for the semi-automatic determination of the first arrival time was tested on a synthetic ultrasonic signal with and without noise. Figure 4 demonstrates the results for the noise-free synthetic signal. Figure 4a shows the noise-free synthetic signal calculated by the convolution of a representative source wavelet with a random spike series. In the calculation of the synthetics, a minimum phase Berlage wavelet with 30 kHz center frequency, 1.0 µs sampling time, 200 µs signal duration and exponential decay rate $\alpha = 50$ were used as the source wavelet. In Fig. 4a, the theoretical first arrival time is picked as 54 µs (red vertical line). The operator signal required for the application of the CC technique was estimated from the signal obtained using the Kolmogorov factorization technique (Fig. 4b). Thus, the cross-correlation between the input signal in Fig. 4a and the operator signal in Fig. 4b is calculated based on the zero delay value (positive delays only). The calculated correlation signal (red line) and input signal are shown in Fig. 4c. Here, the possible range in which the first arrival time will be read is specified by the user (between the vertical dashed blue lines), and the first arrival time is automatically determined over this selected limited area. It can be clearly seen that the maximum peak value (green plus marker) of the correlation trace in the bounded area in Fig. 4c matches the theoretically determined time value of the input signal. This match is shown above the input signal in Fig. 4d (purple vertical line).

In Figs. 5 and 6 the method is implemented by adding some Gaussian-type random noise to the input signal in Fig. 4a, making it difficult to read the time of first arrival. Before applying the CC technique to noisy recording in Fig. 5a, a bandpass filter with [1.8 2.0 80 100] kHz frequencies was applied, and therefore the very low frequencies and high frequency random noises were suppressed (Fig. 5b). When the Fourier amplitude spectra of the signal (Fig. 5c, d) are examined, noise efficiency is observed, especially in the high-frequency region. Figure 6 illustrates the results obtained from the application of the CC technique. In the band-pass filter result in Fig. 6a (or Fig. 5b), there is still uncertainty regarding the first arrival reading. At this stage, the CC technique was first applied to the signal in Fig. 6a, then a correlated trace in Fig. 6c (red line) is calculated by using estimated operator signal (Fig. 6c) and compared to input signal (black line) in Fig. 6a. Lastly, the time of first arrival

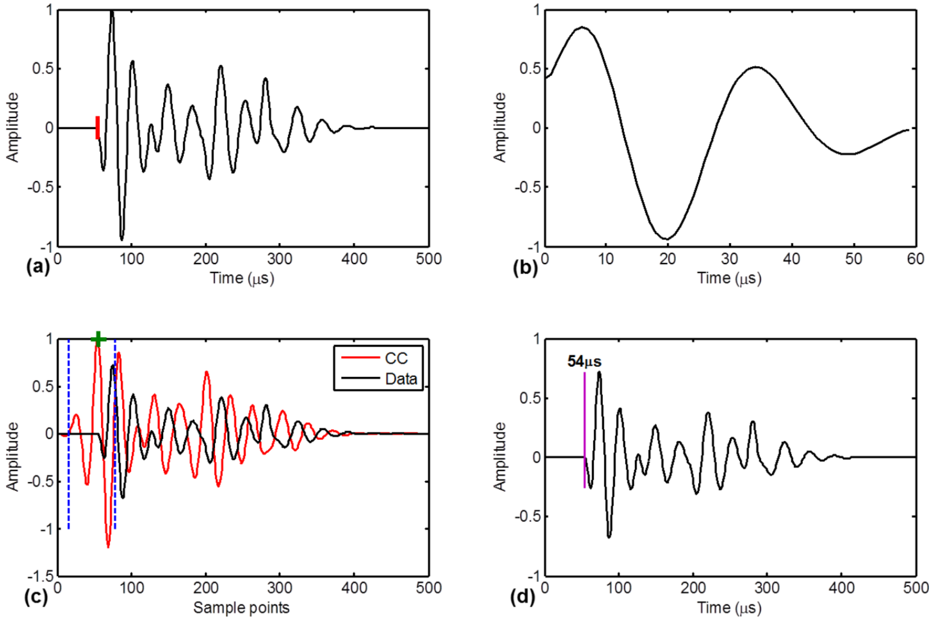

Fig. 4 Semi-automatic first arrival time reading of a noise-free signal with cross-correlation technique. **a** convolutional synthetic trace including theoretical first arrival time, 54 μs as seen by a vertical red line, **b** estimated operator to be used in the CC technique, **c** correlation signal (red line) obtained by cross-correlation of operator signal in (b) with the input signal (black line). The vertical dashed blue lines indicate the boundaries of the area to be read at the time of first arrival and the maximum peak value is marked by green plus, and **d** Location of the determined first arrival time of the input signal (purple line)

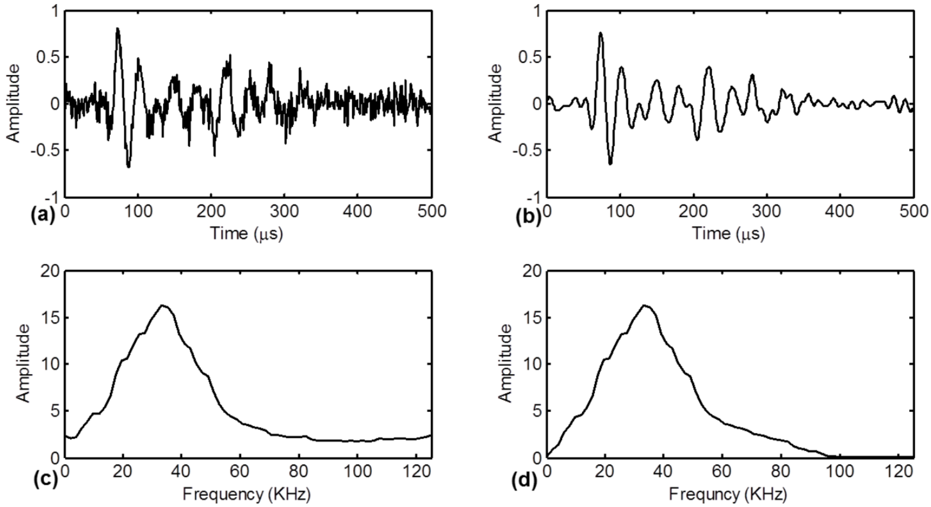

Fig. 5 Application of a bandpass filter to a Gaussian-type random noise-added signal. **a** and **c** noisy signal and Fourier amplitude spectrum and bandpass filter results, **b** and **d** its Fourier amplitude spectrum

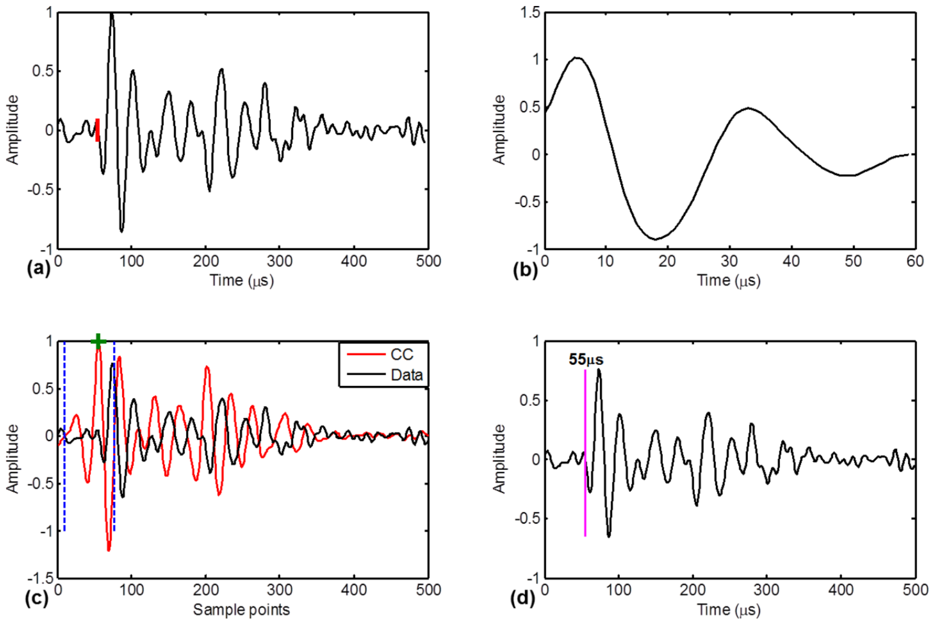

Fig. 6 Semi-automatic first-arrival time reading of the noise-filtered signal in Fig. 5b with cross-correlation technique. **a** Convolutional synthetic trace in Fig. 5b which includes the theoretical first arrival time, 55 µs as seen by a vertical red line, **b** estimated operator to be used in CC technique, **c** correlation signal (red line) obtained by the cross-correlation of operator signal in (b) with input signal (black line). Vertical dashed blue lines indicate the boundaries of the area to be read at the time of first arrival and the maximum peak value is marked by green plus, and **d** the location of the determined first arrival time on the input signal (purple line)

was read as 55 µs with semi-automatic reading as shown in Fig. 6d. When compared with noiseless case, the time reading error is +1 µs. As a result of our tests, it was determined that the reading time had an error of ±2.0 µs, which mostly leads to a ±200 m/s velocity difference. Moreover, as the length of the samples increased, error in the velocity decreased. Thus, the most crucial feature of the CC technique is that it contributes to the first arrival reading with confidence and precision in noise-containing signals. However, if the character of the estimated operator is close to the real thing, the operator can precisely identify the signal segments that are similar or compatible with itself, even if the signal is noisy.

4.2 Testing on real data

Firstly, in order to test whether the CC technique can reliably determine the first arrival time on real data, a testing was performed on an aluminum material with a more homogeneous structure and a known elastic modulus. The size of the material used is 6 cm in diameter and 5.7 cm in length (Fig. 7a). P (54 kHz transducers) and S (40 kHz DCP transducers) wave velocities of 6196 m/s and 3433 m/s, respectively, were measured with the Pundit PL-200 instrument (Fig. 7b, c). By applying the CC technique to the S-signal in Fig. 7c recorded on the sample, the first arrival time was picked semi-automatically as 17 µs (Fig. 7d), and the S-wave velocity was calculated as 3352 m/s. Therefore, the values of elastic module of the aluminum material were 81.7 GPa (for Vs=3433 m/s) and 78.7 GPa (for Vs=3352 m/s), respectively. The density of aluminum was used as 2.70 g/cc in the calculation. As can be seen, there is a 3.7% difference between the elastic modulus values obtained from manual picking carried out by a human analyst and semi-automatic picking from the CC technique. In this case, considering that both measurements give values close to each other, the first arrival times obtained from the CC technique were found to be reliable. Moreover, since a DCP transducer was used, the low-amplitude P-wave arrivals seen on the S-wave signals were not seen on the S signal obtained from the aluminum sample. Therefore, there was no difficulty in S-wave phase selection.

In data acquisition, PP was used for measurements on rock samples, and PPL200 devices were used for measurements on concrete surface surfaces. The first arrival time reading applications on the recorded data groups using trend removal, band-pass filtering, and CC techniques are shown below. The ultrasonic signal recorded from the rock samples is shown in Fig. 8a. The sampling time of the signal is dt=2e-8 s (0.02 µs). As can be seen, the signal contains considerable noise, and it is extremely difficult to read the first arrival time. When the Fourier amplitude spectrum of the signal was examined (Fig. 8c), it was seen that the signal was under the influence of very high-frequency noise components. By applying a band-pass filter with a cut-off frequency of [250, 312, 1805, 2030] kHz to the signal, the noise components were significantly removed (Fig. 8b, d).

Although it is easy to read the first arrival time on the obtained filtered signal, it is clear that it is still insufficient (see circle area). At this stage, the CC technique was applied to the filtered data, and the results are presented in Fig. 9. In Fig. 9a, the time of the first arrival can

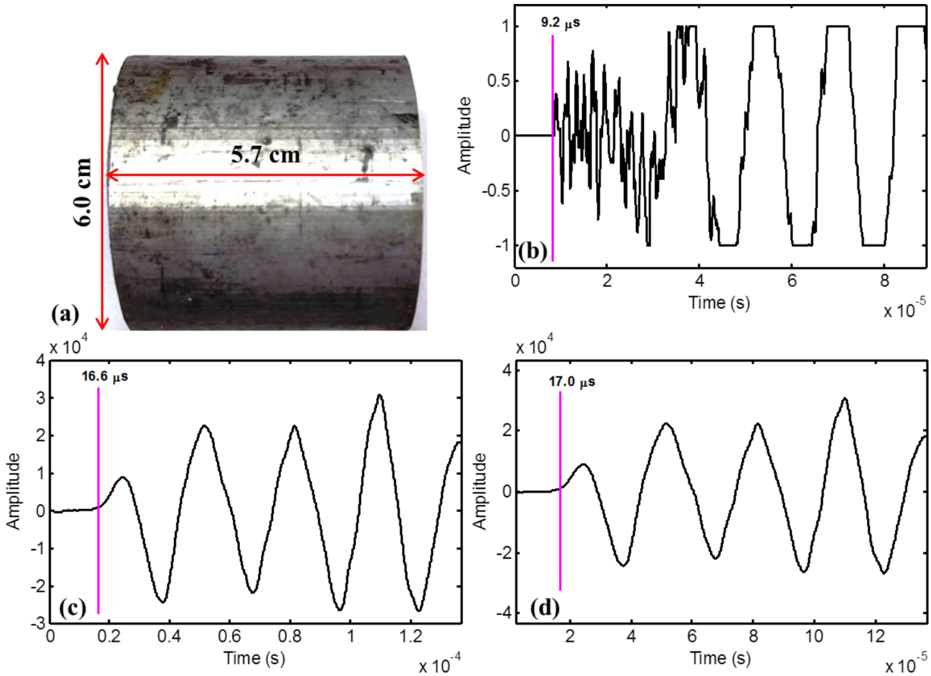

Fig. 7 Testing the first arrival time reading on an aluminum sample. **a** An example of aluminum material with a density of 2.7 gr/cc, **b** P-wave signal, **c** S-wave signal, **d** reading the first arrival time on the S-waveform with CC technique. The first arrival times read in (b) and (c) refer to the times read manually directly in the ultrasonic recorder

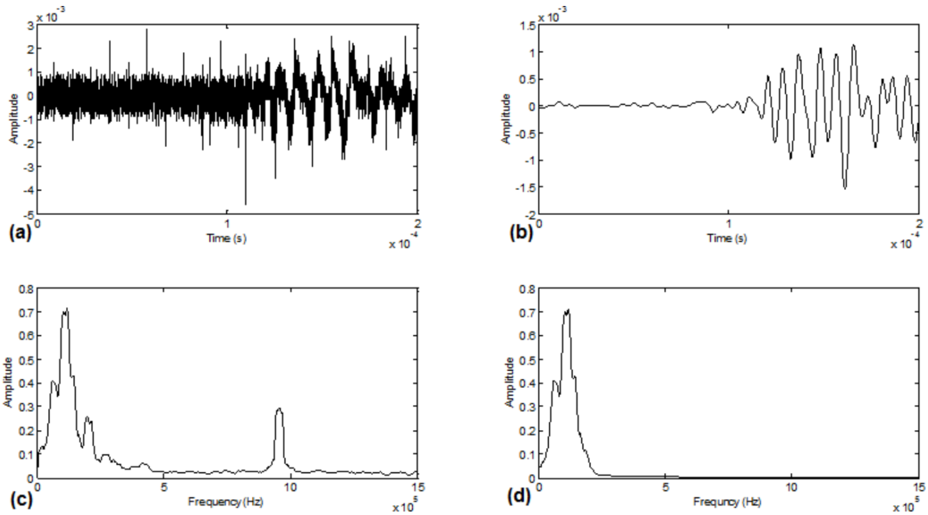

Fig. 8 Application of a band-pass filter to a noisy real signal. **a** recorded noisy signal, **b** result from band-pass filtering, **c** and **d** Fourier amplitude spectra of input and output signals

be read by any user from anywhere within the area determined by the red ellipse, and this would not be an erroneous reading. However, in order to determine the most optimal value of the first arrival time, wavelet estimation in Fig. 9b was first made with Kolmogorov spectral factorization from the signal in Fig. 9a and then the CC technique was applied (Fig. 9c), this time value as seen in Fig. 9d (vertical purple line) was determined as 114.1 µs.

Another ultrasonic signal was obtained from a 10 cm long limestone rock sample, and the results of applying the CC technique to this signal are given in Fig. 10. It is clear that the signal quality is at a level that makes the first-arrival reading difficult. Therefore, to clean the first arrival read region from noise, a band-pass filter was applied to the signal in Fig. 10a with appropriate cut-off frequencies (Fig. 10b). The first arrival time reading was performed semi-automatically with the CC technique to eliminate user dependency on the obtained filtered signal, and it was determined as 37.1 µs.

Samples on two different concrete surfaces with the PPL200 measurement set were made from the columns at the foundation of the KTU Geophysical Engineering Department and from the pouring concrete prepared in the laboratory. One of the concrete surfaces was completed in 2008 (column, L=41 cm), and the other was created in 2018 (pouring concrete, L=52.5 cm). As a result of processing the recorded signals from both samples (Fig. 11a, c) with the band-pass filter and CC techniques (Fig. 11b, d), the first arrival times could be read semi-automatically. Although the PPL200 device provided high signal-to-noise ratio data, the first arrival read region of both signals was still influenced by noise. However, high-amplitude oscillations in the first arrival reading region of both signals can cause instability in reading the first arrival time value. However, thanks to the CC technique, this uncertainty was reduced, and the time values (vertical purple lines) in Fig. 11b, c were determined with high consistency.

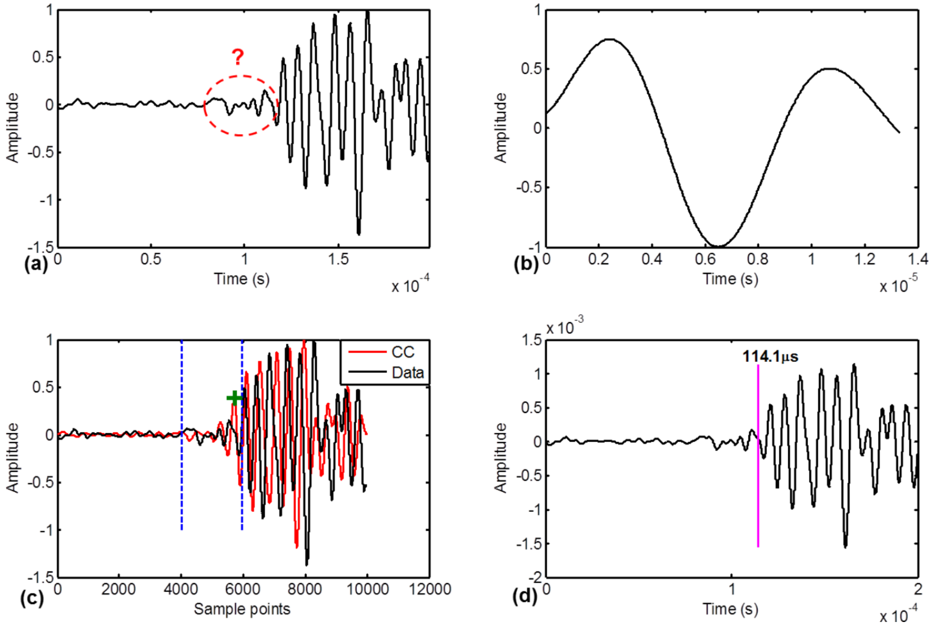

Fig. 9 Semi-automatic first-arrival time reading of real data. **a** filtered version of the data shown in Fig. 8a. The red dashed ellipse shows the possible first arrival times of the signal, **b** estimated operator to be used in the CC technique, **c** correlation signal (red line) obtained by cross-correlation of operator signal in (b) with the input signal (black line). The vertical dashed blue lines indicate the boundaries of the area to be read at the time of first arrival and the maximum peak value is marked by green plus, and **d** location of the determined first arrival time on the input signal (purple line) is 114.1 μs

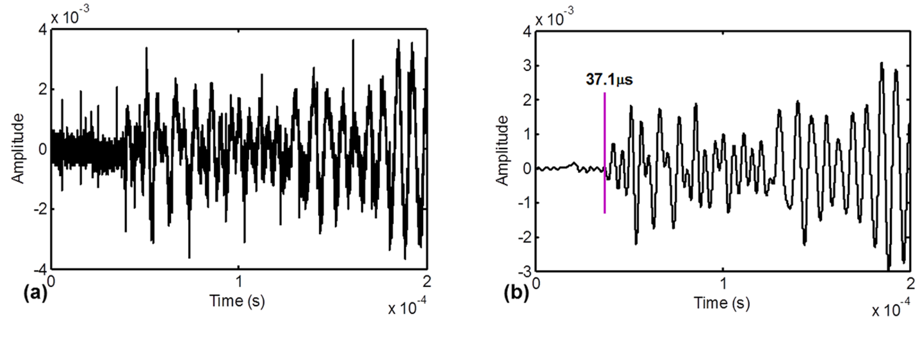

Fig. 10 Semi-automatic first arrival time reading of the rock sample with CC technique. **a** Input signal, and **b** result of band-pass filtering. The purple vertical line shows the first arrival time

5 Discussion

In the characterization of rock, concrete, medical and industrial materials, determination of first arrival times is mostly based on human analyst and there may be differences in repeated measurements. This study used a semi-automatic technique based on the cross-

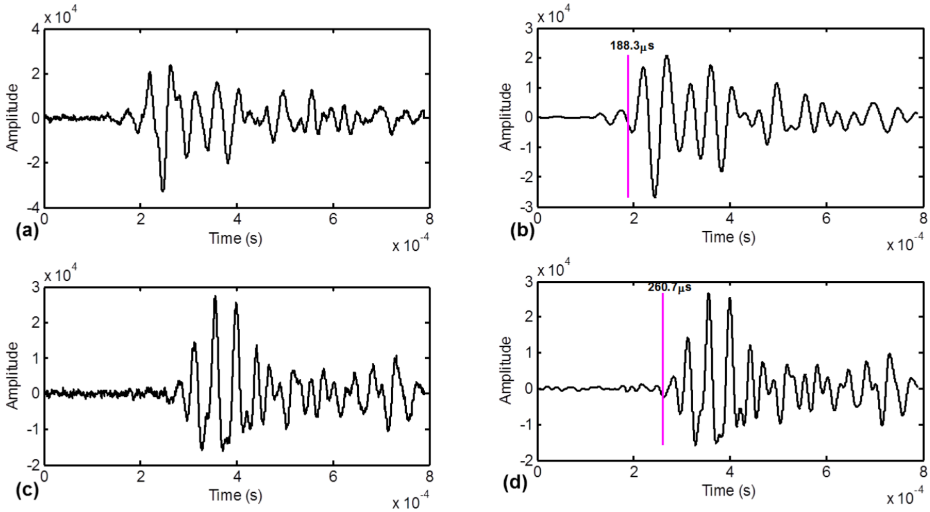

Fig. 11 Semi-automatic first arrival time reading using the CC technique for two different concrete samples. **a** and **b** input signals from the concrete column and pouring concrete, **c** and **d** show the results from band-pass filtering, respectively. The purple vertical line indicates the first-arrival time position

correlation of two signals and reducing the human factor. Although the proposed approach has a similar procedure to other semi-automatic techniques used in the literature, the most important advantages are that the operator signal (or wavelet) is estimated from the signal itself and can be applied to signals with low signal-to-noise ratio. On the other hand, considering that there may be more than one peaking point within the time-restricted area where the first arrival time will automatically peak, it is necessary to be experienced and careful in the selection of these limits. While most of the methods (STA/LTA, neural networks, autoregressive, AIC, etc.) developed for analyzing ultrasonic P signals in the literature were developed and widely used, this study focused on the analysis of S signals recorded from rock and concrete materials. However, applying another semi-automatic technique (Sarout et al. 2009) using CC and AIC techniques to the ultrasonic P wave signal, the operator signal obtained with the highest pressure (compression of the transceiver probes) was chosen. This process needs to be repeated for different samples and can be time-consuming. On the other hand, in the present study, the operator signal was estimated directly from the signal to be analyzed by Kolmogorov spectral factorization technique without the need to apply any pressure.

6 Conclusions

In this study, a procedure was developed to correctly pick the first arrival time of ultrasonic S-wave signals, leading to accurate velocity determination of the materials (rock and concrete samples) in the case of that recorded ultrasonic signals are distorted by sort of the noises. The procedure involves applying trend removal, band-pass filtering, estimation of the operator signal, and a cross-correlation technique within a workflow. In this process, a correlation signal is first obtained, a time part is bounded on this signal by the user, and finally an automatic search is performed to determine the optimal first arrival time position, which corresponds to the maximum amplitude of the correlation signal in that bounded time part. This process can be referred to as a semi-automatic first-arrival picking technique for analyzing the ultrasonic signals. In the proposed technique, an operator representing the ultrasonic source pulse is estimated from the bandpass-filtered signal using the Kolmogorov factorization technique and then it is cross-correlated with the filtered signal. Tests on synthetic and real data indicate that the CC technique provides a clearer ultrasonic signal, leading to accuracy in picking the first arrival times, and it has been observed that the reading error is up to ± 2.0 µs, which may mostly cause an error in velocity of ± 200 m/s. The main advantage of this proposed method is that first arrival time picking is done on the maximum amplitude, which is more precise than conventional picking, of beginning time of S-waves. On the other hand, the most essential point to be considered in applying the method is the accurate and rounded estimation of the operator signal (or wavelet) from the input data and the correct determination of the time interval for automatic picking. Consequently, this procedure provides us with a more precise and reliable S-wave velocity which, leads to the interpretation of velocities in terms of their quality and other physical properties that are primarily used in engineering construction and design.

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Declarations

Conflict of interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Ethical approval This study and included experiments have no ethical issues.

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