EXPERIMENTAL RESEARCH ON THE PROPAGATION PARAMETERS OF EXPLOSIVE STRESS WAVE IN CORAL CONCRETE

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Abstract

This study investigates the propagation of stress waves in coral concrete material under explosive conditions. The experimental system was designed to analyze the stress wave characteristics in coral concrete, focusing on the velocity and attenuation of the stress waves as they pass through the material. The study used explosive charges placed at specific depths within boreholes to generate the stress waves, with pressure sensors deployed to record the intensity of the waves at different distances from the center of the explosion. The results obtained are the stress wave intensity over time at different distances from the center of the explosion. Using regression analysis, the propagation velocity of the stress waves was determined, and the attenuation coefficient was calculated based on distance. It was found that the blast-induced stress wave attenuation coefficient in coral concrete with a compressive strength class equivalent to B22.5 is 1.272, while the propagation velocity of the blast-induced stress wave ranges between 3658 m/s and 3817 m/s, with a minimal measurement error of 1.18%. These findings provide valuable insights into the dynamic behavior of coral concrete, contributing to the establishment of formulas for calculating stress wave intensity and blast loading in coral concrete.

Keywords: *Blast-induced stress wave; stress wave attenuation coefficient; propagation velocity; blast stress wave measurement; coral concrete.*

1. Introduction

When an explosive charge is detonated, the high-pressure products of the explosion act on the walls of the blast hole, causing the surrounding rock and soil particles to displace. This displacement propagates to adjacent particles, generating stress waves through the transmission of particle vibrations. The destructive effects of stress waves on rock and soil media have been the subject of significant scientific investigation since the last century, leading to the development of the stress wave fracture theory. According to this theory, researchers such as Khanukaev and K. Hino have proposed that when the stress wave intensity exceeds the temporary strength of the material, the material particles at that location fail [1]. Therefore, stress waves are critical in fracturing rock and material structures during blasting.

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However, as stress waves propagate through an infinite rock medium, their intensity diminishes, and beyond a certain range, the waves no longer possess sufficient energy to fracture the rock. Thus, understanding the propagation characteristics of stress waves in rock or other materials is a critical aspect of blasting research.

Research on the propagation of blast-induced stress waves in rock media has been conducted by numerous scientists both domestically and internationally. For instance, L. Y. Chi and collaborators utilized strain gauge sensors to measure stress wave pressures in rock near blast holes. Based on experimental results, the team constructed attenuation curves for stress wave intensity near the blast center in granite [2]. The attenuation and waveform characteristics of stress waves in sandstone were examined by Y. Cheng *et al.* using a one-dimensional bar model and an improved Split Hopkinson Pressure Bar (SHPB) test system. Their study revealed that different axial stresses affect both the attenuation and waveform characteristics of stress waves during propagation in the bar [3]. By measuring the stress wave field transmitted from rock to water and applying regression analysis, T. T. Dam *et al.* have predicted the blast pressure exerted on the borehole wall during rock blasting [4]. Using numerical simulations, T. T. Dam and his team analyzed stress wave propagation during blasting in limestone environments and determined the attenuation coefficient of stress wave intensity for finite-length charges in limestone [5].

To enhance the utilization of locally available materials, especially for construction projects in marine and island regions, coral-based materials have been explored. Coral concrete is a novel material that has attracted significant global research interest. Y. Huang and his colleagues investigated the effects of mix proportions in coral concrete compared to conventional concrete on the axial compressive strength of prismatic specimens [6]. B. Liu and collaborators conducted experimental studies on the impact resistance of carbon-fiber-reinforced coral concrete with varying concrete grades and carbon fiber contents [7]. Several countries and territories have also studied the application of coral concrete in construction projects. Early examples include facilities by the Atomic Energy Commission in Eniwetok and Bikini in the late 1940s and early 1950s, as well as the Advanced Early Warning (AEW) system of the U.S. Navy at Midway in the mid-1950s [8].

In Vietnam, research on coral concrete has been primarily conducted by scientists at Le Quy Don Technical University, N. T. Ngo and collaborators studied the partial replacement of conventional sand and aggregate with coral sand and aggregate, combined with seawater and additives, to produce 35 MPa-strength concrete [9]. L. H. Duong *et al.* developed concrete mixes for producing coral concrete specimens with compressive strength grades of B15, B20, and B22.5 [10]. However, in Vietnam, coral concrete has not been widely applied in construction projects and structures due to the limited number of studies on this material, particularly regarding its mechanical properties under explosive loads and the propagation of stress waves in coral concrete. Therefore, research on the propagation and attenuation of blast-induced stress waves in coral concrete is of profound significance.

2. Theories

When an explosive charge is detonated, chemical reactions occur that transform the explosive material into high-temperature, high-pressure gaseous products, which exert force on the walls of the blast chamber.

This pressure compresses and displaces the rock and soil particles immediately surrounding the explosive charge. The displacement of these particles subsequently causes the next layer of rock and soil particles to be compressed and displaced. This continuous process propagates layer by layer, forming stress waves that travel through the rock and soil medium.

Based on the assumption that detonation occurs instantaneously, M. M. Protodiakonov proposed a formula for calculating the pressure exerted by explosive products on the rock at the walls of the blast chamber, expressed as follows [11]:

$$p(t) = p_0 e^{-\alpha t} \tag{1}$$

where p_0 is initial maximum pressure of the explosive products, Pa, $p_0 = \dfrac{\rho_T D^2}{2(k+1)}$ (2)

ρ_T is explosive density, kg/m^3; D is detonation velocity, m/s; k is polytropic index for explosive products; for TNT, k = 2.54; t is time of observation after detonation, s; α is coefficient characterizing the pressure decay of blasting pressure in the blasthole, which depends on the chamber's characteristics, the charge amount, and the rock properties.

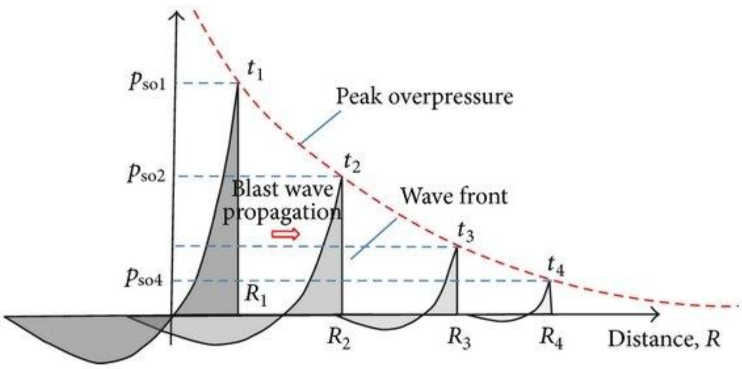


Fig. 1. Stress wave pressure attenuation graph with distance [12].

During propagation, the intensity of the stress wave acting on the rock decreases due to attenuation. The intensity of the stress wave in rock during propagation can be determined using the formula [1]:

$$\sigma_1(\bar{r},t) = \frac{1}{(\bar{r}-1)^{\beta}} p(t)\ ; \quad \frac{(\bar{r}-1)r_0}{c} \le t \le \frac{(\bar{r}-1)r_0}{c} + \theta \tag{3}$$

where $\bar{r}$ is relative distance from the charge axis to the point of investigation, $\bar{r} = \frac{r}{r_0} \ge 1$; c is propagation velocity of the stress wave in the rock medium, m/s; θ is duration of the positive phase of the explosion pressure function, s; $p(t)$ is pressure of the explosion as a function of time at the borehole wall, Pa; r is distance from the charge axis to the point of investigation, m; r_0 is radius of the explosive charge, m; β is stress wave attenuation coefficient depending on the natural characteristics of the rock medium, with values ranging from $\beta = 1 \div 3$. Thus, according to formula (3), the propagation velocity and the intensity attenuation coefficient as a function of distance are two key material-dependent characteristics that determine the stress wave propagation in rock media during blasting.

The propagation velocity of stress waves in materials has been extensively studied by scientists, who have proposed preliminary calculation methods based on the material's elastic modulus, Poisson’s ratio, and density.

For stress wave propagation in an infinite medium, the propagation velocity can be calculated using the formula [13]:

$$c_p = \sqrt{\frac{E(1-\nu)}{\rho(1+\nu)(1-2\nu)}}; \tag{4}$$

$$c_s = \sqrt{\frac{E}{2\rho(1+\nu)}} = \sqrt{\frac{G}{\rho}} \tag{5}$$

where c_p is propagation velocity of the P wave in the rock medium, m/s; c_s is propagation velocity of the S wave in the rock medium, m/s; E is Young’s modulus, Pa; G is shear modulus, Pa; ν is Poisson’s ratio; ρ is material density, kg/m^3.

In the case of propagation in a one-dimensional bar where lateral expansion of the material is not considered, the propagation velocity of the stress wave is calculated using the following formula:

$$c_p = \sqrt{\frac{E}{\rho}} \tag{6}$$

When a stress wave propagates to the interface between two media, part of the energy in the stress wave is transmitted into the subsequent medium as a refracted wave, while the remaining portion is transformed in the original medium as a reflected wave (Fig. 2).

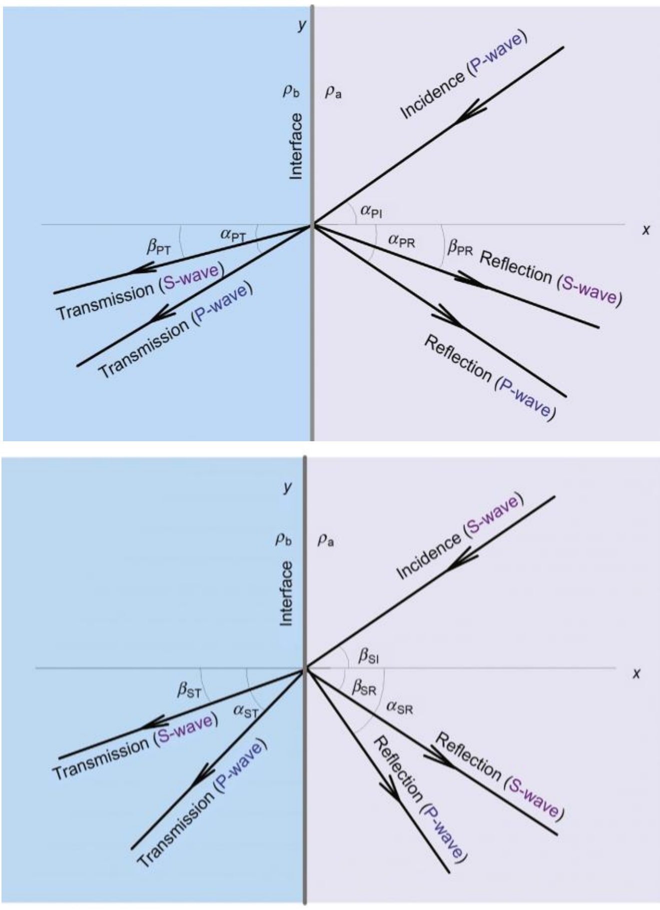


Fig. 2. Reflection and transmission as stress waves propagate to interfaces [14].

Since both materials keep continuum in the interface, scientists have derived formulas for calculating the intensity of reflected and transmitted waves based on the incident wave intensity and the acoustic properties of the media (wave propagation velocity and material density) [1], [11], [14].

$$\begin{aligned} \sigma_{R1} &= R_{12}\sigma_{I1} \\ \sigma_{T1} &= T_{12}\sigma_{I1} \\ \upsilon_{R1} &= -R_{12}\upsilon_{I1} \\ \upsilon_{T1} &= \xi_{12}T_{12}\upsilon_{I1} \end{aligned} \tag{7}$$

where σ_{I1}, υ_{I1} are stress and particle velocity of the incident wave; σ_{R1}, υ_{R1} are stress and particle velocity of the reflected wave; σ_{T1}, υ_{T1} are stress and particle velocity of the transmitted wave; R_{12} is stress wave reflection coefficient,

$$R_{12} = \frac{1-\xi_{12}}{1+\xi_{12}} \tag{8}$$

T_{12} is stress wave transmission coefficient,

$$T_{12} = \frac{2}{1+\xi_{12}} \tag{9}$$

ξ_{12} is acoustic impedance ratio between the two material,

$$\xi_{12} = \frac{\rho_1 c_1}{\rho_2 c_2} \tag{10}$$

ρ_1 and c_1 are the density and longitudinal wave velocity of medium 1; ρ_2 and c_2 are the density and longitudinal wave velocity of medium 2.

According to the formula (7), if the acoustic impedance ratio between the two media and the intensity of the transmitted wave are determined, the intensity of the incident wave can be calculated. This serves as the scientific basis for developing stress wave intensity measurement methods using water pressure sensors placed in fractures along the wave propagation path. The parameters of the incident stress wave can be determined from the readings of the water pressure sensor and the transmission coefficient, as expressed in the formula [11], [15]:

$$\sigma_{I1} = \frac{\sigma_{T1}}{T_{12}} \tag{11}$$

3. Experimental investigation to determine the propagation velocity of blast induced stress waves in coral concrete

3.1. Experimental model

A coral concrete specimen with dimensions L × B × H = (4.8 × 0.8 × 0.5) m was prepared. The specimen included a borehole with a diameter of ϕ = 27 mm and a depth of 25 cm for placing the explosive charge, which was positioned at the bottom of the borehole. Along the wave propagation path, two additional boreholes with diameters of 14 mm were drilled at varying distances from the explosion center. These boreholes were filled with water to accommodate pressure sensors.

3.2. Materials and experimental equipment

Coral concrete: The coral concrete used had a compressive strength corresponding to grade B22.5. The concrete mix design was based on research by L. H. Duong *et al.* [10].

During the specimen preparation process, samples of the coral concrete were tested for compressive strength, with results presented in Tab. 2.

Explosive charge: A custom-made explosive charge, equivalent to 1 gram of TNT, was provided by factory Z121. The cylindrical charge had dimensions r = 6 mm and h = 45 mm, and was placed at a depth of h = 25 cm within the borehole (Fig. 3).

Measurement system: A multi-channel NI-SC1000DC data acquisition system from National Instruments, with a maximum signal recording frequency of 200 kHz, was employed to capture measurement signals. The water pressure sensors used were Model W138A05/-0023 from PCB Piezotronics (USA), with a maximum pressure capacity of 5000 psi. The sensors were set to a sampling frequency of 100 kHz for the measurements.

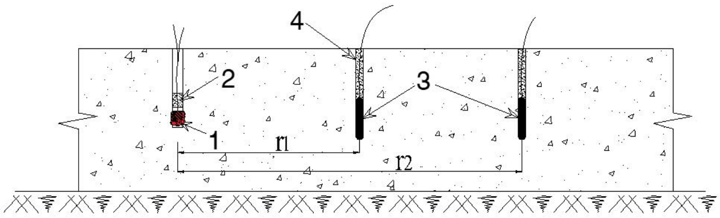


Fig. 3. Experimental setup diagram

1 - explosive charge; 2 - stemming; 3 - water pressure sensor; 4 - ϕ14 mm water-filled borehole.

Fig. 4. Installation of water pressure sensors.

3.3. Results

After conducting the explosions and recording the signals, the results are presented in Fig. 5 and Tab. 1. These results provide the stress wave pressure over time measured using water pressure sensors at different distances from the explosion center.

The experimental results indicate that the propagation velocity of stress waves in coral concrete with a compressive strength equivalent to grade B22.5 ranges between 3658 m/s and 3817 m/s. A regression function was established to correlate the distance and time, yielding an average propagation velocity of approximately 3690.2 m/s with a coefficient of determination R^2 = 0.9998. These findings demonstrate that the measured values exhibit exceptionally high consistency.

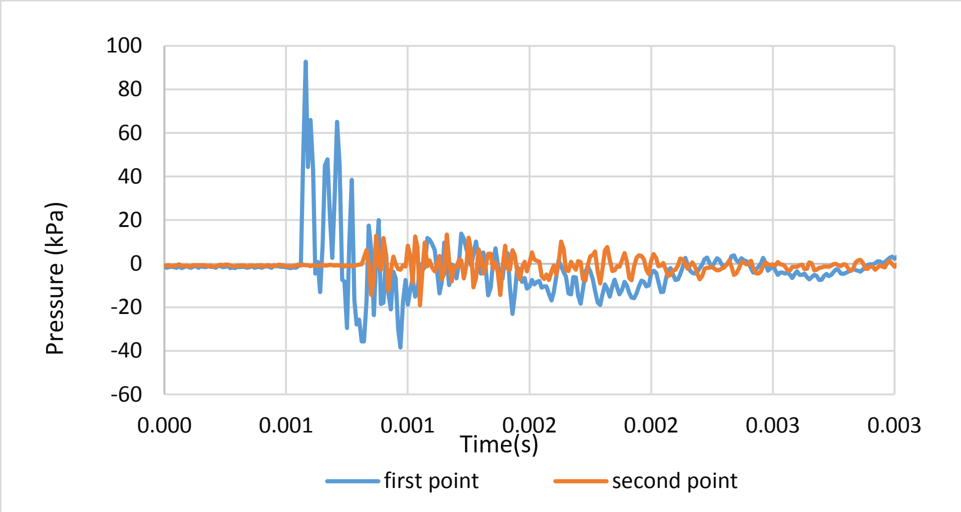


Fig. 5. Stress wave pressure graph over time.

Tab. 1. Experimental results: Wave propagation velocity in coral concrete material

No.	Distance Δr (m)	Time of signal reception t_1	Time of signal reception t_2	Wave propagation velocity (m/s)
1	1.0	0.07974	0.080002	3816.794
2	1.0	0.00075	0.00102	3703.704
3	1.0	0.00084	0.00111	3703.704
4	1.5	0.00071	0.00112	3658.537
5	1.5	0.00094	0.00135	3658.537

Based on the experimental results for the compressive strength of the concrete samples (f_c) the elastic modulus of concrete is calculated according to formula [16]:

$$E = 0.043\rho^{3/2}\sqrt{f_c} \quad (12)$$

Applying Eq. (4), the calculated stress wave propagation velocities in coral concrete are presented in Tab. 2.

Tab. 2. Results of compressive strength testing of concrete samples and theoretically calculated propagation velocities

No.	Manufacturing date	Test date	Strength (MPa)	Velocity of stress wave (m/s)
1	26/01/2024	26/02/2024	32.444	3805.139
2	27/01/2024	29/02/2024	29.481	3715.117
3	28/01/2024	26/02/2024	29.037	3701.049

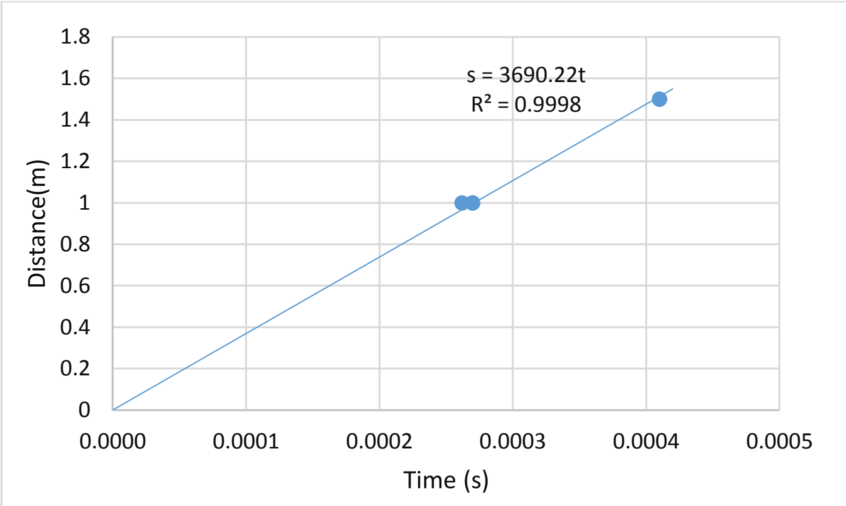


Fig. 6. Determining average velocity based on regression function.

When applying the theoretical calculation formula based on the compressive strength results of the material, the stress wave propagation velocity in coral concrete is determined to range between 3701 m/s and 3805 m/s.

A comparison of the experimental results with the theoretical calculation results reveals that the measurement (3658 m/s and 3817 m/s) error is only approximately 1.18%. This minimal and negligible error confirms the reliability of the experimental research model.

4. Experimental investigation of stress wave intensity attenuation with distance in coral concrete

4.1. Experimental setup

The measurement of stress wave pressure was conducted in water-filled boreholes along the wave propagation path. The experimental model consisted of a coral concrete block with dimensions L × B × H = (4.8 × 0.8 × 0.5) m. Drilling holes with diameters ϕ = 27mm and ϕ = 14 mm were drilled into the block.

The ϕ = 27 mm drilling holes were used to place the explosives.

The ϕ = 14 mm drilling holes were filled with water to house pressure sensors.

The distances from the ϕ = 14 mm boreholes to the explosive charge varied as *r* = 20 cm, 30 cm, 40 cm, 50 cm and 60 cm.

4.2. Experimental procedure

Explosions were initiated with explosive charges of 1.0 g TNT, and stress wave pressures were recorded at various borehole locations corresponding to the specified distances from the explosive center. For each distance, the experiment was repeated 3-4 times to ensure data reliability.

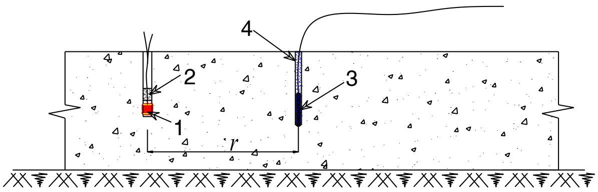


Fig. 7. Experimental setup diagram.

1 - Explosive charge; 2 - Stemming; 3 - Pressure sensor; 4 - ϕ14 mm water-filled borehole.

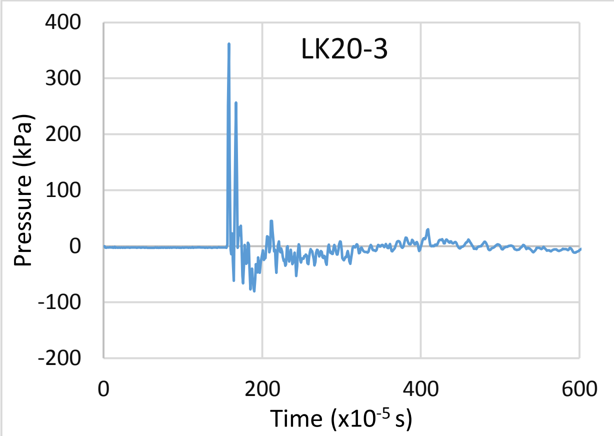
4.3. Results

The pressure-time graph of the stress waves (refracted waves) in water-filled boreholes is shown in Fig. 8. From the graph, it is evident that the stress waves exhibit distinct compressive and tensile phases. The intensity of the compressive phase is significantly higher than that of the tensile phase.

The maximum stress intensity values at various measurement distances for each test are summarized in Tab. 3.

Tab. 3. Maximum stress values at measurement points

No.	Code	Distance r (cm)	Normalizied distance r/r_0	Pressure (kPa)
1	LK20-1	20	14.81481	368.24
2	LK20-2		14.81481	370.8869
3	LK20-3		14.81481	362
4	LK20-4		14.81481	409.4039
5	LK30-1	30	22.22222	181.3285
6	LK30-2		22.22222	215.9789
7	LK30-3		22.22222	256.1552
8	LK30-4		22.22222	222.734
9	LK40-1	40	29.62963	187.0356
10	LK40-2		29.62963	167.4683
11	LK40-3		29.62963	181.7726
12	LK40-4		29.62963	178.512
13	LK50-1	50	37.03704	102.2439
14	LK50-2		37.03704	115.4926
15	LK50-3		37.03704	138.9326
16	LK60-1	60	44.44444	101
17	LK60-2		44.44444	82.06508
18	LK60-3		44.44444	83.28804
19	LK60-4		44.44444	93.48



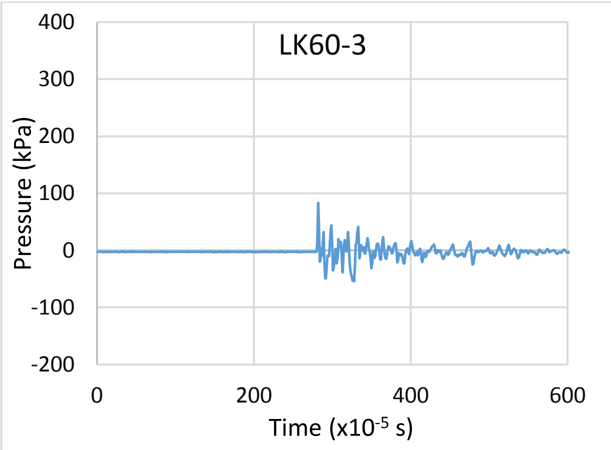


Fig. 8. Results of stress wave pressure graphs.

4.4. Analysis of experimental results

Based on the results presented in Tab. 3, the least-squares method was employed to establish the distribution law for the maximum stress wave intensity as a function of distance. The resulting relationship is shown in Fig. 9 and expressed as follows:

$$\sigma_T\left(r\right)=17278\cdot r^{-1.272} \text{ (kPa) with } R^2 = 0.964 \tag{13}$$

where $\sigma_T\left(r\right)$ the maximum stress wave intensity in the water-filled borehole at a distance r from the explosion center.

From the above expression, the blast-induced stress wave attenuation coefficient (β) for wave propagation in coral concrete, with compressive strength equivalent to grade B22.5, is determined to be β = 1.272. This is a crucial parameter for analyzing and calculating the stress wave intensity during propagation.

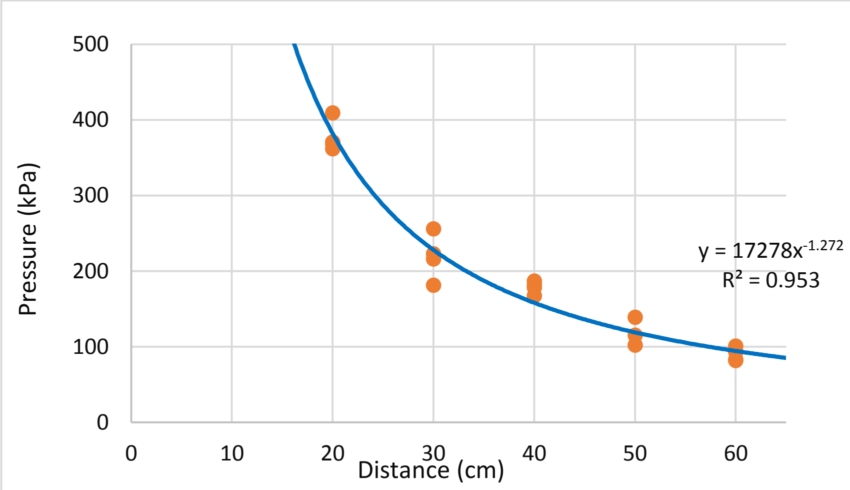


Fig. 9. Stress wave attenuation as a function of distance.

5. Conclusion

Coral concrete is a novel material with potential applications in construction, particularly in marine and island projects, as well as in regions where transportation of traditional construction materials is challenging. It is crucial to thoroughly study the advanced properties of coral concrete before practical application. The research demonstrates that explosive-induced stress waves propagating through coral concrete experience attenuation in intensity with increasing distance. The attenuation coefficient of stress wave intensity for coral concrete with a compressive strength equivalent to B22.5, under the effect of concentrated explosive charges, is determined to be 1.272. Additionally, the propagation velocity of stress waves in coral concrete is measured to range between 3633 m/s and 3805 m/s. These are key parameters for determining the behavior of stress waves in coral concrete under explosive loads. To enable the use of coral concrete in protective structures subjected to explosive loading, further studies on parameters such as fracture coefficients and spalling factors are necessary.

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NGHIÊN CỨU THỰC NGHIỆM CÁC THAM SỐ LAN TRUYỀN SÓNG ỨNG SUẤT NỔ CỦA BÊ TÔNG SAN HÔ

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Tóm tắt: Nghiên cứu này khảo sát sự lan truyền sóng ứng suất nổ trong vật liệu bê tông san hô. Hệ thống thí nghiệm được thiết kế nhằm phân tích các đặc trưng của sóng ứng suất trong bê tông san hô, tập trung vào vận tốc và sự suy giảm cường độ sóng trong quá trình lan truyền. Các thử nghiệm được tiến hành bằng cách đặt lượng thuốc nổ ở các độ sâu xác định trong lỗ khoan để tạo sóng ứng suất, đồng thời sử dụng cảm biến áp suất để ghi nhận cường độ sóng tại các vị trí khác nhau so với tâm nổ. Kết quả nghiên cứu thu được là sự biến đổi cường độ sóng ứng suất theo thời gian tại các khoảng cách khác nhau so với nguồn nổ. Thông qua phân tích hồi quy, vận tốc lan truyền sóng ứng suất được xác định, đồng thời hệ số suy giảm sóng theo khoảng cách cũng được tính toán. Nghiên cứu cho thấy hệ số suy giảm trong bê tông san hô có cường độ tương đương cấp bền nén B22,5 là 1,272; vận tốc lan truyền sóng ứng suất nằm trong khoảng 3658-3817 m/s, với sai số đo lường nhỏ chỉ khoảng 1,18%. Những kết quả này cung cấp các dữ liệu quan trọng về đặc tính của bê tông san hô chịu tác động nổ, góp phần xây dựng công thức tính toán cường độ sóng ứng suất và tải trọng nổ trong loại vật liệu này.

Từ khóa: *Sóng ứng suất do nổ; hệ số suy giảm sóng ứng suất; vận tốc lan truyền; đo đạc sóng ứng suất do nổ; bê tông san hô.*

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