Using P-wave Velocity to Monitor the Early Hydration Process of Cemented Paste Backfill for Disaster Prevention and Prediction

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Abstract. Cemented paste backfill (CPB) is a widely used filling material in mine backfilling and underground engineering. Understanding the hydration process of CPB is essential for ensuring its stability and safety. The study utilized P-wave velocity to characterize the early hydration process of CPB. Three stages of CPB evolution were identified: dissolution and induction period, acceleration period, and deceleration period. In the first stage, the rapid increase in P-wave velocity corresponded to particle settlement within the CPB, leading to compaction. In the second stage, hydration accelerated, resulting in a rapid increase in P-wave velocity. In the third stage, as hydration slowed down, the increase in P-wave velocity was gradual. The hydration process affected CPB's pore structure and moisture content, thereby influencing P-wave velocity. These findings were corroborated by the changes in electrical conductivity and matrix suction measurements. The study established the relationship between P-wave velocity and the early hydration process of CPB, providing valuable insights for disaster prevention and prediction.

Keywords: P-wave velocity; cemented paste backfill; early hydration process.

1 Introduction

Acoustic velocity, as a convenient and non-destructive testing method, has been proven effective in the detection of cement mortar and concrete by many researchers[1]. Previous studies have shown a clear correlation between acoustic velocity and the hydration process of cementitious materials such as cement, effectively characterize the subtle changes in the early hydration process[2, 3]. Moreover, the utilization of P-wave velocity allows for the differentiation of various stages of cement hydration. For example, Wei[4] identified three characteristic stages of foamed concrete using P-wave velocity: dormancy, acceleration, and deceleration, demonstrating the effectiveness of P-wave monitoring in detecting hydration and microstructural changes in foamed concrete. Although many studies have investigated the relationship between acoustic velocity and hydration in cement mortar and concrete, research on monitoring the early hydration

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process of cemented paste backfill (CPB) using acoustic velocity is limited. CPB differs from cement mortar and concrete in composition and properties, often having higher aggregate content, lower binder ratios, and looser pore structures, which may manifest in variations in velocity changes[5]. Common methods for characterizing CPB hydration, such as X-ray diffraction (XRD), scanning electron microscopy (SEM), and thermal analysis (TG), are costly and challenging to implement for continuous monitoring. Therefore, continuous monitoring of CPB hydration using acoustic velocity remains essential. The purpose of this study is to establish the relationship between P-wave velocity and the early hydration process of CPB. Continuous measurements of P-wave velocity were conducted on CPB within 7 days to observe its evolution over time, and hydration stages were delineated accordingly. Additionally, simultaneous measurements of electrical conductivity and matrix suction were performed for validation. The results demonstrate that P-wave velocity effectively characterizes the early hydration process of CPB.

2 Methods and materials

2.1 Specimen preparation

Weigh out gypsum, cement, and water according to mass concentrations of 55%, with binder contents of 5%, 15%, and 25%, respectively. Mix them thoroughly for 15 minutes, then pour the mixture into acrylic molds for subsequent testing. The curing process was conducted in a constant temperature and humidity curing chamber at 20°C and 95% humidity.

2.2 Acoustic measurements

This study employed a combined acoustic wave system to monitor the P-wave velocity of CPB. A pulse wave signal with a frequency of 10 Hz and a pulse width of 5 μs was emitted by the TiePie engineering instrument (Handyscope HS5). After amplification by a 40 dB amplifier, the signal was received by the acoustic emission sensor (GTR 150a) and displayed on multi-channel software. By measuring the propagation path length ‘l’ and propagation time ‘t’, the P-wave velocity through the CPB is calculated as $v=l/t$.

2.3 Electrical Conductivity and Matric Suction Detection

The MPS-6 matric suction sensor was used to detect changes in matric suction in the CPB, connected to the Em60 data logger for data acquisition and recording, and then the Em60 data logger was connected to the ZENTRA Utility software on the PC for data export.

The 5TE sensor was employed to detect changes in electrical conductivity in the CPB, connected to the Em50 data logger for data acquisition and recording, and then the Em50 data logger was connected to the ECH_2O software on the PC for data export.

3 Results and Discussion

The P-wave velocity curves and their first derivative curves of CPB with different binder contents are illustrated in Figures 1. It can be observed from the figure that all groups exhibit similar trends in P-wave velocity variation, which can be roughly divided into three stages: dissolution and induction period (Stage I), acceleration stage (Stage II), and deceleration stage (Stage III). In Stage I, the P-wave velocity initially increases rapidly, followed by minor fluctuations within a small range. Correspondingly, on the derivative curve, the initial value of the first derivative is relatively large and gradually decreases. In Stage II, the P-wave velocity similarly increases rapidly, corresponding to a relatively high value of the first derivative, around 10. In Stage III, the rate of increase in P-wave velocity decreases compared to Stage II, and the first derivative fluctuates within the range of 0-5. During the early hydration process of CPB, particle settlement, dissolution, and cement hydration occur, significantly affecting the pore structure and water content of CPB. These parameters, in turn, influence the P-wave velocity. Therefore, it is possible to analyze the reasons for the changes in P-wave velocity at different stages by considering the hydration characteristics of cement, and simultaneously verify them by measuring the changes in electrical conductivity and matrix suction. The relationship between P-wave velocity, electrical conductivity, and matrix suction is illustrated in Figure 2.

Based on Figure 2, Stage I (oa section) represents the dissolution and induction period, lasting approximately 25 hours. Initially, particles in CPB mainly undergo dissolution and settlement[4]. The dissolution process leads to a continuous increase in ion concentration in the solution, accompanied by a rapid rise in electrical conductivity. Meanwhile, the settlement results in partial seepage of free water, and trapped air bubbles gradually migrate to the surface and escape[3]. This leads to denser CPB and a rapid decrease in overall porosity, thus causing a rapid increase in P-wave velocity. However, at this stage, the particles are still relatively dispersed, resulting in minor changes in matrix suction. As particles gradually come into contact, the hydration process enters the induction period. Dissolved cement particles begin to react, gradually depleting free water in the pores, increasing negative pore water pressure, and consequently enhancing matrix suction. Simultaneously, hydration products formed during the reaction fill the gaps between the particles, forming an electrically insulating layer. This elongates the path for ion movement within CPB, reducing its mobility and causing a decrease in electrical conductivity. Moreover, the continuous formation of hydration products gradually connects between the aggregates, forming a solid propagation path, leading to an increase in P-wave velocity over time. However, due to the encapsulation of cement surfaces by water films, the rate of hydration reaction is low, resulting in a slow increase in P-wave velocity.

Approximately 25 hours later, Stage II (ab section) is entered. At this point, due to osmotic pressure, the thin films encapsulating the cement surfaces rupture, leading to an increase in the hydration rate and the onset of an acceleration phase of hydration reaction[6]. During this stage, the rapid consumption of free water within the pores and the subsequent increase in hydration products, such as ettringite and C-S-H gel, lead to a rapid decrease in matrix suction. As hydration proceeds, the movement of ions further diminishes, causing electrical conductivity to decrease rapidly[7]. The hydration products connect with each other, forming numerous solid propagation paths. The continuous generation of hydration products fills the pores between the solid frameworks, making the internal structure of CPB denser and reducing overall porosity, resulting in a rapid increase in P-wave velocity.

The acceleration phase lasts for approximately 50 hours before transitioning to the deceleration phase of cement hydration, Stage III (bc section). At this stage, smaller cement particles have already undergone complete hydration, while larger cement particles gradually diminish due to the hydration process, reducing the surface area of unhydrated cement particles. Additionally, hydration leads to the formation of insoluble ettringite on the surface of cement particles, encapsulating them and impeding further hydration[8]. Consequently, the hydration rate of cement gradually slows down. As the hydration rate slows, the rate of hydration product formation also decreases, leading to a deceleration in the formation of the solid framework and a decrease in the rate of pore filling. Consequently, the upward trend of P-wave velocity also begins to slow down, showing a steady increase. Correspondingly, the decreasing trends of electrical conductivity and matrix suction also slow down.

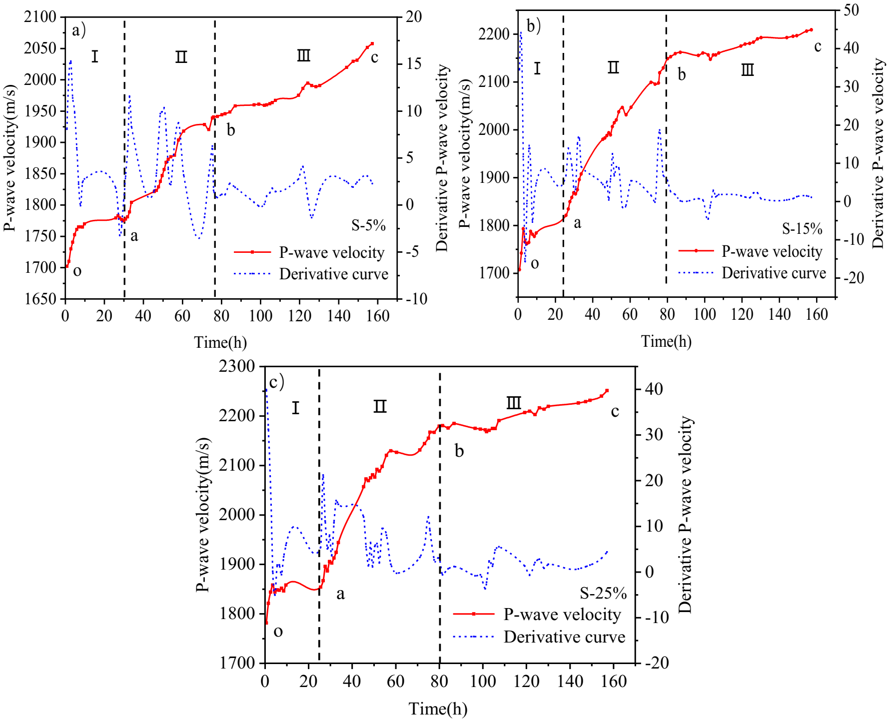

Fig. 1. P-wave velocities and their first derivative evolution curve of CPB with different binder contents; a) 5% binder content b) 15% binder content c) 25% binder content

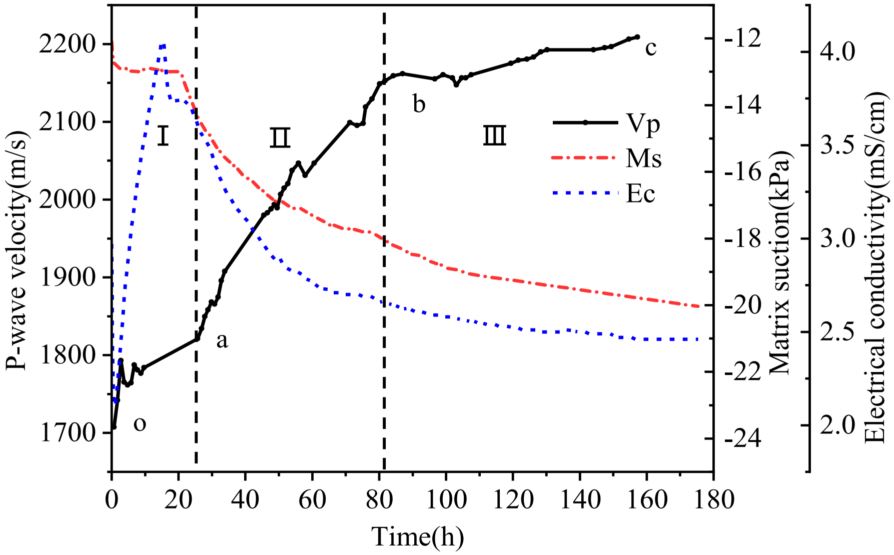

Fig. 2. Relationship between P-wave velocity, electrical conductivity, and matrix suction

4 Conclusion

This study utilized P-wave velocity as a non-destructive method to monitor the early hydration process of CPB, while also measuring matric suction and electrical conductivity for validation. According to the experimental results, the P-wave velocity can reflect the microstructural changes of cement hydration and the rate of hydration product generation, aligning well with changes in electrical conductivity and matric suction. This indicates that P-wave velocity serves as a robust parameter to characterize the early hydration process of CPB, aiding in the timely detection of potential issues during the filling process to prevent structural damage or engineering accidents. However, this study also has certain limitations, such as its applicability in environments like underground or mining areas. Future research could further explore the accuracy and reliability of monitoring under different conditions, such as varying pressure and pH levels.

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