Use of Ultrasonic Pulse to Monitor Setting Process in Concrete: Effect of Aggregate Size and Content

Piti Sukontasukkul[1]* Bariboon Sanpetch[2] and Smith Songpiriyakit[3]

บทคัดย่อ

งานวิจัยนี้ ประกอบด้วยการทดลอง 2 ส่วน ส่วนที่ 1 เป็นการศึกษาผลกระทบของขนาดใหญ่สุดและปริมาณของมวลรวมหยาบต่อการทดสอบกระบวนการก่อตัวของคอนกรีตด้วยคลื่นอัลตร้าโซนิกส์ ขนาดมวลรวมหยาบใหญ่สุดที่นำมาใช้ประกอบด้วย 12.5, 19 และ 25 มม. โดยผสมมวลรวมละเอียดต่อมวลรวมหยาบใน 3 สัดส่วน คือ 30/70, 40/60 และ 50/50 การทดสอบกระทำโดยใช้คลื่นอัลตร้าโซนิกส์ที่ความถี่ 54 กิโลเฮิร์ตซ์ ภายใต้อุณหภูมิ 30 องศาเซลเซียส ในส่วนที่ 2 เป็นการทดสอบผลกระทบของอุณหภูมิขณะทดสอบ โดยทำการทดสอบเพิ่มเติมที่อุณหภูมิ 10, 20 และ 40 องศาเซลเซียส ผลการทดลองพบว่าขนาดใหญ่สุดและปริมาณของมวลรวมหยาบไม่ส่งผลกระทบต่อการเปลี่ยนแปลงอัตราเร็วคลื่นในช่วง 3 ถึง 6 ชม. แรก โดยพบค่าระยะเวลาก่อตัวตั้งต้นและอัตราการเปลี่ยนแปลงความเร็วคลื่นใกล้เคียงกันในทุกสัดส่วนผสม อย่างไรก็ตาม หลังจาก 6 ชม. แล้วพบว่าขนาดและปริมาณของมวลรวมเริ่มส่งผลกระทบต่ออัตราเร็วคลื่น โดยเฉพาะค่าอัตราเร็วคลื่นที่ 24 ชม. พบว่ามีค่าแตกต่างกันตามขนาดและปริมาณของมวลรวม ในส่วนของอุณหภูมิพบว่ามีผลต่อค่าระยะเวลาก่อตัวตั้งต้นรวมค่าอัตราเร็วคลื่นที่ 24 ชม. เช่นกัน โดยการลดลงของอุณหภูมิบ่มจะมีผลทำให้การก่อตัวช้าลงและอัตราเร็วคลื่นที่ 24 ชม. มีค่าลดลง

คำสำคัญ: การก่อตัว คลื่นอัลตร้าโซนิกส์ ขนาดใหญ่สุดของมวลรวมหยาบ สัดส่วนมวลรวมหยาบต่อละเอียด

Abstract

This study consists mainly of 2 parts. In the 1st part, the effect of maximum size and content of the coarse aggregate on the ultrasonic pulse velocity used for monitoring the setting process of concrete is investigated. Aggregate with three different maximum sizes (MSA) of 12.5, 19 and 25 mm are used at three different fine/coarse ratios of 30/70, 40/60, and 50/50. The tests were carried out with a 54 kHz ultrasonic pulse generator in a temperature control chamber at 30°C. The 2nd part is the investigation on the

1 Associate Professor, Department of Civil Engineering, Faculty of Engineering, King Mongkut's University of Technology North Bangkok.

2 Student, Department of Civil Engineering, Faculty of Engineering, King Mongkut's University of Technology North Bangkok.

3 Assistant Professor, Department of Civil Engineering and Technology, College of Industrial Technology, King Mongkut's University of Technology North Bangkok.

* Correspondent Author, Tel. 0-2913-2500 Ext. 8620, E-mail: piti@kmutnb.ac.th.

Received 8 March 2011; Accepted 16 August 2011

effect of curing temperature at 10, 20 and 40^{o}C. Results indicate that the maximum size and the content of coarse aggregate do not have significant affect on the pulse-time curves during the first 3 to 6 hours. The initial setting times and rates of change are found to be in closed ranges for all aggregate sizes and contents. However, after 6 hours, the effect of the maximum size and the content of coarse aggregate can be observed clearly as the curves begin to separate. The final 24-hr pulse velocity is found to depend strongly on the aggregate's maximum size and content. For the curing temperature, it is found to affect both the initial setting time and the rate of change. With decreasing curing temperature, the initial setting time is shifted forward (delayed) and the slope is also decreased.

Keywords: Setting Process, Ultrasonic Pulse Velocity, Maximum Size of Aggregate, Fine/Coarse Ratio

1. Introduction

In practice, the setting time of concrete is measured using a standardized test like ASTM C403 (the Penetration Resistance). Although the standardized test is meant for concrete, the actual test is, in fact, carried out on cement mortar. On the process of testing, because the aggregates inside could interfere with the penetrating needle and also mixing concrete in form of mortar does not represent concrete in actual practice (it is not taken into account of the aggregates' absorption), the sample must be prepared in form of concrete first, and then the aggregates are extracted from the mix before the test begin. For concrete with low water content (low w/c ratios), the process of extracting coarse aggregates from the mix is difficult and time consuming, and could also interfere with the water content of the concrete.

On an attempt to find alternate method to monitoring the setting process directly from concrete (without having to remove the aggregates), the ultrasonic pulse test emerged in early 1990s [1],[2]. Since then, it has been investigated by several researchers [3]-[8]. In the most recent ones, Reinhardt et al [7] showed a new testing device with allow the ultrasonic wave to transmit directly to the cement mortar without passing through the container's wall. The new device also allows the test to be monitored continuously. Typical patterns of the pulse velocity are found to increase quickly during the setting process and slow down process as concrete become hardened. Lee et al [8] also used similar device as of Reinhardt [5],[7] to investigate the setting time of high performance concrete mixed with fly ash. According to their results, the initial slope was found to depend on the w/cm ratio in which the slope increased with the decreasing w/cm ratio. They also suggested the ranges of initial setting time of OPC and FA mortars to range between 800-980 m/s and 920-1070 m/s, respectively.

Since the objective of using the ultrasonic pulse velocity is to find a method to measure setting process of concrete directly without having to remove the aggregates. Therefore it would be interested to see the effect of aggregate on this particular test, after all, about 75% of concrete are made up of aggregates (both fine and coarse). Therefore, in this study, the effect of aggregate size and content on the variation of the ultrasonic pulse velocity in fresh concrete is investigated extensively. Three sizes of aggregate were used (12.5, 19.0 and 25.0 mm) together with five different coarse-fine aggregate ratios. In addition, the effect of curing temperature is also investigated at temperature range from 10 to 40^{o}C.

2. Experimental Procedure

2.1 Materials

Materials used in this study consist of Portland cement type I, tap water, river sand and crushed stone. The water cement ratio for the control mix is set at 0.40. Three maximum sizes of coarse aggregate are used: 12.5, 19 and 25 mm at three different fine/coarse ratios of 30:70, 40:60 and 50:50. The effect of temperature is carried out on concrete with MSA 25 and F/CR ratio of 40:60. Details mix proportions are given in Table 1 and 2.

To prepare the specimen, cement and aggregates are dry-mixed in a mixing pan for about 2-3 minutes. Then water is added into the mixture, the mixing continues for another 2-3 minutes. After that it is poured into a 100x100x100-mm wooden mold to begin the test.

Table 1 Mix Proportion for Concrete with Different MSA an d F/CR Ratios

Name	MSA (mm)	F/CR Ratio	Mix Proportion (kg/m^3)			
			W	C	F	CR
M12(40/60)	12	40:60	195	488	650	1,040
M19(40/60)	19	40:60	195	488	650	1,040
M25(30/70)	25	30:70	195	488	508	1,183
M25(40/60)	25	40:60	195	488	676	1,014
M25(50/50)	25	50:50	195	488	845	845

Note: W-water, C-cement, F-fine agg. and CR-coarse agg.

Table 2 Mix Proportions for Concrete tested under Different Curing Temperatures

Name	MSA (mm)	Temp (C)	Mix Proportion (kg/m^3)			
			W	C	F	CR
M25T10	25	10	195	488	650	1,040
M25T20	25	20	195	488	650	1,040
M25T30	25	30	195	488	650	1,040
M25T40	25	40	195	488	650	1,040

Note: W-water, C-cement, F-fine agg and CR-coarse agg.

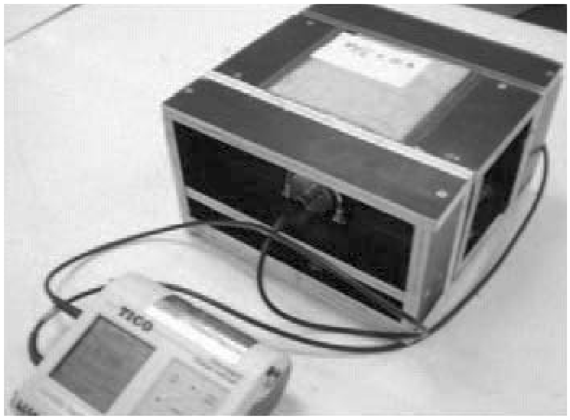

Figure 1 Test Setup.

2.2 Specimen Preparation and Testing

The wooden mold used in this study is designed and constructed as shown in Fig.1. The mold has two openings on both sides for placing probes. The openings allow the fresh concrete to have direct contact with the probes. The capacity of the mold is 0.001 m^3 (100 x 100 x 100 mm). Prior to the test, both transmitter and receiver are aligned and set opposite to each other to allow the pulse to travel straight to the receiver through the concrete with minimum escaping. During the test, a 54 kHz ultrasonic pulse is generated and transmitted into concrete every 5 minutes up to 12 hours. The results from the ultrasonic test are recorded and plotted.

3. Results and Discussion

3.1 Typical Pattern

Typically, pattern of change of the ultrasonic pulse velocity in fresh concrete consists of three stages [8] (Fig.2). The first stage is where the setting has not yet taken place, the concrete is in fluid form and the rate of change (slope) is slow. The second stage is where the setting begins and the slope increases dramatically. A steep slope indicates that there is a quick change on the physical properties of concrete

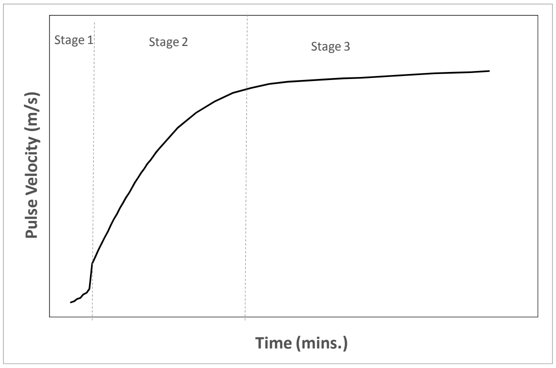

Figure 2 Typical Relationship between Pulse Velocity and Time.

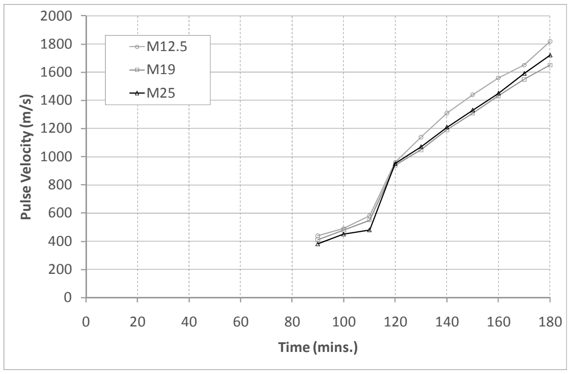

Figure 3 Variations of ultrasonic pulse velocity of concrete with different aggregate size (first 3 hours).

(from fluid to solid phase). The time where the two slopes meet (or the time of the maximum velocity of the stage1) could be defined as the initial setting time [7]. In the third stage, the phase change is almost completed as the slope begins to decline and becomes steady at the end.

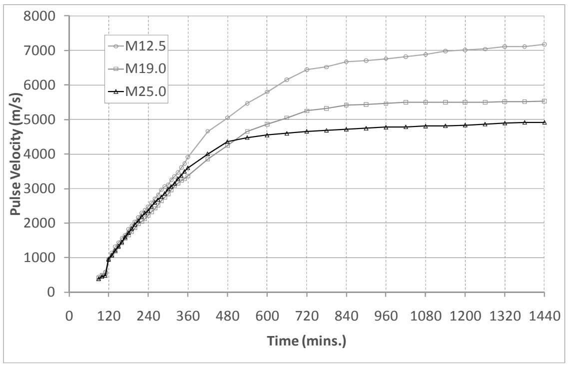

Figure 4 Variations of ultrasonic pulse velocity of concrete with different aggregate size (24 hours).

3.2 Effect of Maximum Size of Aggregate

Results on the effect of the maximum size on the change of the ultrasonic pulse velocity at different time frames are shown in Fig. 3 to 4.

During the first 2 hours (stage 1), all concrete shows similar pattern of change in the ultrasonic pulse velocity. The times to obtain the first values fall at about 90 minutes. The initial velocities are also in the similar range of about 390 to 430 m/s. The point of slope changes (which is defined at the initial setting time) is found when the pulse velocities reach the values of about 900 to 1000 m/s at about 120 minutes. Similar patterns and times indicate that the maximum size of the aggregate does not affect the change of the ultrasonic pulse velocity of fresh concrete prior to the slope changing point (initial setting).

Beyond the point of slope change in which the setting process is believed to already taken place, the effect of aggregate size still cannot be seen. The slope of all concrete is very much in similar range. This means that the maximum size of aggregate also does not affect the change of the pulse velocity during the early setting process.

The curves of all concrete remain closed to each other up to about 4 hours before the separation begins (Fig. 4). As the concrete enters the hardening stage, the effect of aggregate size comes into play. Concrete with smaller aggregate size seems to exhibit higher pulse velocity than the one with larger aggregate size. The higher pulse velocity indicates that, at the same mixed proportion, the concrete with smaller aggregate tends to be denser (less porous) than the one with larger aggregate. Porosity especially at the interface is caused partly by the mismatch between the elastic modulus of aggregate and cement matrix. When drying, this mismatch causes internal stresses and microcracking around the interfaces. For the concrete with larger aggregate, the effect of mismatch is more pronounced than for the concrete with smaller aggregate.

3.3 Effect of Fine/Coarse Ratio

Results on the effect of F/CR ratio are shown in Fig. 5 to 7 at two different time frames (6 hours and 24 hours). During the first 6 hours, the fine/coarse aggregate (F/CR) ratios do not appear to have any significant effect on the pulse-time curves. The times of slope change (initial setting) are found at 120 minutes for all types of concrete. The rates of change (slope) after the initial set are also in same range of about 10.5 to 11.5 (Fig. 6).

The effect of F/CR ratio begins to take place after 6 hours, as seen by the separation of the curves (Fig. 7). After 6 hours, all concrete begin to enter the 3rd stage, without much physical change inside the concrete, the pulse velocities become constant. The 24-hr pulse velocity of M25(50/50) is found to be the lowest among the three of them. The highest pulse velocity is found at the F/CR ratio of 30/70 which implies that the highest density is obtained with F/CR ratio of 30/70.

3.4 Effect of Curing Temperature

In the case of the temperature, the tests are carried out in a controlled chamber at four different

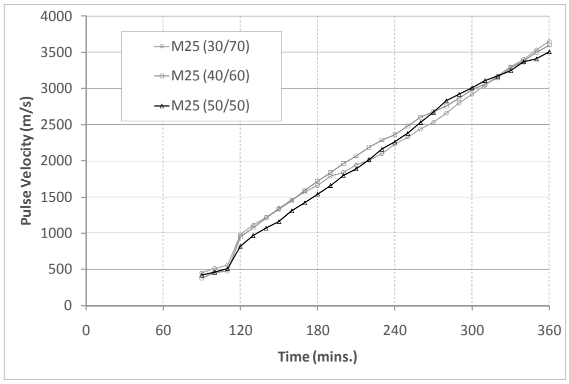

Figure 5 Variations of ultrasonic pulse velocity of concrete with different F/CR ratios (6 hours).

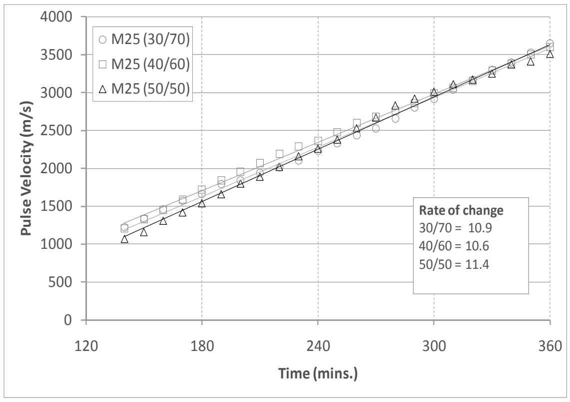

Figure 6 Rate of change during the first 6 hours.

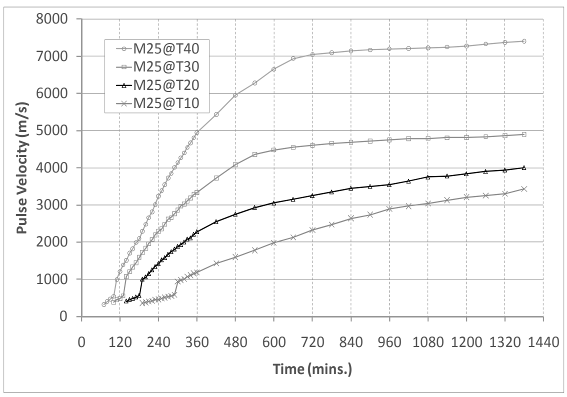

Figure 7 Variations of ultrasonic pulse velocity of concrete with different F/CR ratios (24 hours).

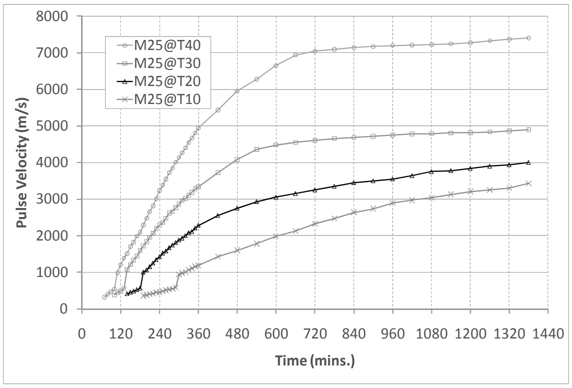

Figure 8 Effect of temperature on the variations of ultrasonic pulse velocity.

temperatures: 10, 20, 30 and 40^{o}C for 24 hours. Results show that the temperature has a significant effect on the pulse-time curves on several aspects (Fig. 8). First, with decreasing temperature, the duration of the stage I is increased longer and the point of the slope change (which is defined as the initial setting time) is found to shift forward (slow down). At temperature of 40^{o}C, the initial setting is measured around 110 minutes. As the temperature is decreased to 30, 20 and 10^{o}C, the initial setting time increases to about 140, 190 and 300 minutes, respectively.

Secondly, the temperature also affects the pattern of change on the stage II as seen by the decreasing rate of change (slope) of the curve with the decreasing temperature. The decreasing slope implies that the rate of hydration and also the setting process are slowing down. The decreasing temperature also extends the hardening stage (3rd stage) further away. When cured at temperature of 30 and 40^{o}C, the beginning of the 3rd stage is found at about 600 minutes, with the temperature lowering to 10 and 20^{o}C, the hardening stage is extended beyond 24 hours.

4. Conclusions

The maximum size (MSA) and the content of coarse aggregate (F/CR ratio) appear to have no effect on the change of the ultrasonic pulse velocity of fresh concrete during the first 3 to 6 hours (Stage 1 and 2). As the concrete enters the 3rd stage (hardening), both MSA and F/CR begin to play an important role on the rate of change and the final pulse velocity (24-hr pulse velocity). Concrete with smaller MSA appears to have higher 24-hr pulse velocity value. For the mixed proportion used in this study, the F/CR ratio of 30:70 gives the highest 24-hr pulse velocity.

On the effect of temperature, decreasing temperature seems to slow down the setting process of concrete as seen by the increasing initial setting time (time of slope change), the decreasing slope and the extended beginning of the 3rd stage.

5. Acknowledgement

The authors would like to thank Thailand Research Fund on TRF-MAG program for providing financial support for this study. Also, thanks to Prof. Somnuk Tangtermsirikul for his advices during the experiment.

References

[1] J. Keating, D.J. Hannant, and A.P. Hibbert, “Correlation between Cube Strength, Ultrasonic Pulse Velocity and Volume Change for Oil Well Cement Slurries,” *Cement and Concrete Research*, vol. 19, pp. 715– 726, 1989.

[2] S. Popovics, R. Silva-Rodriguez, J.S. Popovics, and V. Martucci, *Behavior of ultrasonic pulses in fresh concrete, New Experimental Techniques for Evaluating Concrete Materials and Structural Performance*, SP- 143, ACI, Detroit, MI, USA,

1993, pp. 207–225.

[3] A. Boumiz, C. Vernet, and F. Cohen Tenoudjif, “Mechanical Properties of Cement Pastes and Mortars at Early Ages Evolution with Time and Degree of Hydration,” *Advanced in Cement Based Material*, vol. 3, pp. 94-106, 1996.

[4] T. Ozturk, J. Rapoport, J.S. Popovics, and S.P. Shah, “Monitoring the Setting and Hardening of Cement-based Materials with Ultrasound,” *Concrete Science and Engineering,* vol. 1, no.2, pp 83-91, 1999.

[5] H.-W. Reinhardt, C. GroBe, and A., Herb, “Ultrasonic Monitoring of Setting and Hardening of Cement Mortar - a New Device,” *Materials and Structures*, vol. 33, no. 233, pp. 580-583, 2000.

[6] Y., Akkaya, T. Voigt, K.V. Subramaniam, and S.P. Shah, “Nondestructive Measurement of Concrete Strength Gain by an Ultrasonic Wave Reflection Method,” *Materials and Structures / Matdriaux et Constructions*, vol. 36, pp 507-514, October 2003.

[7] H.W. Reinhardt and C.U. Grosse, “Continuous Monitoring of Setting and Hardening of Mortar and Concrete,” *Construction and Building Materials*, vol. 18, pp. 145–154, 2004.

[8] H.K. Lee, K.M., Lee, Y.H. Kim, H. Yim, and D.B. Bae, “Ultrasonic In-situ Monitoring of Setting Process of High-Performance Concrete,” *Cement and Concrete Research*, vol. 34, Issue 4, pp. 631-640. April 2004.