

Application of Ultrasonic Testing Technique to Evaluation of Strength Development in Early Age Mortars

Abid A. Shah, and Yousef A. Al-Salloum

Abstract— This research consists of the usage of ultrasonic through transmission and wave reflection methods in evaluating the hydration reaction process of early age mortars with three different w/c. The acoustic wave characteristics were continuously monitored and compared with the strength development provided by the standard penetration resistance test. The experimental results reveal that the ultrasonic wave velocity and reflection coefficient have a strong linear relationship with the strength development in a log-log coordinate. Additionally, an abrupt increase in the wave velocity and frequency amplitude may be utilized as a tool to indicate an onset of the strength in the fresh mortars.

Index Term— mortar, penetration resistance, reflection coefficient, ultrasonic, velocity.

I. INTRODUCTION

WHEN cement is mixed with water, the constituents of chemical compound in cement powder undergo a series of chemical reactions, causing the mixture to get harden. For workability of the cement mix, gypsum is usually added to cement clinker in order to regulate hydration reaction process. Consequently, the mixture maintains considerable plasticity for several hours after mixing. The temperature stays relatively constant during this period. At the end of this dormant period, the rate of hydration accelerates sharply. The initial set is obtained when the mixture is no longer workable. An increase in the mixture stiffness and temperature during the setting period corresponds to the hydration reaction between water and tricalcium silicate (C_3S). The hydration reaction process continues until the plasticity disappears. The final set occurs when the mixture can sustain some load. The hardening stage begins after the final set. The rate of hydration and temperature decrease during this stage; however, the mixture strength still develops continuously. An accurate evaluation of the initial and final setting times is essential to obtain an optimized time for formwork removal and for an assessment of concrete quality. The American Society of Testing and Materials (ASTM C 403) provides a standard testing procedure for determining the initial and final setting times of fresh mortar and concrete [1]. The initial and final sets are defined as the times when the resistances of the

mortar to penetration by standard needles are equal to 3.5 and 27.6 MPa, respectively. While the penetration resistance test can be utilized to evaluate the strength development, the procedure does not, however, provide physical properties of the mixture. Several investigations have been performed to use ultrasonic testing techniques to evaluate the setting times and the quality of concrete mixture [2], [3]. However, a reliable evaluation procedure has not been established.

This study is, therefore, aimed to investigate the potential benefits of using ultrasonic testing techniques as a tool to evaluate the hydration reaction process in the early age mortars. The ultrasonic wave measurements were performed on the mortars with various water-cement ratios. The acquired data were compared with the strength development evaluated using the standard penetration resistance test.

II. ULTRASONIC MEASUREMENTS

Numerous attempts have been made to use ultrasonic testing techniques to assess the compressive strength and quality of cement-based material. Among these techniques, an application of the through transmission and wave reflection measurements was investigated in the present study.

A. Through Transmission

The through transmission technique is conducted by locating two transducers in line on opposite sides of the specimen. The elastic stress waves are generated by an electro-acoustical transducer and propagate through the specimen. The pulses received by the second transducer are converted into electrical energy, and the transit time is determined. The ultrasonic pulse velocity can then be calculated from a known distance between the two transducers and the transit time. The ultrasonic pulse velocity correlates with the material properties; therefore, it is generally used to imply the compressive strength and quality of the testing material.

Based on the theory of wave propagation, the ultrasonic pulse velocity (C_p) can be written as ASTM C 597 [4]:

$$C_p = \sqrt{\frac{E(1-\nu)}{\rho(1+\nu)(1-2\nu)}} \quad (1)$$

where E is the modulus of elasticity, ρ is the mass density, and ν is the Poisson's ratio of the material. Although the ultrasonic pulse velocity is expressed as a function of material constants in the equation, the experimental results indicate that

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the measured wave velocity is influenced by many factors such as temperature, humidity, size and shape of the specimen [5]. Therefore, the assessment of compressive strength is usually obtained with the help of a calibration curve for a given concrete.

B. Wave Reflection

The wave reflection technique is based on a measurement of the wave amplitude reflected at an interface of two media. When the direction of the ultrasonic wave propagation is normal to the interface, some ultrasonic energy is transmitted through the boundary and some is reflected. The amplitude of the reflected wave depends upon the acoustic impedance (Z), defined for each material as:

$$Z = \rho C_p \quad (2)$$

Table I provides the density, wave velocity, and acoustic impedance of materials commonly used in ultrasonic testing. The amplitude ratio between the incident and reflected waves can be represented by the reflection coefficient as:

$$R = \frac{A_{\text{Reflected}}}{A_i} = \frac{Z_2 - Z_1}{Z_2 + Z_1} \quad (3)$$

where R is the wave reflection coefficient, $A_{\text{reflected}}$ and A_i are the amplitudes of the reflected and incident waves, Z_1 is the acoustic impedance of the region in which the wave is approaching the interface, and Z_2 is the acoustic impedance of the region beyond the interface.

It is obvious from the expression that the negative sign of the reflection coefficient is obtained when ultrasonic wave propagates from a high impedance material to one of a lower impedance. This negative sign indicates the change in phase for the reflected wave.

TABLE I
DENSITY, WAVE VELOCITY, AND ACOUSTIC IMPEDENCE OF AIR, WATER, ACRYLIC, AND STEEL (BRAY AND STANLEY 1997) [6]

Material	Density ($\text{kg/m}^3 \times 10^3$)	Wave Velocity (m/s)	Acoustic Impedance ($\text{kg/m}^2\text{s} \times 10^6$)
Air	0.0012	330	0.0004
Water	1	1483	1.5
Acrylic	1.18	2730	3.2
Steel	7.7	5900	45

III. EXPERIMENTAL PROCEDURE

Three batches of mortar with of w/c 0.4, 0.5, and 0.6 were prepared for ultrasonic wave measurements and standard penetration resistance test. Each batch was mixed with ordinary Portland cement and a sand-to-cement ratio of 2. The freshly mixed mortar was placed into a standard 150×300 mm cylindrical mold for the penetration resistance test and a 150×150×150 mm acrylic mold for ultrasonic testing. The penetration resistance test was conducted in accordance with ASTM C 403 [1]. The test was first performed at three and a half hours after the initial contact was made between cement and mixing water. The readings were obtained with a 30-minute interval until at least one penetration resistance of greater than or equal to 27.6 MPa was obtained.

Fig. 1 shows the experimental setup for the ultrasonic testing. Two ultrasonic transducers with a central frequency of 500 kHz were located in line on opposite sides of the acrylic mold. The RITEC diplexer was employed to provide the ability to conduct both through transmission and wave reflection measurements at the same time. In parallel to the ultrasonic testing, the heat evolution inside the specimen was monitored by thermocouple placed at the mid-depth of the specimen. The measurements were performed for the first 12 hours after mixing. The interval for data collections was set to 30 minutes.

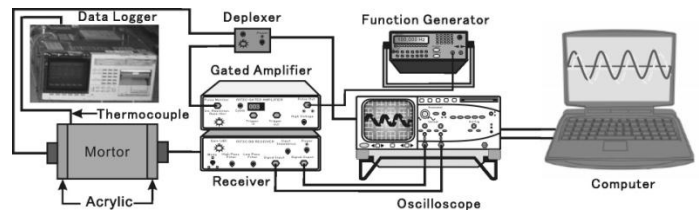
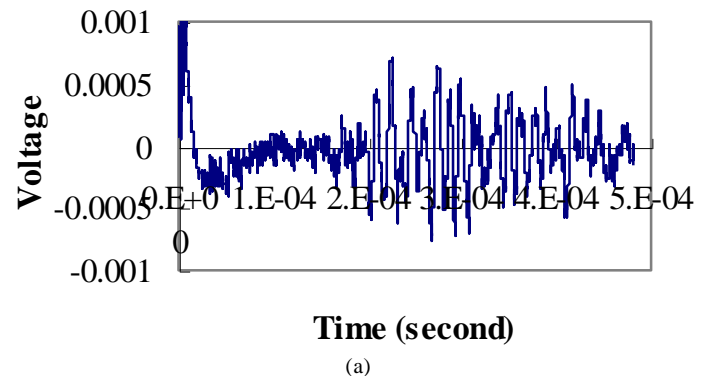


Fig. 1. Experimental setup

IV. EXPERIMENTAL RESULTS

The ultrasonic waveforms recorded using through transmission and wave reflection measurements are presented in Figs. 2 and 3. A high attenuation of the ultrasonic waves in the through transmission measurement was observed for several hours after the initial contact of cement and water, while the mortars still had considerable plasticity. Consequently, the first arrival time of the ultrasonic pulse waves cannot be accurately determined during this period. Nonetheless, as the mortars become hardened, a high signal-to-noise ratio of the ultrasonic waveforms is obtained. The arrival time can be accurately estimated at this stage. In contrast to the through transmission measurement, the reflected wave amplitudes during the initial period of hydration were found to be higher than those obtained after a substantial stiffness was developed in the mortars, as shown in Fig. 3. Additionally, the phase change of the reflected waves at different stages of hydration can be clearly observed in the fig.. This is due to a substantial increase in the acoustic impedance of the mortars as they transform from a suspension system to a porous solid material.



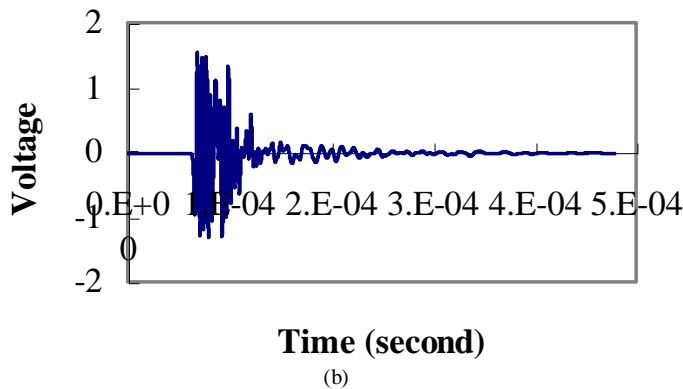


Fig. 2. Waveforms obtained from through transmission measurement on 0.5-w/c mortar (a) 1 hours after mixing, and (2) 12 hours after mixing

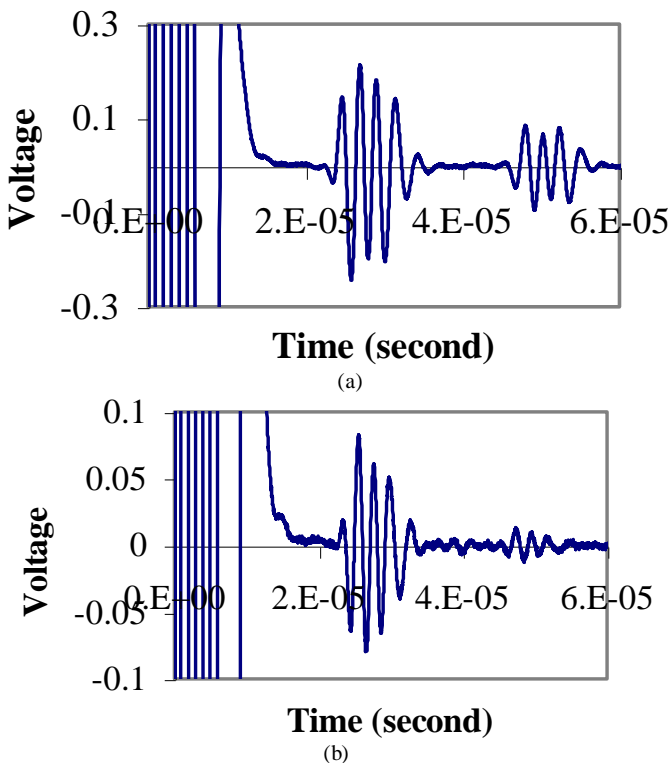


Fig. 3. Waveforms obtained from wave reflection measurement on 0.5-w/c mortar (a) 1 hours after mixing, and (2) 12 hours after mixing

Fig. 4 graphically presents the experimental results of the mortar with w/c equal to 0.5. The results reveal that during the initial period of hydration, the ultrasonic wave velocity is relatively low and slowly increasing. An abrupt increase in the ultrasonic wave velocity occurs at several hours after mixing when certain strength is developed in the mortar. The results indicate that the through transmission measurement does not provide sufficient sensitivity to the change in mechanical properties of the fresh mortars during the initial period of hydration; however, it may be used to evaluate an onset of the strength development in the specimen.

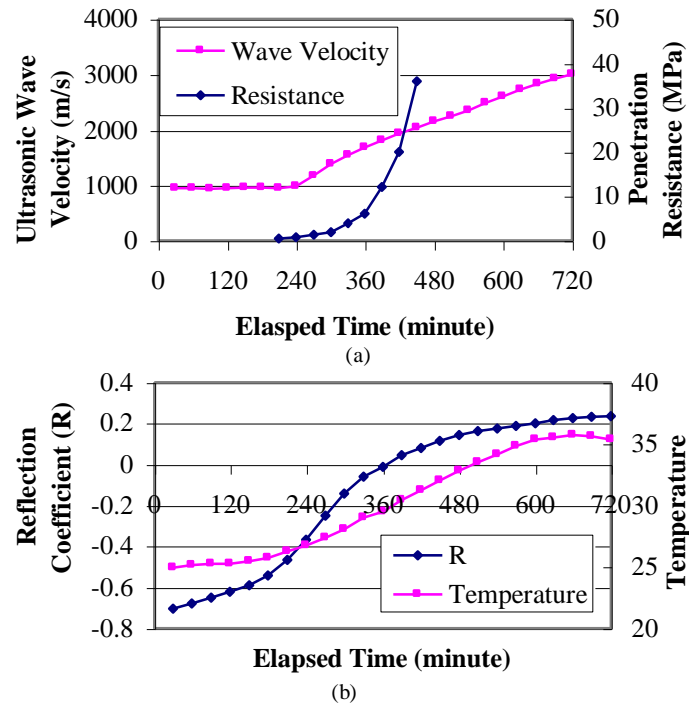
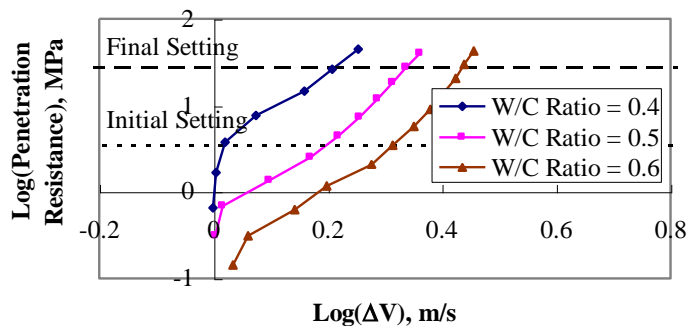


Fig. 4. Experimental results of 0.5-w/c mortar (a) relationship between wave velocity and penetration resistance with elapsed time, and (2) relationship between reflection coefficient and temperature with elapsed time

To calculate the reflection coefficient, the first reflected pulse wave in the time domain recorded at each time interval was transformed into the frequency domain using a fast Fourier transform (FFT) algorithm. The frequency amplitude of the waveforms at 500 kHz, corresponding to a central frequency of the transducers, was determined. The value of this amplitude is, however, affected by signal losses of the ultrasonic waves in the acrylic mold and a reflection coefficient at the interface of the mold and mortar. To eliminate the effect of the signal losses from the calculation, the frequency amplitude of the reflected wave at 500 kHz was determined for the empty mold. A reflection coefficient can be obtained from a ratio of the frequency amplitudes obtained from the mold filled with mortar and the empty mold.

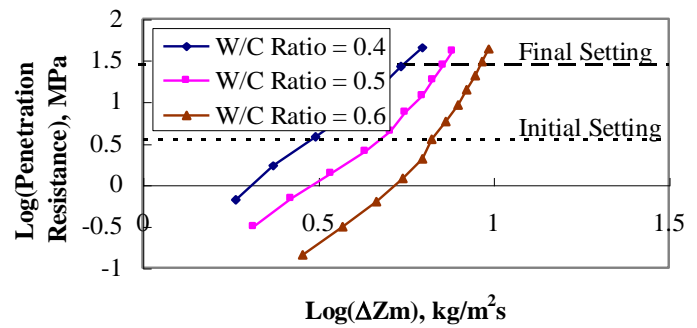
The reflection coefficient was found to be gradually increasing with time, as shown in Fig. 4. The results correspond to the heat evolution developed in the specimen. This suggests that the wave reflection coefficient is sensitive to the kinetics of hydration reaction. It should be mentioned that the negative sign of the reflection coefficient in the fig. indicates a lower value of acoustic impedance for the fresh mortars than the value of the acrylic plate.

To investigate the possibility of using the ultrasonic wave velocity in strength assessment of fresh mortars, the relationship between the two parameters was examined. Fig. 5 presents the relationship between the logarithms of the change in ultrasonic wave velocity and the penetration resistance.

Fig. 5. Relationship between penetration resistance and ΔV

The parameter $\text{Log}(\Delta V)$ used in the fig. is the difference between the logarithms of the wave velocity at a given time and the value corresponding to the initial period of hydration. The wave velocity at the elapsed time of 30 minutes was selected in the present study. It should be noted that the change in the wave velocity is not sensitive to this selected time because the velocity stays relatively constant for several hours after mixing. The fig. reveals that the penetration resistance and the change in wave velocity tend to have a linear relationship in a log-log coordinate after a certain amount of strength developed in the specimens. Using a linear regression analysis on the two parameters after the initial set, the coefficient of correlations in a range of 0.993 and 0.998 were obtained. Additionally, a significant increase in the wave velocity at the initial and final sets was observed for the mortar with a high value of w/c. This indicates a substantial change in the mechanical properties of the mixture at the setting times.

In addition, the relationship between the strength development in fresh mortars and the acoustic impedance was investigated. The change in the acoustic impedance of the mortars is compared to the strength development provided by the penetration resistance test in Fig. 6. The parameter $\text{Log}(\Delta Z_m)$ is the difference between the logarithms of the acoustic impedance at a given time and the value corresponding to the initial period of hydration. Similar to the change in the wave velocity, the acoustic impedance at the elapsed time of 30 minutes was used in the calculation. The results indicate a strong linear relationship between the penetration resistance and the change in the acoustic impedance in a log-log coordinate. The coefficient of correlations between these two parameters were found to be in a range of 0.965 and 0.997. Additionally, a higher value of the w/c ratio corresponds to a greater increase in the acoustic impedance at the initial and final setting times. The results obtained from the ultrasonic testing suggest that the ultrasonic wave characteristics may be used as a tool to evaluate the physical change developed in the fresh mortars.

Fig. 6. Relationship between penetration resistance and ΔZ_m

V. FREQUENCY ANALYSIS

The time-domain waveforms collected from the through transmission measurement were transformed into the frequency domain by using the fast Fourier transform to investigate an attenuation behavior of the fresh mortars. Fig. 7 presents the amplitude spectra of the ultrasonic pulse wave generated from the transmitter and the waveforms obtained from the receiver in the through transmission measurement of the 0.5-w/c mortar. The transmitted wave has a central frequency of 500 kHz with the three following peaks of 276, 720, and 136 kHz, respectively. Fig. 7b indicates a high attenuation of the ultrasonic waves for frequencies greater than 200 kHz. Accordingly, although the central frequency of the transmitted wave is equal to 500 kHz, a low frequency range is more pronounced in the amplitude spectra for all w/c.

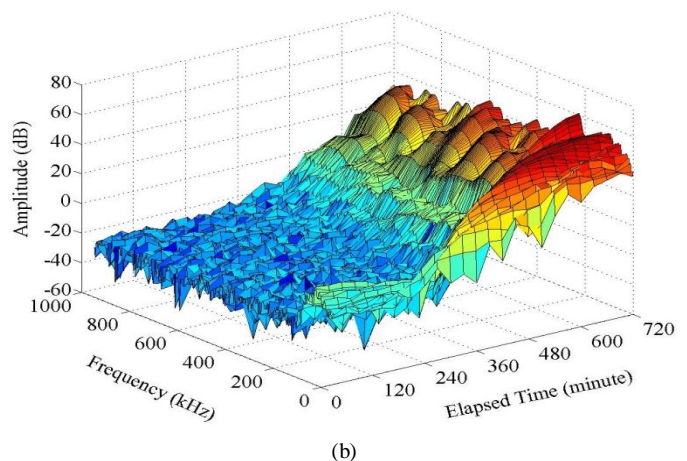
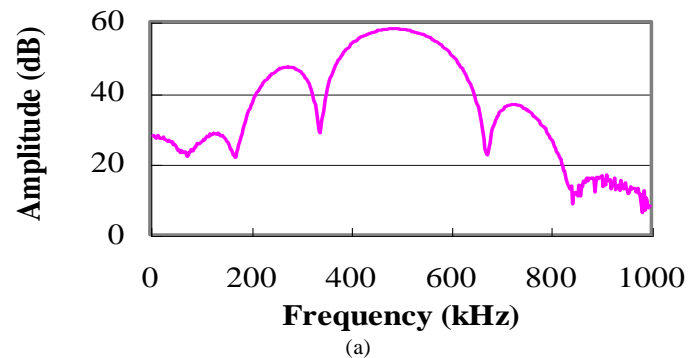


Fig. 7. Amplitude of waveforms obtained from through transmission measurement of 0.5-w/c mortar in frequency domain (a) wave generated from transmitter, and (b) waves obtained from receiver

To provide intuitive information on the relationship between the strength development and the frequency amplitude, variations of the two parameters with elapsed time are examined and graphically depicted in Fig. 8. The amplitudes corresponding to the frequency of 136 kHz were used in the fig.. For all w/c, the frequency amplitudes are relatively constant when slight strength is developed in the specimens.

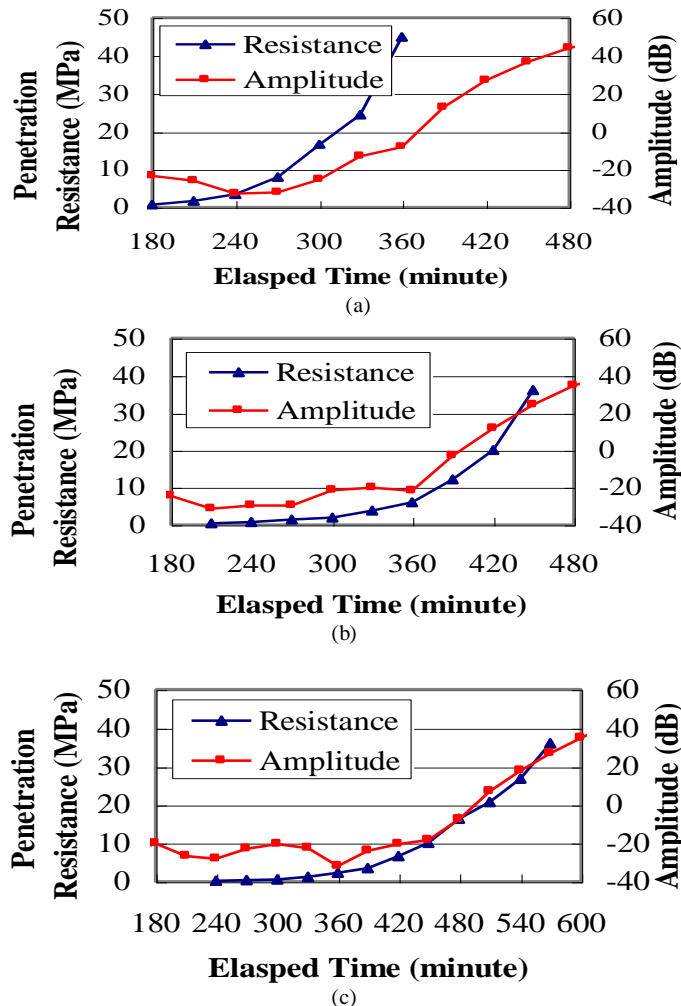


Fig. 8. Comparison of penetration resistance and waveform amplitude at 136 kHz obtained from through transmission measurement (a) w/c = 0.4, (b) w/c = 0.5, and (c) w/c = 0.6

However, the frequency amplitude starts to increase considerably after a penetration resistance of 10 MPa is obtained. The results suggest that an increase in the amplitude of the low frequency range may be used to evaluate a strength development in the fresh mortars.

VI. CONCLUSIONS

Two different ultrasonic testing techniques for evaluating the strength development in early age mortars were investigated in the present study. The experimental results reveal the strong relationship between the ultrasonic wave characteristics and the penetration resistance. Additionally, an increase in the ultrasonic wave velocity provided by the through transmission measurement and a decrease in the degree of attenuation in a low frequency range may be employed to indicate an onset of the strength development. Meanwhile, the reflection

coefficient is sensitive to the physical change of the fresh mortars. The results indicate a promise of using the ultrasonic testing techniques to evaluate the strength development in the early age mortars.

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