Factors Affecting the Monitoring of the Early Setting of Concrete by Ultrasonic P-Waves

N. Robeyst, C.U. Grosse and N. De Belie

Abstract Ultrasonic P-wave measurements are widely used to monitor concrete setting. Although the largest wave velocity increase occurs during setting, the earliest increase is rather caused by other factors. Air bubble migration, internal settling, formation of ettringite and early C-S-H, workability loss and thixotropy might affect the velocity change in time. Tests on mortar in which cement was replaced by bentonite, confirmed the possible influence of thixotropy on the measurements. The effect of air bubble migration, internal settling and workability loss was proven to be restricted by testing a mixture in which the cement was replaced by inert material. In a cement mixture, the precipitation of hydration products might however accelerate settling and workability loss. During cement hydration simulations, the change in porosity due to the formation of early C-S-H and ettringite was considered for the calculation of the elastic properties of the granular framework. Nevertheless, the calculated velocity hardly increased before percolation and thus could not confirm that the first velocity increase is attributed to formation of early hydration products. Thus, apart from thixotropy, none of the other factors could unarguably be indicated as the cause of early velocity increase.

Keywords Concrete • Early setting • Monitoring • P-waves • Ultrasound

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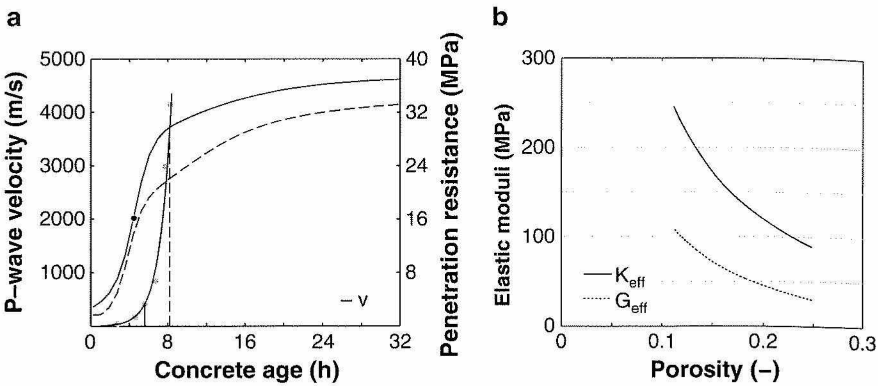

Fig. 1 (**a**) P-wave velocity of concrete (—), mortar (--) and penetration resistance (•); (**b**) Effective elastic bulk modulus K_{eff} and shear modulus G_{eff} of the solid framework vs. porosity for fresh mortar (water-to-binder w/b = 0.5)

Introduction

The setting of concrete and other cement-based materials can be measured by ultrasonic P-wave measurements [1, 2]. The largest velocity increase occurs during setting, when the cement hydrates start to percolate and form complete pathways of connected particles [3]. Nevertheless, the earliest increase is rather caused by other factors than by setting. During calorimetric measurements, a clear dormant period is observed, which would also be expected during the ultrasonic measurements. In addition, comparison with the traditional penetrometer or Vicat needle, demonstrated that the P-wave velocity starts to increase before the penetration resistance starts to develop (Fig. 1a) [2]. Thus, a good identification of the factors affecting the earliest ultrasonic signals benefits the correct interpretation of the velocity curves.

Literature Review

Robeyst *et al.* [2] described fresh mortar or concrete as water-saturated porous solid. To calculate the initial velocity, the theory of Biot was applied. In this case, the wave velocity can be written as shown in Equation (1)

$$V_P^{\,2} = \beta \cdot \frac{K + \frac{4}{3}G + \frac{K_f\left(K_s - K\right)^2}{K_f\left(K_s - K\right) + K_s\left(K_s - K_f\right)n}}{\left(1 - n\right)\rho_s + n\rho_f} \qquad (1)$$

with porosity *n*, bulk and shear modulus of the granular framework *K* and *G* and bulk modulus of the solid and fluid phase K_s and K_f. The coefficient β depends on the frequency regime [2]. In the fresh state, the solid frame consists of packed sand and cement with a bulk modulus K of 89 MPa.

Air bubble migration

According to Ye [3], the migration of air bubbles to the surface due to bleeding contributes to the early increase in the measured ultrasonic P-wave velocity. The initial value of the ultrasonic P-wave velocity is lower than the values measured on water due to this entrapped air which decreases the bulk modulus of the fluid phase K_f significantly [2]. These air bubbles escape under the force of buoyancy when the aggregate particles move during placing and compaction. Bleeding water drags air bubbles with it. This effect is however mainly restricted to the first minutes after placing so that the corresponding air loss cannot explain the large increase in velocity. In addition, until cement setting, the smaller air bubbles dissolve into water, while larger bubbles increase in size because of air release from the saturated water. The result is an increase in air content of the concrete and a decrease of the specific area of the bubbles [4]. This process might change the tortuosity and low-frequency resonant scattering of the air bubbles. However, it has not been proven that this will increase the velocity and decrease the attenuation.

Internal settling or consolidation, and workability loss

According to [5], internal settling or consolidation causes the very early increase in P-wave velocity. Due to gravity, heavier aggregate particles tend to sink (segregation) and water appears at the surface (bleeding). Internal settling densifies the internal structure and causes a better mechanical coupling of the particles. According to Dvorkin's uncemented sand model, the effective value of the bulk and shear modulus, indicated with K_{eff} and G_{eff}, will increase with decreasing porosity according to Eq. (2) [6]. The quantities in these equations are porosity n, initial porosity n_0, bulk and shear modulus of the granular framework K and G (corresponding with n_0) and bulk and shear modulus of the solid phase K_s and G_s. Figure 1b shows the change of the effective moduli in function of the porosity for the fresh mortar mixture. According to simulations with CEMHYD3D, the porosity of a mixture with OPC decreases from 0.25 to 0.16 during the first 2 d. Although the bulk modulus of the granular framework clearly increases with decreasing porosity, the P-wave velocity is also determined by the bulk modulus of the fluid phase K_f according to Eq. (1).

Freshly mixed concrete stiffens with time even before setting. Some amount of mixing water is absorbed by the unsaturated aggregate, lost by evaporation and

$$K_{eff}(n) = \left[\frac{n/n_0}{K + 4/3G} + \frac{1 - n/n_0}{K_s + 4/3G} \right]^{-1} - \frac{4}{3}G \quad (2a)$$

$$G_{eff}(n) = \left[\frac{n/n_0}{G + G/6 \cdot (9K + 8G)/(K + 2G)} + \frac{1 - n/n_0}{G_s + G/6 \cdot (9K + 8G)/(K + 2G)} \right]^{-1} - \frac{G}{6}\left(\frac{9K + 8G}{K + 2G} \right) \quad (2b)$$

Ettringite and early C-S-H hydration products

According to [7], ettringite is formed during the first 3 h of cement hydration. These ettringite needles have merely a small influence on the stiffening of the cement paste. However, the P-wave velocity and energy might be strongly affected, since ettringite fills pore space. Consequently, the porosity n decreases, the bulk moduli K_{eff} and G_{eff} of the solid framework increase and the velocity increases. Kamada *et al.* [8] demonstrated for high-early strength cement that the formation of ettringite coincides with the early increase in ultrasound velocity; although ettringite formation was limited ($C_3A < 5\%$), also the earliest C-S-H hydration products can contribute to the velocity increase before setting.

Thixotropy

Some mortar mixtures exhibit thixotropic behaviour: they flow during mixing and placing, but become rigid at rest. Thixotropy is attributed to inter-particle forces. Each particle has an equilibrium position for which the potential energy due to colloidal interactions is minimum. Only particles smaller than 40 μm are influenced by potential energy effects. These particles can coagulate reversibly or permanently by combined van der Waals forces, electrostatic repulsion and steric hindrance. After placing the concrete, the reversible particle coagulation and linking will increase the velocity, before setting occurs. However, since coagulation is considered as the first step in the setting process, the distinction between thixotropic and setting behaviour might be unclear.

Materials and Methods

Specific gravity of CEM I 52.5 N, quartz and bentonite was 3.12, 2.65 and 2.15, while Blaine specific surface area amounted to 390, 355 and 810 m²/kg. Ultrasonic P-wave transmission measurements on mortar (w/b = 0.5; s/b = 3) were performed at 20°C with the FreshCon [1], using broadband transducers with central frequency of 0.5 MHz. The velocity v is calculated and the energy E is determined by integration of squared amplitude values following the onset time. The energy ratio E/E_{ref} (E_{ref} measured on water), allows to eliminate energy loss due to divergence and reflection at interfaces. To simulate the early microstructure development, the pixel model CEMHYD3D was used [9]. The chemical reactions of the mineralogical phases are simulated by cellular automaton rules, applied iteratively to all pixels comprising the microstructure [9]. The change in P-wave velocity was calculated based on the simulated porosity change by combining Eqs. (1) and (2).

Results and Discussion

Air bubble migration, internal settling and workability loss

Internal settling and migration of air bubbles were investigated by replacing the cement by non-reactive quartz filler in a standard mortar mixture (Fig. 2).

The particle size distribution of the latter was in the same range as the cement. The velocity increased from 240 to 285 m/s during the first 48 h and to 340 m/s after 70 h due to internal settling and air bubble migration. Analogously, the energy ratio increased from $1.17 \cdot 10^{-6}$ to $5.19 \cdot 10^{-5}$ during the first 48 h and to $2.71 \cdot 10^{-4}$ after 70 h. Though the effect of internal settling and bleeding seems to be limited, this process will be accelerated in mortar by the cement hydration and coagulation. Also workability loss was partly included in the experiment since mixing water was absorbed by the unsaturated aggregate. The water reduction by initial reactions was however not incorporated and evaporation was restricted by the sealing tape.

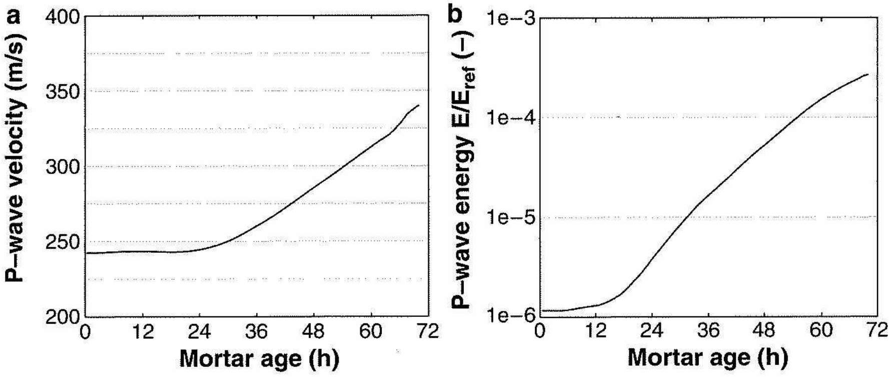

Fig. 2 Ultrasonic P-wave (**a**), velocity and (**b**) energy ratio vs. mortar age for a mortar mixture in which the cement was replaced by non-reactive quartz filler

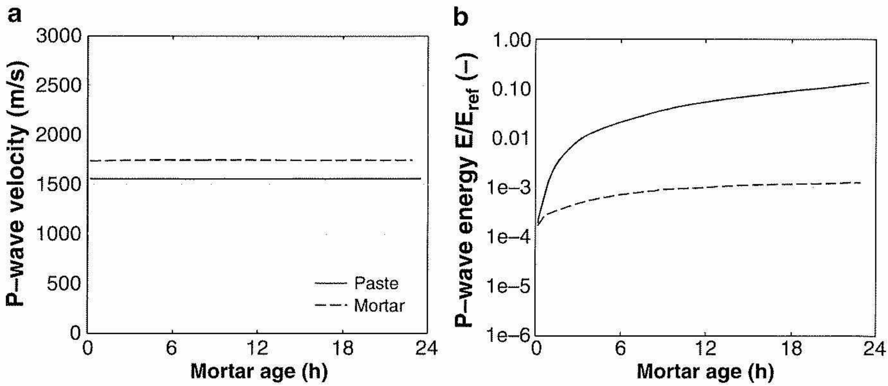

Fig. 3 Ultrasonic P-wave (**a**) velocity and (**b**) energy ratio vs. mortar age for a standard mortar mixture in which the cement was replaced by bentonite

Thixotropy

Thixotropic behaviour was simulated by testing a paste and mortar in which cement was replaced by bentonite (Fig. 3). Bentonite suspensions are thixotropic if the concentration is high enough (> 60 g/l). Due to the large specific surface area (810 m^2/kg), the water demand in a betonite paste is much higher than in a cement paste. Only the results of the first 24 h are presented in Fig. 3a, but the velocity did not increase during the first 72 h in both paste and mortar sample. The initial velocity is however immediately higher than the ones measured on the actual concrete and mortar samples. Probably, the reversible structure was formed too rapidly to be captured by the measurements. A significant further increase in wave energy ratio is noticed on the paste sample, but was not reproduced with the mortar (Fig. 3b). The initial value of the energy ratio is also higher than the commonly measured values (10^{-7} to 10^{-6}).

Ettringite and early C-S-H hydration products

The hydration of the cement paste was simulated with the CEMHYD3D model. Figure 4 shows the simulated velocity increase due to formation of ettringite and early C-S-H hydration products without considering setting. The change in elastic properties of the granular framework was calculated with Eq. (2) and (1) based on the changing porosity as indicated by the CEMHYD3D simulations due to the formation of hydrates, while the particles were not assumed to be connected with each other (no setting). The presence of air still dominated the calculated velocity so that it merely increased with 50 m/s during the first 24 h.

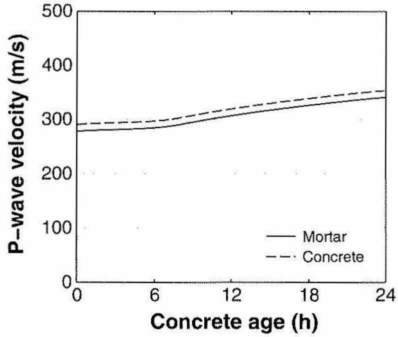

Fig. 4 Simulated velocity increase (CEMHYD3D) due to the formation of ettringite and early C-S-H hydration products without considering setting for a mortar and concrete mixture (w/b = 0.5) with OPC (CEM I 52.5)

Conclusion

Air bubble migration, internal settling and workability loss were proven to have a limited effect on the ultrasound velocity and energy. However, due to the precipitation of hydration products settling and workability loss might be accelerated. The modelled change in porosity due to formation of early C-S-H and ettringite hardly affected the calculated velocity. The possible influence of thixotropy was confirmed. However, not all concrete mixtures show thixotropic behaviour. None of the mentioned factors could unarguably be indicated as the cause of the early velocity and energy ratio increase. More likely, a combination of these factors affects the ultrasonic measurements.

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