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Comparison of ultrasonic wave reflection method and maturity method in evaluating early-age compressive strength of mortar

Thomas Voigt [a,*], Zhihui Sun [b], Surendra P. Shah [c]

[a] *USG Corporation, Research and Technology Innovation Center, 700 North Highway 45, Libertyville, IL 60048, USA*
[b] *University of Louisville, Department of Civil and Environmental Engineering, 112 W.S. Speed Hall, Louisville, KY 40292, USA*
[c] *Northwestern University, Center for Advanced Cement-Based Materials, 2145 Sheridan Road, Suite A130, Evanston, IL 60208, USA*

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Abstract

This paper focuses on the comparison between the ultrasonic wave reflection method and the widely known maturity method in their ability to evaluate compressive strength development of portland cement mortars. The experiments were conducted under laboratory conditions on cement mortars with different water–cement ratios (0.35, 0.5, 0.6) cured under different isothermal and non-isothermal conditions (15 °C, 25 °C, 35 °C, 15–35 °C). The results show that the application of the maturity method for accurate strength estimation requires the knowledge of the limiting strength of the mixture for the specific curing condition that is considered. It is not sufficient to base this estimation on the values of the limiting strength obtained from the calibration tests. The relationship between reflection loss and compressive strength was found to be independent of curing temperature. This finding is an important step towards establishing the wave reflection method as a non-destructive method for estimating early-age strength in cement-based materials.

Keywords: Nondestructive testing; Ultrasonics; Early-age properties; Cement hydration; Compressive strength; Maturity method; Cement mortar

1. Introduction

A significant amount of today's infrastructure incorporates concrete or similar cementitious materials. To meet the constantly increasing expectations of the user community, concrete structures are required to be highly serviceable and durable. This calls for concrete materials with consistent properties that can be adjusted to meet different criteria. The properties of concrete are solely determined by the composition of its ingredients, the mixing and placing process, and the conditions during the setting and hardening process. Damages and unintentional properties occurring to the concrete during this process are not, or only with great expense, repairable.

Concrete is also especially vulnerable during the period immediately following final setting, which is understood as the end of the concrete's transition from a fluid to a solid state. Concrete structures may be subjected to severe loading during construction. If early-age properties are not considered, this can lead to the failure of concrete elements, such as excessive floor sagging, or increased long term deflections.

It was shown, for example, by Gardner and Scanlon [1] that high construction loads applied to immature concrete slabs lead to large non-recoverable creep deflections that have a significant impact on the long term deflections of the structure. In several cases, excessive loading has lead to the total collapse of buildings during construction [2].

These circumstances emphasize the importance of the detailed knowledge of early-age concrete properties in structures under construction. Given this background, non-destructive test methods that can be applied to determine early-age concrete properties can be useful tools to ensure safety during construction.

This paper compares two such non-destructive test methods, the widely known and established maturity

* Corresponding author. Tel.: +1 847 970 5102; fax: +1 312 214 1466.
E-mail address: mail@tvoigt.com (T. Voigt).

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method and an emerging technology, the ultrasonic shear wave reflection method. The application of the maturity method for estimating early-age concrete strength has been investigated extensively by many researchers (e.g., [3–6]). The method has been proven to be very useful for field application because, after laboratory calibration, the only quantity needed for strength estimation is the easily measurable in situ temperature development of the concrete. However, the method suffers from one inherent limitation. If the early-age curing temperatures of the calibration and field concrete differ significantly, the maturity method cannot be applied for a reliable estimate of the absolute compressive strength of the field concrete [7]. Additionally, since the maturity method does not measure a physical or mechanical material property, it cannot give any information on how well the field concrete matches the concrete that was used to develop the strength–maturity relationship in the lab. Differences resulting from composition, handling, and/or curing remain undetected and impose inaccuracies on the estimated strength. Because of these and other limitations, the ‘‘Standard Practice for Estimating Concrete Strength by the Maturity Method’’, ASTM C1074 [8], requires that the maturity method is ‘‘to be supplemented by other indications of the potential strength of the concrete mixture’’.

The wave reflection (WR) method, which is the technique to be compared with the maturity method in this paper, follows a different approach. The measurements are conducted with shear waves, which yields test results that are directly related to a mechanical property of the concrete, the dynamic shear modulus. Extensive investigations have shown that the WR-method is a sensitive indicator of macroscopic parameters such as time of setting or compressive strength as well as microstructural characteristics such as capillary porosity, gel-space ratio, and degree of hydration [9].

It was shown that early-age reflection loss measurements on concrete and mortar are qualitatively and quantitatively comparable to those obtained with wave transmission measurements [10]. The wave transmission method that is referred to here was developed by Reinhardt and Grosse [11].

2. Experimental program

2.1. Wave reflection (WR) method

The wave reflection method used for the experiments described in this paper was introduced by Öztürk et al. [12] and Rapoport et al. [13]. The technique monitors the reflection loss of transverse or shear waves (S-waves) at the interface between a steel plate and the cementitious material over time. The decrease in wave amplitude depends on the reflection coefficient, which in turn is a function of the acoustical properties of the materials at the interface.

A schematic of this experimental technique is shown in Fig. 1. A steel plate is brought in contact with fresh mortar and a transducer with a frequency of 2.25 MHz, which is attached to the steel plate, transmits an S-wave pulse into the steel. When the mortar is in liquid state the pulse is nearly entirely reflected at the steel–concrete interface, since S-waves do not propagate in liquids (Fig. 1(a)). Depending on the viscosity of the tested material, a small fraction of the wave energy is transmitted over the interface. Thus, the reflection coefficient is close to unity. With subsequent hydration, the cement grains percolate and build up a rigid skeleton allowing the shear waves to propagate. This allows a portion of the shear waves to pass the interface resulting in losses during the reflection process (Fig. 1(b)). Consequently, the reflection coefficient starts to decrease. With further hydration, the ability of the mortar to transmit shear waves increases. More and more wave energy is transmitted into the mortar and the reflection coefficient decreases further. After a certain time, this process decelerates and the reflection coefficient approaches a final value. At this time, changes in the microstructure of the cement mortar due to hydration are too small to alter the shear wave propagation properties significantly.

In general, the reflection loss can be calculated from the amplitudes of two consecutive reflections from the steel–mortar interface with Eq. (1). The amplitudes (A_1 and A_2) can be determined from the representation of the reflections in time domain or in frequency domain. As an example, the time domain of received shear wave reflections

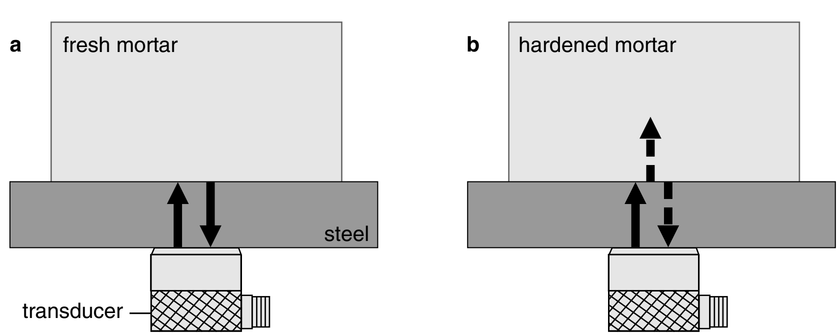

Fig. 1. Principle of wave reflection method: (a) complete wave reflection for fresh mortar; (b) partial wave reflection and transmission for hardened mortar.

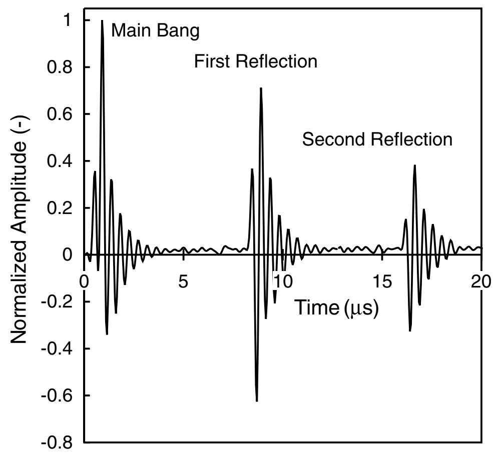

Fig. 2. Time domain of multiple reflection process of shear waves at a steel–concrete interface.

from an interface between a steel plate (thickness 12 mm) and mortar is shown in Fig. 2. The separation of the reflections in the time domain is about 8 µs for the given steel plate thickness. Each single reflection can be transformed into the frequency domain using a fast Fourier transform (FFT) algorithm, which is shown in Fig. 3. The reflections have their maximum amplitude at approximately 2.25 MHz, which corresponds to the center frequency of the used shear wave transducer. In both representations, the time and the frequency domain, the reduction of the amplitude of the reflections due to transmission losses at the steel–concrete interface can clearly be seen

$$r = \frac{A_2}{A_1} \tag{1}$$

The reflections shown in Figs. 2 and 3 include also amplitude losses due to transducer coupling and the attenuation of the waves when propagating through the steel plate. To eliminate those influences and isolate the reflection coefficient a procedure was developed by Öztürk et al. [12]. The procedure applied for the work presented in this paper used the amplitudes of the reflections derived from the frequency domain, but the calculations can also be applied to reflections represented in time domain. More details on the signal analysis are also given in Voigt et al. [14].

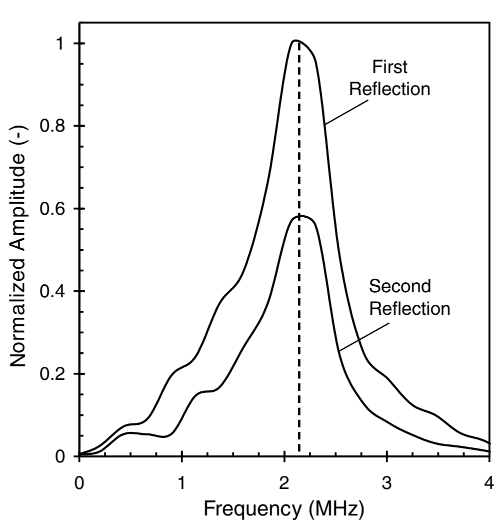

Fig. 3. Frequency domain of first and second reflections.

The reflection coefficient as calculated in Eq. (1) represents an amplitude ratio and describes the relative loss in amplitude between the first and second reflection at a given time t. In ultrasonics amplitude ratios are usually measured in decibel [15]. The reflection coefficient $r(t)$ expressed in decibel becomes the reflection loss $R_L(t)$. The conversion of r into R_L can be done with Eq. (2) with $R_L(t)$ as the reflection loss at time t and $r(t)$ as the reflection coefficient at time t

$$R_L(t) = -20\log[r(t)] \tag{2}$$

The experimental setup that is used to measure the reflection loss consists of a laptop computer, a pulser-receiver and a shear wave transducer. The shear waves are being sent and received by the same transducer and the reflections are recorded in regular time intervals (10 min). This results in a continuous measurement of the reflection loss.

Extensive experimental work has been conducted to evaluate the fundamental relationships among evolving microstructure, mechanical properties, and reflection loss measured with the WR-method. A wide range of material properties of different cement pastes, mortars, and concretes was evaluated by starting from phenomenological parameters, such as setting, and then moving to defined physical and physico-chemical properties, such as elastic moduli, degree of hydration, and porosity. To complement the experimental work, numerical models simulating cement hydration were employed.

The reflection coefficient, and by this also the reflection loss, at the interface is related to the acoustic impedance of the cementitious mixture, which is the product of density and shear wave velocity. The wave velocity is in turn a function of the shear modulus of elasticity. The shear modulus of elasticity increases with hydration. Therefore, any other property or characteristic that is related to degree of hydration will have a relationship with reflection loss.

The investigations have confirmed this general statement. It was shown that the measured reflection loss is closely related to setting, compressive strength [16,17]; dynamic shear modulus, degree of hydration, and gel-space ratio [9] as well as parameters describing the connectivity of the hydrating cement particles [18]. It was also demonstrated that the measured reflection loss can be used to determine rheological parameters, that is the dynamic viscosity, of the fresh cement paste [19]. In this case, the phase shift of the reflected signals and the reflection loss is evaluated.

The high potential of the wave reflection method for practical application was proven by first successful field tests that were conducted in a precast concrete plant [20]. The tests have shown, that even though the WR-method measures the properties of the material immediately next to the steel plate, the method can be used to follow the setting and hardening process of the bulk concrete in a structure. This can be accomplished by combining reflection loss readings with in-place temperature measurements at the steel plate and the bulk of the concrete member.

For the general practical application of the method it should be considered that the reflection loss is influenced by a number different physical parameters of the cementitious material. These parameters can be time dependent, that is, they change as a result of curing, or material specific, for example, a dense microstructure due to the addition of silica fume. These dependencies need to be investigated before applying the method.

2.2. Maturity method

The maturity method makes use of the combined effects of time and temperature on the strength gain of concrete. By knowing the age and the temperature history of the concrete an equivalent age value can be calculated which is, with some limitations, uniquely related to the concrete compressive strength. The equivalent age is the length of the curing period at a certain reference temperature that would result in the same maturity as the curing period at a given (variable) temperature.

One of the inputs for applying the maturity method is the in-place temperature history of the concrete. This can be obtained easily by embedding a thermocouple in the concrete member and recording the temperature. The second important input is the maturity function that accounts for the effect of time and temperature on the strength gain of the concrete. In this investigation, the equivalent age maturity function based on the Arrhenius equation has been used. The equivalent age t_e is calculated with Eq. (3), where E is the activation energy, R is the universal gas constant (8.315 J/mol K), T is the temperature in °C, T_r is the reference temperature in °C and Δt is the time interval during which temperature T was measured

$$t_e = \sum_0^t e^{\frac{-E}{R}\left[\frac{1}{273+T} - \frac{1}{273+T_r}\right]} \cdot \Delta t \tag{3}$$

An important parameter of the Arrhenius equation is the activation energy, which describes the temperature sensitivity of the initial rate constant. The activation energy depends on the chemistry and the fineness of the cement, and the amounts of mineral and chemical admixtures [21]. General rules were developed to estimate the activation energy that gives results with reasonable accuracy [22]. However, to maximize the accuracy of the maturity method the activation energy should be determined for each cementitious system in use by laboratory testing of appropriate mortar mixtures. This was done also for the investigations presented here. The guidelines given in ASTM 1074 [8] were followed and an activation energy value of $E = 38$ kJ/mol was determined.

To finally apply the maturity method to estimate compressive strength a relationship between compressive strength and equivalent age must be developed by laboratory testing as well. The hyperbolic function, which is given by Eq. (4), was used for this purpose

$$S = S_\infty \frac{k_r(t_e - t_0)}{1 + k_r(t_e - t_0)} \tag{4}$$

In Eq. (4), the parameters S and S_∞ are compressive strength and limiting compressive strength, respectively, k_r is the rate constant at the reference temperature, and t_0 is the age at which strength development is assumed to begin. The application of the maturity method to estimate in-place strength requires measurement of the in-place temperature of the concrete member to be tested. This temperature is used to determine the equivalent age, which in turn allows estimation of the compressive strength by using the predetermined strength–equivalent age relationship. This requires that the field concrete is identical to the concrete that was used for the laboratory testing. Furthermore, the field concrete must be cured properly, that is, moisture must be available to allow for hydration.

Additionally, Carino [7] points out that research has identified that the early-age temperature history affects long-term strength of a given concrete mixture. Since the long-term strength is a parameter of the strength–equivalent age relationship, this relationship cannot be considered to be unique. In other words, if the early-age temperature history of the field concrete differs significantly from that of the laboratory concrete, the maturity method produces erroneous strength estimates. This problem can be addressed by using a relationships to estimate the relative strength gain of the concrete. This, however, requires the application of additional techniques to estimate the absolute strength level of the concrete, which is most often of interest.

2.3. Materials and curing conditions

The experiments were conducted on mortars containing Type I portland cement type I and silica sand or natural river sand as fine aggregate. The mortars had three different water–cement ratios: 0.35, 0.5, 0.6. The mixture proportions of the mortars are given in Table 1.

The mortar specimens were cured isothermally at three different temperatures: 15 °C, 25 °C and 35 °C (mixtures A and C were cured at 25 °C only). Additionally, the mortar specimens with a water–cement ratio of 0.5 were also subjected to curing temperatures alternating between 15 °C and 35 °C. To maintain the curing temperature, the specimens were submerged in a water bath connected to a microprocessor controlled refrigerating/heating circulator. The circulator continuously adjusted the temperature of the circulating water to the respective values given in Table 1.

The investigations described in the following paragraphs were conducted on mortar because of the higher homo-

Table 1
Mixture proportions by mass of cement and curing conditions for tested mortars

Mixture	Cement	Water	Sand	Curing temperature (°C)
A	1	0.35	2[a]	25
B	1	0.50	2[b]	15, 25, 35, 15/35
C	1	0.60	2[a]	25

[a] Silica sand.
[b] Natural river sand.

geneity of this material compared to concrete. Experiments on concrete have shown a higher scatter in the data obtained from compressive strength and reflection loss measurements [17]. The application of the WR-method for concrete will be subject to future research.

3. Derivation of relationships between compressive strength, equivalent age, and reflection loss

3.1. Compressive strength development

The compressive strength development of the mortar mixtures was determined according to ASTM-Test Method C 109 [23]. Mortar cubes with the size of 50 × 50 × 50 mm were used for the compression tests. Depending on the water–cement ratio of the mortars, the tests were started between three and six hours after casting. Three specimens were tested at each age and the average strength was calculated. The age of strength testing did not extend beyond 7 days.

The compressive strength development of the mortars is shown in Fig. 4(a) and (b). The data in Fig. 4(a) show that the mortar cured at 35 °C has the lowest compressive strength at later ages, whereas the mortar cured at 15 °C exhibits the highest potential later age strength. This can be seen from the trends of the strength curves shown in Fig. 4(a) and the strength values at 28 days. This effect has been described earlier by Carino and Lew [24]. The data presented in Fig. 4(b) show the effect of water–cement ratio on the compressive strength development. As expected, the rate of early-age strength gain and the later age strength value is affected by the water–cement ratio.

3.2. Reflection loss development

The reflection loss development of the different mortar mixtures as measured with the WR-Method is given in Fig. 5. If the reflection loss curves in this figure are compared to the development of the compressive strength in Fig. 4(b), it can be seen that compressive strength and reflection loss exhibit similar trends with age. This confirms earlier research that found a close relationship between these two parameters for cementitious materials [9,17]. In the following sections, the reflection loss measurements will be taken as an indicator of compressive strength development of the mortars.

3.3. Temperature and equivalent age development

The application of the maturity method relies on measurement of the in-place temperature during hydration. The temperature development inside the isothermally cured mortar specimens is given in Fig. 6. The equivalent ages of the mortar specimens are calculated using these temperature profiles according to Eq. 3, and are plotted as a function of real time in Fig. 7. For the equivalent age calculations, the reference temperature was 25 °C and the activation energy was 38 kJ/mol. It is clear from Fig. 7 that at any given time the mortar cured at higher temperatures has a higher equivalent age.

3.4. Compressive strength–equivalent age relationship

The strength–equivalent age (S–t_e) relationship for the mortar was determined for curing under standard laboratory conditions. Fig. 8 shows the compressive strength versus equivalent age curves for the mortar mixtures cured at 25 °C. Also shown are the strength–equivalent age data for curing at 15 °C and 35 °C. Ideally, the data should fall close to a common curve, which is the case for temperatures of 15 °C and 25 °C. However, the curve for the curing temperature of 35 °C does not follow this trend.

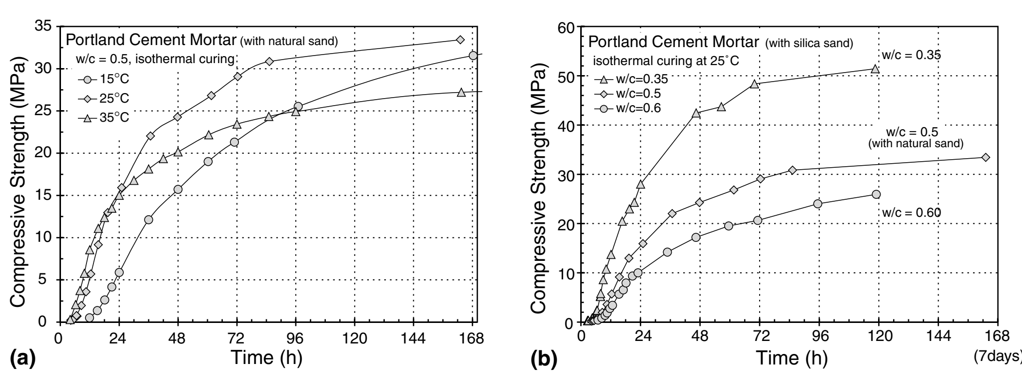

Fig. 4. Compressive strength development of mortars. (a) Influence of curing temperature ($w/c = 0.5$). (b) Influence of water–cement ratio (25 °C).

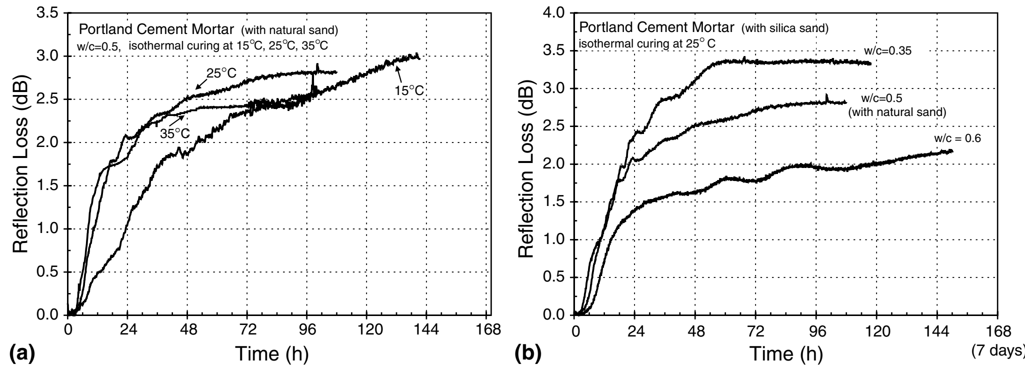

Fig. 5. Reflection loss measurements of mortars. (a) Influence of curing temperature ($w/c = 0.5$). (b) Influence of water–cement ratio (25 °C).

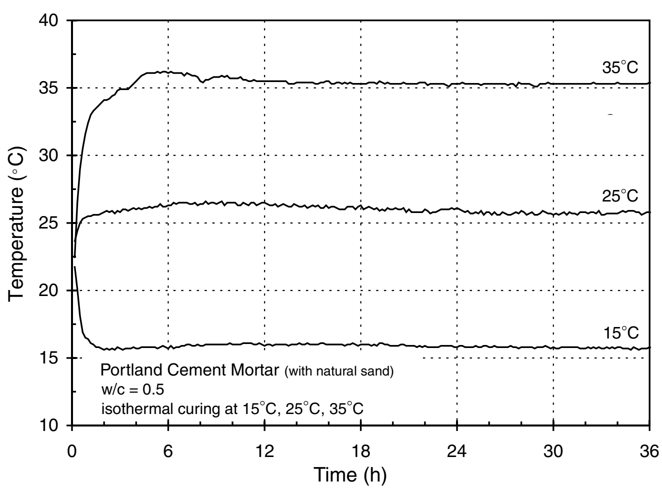

Fig. 6. Temperature development for mortar specimens.

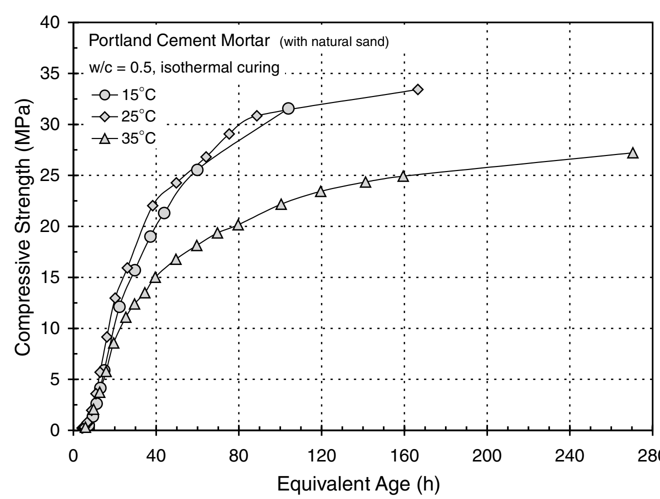

Fig. 8. Compressive strength development versus equivalent age at 25 °C.

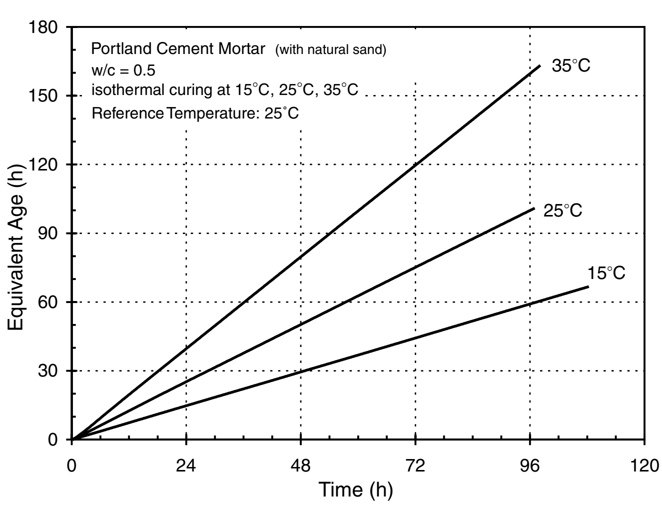

Fig. 7. Development of equivalent age at 25 °C with time for mortars tested at different temperatures.

This difference is due to the high early-age temperature of this particular mortar mixture, which reduces the limiting (final) strength. This demonstrates a major limitation of the maturity method. Because of the influence of the early-age temperature there is no unique strength–maturity relationship for a given mixture.

This phenomenon has been observed repeatedly and has been discussed in the literature. To mitigate the problem, Carino has suggested using the relative compressive strength gain instead of the absolute compressive strength values [6]. Fig. 9 shows the compressive strength development normalized with respect to the calculated limiting strength of the individual mortars. This procedure brings the three data sets closer to each other, and a single relationship between relative compressive strength and equivalent age can be determined. The general form of this relationship is given in Eqs. (5) and (6), where k_r is the rate constant of relative compressive strength development. The relationship between relative compressive strength and equivalent age derived from the data in Fig. 9 is given by Eq. (6):

$$\frac{S}{S_\infty} = \frac{k_r(t_e - t_0)}{1 + k_r(t_e - t_0)} \tag{5}$$

$$\frac{S}{S_\infty} = \frac{0.025(t_e - 8)}{1 + 0.025(t_e - 8)} \tag{6}$$

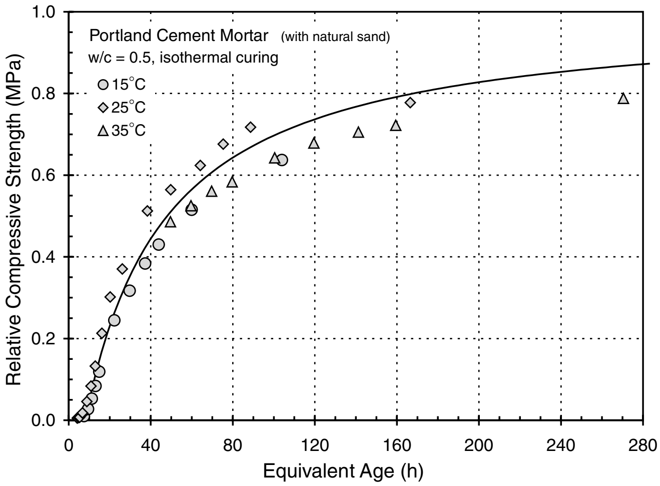

Fig. 9. Relative compressive strength versus equivalent age at 25 °C.

The use of the relative strength vs. equivalent age relationship implies that it is not sufficient to measure only the in-place temperature for an accurate estimate of the absolute compressive strength. In order to do so, additional information is necessary.

3.5. Compressive strength–reflection loss relationship

To apply the WR-method for estimating in-place compressive strength, the relationship between compressive strength and reflection loss needs to be defined. This relationship is shown in Fig. 10. As can be seen, the data points for all three curing conditions are grouped close to a single curve, which can be represented as a power law function. The different curing temperatures do not affect the uniqueness of the relationship. This curing temperature independence of the relationship between compressive strength and reflection loss was investigated in more detail by Sun et al. [17]. The relationship between compressive strength and reflection loss derived from the data presented in Fig. 10 is given in Eq. (7), where S is compressive strength and R_L the measured reflection loss

$$S = 4.224 \cdot R_L^{1.9158} \tag{7}$$

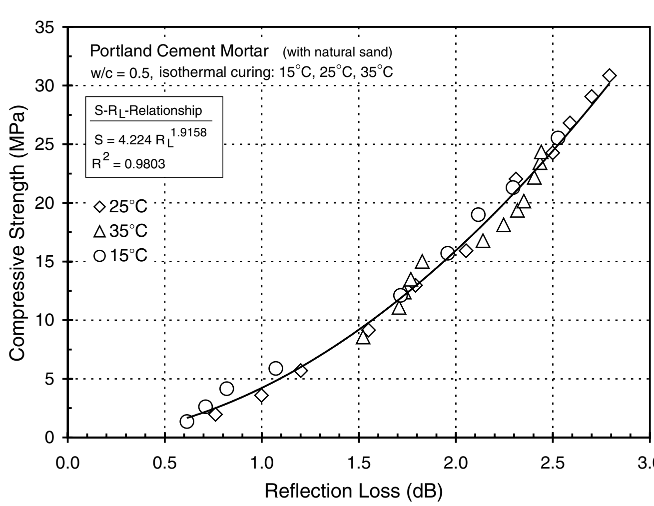

Fig. 10. Compressive strength–reflection loss relationship for mortars with $w/c = 0.5$.

The relationship given in Eq. (7) covers the time range of 9 h to approximately 3.5 days after casting. Determining the strength versus reflection loss relationship before 9 h is not practical, since measuring strength at this early stage is difficult and not feasible. It should be noted that reflection loss readings will start to increase close to the time of initial setting, at a time when conventional strength testing is not possible.

In previous investigations, the relationship between compressive strength and reflection loss was found to follow a bilinear function, with the first part having a smaller slope than the second [25]. A similar bilinear function could be fitted to data shown in Fig. 10 as well. However, to simplify the data analysis, a single power law function was chosen.

4. Strength estimates for non-isothermal curing

4.1. Test results for non-isothermally cured mortar

It will now be investigated how the established relationships between compressive strength, equivalent age, and reflection loss can be used to estimate the compressive strength of a portland cement mortar that is cured under non-isothermal conditions. Mortar with a water–cement ratio of 0.5 was cured in a water bath whose temperature was varied between 15 °C and 35 °C. The water temperature was first set to 15 °C and held for 12 h at that level. Then the temperature was increased rapidly to 35 °C and after 12 h again decreased to 15 °C. This cycle was continued for a period of four days as shown in Fig. 11(a). The computed equivalent age and measured reflection loss are given in Fig. 11(b) and (c), respectively. The compressive strength development was determined by testing cubic specimens to verify the strength estimates and is given in Fig. 11(d).

4.2. Comparison of strength estimates

In this section, the strengths estimated on the basis of the previously determined relationships between compressive strength, equivalent age and reflection loss will be compared. The strength–equivalent age relationship for curing at 25 °C shown in Fig. 8 was used to estimate strength development under the non-isothermal conditions. Strengths estimated by the maturity method and WR-method are shown in Fig. 12.

It can be seen that, except for the first 24 h after casting, the compressive strengths measured on the mortar cubes are lower than the strengths estimated from the maturity method. This reinforces the limitation of the current maturity method when early-age temperatures in the field differ

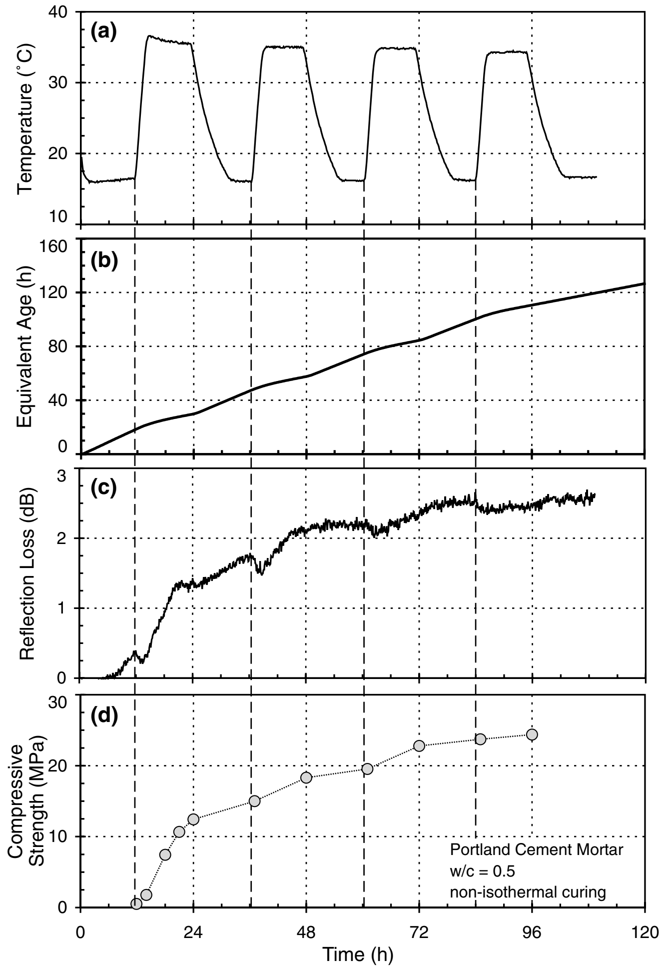

Fig. 11. (a) Temperature history for non-isothermally cured mortar specimens ($w/c = 0.5$), (b) calculated equivalent age, (c) measured reflection loss, and (d) measured compressive strength.

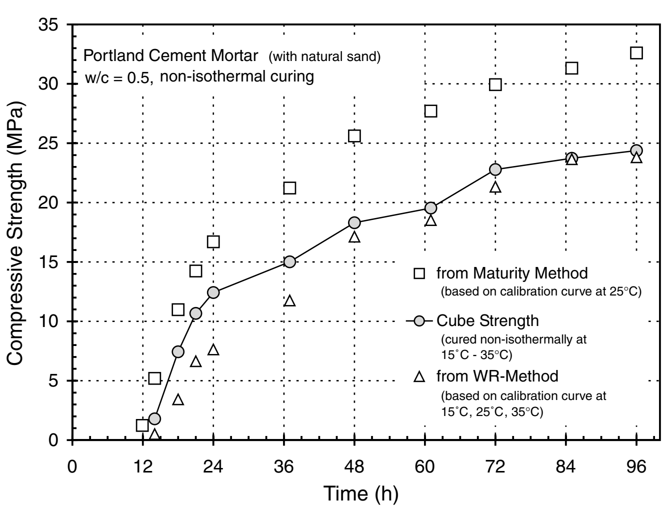

Fig. 12. Comparison of strength prediction for non-isothermally cured mortar ($w/c = 0.5$) obtained from WR- and maturity method.

from those used to establish the strength–maturity relationship.

The reflection loss values measured on the non-isothermally cured mortar and the relationship given in Eq. (7), were used to obtain the estimated compressive strengths shown in Fig. 12. The estimated strength values by the WR-method show good agreement with the measured values cube strengths for ages after 36 h. The deviation between 18 and 36 h is somewhat larger. As mentioned before, it needs to acknowledge that experiments conducted on concrete would most likely yield results with higher scatter. This is due to the higher heterogeneity of concrete compared to mortar and will be addressed in future work.

5. Strength estimates for different water–cement ratios

For the purpose of practical application of both methods it would be of interest if the validity of the determined relationships between (relative) compressive strength, equivalent age, and reflection loss can be extended to different water–cement ratios. This can be investigated using the data obtained from the mortars with water–cement ratios of 0.35 and 0.6 given in Figs. 4(b) and 5(b). The comparison of the relationships between relative compressive strength and equivalent age for the two water–cement ratios is given in Fig. 13. The plotted curves exhibit minor differences, which lets one conclude that there is not a unique relation between relative strength and equivalent age for mixtures with significantly different water–cement ratios. This seems logical since the water–cement ratio affects the rate constant k_r at the reference temperature.

The relationships between compressive strength and reflection loss for two mortar mixtures are given in Fig. 14. The figure shows the relationship for each individual water–cement ratio as well as a global relationship for both mixtures. It can be seen that the highest accuracy (in terms of the R^2-value) is achieved by using the relationship for each individual water–cement ratio. However, it seems

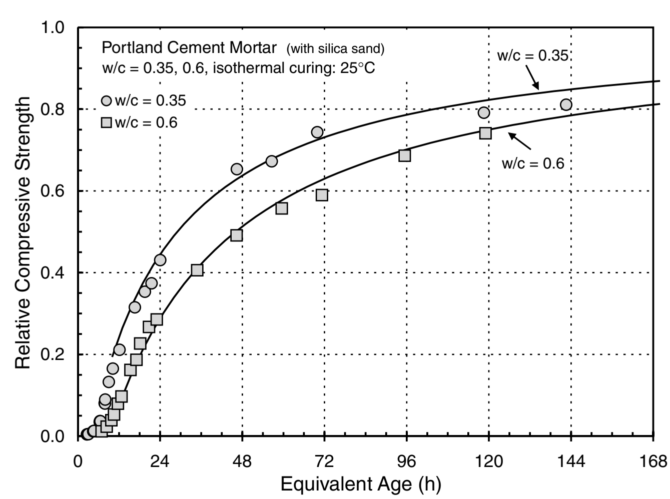

Fig. 13. Compressive strength–equivalent age relationship for mortars with $w/c = 0.35$ and 0.6.

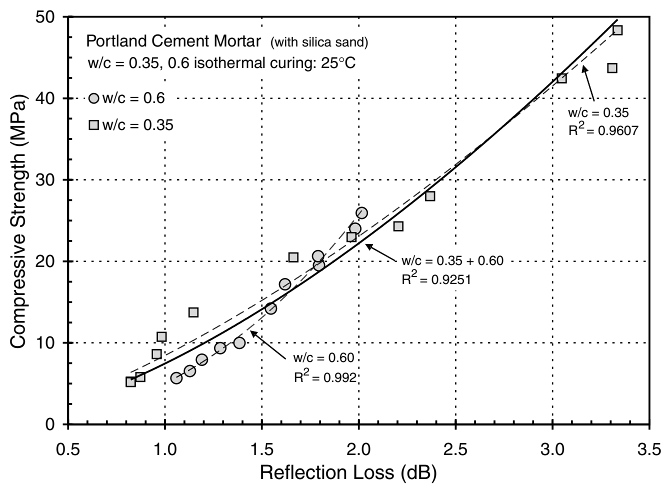

Fig. 14. Compressive strength–reflection loss relationship for mortars with $w/c = 0.35$ and 0.6.

reasonable to use a common relationship between compressive strength and reflection loss for both water–cement ratios. Voigt and Shah [9] and Sun et al. [17] also showed that reflection loss was independent of the water–cement ratio.

The example given in Fig. 14 shows the potential of the WR-method to reduce the amount of necessary laboratory calibration by yielding relationships between the measured reflection loss and compressive strength that is relatively independent of environmental influences (initial curing temperature) and mixture composition (water–cement ratio).

6. Conclusions

The following conclusions can be drawn from the investigations presented in this paper:

1. Differences in the early-age curing temperature of mortars with the same water–cement ratio have a significant effect on the limiting compressive strength and there is a unique relationship between compressive strength and equivalent age. Instead a function describing the relationship between the relative strength gain and equivalent age for a mortar mixture cured at three different temperatures was found. The application of this relationship for estimating the compressive strength of a non-isothermally cured mortar with the same water–cement ratio requires an estimate of the limiting strength under the actual initial curing conditions, which is difficult to do.
2. The relationship between compressive strength and reflection loss of a mortar mixture cured at three different temperatures was found to be unique. This relationship can be used for estimating the strength development of a non-isothermally cured mortar of the same water–cement ratio without further modification.
3. There is not a unique relationship between relative compressive strength and equivalent age for mortars with significantly different water–cement ratios.
4. The relationship between compressive strength and reflection loss for mortars is relatively independent of the water–cement ratio. While there are some differences between the relationships for the different water–cement ratios, they are much less significant than those observed for the relative strength versus equivalent age relationship.

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