HEALTH MONITORING OF EARLY AGE CONCRETE

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Abstract

The setting and hardening process of concrete can be considered as the most critical time period during the life of a concrete structure. To assure high quality and avoid problems in performance throughout the life of the material, it is essential to have reliable information about the early age properties of the concrete. This paper presents a new method to monitor the hydration process of cementitious materials at early ages. The technique is based on the measurement of the reflection coefficient (or reflection loss) of high frequency shear waves at an interface between a steel plate and e.g. concrete. Several experimental studies that examine the ability of the wave reflection method to qualitatively and quantitatively describe the setting and hardening process of cement paste, mortar and concrete are presented. The results show that parameters such as setting time, compressive strength, elastic and visco-elastic moduli and degree of hydration of cementitious materials can reliably monitored with the wave reflection method. The relationship between the measured reflection loss and the compressive strength was successfully used in a first field trial of the method to determine the in-place strength of precast concrete elements.

1 Introduction

A significant amount of today's infrastructure is partially or completely made out of cementitious materials. To meet the constantly increasing expectations of the user community, concrete structures are required to be a highly serviceable, durable, flexible and esthetic. The properties of concrete are solely determined by the composition of its ingredients and the conditions during the setting and hardening process. Damages and unintentional properties occurring to the concrete during this setting and hardening process cannot or only with great financial effort repaired. For example the exposure of fresh concrete to direct sun light, an erroneous dosage of an admixture or the disregard of the water adsorption of the aggregates can be sufficient to render a concrete completely useless for its intended purpose. In this context information about the properties of early age concrete and their development in time are essential. It is of considerable importance that this information represents the condition of the concrete in the structure and not that of concrete specimens that have no or little relationship to the actual concrete in the structure. This calls for nondestructive test methods that offer the possibility to determine in-situ material properties of the concrete directly in the structure without significantly damaging it. By using of modern techniques and equipment the test results are often immediately available and allow for the initiation of repair measures is necessary.

In this paper a nondestructive method is proposed that uses high-frequency ultrasonic waves to continuously monitor the setting and hardening of cementitious materials. The principle of the wave reflection (WR) -measurements consists of monitoring the reflection coefficient of ultrasonic shear waves at an interface formed by a steel plate and the cementitious material to be tested. In several studies it was investigated how the development of the reflection coefficient is related to the progress of hydration in cementitious materials and how the WR-method can be used to determine material properties of e.g. concrete [1-4]. The proposed WR-method has a high potential for the application of nondestructive testing of concrete under field conditions. The results of a field trial that emphasize this potential are also presented.

2 Principle of the Wave Reflection Method

The principle of the WR-measurements consists of monitoring the reflection coefficient of ultrasonic waves with a frequency of 2 MHz at an interface formed by a steel plate and the cementitious material to be tested. An ultrasonic transducer is coupled to the steel plate, which in turn has to be brought in contact with the test material when it is still in liquid or unhydrated state. With proceeding hydration the wave propagation properties of the test material change, which results in a variation in the reflection coefficient. The reflection coefficient is obtained from the amplitudes of successive reflections received from the interface between the steel plate and the test material.

When shear waves are used for the measurements and the test material (e.g. cement paste) is in liquid state, the entire wave energy, which is approaching the interface, is reflected, since shear waves cannot propagate in liquids (Fig. 1a). Thus, the reflection coefficient is unity. With proceeding hydration the cement grains percolate and build up a skeleton allowing the shear waves to propagate. This allows the shear waves to pass the interface resulting in reflection losses at the interface (Fig. 1b). Consequently, the reflection coefficient starts to decrease. With proceeding hydration the ability of the cement paste to transmit shear waves gains higher levels. More and more wave energy is transmitted into the cement paste and the reflection coefficient decreases further. After a certain time this process slows down and the reflection coefficient approaches a final value. At this time changes in the microstructure of the cement paste due to hydration are too small to alter the shear wave propagation properties significantly.

The amount of the reflected and transmitted wave energy depends on the difference of the acoustic impedances of the materials that form the interface and is described by the reflection coefficient *R* (Eq. 1). The acoustic impedance *Z* is determined by the wave velocity *v* and the density *ρ* of the material (Eq. 2).

$$R = \frac{Z_2 - Z_1}{Z_2 + Z_1} \quad (1)$$

$$Z = \rho \cdot v \quad (2)$$

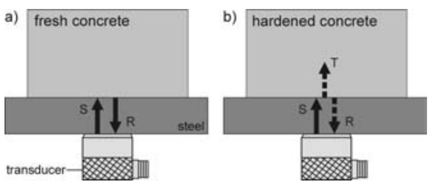

Fig. 1. Principle of HFWR-method

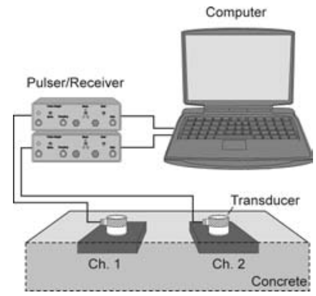

Fig. 2. Experimental apparatus for wave reflection measurements

2.1 Experimental Apparatus

The schematic of the experimental apparatus that is used for the wave reflection measurements is given in Fig 2. In general, it consists of a laptop computer, a pulser/receiver unit, a transducer, and a steel plate. The transducer, which generates the ultrasonic waves, is connected to the computer via the pulser/receiver. This unit excites the transducer and transmits the information of the received reflections from the transducer to the computer. The computer performs the signal analysis using a program written in the LabView ™ environment. The shown configuration of the setup is capable to measure the reflection coefficient at two separate channels. Consequently, by using two transducers, which are each connected to a separate pulser/receiver the reflection coefficient can be measured at two different points at the specimen or structure simultaneously.

2.2 Signal Analysis

The reflections of the shear waves from the steel-concrete interface are received from the transducer in time domain. To calculate the reflection coefficient the time domain of the received reflections is transformed into the frequency domain by using a fast-Fourier transform algorithm. The reflection coefficient *R* is then calculated from the ratio of the amplitudes of the first (A_1) and second reflections (A_2) received from the steel/mortar interface (Eq. 3). A detailed explanation of the calculation of the reflection coefficient can be found in [2].

Basically, the reflection coefficient 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. 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. (4) with $R_L(t)$ as the reflection loss at time *t* and *R(t)* as the reflection coefficient at time *t*.

$$R = \frac{A_2}{A_1} \tag{3}$$

$$R_L(t) = -20 \cdot \log(R(t)) \tag{4}$$

3 Experimental Results

3.1 Setting Behavior

First the qualitative relationship between the setting of concrete and the measured reflection loss should be investigated. This can be done by comparing the reflection loss measured on plain, accelerated and retarded concrete with the same water/cement (w/c)-ratio. The development of the reflection loss measured on the concretes is given in Fig. 3. It can be seen that the WR-measurements are clearly affected by the differences in the setting process caused by the admixtures. The curve measured on the accelerated concrete starts to increase first and with the highest rate of change, whereas the retarded concrete causes the reflection loss to increase much later with a lower rate.

The quantitative relationship between initial setting time and the WR-measurement were investigated in [1,2]. In these investigations plain concrete and concrete mixtures containing accelerator, silica fume, superplasticizer, and retarder have been tested. In each of the measured reflection curves loss a distinct point (Point A) was identified that marks the time when the curve starts to increase as a result of the onset of hydration. To evaluate the significance of Point A in terms of the setting process, its time of occurrence was compared to the initial setting time determined with the pin penetration method. In Fig. 4 the relationship between initial setting time and time of increase of reflection loss for the five tested concrete mixtures is presented. It can be seen that the shift of occurrence of Point A caused by the admixtures is proportional to the change in initial setting time. These studies show that the development of the reflection coefficient measured with shear waves is directly related to the setting behavior of concrete.

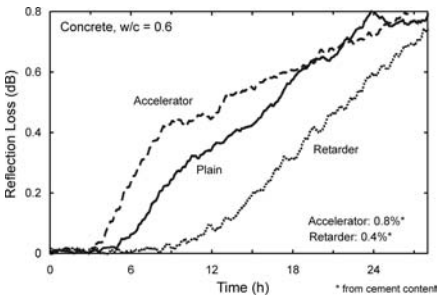

Fig. 3. Influence of admixtures on reflection loss development

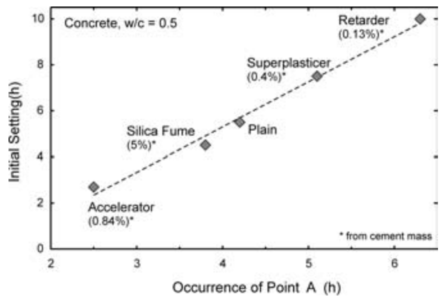

Fig. 4. Relationship between initial setting time and time of increase of reflection loss

3.2 Compressive Strength

The sensitivity of the wave reflection method to the compressive strength development of cementitious materials will be analyzed in this section. As an example, the development of reflection loss and compressive strength for a Portland cement mortar with w/c = 0.5 is given in Fig 5. It can be seen that both parameters develop after the same pattern. First, reflection loss and strength start to increase according to a power law. This phenomenon agrees with studies conducted by Popovics [5] who concluded that physical characteristics of the setting of cementitious materials can be approximated by a power function. After the setting process the growth characteristic of reflection loss and strength changes to a hyperbolic trend. The hyperbolic trend function is the linear hyperbolic model for the compressive strength development at isothermal conditions introduced by Carino [6] and Knudson [7]. The similarities in the growth characteristics of reflection loss and compressive strength let conclude that both parameters are very closely related.

The relationship between reflection loss and compressive strength for Portland cement mortars with w/c = 0.35, 0.5 and 0.6 is given in Fig. 6. It can be seen that a single bi-linear trend can be defined for the plotted data independent from the w/c-ratio. The strength-reflection loss ($S–R_L$) relationship exhibits a strong bilinear pattern, dividing the relationship into two parts. The first part at very early ages has a clearly lower slope compared to the second part of the relationship at later ages. It is believed that the change of the slope is related to differences in the kinetics of the strength and reflection loss gain at early ages. The transition between the two trends occurred within the first 15 hour after mixing, which means that after this time strength and reflection loss are related by a single linear trend function. This offers various possibilities for the practical application of the WR-method to nondestructively determine the compressive strength development in concrete structures. A first field test where this relationship was successfully used is presented later in this paper.

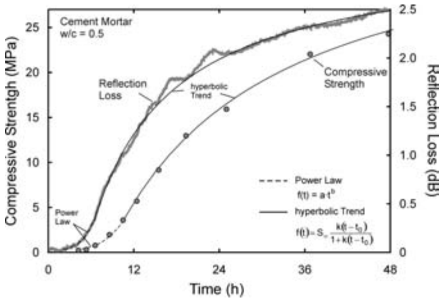

Fig. 5. Comparison of reflection loss and compressive strength of mortar with w/c = 0.5

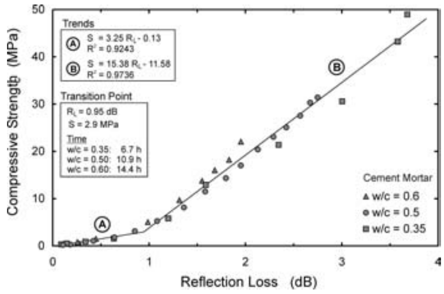

Fig. 6. Relationship between reflection loss and compressive strength for cement mortar

3.3 Shear Modulus

The investigations presented so far relate the reflection loss and the parameters of the tested cementitious materials mostly on an empirical basis. But to develop a reliable test method, this technique must be based on physical theories rather than relying solely on empirical relationships. The reflection loss is theoretical related to the dynamic shear modulus of the tested material. By combining equations (1) and (2) with the relationship between shear wave velocity and shear modulus, an expression is obtained that allows the calculation of the dynamic shear modulus from the WR-measurements (Eq. (5)). In this equation Z_s is the acoustic impedance of the used steel plate, ρ_m the density of the test material (here: mortar) and R the reflection coefficient.

$$G_{WR} = \frac{Z_s^2}{\rho_m} \cdot \frac{(1+R)^2}{(1-R)^2} \tag{5}$$

To investigate the sensitivity of the wave reflection method to the shear modulus the reflection loss of different cement pastes was measured and used to calculate the dynamic shear modulus. These results were compared with results of another nondestructive test method: the resonant frequency method. This method allows the determination of the dynamic shear modulus based on a different independent principle. The modulus obtained from the resonant frequency method is labeled G_{RF}.

The results for the measured shear moduli of a cement paste with *w/c* = 0.4 are given in Fig. 7. First, it can be noted that the curves of the two moduli have a similar shape. The moduli start to increase at approximately the same time and the time when the moduli start to approach their final values is also similar. Furthermore, it can be seen that the shear moduli G_{RF} and G_{WR} are almost equal. It is believed that the wave reflection method, which was used to determine G_{WR}, measures the properties of the mortar located next to the steel plate. This result proves that the development of the reflection loss is governed by the shear modulus of the tested material.

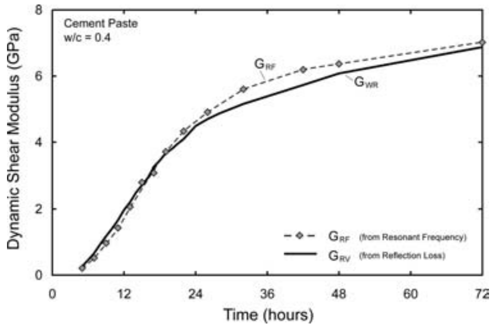

Fig. 7. Comparison of dynamic shear moduli and the principles of the applied test methods

The relationship between the dynamic shear moduli measured with the wave reflection method and an alternate test method is an essential part for understanding how the wave reflection measurements are related to basic parameters of the tested material. It could be shown that the shear modulus measured with the wave reflection method develops after the same pattern that is detected by the resonant frequency method.

3.4 Viscoelastic Properties

Concrete is a typical viscoelastic material. The porous structure of the paste matrix and the interfacial transition zone between cement paste and aggregates make the properties of concrete more complex. Understanding the viscoelastic properties of Portland cement paste can be helpful to understand the behavior of concrete better.

In a viscoelastic material, the acoustic impedance can be written in a complex format Eq. (6). The complex shear modulus consists of two components [8]. Parameter G' is the storage modulus that governs the elastic property of the material and G" is the loss modulus that governs the viscous property of the material. Parameter G" can be represented by the product of the angular frequency of applied force (ω) and the viscosity (η) [9,10].

$$Z^* = \sqrt{\rho(G'+jG'')} = \sqrt{\rho(G'+j\omega\eta)} \tag{6}$$

$$R^* = R_o e^j = \frac{Z^* - Z_s}{Z^* + Z_s} \tag{7}$$

Similar to shear modulus, the reflection coefficient measured at the interface between the steel plate and the cementitious material can also be expressed in a complex format as shown in Eq. (8), where R_0 is the magnitude of the reflection coefficient and φ is the phase shift between the incident and reflected waves. Both R_0 and φ can be obtained directly from the wave reflection measurements. By substituting Eq. (6) into Eq. (7), the storage modulus and the viscosity of the measured material can be solved as shown in Eq. (8) and (9). By considering the measured phase angle shift and the reflection loss, the dynamic storage shear modulus can be calculated according to Eq. (8).

$$G' = Z_s^2 \frac{(1 - R_0^2) - 4R_0^2 \sin^2}{\rho(1 - 2R_0 \cos \quad + R_0^2)^2} \tag{8}$$

$$\eta = Z_s^2 \frac{4R_0(1 - R_0^2)\sin}{\omega\rho(1 - 2R_0 \cos \quad + R_0^2)^2} \tag{9}$$

The storage shear modulus of cement paste can also be measured with the oscillatory rheometric method (OR-method), which can be regarded as a non-destructive method from microstructural point of view [11]. In this technique, the corresponding in phase/out of phase shear stresses can be measured by applying an oscillatory shear strain with the amplitude and frequency within the linear viscoelastic region of the cement paste. Storage shear modulus is calculated from the measured shear stress and the applied shear strain.

The storage shear moduli calculated measured with WR-method and the OR-method of cement pastes with *w/c* = 0.4, 0.5 and 0.6 is plotted in Fig. 8. It can be seen that the storage shear modulus obtained from the two techniques have a very similar trend. The moduli first exhibit a moderate increase followed by a steeply increasing part. The time of the sharp increase of the moduli can be considered as the end of the dormant period in the hydration process. It is obvious that the storage shear moduli obtained with the two different methods develop after very similar trends, which shows that the WR-method can monitor the elastic behavior of cementitious materials in fresh state.

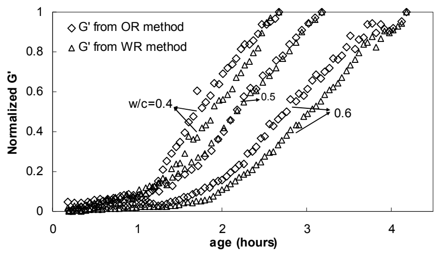

Fig. 8. Normalized dynamic storage shear moduli with WR and OR methods

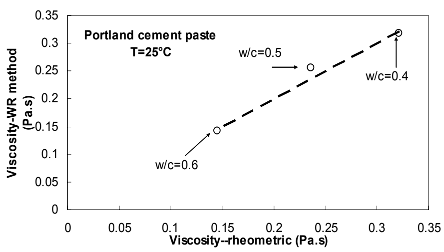

Fig. 9. Comparison of viscosity obtained with WR and RM methods

The viscosity of the cement pastes was calculated with the WR-method according to Eq. (9). The calculated viscosity increases with the decrease of w/c-ratio. The results were compared with the viscosity obtained by applying Bingham Model through a rheometric measurement (RM). In the rheometric measurements, the cement paste was allowed to rest for 10 minutes before applying the shear force. The applied shear rate decreased from $600s^{-1}$ to $10s^{-1}$. In Fig. 9 the comparison of the viscosities of the cement pastes obtained with two different methods is presented. It can be seen that the values obtained with the different methods are very similar and the shift of the viscosity values caused by the w/c-ratio has the same trend with these two methods. This study shows that in addition to elastic material properties the WR-method can also provide information about the viscous properties of cementitious materials.

3.5 Degree of Hydration

The degree of hydration is one of the most fundamental material parameters of a cementitious material. It describes the progress of the hydration reaction and is a governing parameter for many mechanical properties of cement paste, mortar and concrete. Experiments with the objective to relate the reflection loss to the degree of hydration were conducted on Portland cement mortars with w/c = 0.35, 0.5 and 0.6. The degree of hydration of the mortars was determined with thermogravimetry.

The relationship between the degree of hydration and the reflection loss for all tested mortars is given in Fig 10. For each mortar mixture, the presented data show a very strong linear trend over the entire period of time that is plotted. The coefficients of determination R^2 of the plotted trend lines are given in the figure to illustrate the statistical significance of the trends. By comparing the relationships of the different w/c-ratios, it can be seen that the slope of the relationship changes with the w/c-ratio, where a low w/c-ratio corresponds to a high slope. In other words, for a given degree of hydration, the reflection loss of the mortar with w/c = 0.35 is higher than the reflection loss of the mortar with e.g. w/c = 0.6. This variation is due to the different microstructural properties of the mortars caused by the different w/c-ratios. From the results of the thermogravimetric measurements, it was found that the mortar with w/c = 0.6 contains much more capillary water than the mortar with e.g. w/c = 0.35. Since capillary water leads to the formation of capillary pores, both mortars have a different capillary porosity.

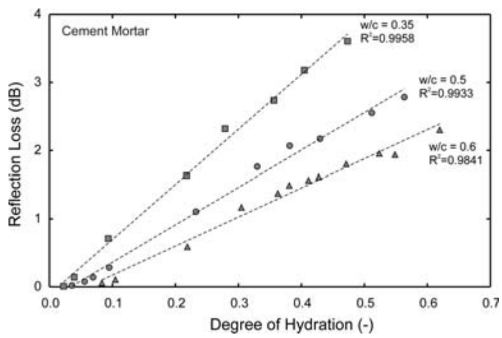

Fig. 10. Relationship between degree of hydration and reflection loss

Consequently, a mortar with a low w/c-ratio has a low capillary porosity resulting in a denser microstructure of the cement paste. This improves the shear wave propagation properties, which in turn increases the reflection loss. These observations indicate that the reflection loss is not only a function of the progress in hydration but also a measure of microstructural properties as influenced e.g. by the w/c-ratio.

4 Field Application

4.1 Introduction

To evaluate the industrial applicability of the wave reflection method a field trial in collaboration with a precast production plant, Rocky Mountain Prestress, Denver, Colorado, was conducted. The objective of this first field trial was to assess the general suitability of the test method to monitor the curing process of full-scale concrete structures during the production process. The field measurements should also give information about how the test arrangement performs under field conditions with respect to measuring location, equipment reliability, and preparation efforts. This field trial can be considered as a first step towards commercial application of the wave reflection method.

4.2 Test Equipment and Procedure

To conduct the field measurements it was necessary to make the test equipment portable. This was achieved by placing the different electronic devices into a portable case. The arrangement of the equipment for the wave reflection test and in-situ temperature measurements in a durable and portable case is shown in Fig 11. All components are connected ready for use, and the case features a main power switch and a main power inlet for all components. The case can easily be moved on the construction site and allows for minimal setup times during field testing.

To assess the applicability of the wave reflection method for monitoring the hardening process of concrete under field conditions, the production of prestressed box girders was chosen. The production schedule of the precast plant required the removal of the girders from the steel bed as soon as the concrete has reached the critical strength that allows lifting the girders with a crane. To evaluate the ability of the wave reflection method to determine the time when the critical concrete strength is reached, a girder was instrumented with two separate transducer-steel plate combinations located on the top-surface of the girder (Fig. 12). The steel plates where put in place after the concrete was completely placed and the top surface was finished with the rake. Additionally, the girder was instrumented with thermocouples at different locations to track the temperature rise in the girder during hydration. A data logger, which was part of the portable test setup, recorded the temperature in regular time intervals throughout the hardening process. The complete test setup is given in Fig. 13.

The determination of the compressive strength from in-situ wave reflection measurements requires knowledge about the relationship between the reflection loss and compressive strength. The current stage of the research required the determination of this relationship in advance with laboratory tests. The original materials and concrete composition of the box girders were used for compressive strength tests and WR-measurements to determine the S–R_L relationship in advance.

Fig. 11. Equipment for WR-measurements for field testing

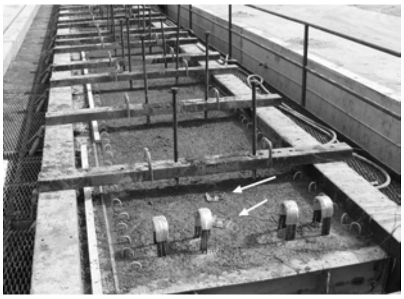

Fig. 12. Field measurements on box girder shortly after placing the concrete

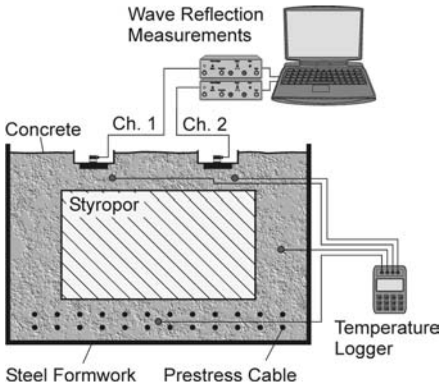

Fig. 13. Schematic of test setup for field trial

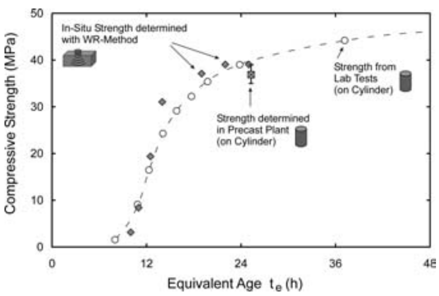

Fig. 14. Strength predicted from WR-measurements, determined in the lab and the precast plant

4.3 Results

The comparison between the in-situ strength predicted from the WR-measurements and the cylinder strength determined in the laboratory and the precast plant is given in Fig. 14. To calculate the compressive strength from the measured reflection loss the S–R_L relationship as determined in the laboratory has been used. First it should be noted that the nondestructively determined strength values agree very well with the strength data determined in the laboratory tests. But more important, it can be seen that the strength predicted from the WR-method is within the range of the four strength values determined by cylinder tests in the quality control lab of the precast plant. These cylinders were tested after ca. 16 hours and were cured at the same temperature as measured in the actual box girder during the hardening process.

5 Conclusions

From the investigation presented in this paper the following conclusions can be drawn:

1. Experiments on concretes with different admixtures have shown that the wave reflection method has the ability to qualitatively describe the hydration progress of cementitious materials. A consistent relationship between the initial setting time and distinctive points in the reflection loss curve could be identified.
2. The relationship between reflection loss and compressive strength has a strong bi-linear character for the tested mortar mixtures at early ages (up to 90 hours). The S-R_L relationship starts with a low slope at very early ages (up to 15 hours) and then changes to a higher slope for the remainder of the monitoring period.
3. The experimental determination of the dynamic shear modulus of cement mortars with a different independent technique has shown that the WR-method is governed by the shear modulus of the test material. The results indicate that the wave reflection method measures the properties of the cement paste, which is the material located next to steel plate.
4. The comparison of the storage modulus measured by the WR-method and that obtained through oscillatory rheometric technique shows that the WR-method can be used to monitor the development of the elastic properties of the material correctly. The WR-method can also be regarded as an efficient method to measure the viscous properties of the material.
5. The comparison of the degree of hydration with the measured reflection loss of mortar mixtures shows that both parameters are linearly related for early ages (up to 90 hours). The slope of the linear relationships varies with the w/c-ratio of the mortar. This suggests that besides chemical properties also the parameters describing the physical and volumetric composition on the microstructural level of the material are of importance.
6. The WR-method was successfully applied in a first field trial. The method was used for the nondestructive determination of the in-place strength of prestressed concrete box girders manufactured in a precast plant.

6 Acknowledgements

The research presented in this paper was funded by the Institute of Technology and Infrastructure of Northwestern University and the Center for Advanced Cement-Based Materials. Their financial support is gratefully acknowledged. The field testing was conducted in collaboration with Rocky Mountain Prestress, Denver, Colorado and Holcim (US) Inc. Their support is also gratefully acknowledged.

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