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Evaluating the damage in reinforced concrete slabs under bending test with the energy of ultrasonic waves

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HIGHLIGHTS

- High deformations of concrete distort acoustic waves and change the waveform.
- We proposed an approach based on energy loss of ultrasonic probe signals.
- This approach appears to be more effective to monitor the crack propagation.

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ABSTRACT

This paper deals with the feasibility and sensitivity of ultrasonic probe waves for characterizing the mechanical damage of reinforced concrete slabs during bending tests either in sound concrete or in concrete affected by alkali–silica reaction (ASR). The results show that the ultrasonic probe waves are capable of distinguishing between the damage phases in the concrete elements (initial structural cracking and bars yielding phases). Three reinforced concrete slabs with dimension of $1.40 \times 0.75 \times 0.3$ m^3 (made with nonreactive aggregates and ASR-reactive aggregate) were used in this experiment. Both the conventional method of load–deflection measurements and the nondestructive testing based on ultrasonic probe signals were applied in order to evaluate the feasibility of ultrasonic testing for tracking crack growth in the reinforced concrete elements. These slabs were assessed under four-point monotonic bending tests over a span of 1400 mm and were subjected to step-loading until failure. The ultrasonic probe signals were recorded at the each step-load and then energy of received signals were extracted in order to evaluate the energy loss of the signals due to the mechanical cracking. Changes in the energy contents of the signals fairly correlate with the increase of the loads. The results show that the ultrasonic testing is a more robust approach for distinguishing the sound concrete slab from the damaged concrete.

1. Introduction

1.1. Background review

Traditionally, the mechanical behavior of concrete elements is evaluated by analyzing the load–deflection or stress–strain behaviors from various types of mechanical tests. These tests have been standardized and have been presented as means of evaluating various static and dynamic properties of the concrete elements. These mechanical testing methods assess the general macro-behavior of concrete elements by measuring the response of concrete elements to external loads. These methods are often not enough robust to detect small changes in concrete properties, such as micro-crack growth. Although these small anomalies typically do no threaten the general serviceability of reinforced concrete elements, they may jeopardize the long-term performance of the structures from a durability point of view. It may also intensify the rate of other chemical and physical damage mechanisms such as the corrosion of the steel bars and tendons [28]. Therefore, the development of methods that allow accurate tracking of the stress changes and concrete cracking would be extremely useful.

It has been demonstrated that acoustoelasticity methods are potentially efficient to monitor the stress changes in concrete with an accuracy far superior to the common structural measurements [15,27,33,30,40]. Indeed, thorough studies conducted on the propagation of the acoustoelastic waves into media showed that there is an analytical expression between the principal stresses and the acoustic wave velocities for an isotopic medium [16,14,8]. Lillamand et al. [15], Schurr et al. [27], Stähler et al. [33], Shokouhi and Niederleithinger [30] applied this physical expression to evaluate small stress-induced changes in uniaxial static compression

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tests. Although there were some differences between the measurements, good correlations were obtained for the small stress-induced changes in concrete specimens and acoustoelastic wave velocity changes based on Murnaghan [16]. A similar study was carried out by Zhang et al. [40] on concrete specimens tested under direct tensile forces, where the results proved to be in agreement with studies performed under uniaxial compressive loads despite the limitations associated with the direct tensile strength of concrete. Acoustoelastic methods are precise in monitoring small stress-induced changes. These methods are more accurate prior to the development of mechanical macro-cracks within the concrete matrix. These methods are based on the assumption of a path-independency of the acoustic waves; whereas the trajectories and paths of the acoustic waves change with the extent of macro-cracks through the medium. This may cause frequency attenuations, absorption of signal energy, and some variations of the waveform [1,24,34,37]. Therefore, these methods would not reliable for tracking stress changes in the case of reinforced concrete; because the reinforced concrete elements are serviceable although the macro-cracks develop within the concrete and the elements go under high deformations. Moreover, Stähler et al. [33], in a field experiment, reported that the attenuation associated with the stress changes in service structures can distort the waveforms because of the high heterogeneity of the concrete. Similar results were observed by Grêt et al. [11], through an experimental study conducted in order to monitor the in-situ stress changes in a hard rock mine. This phenomenon may also limit the implementation of the acoustoelastic approaches for evaluating the stress changes in field experiments.

Nogueira and Willam [17] and Qasrawi and Marie [20] used the Ultrasonic Pulse Velocity (UPV) method to monitor the crack development in a concrete sample under uniaxial compression. This method has two important limitations concerning the monitoring of crack growth: (1) it is difficult to measure the velocity changes at low-levels of damage (micro-crack development phase); (2) there are limitations for distinguishing between the damage phases (i.e. closure of inherent micro-defects at the initial stage of loading, micro-cracking/cracking development, yielding and failure) by tracking stress-induced changes within heterogeneous cementitious materials. Their results showed that there was about a 5% drop in pulse velocity when the stress-strength ratio was of 80%. Generally, the results show no significant variation of the pulse velocity until around 90% of the failure strength. This finding is in agreement with results obtained by Van Den Abeele et al. [36] and Sargolzahi et al. [26], where it was demonstrated that linear acoustical methods, like UPV, are not sensitive enough with regards to the development of damage features (e.g. cracks and flaws) in heterogeneous cementitious materials. The results obtained by Shiotani and Aggelis [29] and Van Hauwaert et al. [37] also showed that the UPV is not sensitive enough to evaluate distributed damage.

1.2. Scope of work

A major challenge addressed in this article is the evaluation of the bending stresses in reinforced concrete slabs using ultrasonic waves. A sound concrete slab and the concrete slabs damaged by alkali–silica reaction (ASR) were selected to assess the effectiveness of the ultrasonic waves to monitor the stress evolutions in both slabs. The attenuation of the frequencies and the distortion of the waveforms in reinforced concrete elements can limit the application of common methods like acoustoelastic-stress change methods. Therefore, the approach of the energy loss of ultrasonic waves is considered in this paper, and applied to track the mechanical behavior of concrete slabs over four-point bending tests. To do so, a step-loading protocol was performed, and the concrete condition was evaluated by computing the energy loss of the ultrasonic waves recorded at each step.

Hu et al. [12] and Song et al. [32] applied the same concept for health monitoring concrete elements in bending test using embedded piezoceramic transducers. Although this method is also useful for long term measurements to track the history of stress change in concrete structures, it is not suitable for service concrete structures that are not pre-instrumented. This research relies on external transducers attached to the concrete surface for evaluating stress evolution, which represent a convenient approach to the monitoring of existing structure.

The energy loss measurements using coherent ultrasonic waves include intrinsic absorption and scattering contributions. Diffusion theory can separate the energy loss contributions due to absorption and scattering [3,18,38]. Quiviger et al. [21], Deroo et al. [7], Punurai et al. [19], Becker et al. [4] and Anugonda et al. [3] applied the diffuse ultrasound in small size cement paste and concrete specimens (not more than few centimeters). Due to the heterogeneous nature of concrete, Punurai et al. [19] suggest taking a building block approach even for small size concrete specimens. With this method, it should be possible to characterize the energy loss due to absorption and scattering from individual elements (i.e. cement paste, aggregate, inherent micro-cracks, etc.). Then, it may be possible to combine into a unified description. For this reason, it is still complicated to apply diffusion theory in large-scale reinforced concrete elements in the field to uncouple the loss contributions due to absorption and scattering. It should be mentioned that, during a mechanical loading test, the heterogeneity of concrete increase dramatically due to the development of macro-cracking. This can limit the application of the diffusion theory in large-scale reinforced concrete elements during a structural test.

2. Experimental program

2.1. Sampling and materials

Tests were conducted on three concrete slabs with dimension of $1.40 \times 0.75 \times 0.3$ m^3. Two slabs were fabricated with alkali–silica reactive coarse aggregates. To boost the reaction, pellets of NaOH were added to the mixing water of the reactive concrete in order to increase the total alkali content of the concrete to 5.0 kg/m^3 Na_2Oeq. The third slab was fabricated with nonreactive aggregates. The composition of the concrete is provided in Table 1. The concrete slabs were reinforced with seven 20M (nominal diameter = 19.5 mm) at the tension face and seven 10M (nominal diameter = 11.3 mm) at the compression face, which both were hooked at the ends. Rebars are made of G30.18-M92 (R2002) grade 400W Canadian steel with nominal yield strength of 400 MPa [6]. The slabs were also reinforced with 10M stirrups at a 100 mm center-to-center constant spacing. The reinforcement layout in both plan and elevation view is illustrated in Fig. 1. The measured steel properties are also given in Table 2.

All concrete slabs went through a 28-day moist curing at normal temperatures. Table 3 shows the average compressive and tensile strengths, as well as the average modulus of elasticity at the 28 days and at the test time (800 days). The nonreactive reinforced concrete slab is referred to as NS and the reactive reinforced concrete slabs to as RS1 and RS2.

2.2. Load testing and acoustic measurements

Fig. 2 shows a sketch of the test set-up with the configuration of the acoustic transducer located both on the tension and compression faces. This configuration enables the generation and measurement of the required ultrasonic waves at

Table 1
Mix design of the concrete slabs for 1.0 m^3.

Components	Values
Water/cement	0.50
Cement	400 kg/m^3
Na_2O_{eq}	5.0 kg/m^3
Coarse aggregate (5–14 mm)	864 kg/m^3
Coarse aggregate (10–20 mm)	216 kg/m^3
Fine aggregate	730 kg/m^3
Water	200 kg/m^3