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Proceeding Paper

Combination of Milimeter Wave Spectroscopy, Ultrasonic Testing Techniques to Monitor Curing Evolution of TRC Plates †

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Abstract: Non-destructive testing (NDT) techniques are used to study the mechanical properties of the materials without destroying, nor compromising, such properties. This paper focuses on two types of NDT methods in order to follow the curing process of textile-reinforced cementitious (TRC) composites and their cementitious matrix for the first 24 h after hydration. Millimeter wave (MMW) spectroscopy has shown sensitivity to the chemical reactions involving water, whereas ultrasonic testing (UT) following the longitudinal wave velocity, as documented in the literature, is able to follow the development of stiffness.

Keywords: curing monitoring; MMW Spectrometry; ultrasound; TRC; mortar

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1. Introduction

Textile-reinforced cementitious (TRC) composites are advanced cement-based materials in which the fabrics (usually made of glass, carbon, aramid fibers), used as reinforcements, have several advantages including: the ability to carry substantial tension loads, corrosion resistance and reduced weight [1,2]. The ability to resist corrosion, besides playing a key role in the durability of the composite, allows for thinner cementitious covers and therefore a reduced energy consumption and environmental impact [3,4]. In order to obtain an efficient composite behavior, an adequate bond is required between the cementitious matrix and the textiles [5]. The mechanical properties of different TRC designs have been widely investigated in the literature [6–8].

At an early age, the cement matrix is liquid; however, strength soon develops due to the cement hydration process, which shows the highest activity in the first days after casting. By monitoring this process, it is possible to speed up the production process of TRC structural elements by calculating the needed strength to remove the molds. NDTs have been widely used by monitoring phenomena related to mechanical or physical changes in materials and structural elements. During the hardening and setting of cement, the TRC matrix presents chemical, physical, thermal, mechanical and electrical changes that can be monitored with different NDT inspection techniques [9–14].

The physico-mechanical changes are monitored with UPV, a well-established elastic wave-based NDT, in which the wave velocity is related to the development of stiffness inside the material and the electromagnetic response is monitored with MMW spectrometry, for the first time in these frequencies.

2. Materials and Methods

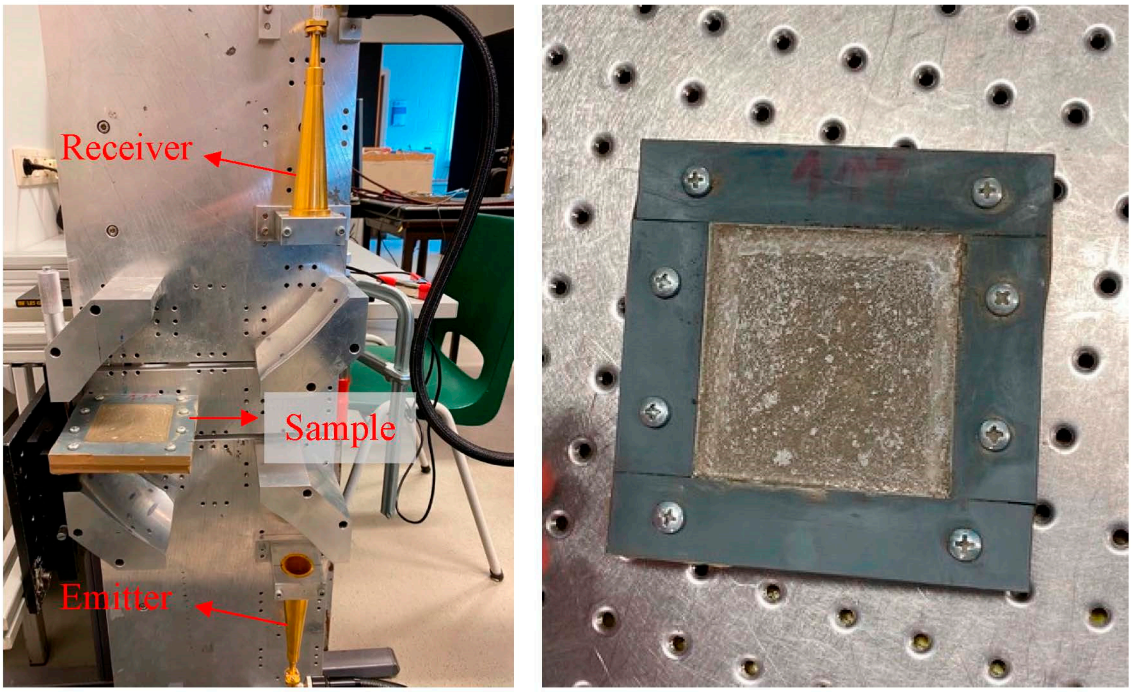
2.1. Materials and Specimen Preparation

In this study, CEM I 52.5 N from Holcim, a commercial brand commonly used in Belgium, was selected. River sand from Cobo Garden was sieved at an aperture of 0.875 mm and added in the cementitious mixture. Glass fiber SITgrid200 textile reinforcement was used with an effective fiber volume fraction of 1.11%. Additional details of the cementitious matrix composition are shown in Table 1.

Table 1. Mortar composition.

Material	Ratio (by Weight)
CEM 52.5 N	1
Riversand	2
Water	0.45
Superplasticizer	0.5%

The specimens dedicated on MMW inspection were cast in 80 × 80 × 10 mm^3 molds (see Figure 1b) by manually placing the textiles during the pouring of mortar, the samples were vibrated for 60 s. The specimens for UPV monitoring were fabricated by pre-fixing the textiles and pouring the mortar through the top in the mold shown in Section 2.3 and vibrated for 60 s.



(**a**) (**b**)

Figure 1. (**a**) MMW spectroscopy setup; (**b**) sample.

2.2. MMW Spectroscopy

MMW spectroscopy (setup in Figure 1a) due to the nature of the technique, provides contactless measurements, allowing correlations between the two NDT techniques. This novel NDT technique—by means of electromagnetic transmission and reflection, measures through a frequency sweep in the frequency band corresponding to the millimeter wavelengths—monitors the physical and chemical parameters, and specifically the changes during curing, showing sensitivity to the chemical processes in particular at the level of intermolecular forces and motion. In addition, it is influenced by the absorption or evaporation of water due to either the exothermal chemical processes during cement hydration (initial exothermal reaction, acceleratory period, or due to cement bleeding), or attributed to changes on the external environmental conditions [15,16].

The calibration procedure consisted of measuring $S11_{air}$, and $S21_{air}$, simulating the maximum transmission of 1, and minimum reflection. Later, an aluminum sheet was placed, and $S11_{metal}$, and $S21_{metal}$, were measured, simulating an ideal reflection coefficient of -1, and minimum transmission. The results obtained by calibration analysis are normalized following Equations (1) and (2):

$$S_{11_N} = \frac{-\left(S_{11}^{meas} - S_{11}^{air}\right)}{\left(S_{11}^{metal} - S_{11}^{air}\right)} \tag{1}$$

$$S_{21_N} = \frac{\left(S_{21}^{meas} - S_{21}^{metal}\right)}{\left(S_{21}^{air} - S_{21}^{metal}\right)} \tag{2}$$

2.3. UPV

At regular intervals of 60 s, ultrasonic pulses were applied to the samples (cast inside the mold shown in Figure 2) through an emitter transducer and caught by a receiver, both standing on a fixed distance. By measuring the wave transit time through the material, the UPV of the material is calculated. For the purpose of this research, an Agilent 20 MHz wave generator was programmed to emit a single sinusoidal wave of 150 kHz with an amplitude of 10 V every minute. The wave is emitted and received by AE sensors with resonant response at 150 kHz. The data were registered with a Micro II PCI-8 board provided by Mistras Group (Princeton, NJ, USA). The evolution of the pulse velocity is related to the development of stiffness as it increases with time due to curing.

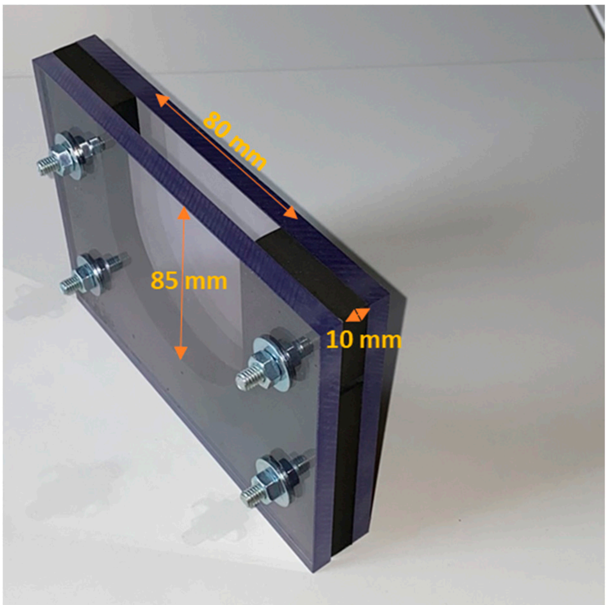


Figure 2. UPV mold dimension.

The dynamic Young's modulus was calculated from the following Equation:

$$E = \rho * \frac{(1+\nu) * (1-2*\nu)}{(1-\nu)} * V_l^2 \tag{3}$$

where ρ is the density, ν is the Poisson's ratio, and V_l is the longitudinal wave velocity.

3. Results and Discussion

3.1. Curing Monitoring by MMW Spectroscopy

Figure 3a shows the electromagnetic reflection response (S11) for a TRC sample immediately after casting, and 24 h later for frequencies ranging from 45 to 65 GHz. The S11 response shows good sensitivity of the technique to track the hydration of the cementitious matrix of TRC, evidenced by a reduction in the amplitude of the reflected waves (in this frequency range). On the other hand, Figure 3b shows the EM transmission response (S21) for the same sample, evidencing an increase in transmission during the first 24 h of hydration and curing. Additionally, Figure 3b exhibits a frequency dependence of the transmitted EM wave, with higher attenuation for higher frequencies.

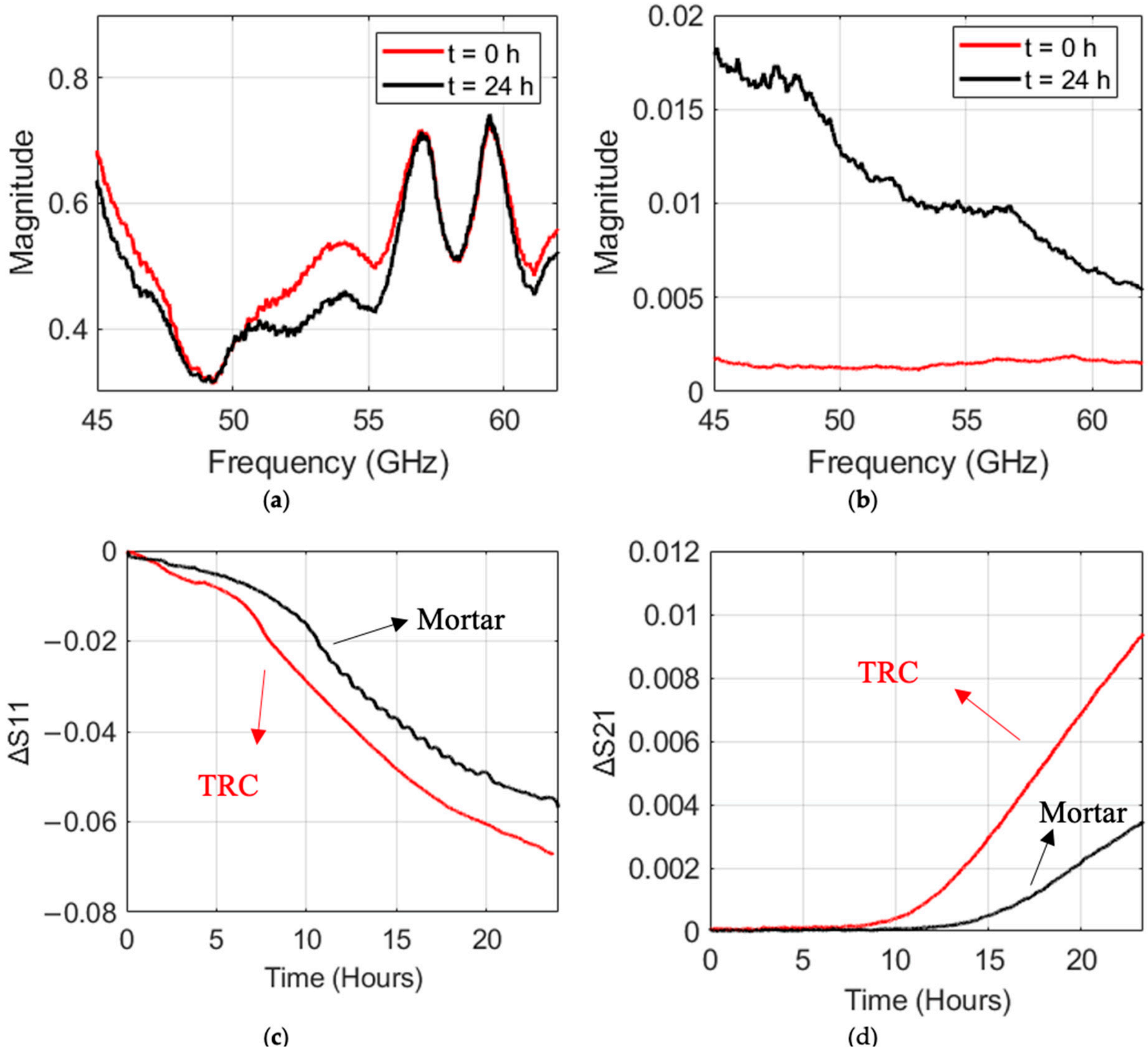


Figure 3. TRC (**a**) S11 and (**b**) S21 immediately after casting, and at 24 h after casting. Change in (**c**) S11 and (**d**) S21 in time for a TRC and a mortar sample for a frequency of 52.5 GHz.

In order to follow the evolution of S11 and S21 in time, a single frequency of 52.5 GHz was selected. Figure 3c,d show this change. Figure 3c depicts small changes in the first 5 h, followed by rapid changes 7 to 24 h after casting. On the other hand, the change in S21 seems to start at 7 h after casting followed by an accelerated amplitude rise. Clearly, TRC and mortar inspection trends present differences, especially in magnitude, which is attributed to the presence of non-reactive textile reinforcement. In any case, it is evident that the EM response, both in transmission, and reflection mode for TRC is driven by the physico-chemical changes produced by the hydration of the cementitious matrix.

3.2. UPV

Figure 4a shows the development of UPV the first 24 h of hydration and curing for both a TRC and a mortar sample. The first 3 h, both samples exhibit a dormant period, followed by a rapid increase in velocity, and after 7 h, the velocity keeps increasing with a decelerated tendence. Additionally, the similarity of both the TRC and mortar sample implies that the changes in the velocity of TRC are mainly affected by the hydration of the cementitious matrix.

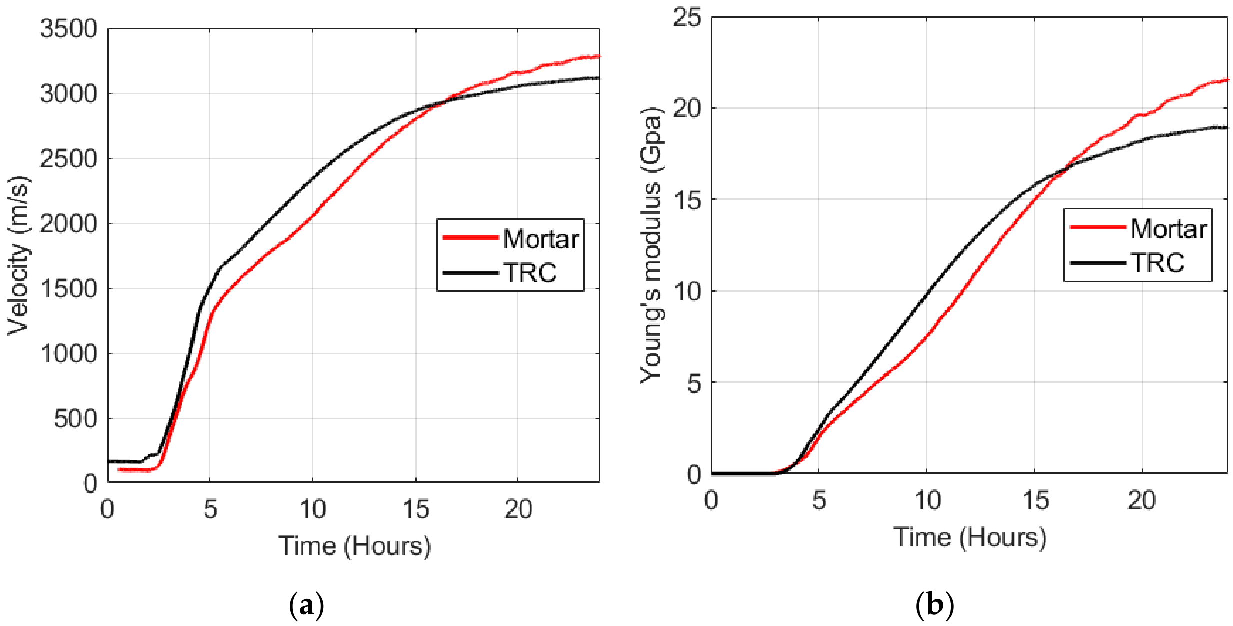


Figure 4. (**a**) Pulse velocity and (**b**) Young's modulus of a mortar and a TRC sample.

Figure 4b shows the development of stiffness (Young's modulus) for both a mortar and a TRC sample, as obtained from Equation (3). As expected, the increase in stiffness shows a similar behavior to the increase in UPV, reaching approximately 22 GPa for the mortar, and 19 GPa for the TRC.

4. Conclusions

A multi-modal approach for monitoring the hydration of TRC and mortar was attempted. Results show high sensitivity of the techniques to the physico-chemical changes occurring due to the hydration of the cementitious matrix:

- MMW shows high sensitivity to the chemical reactions of mortar in transmission and in reflection. It is clear that the EM response in the millimeter wavelengths of TRC and mortar during the first 24 h of hydration and curing are time- and frequency-dependent.
- Ultrasound pulse velocity shows a good sensitivity to the hydration of the cementitious matrix of TRC, being the main contributor to the change in velocity and development of Young's modulus on fresh state.

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