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3D MAPPING OF STIFFNESS EVOLUTION OF HARDENING CONCRETE WITH SAPs USING ELASTIC WAVE TOMOGRAPHY

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Abstract
Phenomena occurring during the delicate phase of concrete curing can have a strong influence on the final mechanical properties. Therefore, monitoring the changes during hydration can provide meaningful information on the material properties. Lately, non-destructive techniques have received great attention for monitoring early-age concrete. This paper aims to assess the ultrasonic velocity and stiffness development of hardening concrete during various curing stages using the Elastic Wave Tomography (EWT) technique. The monitoring of the curing process starts as soon as seven hours after casting and lasts up to seventy hours. A three-dimensional (3D) wave velocity map is created, and conventional concrete is compared to concrete containing SuperAbsorbent Polymers (SAPs), a novel admixture used for shrinkage mitigation by providing internal curing in the cementitious matrix. However, SAPs have been proven to reduce compressive strength when added to concrete, due to the increased porosity they induce. This porosity may also result in the reduction of the wave velocity. However, the internal curing provided by the SAPs can promote the formation of new hydration products in the matrix and thus (partly) compensate for the strength loss making the uniformity of the internal curing another important point of concern. EWT can provide global information on the homogeneity of the influence of the SAPs in the cementitious matrix as opposed to the wave velocity of a single wave path that is usually examined in practice. In addition, the determination of the early-age stiffness evolution can be connected to the final mechanical properties of the material. The dynamic Young's Modulus is calculated and compared to the static Young's modulus at 28 days. Predictions towards the static Young's modulus are also made, showing good agreement.

Keywords: hardening concrete, superabsorbent polymers, elastic wave tomography, dynamic Young's modulus

1. Introduction

Recently, nondestructive evaluation (NDE) methods have been developed to assess the stability and durability of existing structures or to monitor the development of strength and elastic modulus during the construction phase. Monitoring the evolution of the elastic wave velocity which is connected to the elastic, or Young's modulus, is therefore important since it is closely related to the structure's stiffness development. Acoustic techniques such as ultrasonic testing (UT) are generally used to assess the early-age behavior of concrete [1, 2]. However, conventional UT testing provides a point measurement of the elastic wave. Valuable information concerning the uniformity of the velocity in the material's whole volume is lost. More advanced ultrasonic techniques such as Elastic Wave Tomography (EWT) can provide 2D or 3D measurements of the velocity evolution [3] and contribute to damage detection and visualization.
Young's modulus can be divided into static and dynamic. The static Young's modulus (E_s) can be obtained from the stress-strain curve during a uniaxial compression test. E_s is usually the slope of a line drawn from a point representing a longitudinal strain of $50x10^{-6}$ to a point at 40% of ultimate strength [4]. The dynamic elastic modulus (E_d) corresponds to the initial tangent

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modulus where strains are very low. While for calculating E_s destructive methods are needed, E_d can be calculated in a non-destructive manner using the elastic compressional and shear wave velocities [5]. The dynamic modulus is usually 20% greater than static moduli for high-strength concretes, 30% for medium-strength concretes, and 40% for low-strength concretes [6]. The elastic properties of concrete depend largely on the properties of its components and of the interface between the matrix and the aggregates. Knowing the dynamic Young's modulus, equations can be used to predict the static Young's modulus, and therefore, estimate the final quality of concrete from an early age [5].

Monitoring the evolution of the mechanical properties is of even higher importance when novel admixtures, such as SuperAbsorbent Polymers (SAPs), are added to concrete. SAPs are hydrophilic, cross-linked, three-dimensional polymer networks that can be used for internal curing purposes, especially for high-performance concretes, where shrinkage is a major concern. These polymers can swell by entraping large amounts of water, up to a thousand times their dry weight and are used to mitigate or prevent shrinkage in early-age concrete [7, 8]. The internal curing water is stored in the SAP and can therefore be used to protect the material for a longer time against shrinkage until a suitable tensile strength has been gained. Once the internal curing water is exhausted, the SAPs will shrink, leaving behind a macropore, which results in an increased porosity of the overall matrix.

The purpose of this research is to monitor the evolution of the elastic wave velocity of conventional concrete and SAP-modified concrete. The elastic wave velocity is closely related to the dynamic Young's modulus, and therefore to the material's stiffness. The novelty of the study is the 3D mapping of the stiffness evolution of early-age concrete curing, instead of the conventional through-the-thickness ultrasonic measurements. The results show that SAP concrete has a slightly slower stiffness development than conventional concrete, which is attributed to the delayed hydration induced by the overall higher amount of available water in the matrix. However, the stiffness reaches the same value after 3 days of curing. The SAP concrete showed a higher 3D velocity variation in the first 10h of curing compared to the REF concrete, which was mitigated subsequently. Finally, a brief comparison between the dynamic elastic modulus obtained by the EWT method and the conventional UPV method is performed and predictions are made towards the static Young's modulus.

2. Materials and methods

2.1 Materials

Two compositions were studied for this investigation. A reference mixture, named REF in this paper, and a mixture containing Superabsorbent Polymers (SAPs), here named SAP. The concrete composition can be found in Table 1. Portland cement CEM I 32.5 N (Origin Japan) was used and the compositions were made with a low water-to-cement ratio, equal to 0.35. To ensure sufficient workability a superplasticizer (BASF, Japan) was added to the mix at a percentage of 1.4% by cement weight. The second composition investigated contained 0.2% SAPs per cement weight and had the same component proportions as the REF mix. The utilized SAPs were provided by Floerger (SNF, Germany), and are a bulk-polymerized, cross-linked copolymer of acrylamide and acrylate, with a particle size d_{50} of approximately 250 μm. The specific SAP has a swelling capacity of 308.2 ± 4.7 g/g SAP in demineralized water and 37.9 ± 1.6 g/g SAP in cement filtrate solution [9]. This SAP type was used in this study to stimulate internal curing. Since SAPs absorb part of the available water during mixing by swelling, additional water was used for internal curing purposes was equal to 20 grams per gram of SAP. This extra amount of water (an additional 0.04 of the w/c ratio) was entrained in the SAP particles while mixing and was gradually released during hydration, resulting in a cement paste with the same effective water-to-binder ratio of 0.35 as the REF mix. Both mixtures resulted in a slump value of 2 cm.

Table 1. Concrete compositions (all units are in kg/m^3)

Composition	Cement	Sand ($d_{max} = 5$)	Gravel ($d_{max} = 20$)	Water	SP	SAPs	Density
REF	388	981	915	136	5.43	-	2425
SAP	380	963	898	148	5.32	0.78	2395

2.2 Specimens

The studied specimens were concrete cubes with sides of 150 mm. The mixture was prepared using a laboratory concrete mixer. The total mixing time was four minutes – one minute of dry mixing, followed by three minutes of mixing with water. The SAPs were added to the dry components. Then the material was poured into a 150 mm (internal dimensions) wooden mould and vibrated for 1-2 minutes. The cubes were left to cure at room temperature and were then carefully demoulded 4h after casting, when sufficient stiffness was achieved. The specimens were left exposed to air in order to dry so that the AE sensors could be attached directly to the concrete surface. At around 7h, the sensors were attached. The procedure can be seen in Fig. 1. All measurements took place at a temperature of 20 ± 1 °C.

2.3 Methods

2.3.1 Elastic Wave Tomography

The Elastic Wave Tomography (EWT) method is based on the generation of elastic waves using the impact method on the surface of concrete structures. The waves are then received by an arrangement of acoustic sensors that are located on the opposite side of the structure. The data is then used to calculate the distribution of the elastic wave velocity in the examined structure, which can then be visualized in 2D or 3D [10]. Using this method, the evolution of the stiffness of the material can be assessed, while internal inhomogeneities and defects can be detected. EWT follows the seismic approach and uses the SIRT (Simultaneous Iterative Reconstruction Technique). A mesh is initially created representing the specimen's geometry and an initial velocity is assigned at each mesh element. The Akaike Information Criterion (AIC) is used to determine the arrival times of the recorded waves at each sensor [11]. After the arrival time has been determined, the velocity can be calculated through an iterative process, using a ray path trace algorithm, to minimize any errors. More details about the method can be found in [3].
A REF and a SAP specimen were simultaneously cast and monitored. Initially, the concrete cubes were cast in a wooden mould. Around 4h after mixing, the specimen was demoulded and the free surfaces were left to dry on a rubber surface. To avoid restraints, silicon grease was applied between the specimen's bottom side and the rubber surface. Around 6h of curing, the sensors were attached to the concrete surface and the monitoring started at 7h of curing (Fig. 1). A satisfactory stiffness has to be developed in order to perform the EWT by attaching the sensors directly to the material. The acquisition was performed by Micro-II express acquisition system of Mistras Group. The Pencil Lead Break (PLB) method was utilized in this study to generate the elastic waveforms (impact or generating points). For this study, a total of 8 R15α piezoelectric sensors (Physical Acoustics) of 150kHz resonant frequency were used and placed on two opposite sides of the specimen, to record the generated waves, as shown in Fig. 1 and 2.

The sensors were attached to the concrete's surface using hot glue. A 1045S (Fujisera) wideband sensor was used as the reference sensor placed next to the PLB points which served as a trigger and its recorded data was used for the calculation of the arrival times. The reference sensor's coupling was carried out using silicone grease. The PLB was performed at 42 points (21 on each side). The PLB generating points can be found in Fig. 2. A total of 12 sets of PLB tests were performed at various curing stages, starting at 7h after mixing, up to 69h. A 10x10x10 element mesh was initially created to model the velocity evolution, however, a 8x8x8 mesh was eventually used since the elastic waves did not pass through some outer areas of the specimen, resulting in insufficient information. The EWT software used in this study was developed by Kyoto University.

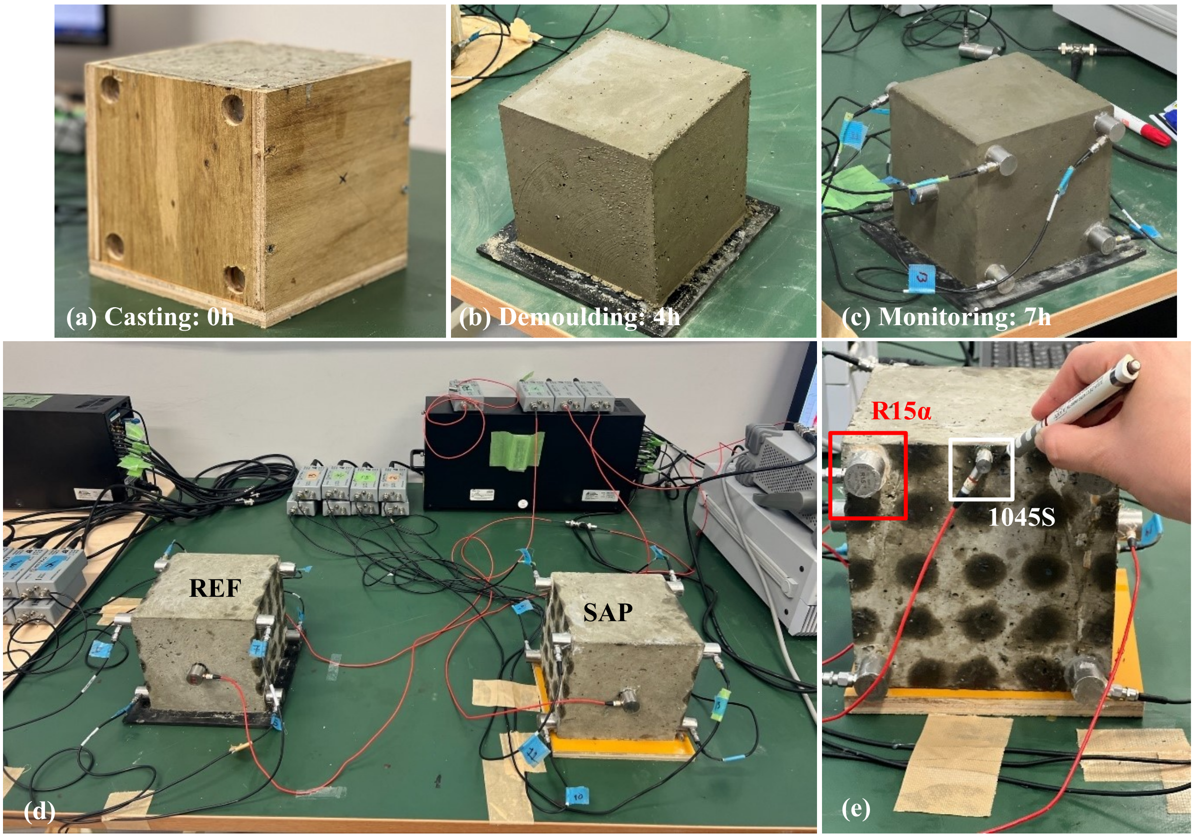

Fig. 1 Experimental setup: (a) freshly cast concrete, (b) demoulded specimen, (c) specimen with attached sensors, (d) simultaneous monitoring of REF and SAP concrete, (e) utilized sensors and PLB testing.

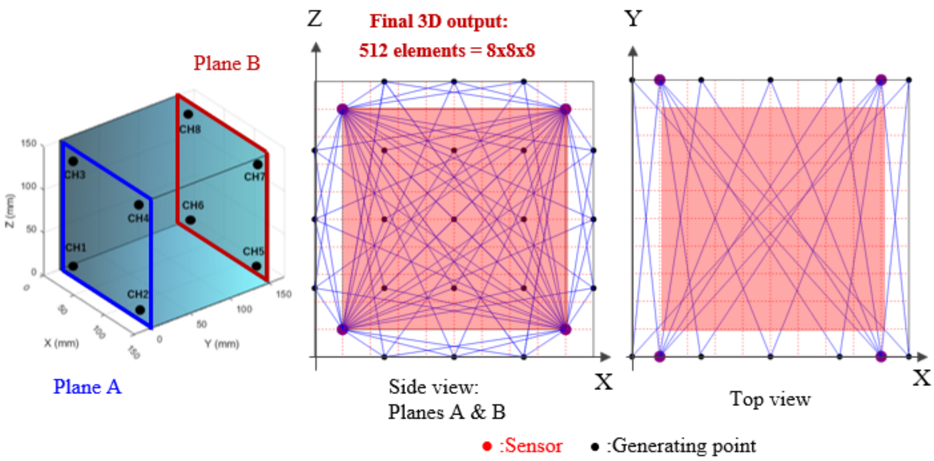

Fig. 2 Mesh, ray path, sensor and generating (impact) point layout.

2.3.1 Confirmation through Ultrasonic Pulse Velocity

The UPV method has been widely used in recent years to calculate the setting time of cementitious materials. To evaluate the results obtained from EWT, the evolution of the E-modulus and Poisson's ratio were also determined using the FreshCon device [2] for the two compositions. The technique is based on the conventional through-the-thickness UPV measurements. The experiments were performed on a 47.5 mm thick, U-shaped mold. More details about the method and the experimental setup can be found in [2]. The monitoring started 5-10 minutes after casting and lasted 3 days. The utilized pulse had a voltage of 450 V and a width of 5 μs and it was sent every 3 minutes.

2.3.3 Compression test

Compression tests were performed on cylindrical specimens at 28 days of age. An automatic pressure testing machine (Makaewa, Japan) was used for the experiments. A total of three specimens were used to evaluate the compressive strength for each composition, while one of them was subjected to a cyclic load 3 times, up to approximately 40% of strength, before being broken, to obtain the static Young's modulus. Two strain gauges were attached diametrically to the specimens to obtain the stress-strain curves.

3. Results and discussion

3.1 Elastic wave velocity evolution

The hydration of cement is a complex chemical process that involves physical changes from the liquid fresh state to the solid, hardened state. Ultrasonic velocity is not very sensitive in capturing the microstructural changes during the very early stage of hydration, due to the high attenuation of the viscous material. During this early stage, it is mainly the entrapped air and water that determine the velocity. As cement particles gradually react with water, those particles connect together, slowly forming a solid network and allowing for the elastic wave to pass with a lower attenuation. Generally, ultrasonic waves in a material are strongly dependent on the stiffness development.

The velocity of the 512 elements was averaged and the mean velocity evolution and the Coefficient of Variation (COV) are displayed in Fig. 3. The velocity values of the SAP concrete at early stages are slightly lower compared to the REF concrete possibly because of the higher overall water present in the matrix (but entrapped in the SAPs), delaying the velocity and stiffness development. Even though the extra water is entrapped in the SAPs initially, it will become free water available for hydration once released, allowing for a longer available free-water timeframe compared to the REF composition. This trend is generally observed in literature where compositions with higher w/c ratios show lower velocity values [1]. The overall w/c ratio in the SAP concrete is 0.39, while for the REF concrete amounts to 0.35, resulting in a difference of approximately 10%. A study found that for a 20% increase in w/c ratio (from 0.45 to 0.55), the UPV of mortar decreased by 8-10% after 50h of curing [12]. A similar result was observed here, where after 50 h of curing, the SAP concrete with a 10% higher water content, showed 4% lower average velocity. However, at approximately 70h, the velocities reach a similar value, showing that SAPs do not lower the overall stiffness of the material in the longer term.

Regarding the COV, initially (7h), it is very high for the SAP concrete (23%) compared to the REF concrete (5%). This is probably because the water-filled SAPs alter the microstructure of the matrix, resulting in further reflections and scattering of the generated signal, affecting therefore the velocity values in the different cells. However, at around 10h, when SAPs are estimated to start releasing their internal curing water, the COV drops to 8% and subsequently, it starts converging to the COV of the REF specimen. After 20h, the COV is lower for the SAP concrete compared to the REF concrete. At that time most of the internal curing water has been released by the SAPs. The lower COV might be an indication of shrinkage and microcracking mitigation and overall better curing in the SAP concrete, resulting in more homogeneous velocity distribution in the cells.

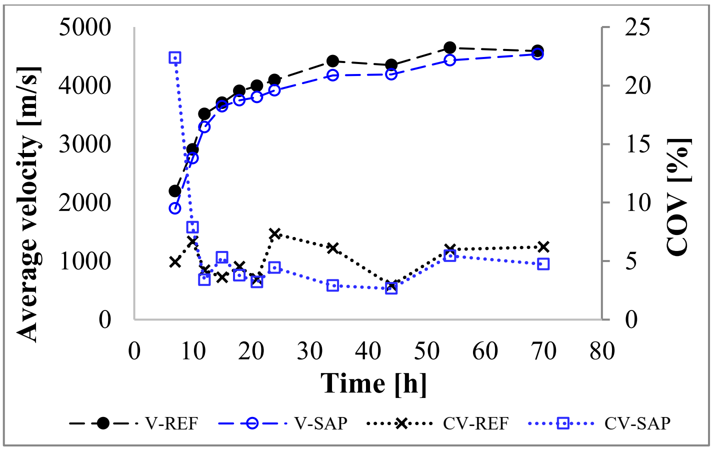

Fig. 3 Average elastic wave velocity evolution for REF and SAP concrete and coefficient of variation (COV) as obtained from EWT.

Fig. 4 shows the 3D velocity evolution of the REF and SAP concrete. No significant variances can be visually observed for SAP concrete, indicating uniform curing. Initially, at 7h the velocity is quite low for both compositions, representing the fresh, uncured nature of concrete. This is accompanied by a high variance in the 3D velocity of SAP concrete, as discussed above. A visible increase is observed at 10h for the REF concrete, where the colour shifts to yellow-green, indicating the formation of hydration reaction products and the increased connection between the solid phases. For the SAP concrete, this increase is more gradual. This visualizes the assumption that the SAPs delay the curing process. Another considerable shift in velocity is observed from 24 to 29h for the SAP specimen. This might be due to the fact that by that time a large amount of the internal curing water was already provided to the matrix. The specific SAP type starts releasing water at 10-12 h (depending on the environmental conditions) and most of their internal curing activity is completed up to approximately 50 h. This is also observed in the contour graphs, where up to 54 h, the activated SAPs seem to delay the velocity evolution, while at 69 h, when the SAP activity is completed, the two specimens seem to reach the same velocity values. In Fig. 5 the average velocity obtained from EWT is compared to the velocity obtained from UPV measurements performed using the FreshCon device. The UPV measurements give relatively higher velocity values at 7 h compared to EWT, probably due to the small thickness of the specimens and high aggregate content, leading to greater initial velocities than expected. Moreover, at early ages, the deviation between the two methods is higher due to the material's high attenuation. This is also observed in the literature, where the measurements during the fresh state are more dependent on the experimental setup and the utilized frequencies [1]. However, at later stages, when the material is hardened, the velocity values derived from the two techniques seem to converge, given that the attenuation is much lower, demonstrating the accuracy of the EWT method.

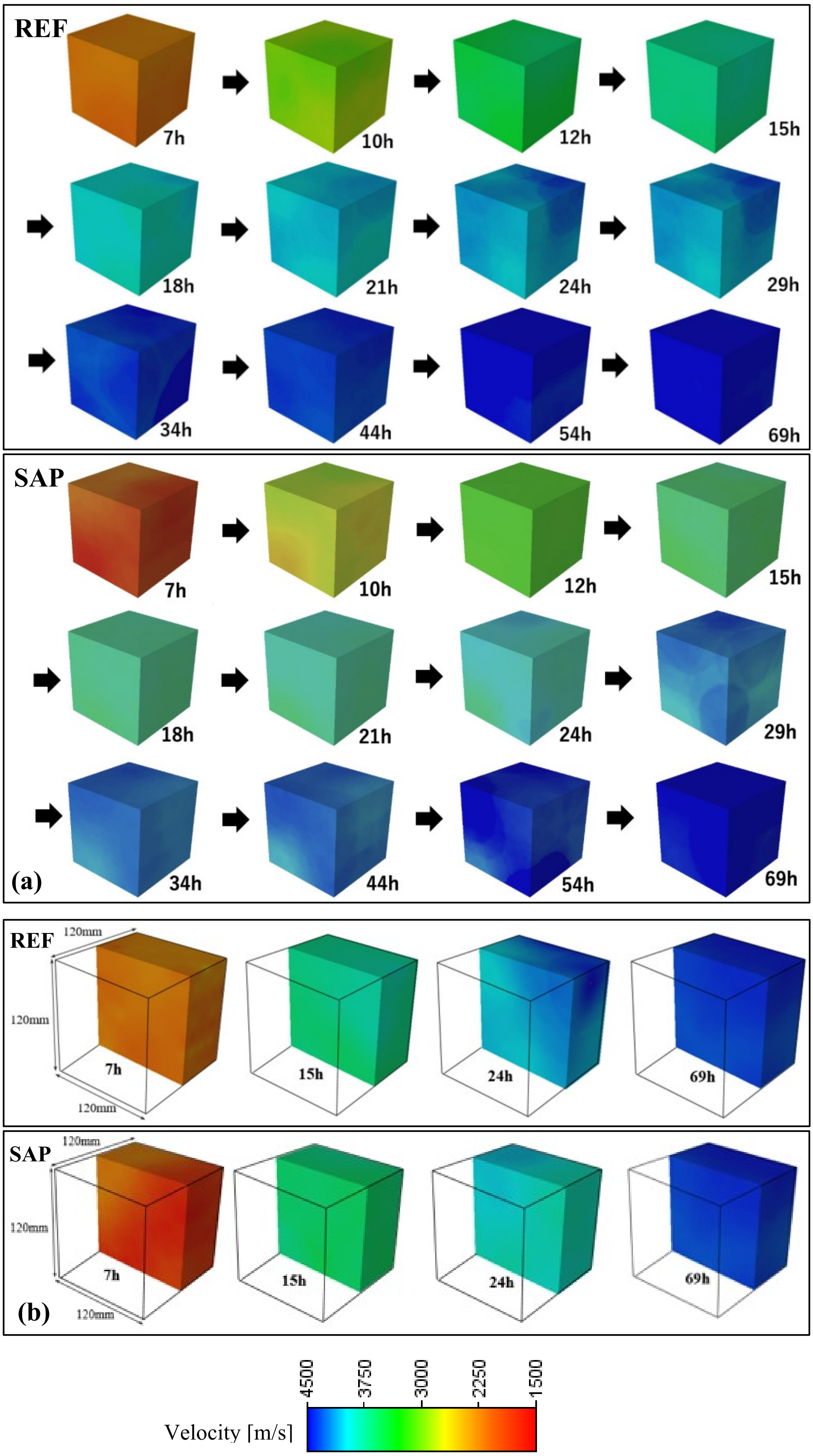

Fig. 4 3D evolution of elastic wave velocity for REF and SAP concrete (a) in the whole volume and (b) mid-cross-section.

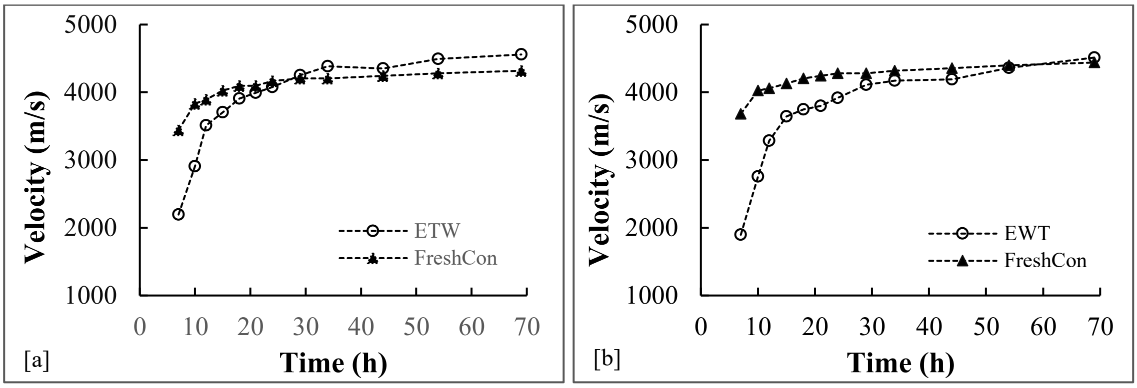

Fig. 5 **Elastic wave velocity evolution for (a) REF and (b) SAP concrete obtained from EWT and FreshCon.**

3.2 Dynamic Young's modulus evolution

The dynamic modulus of elasticity of concrete can be calculated using the following equation if the density and the Poisson's ratio of concrete are known [13]:

$$E_d = \rho {V_p}^2 \frac{(1+v)(1-2v)}{(1-v)} \tag{1}$$

where, density ρ was taken equal to 2425 $\frac{kg}{m^3}$ for REF composition and 2395 $\frac{kg}{m^3}$ for the SAP composition, V_p is the velocity obtained from EWT, and v is the Poisson's ratio. The Poisson's ratio value was adapted to the curing time, and the values were taken from the FreshCon measurements performed on the same compositions. The results are shown in Fig. 6.

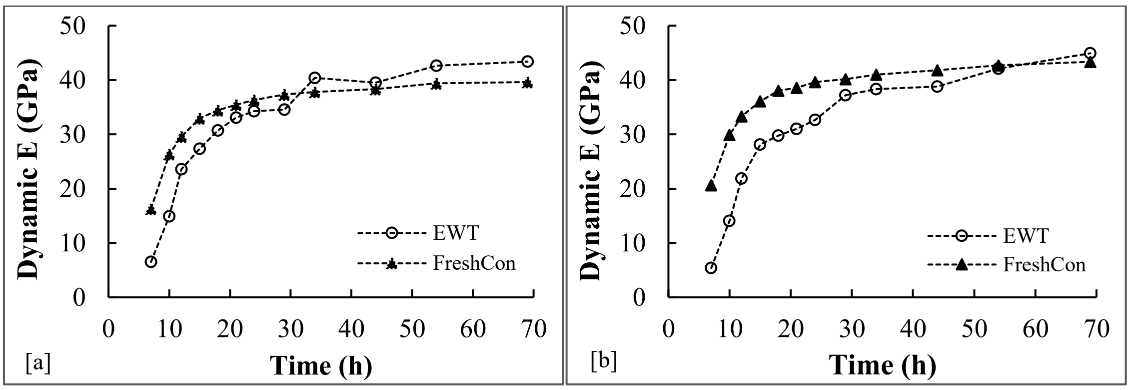

Fig. 6 **Dynamic Young's modulus evolution for (a) REF and (b) SAP concrete obtained from the EWT and UPV techniques.**

E_d is slightly higher for the SAP composition, which is attributed to the generally lower Poisson's ratio of SAP concrete obtained by the FreshCon device. This will result in possible different trends in the evolution of Young's modulus when compared to the velocity. Moreover, the densities of the two materials are slightly different due to the increased porosity of SAP concrete.

In the fresh state, the deviation is higher due to the material's high attenuation. However, at later stages, when the material is hardened, Young's modulus values derived from the two techniques seem to converge. For both compositions, up to approximately 30h of curing, a deviation is obvious. This deviation between the two methods is higher for the SAP composition compared to the REF. For the SAP concrete, it seems that from 30 h of curing onwards, the values from the two methods start to converge. This might be because during the first 30 h, SAPs are most active, and most of the internal curing takes place. This will result in reflections and scattering of the elastic waves, causing higher differences between the two methods. Another observation is that E_d, as obtained from EWT, increases at a higher rate, compared to the one obtained from the UPV method, especially at later ages. UPV monitors only the microstructural changes occurring in the center of the specimen's volume, and this part will develop its strength faster, due to higher internal temperature compared to the outer part. The latter, along with the smaller thickness of the specimen, and variation in the experimental setup and frequencies, would explain the fact the velocity obtained by FreshCon reaches a plateau relatively early. However, EWT takes into account the whole volume of the material, where the hydration is still ongoing in the external parts of the specimen, and this is reflected in the continuous growing velocity, and therefore, E_d, for both concrete compositions.

3.3 Final mechanical properties

After SAPs release all of their entrained water, they collapse leaving behind voids in the hardened cementitious matrix. Literature suggests that SAPs generally result in a reduction of compressive strength at early ages compared to standard concrete, which might however be compensated at later ages by the enhanced hydration achieved by the internal curing water [7]. Most studies show a reduction in strength [14, 15]. However, other studies don't seem to observe a decrease in the compressive strength of SAP concrete [16, 17]. The impact of SAPs on the mechanical properties depends on the mixture composition, curing conditions, SAP content and type and testing age. The results of this study are shown in Fig. 7.

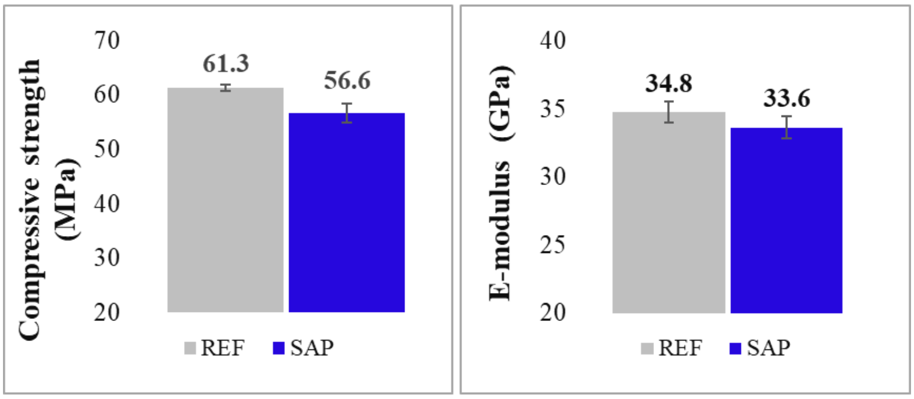

Fig. 7 (a) Compressive strength and (b) static Young's modulus at 28 days.

The compressive tests performed at 28 days of curing showed a slight decrease in strength for SAP concrete, which is due to the increased porosity, as aforementioned. This decrease is also reflected in the value of the static Young's modulus. However, the compressive strength and static Young's modulus, decrease only by 9.1% and 3.2%, respectively, showing that the SAPs can be used for internal curing purposes without having a significant impact on the mechanical properties.

3.4 Prediction of 28-day static modulus based on early-age dynamic measurements

The dynamic Young's modulus of concrete can be correlated to the static Young's modulus through the following equation proposed by Han et al. [18]:

$$E_s = E_d\,(1 - \alpha e^{-bE_d}) \tag{1}$$

Where α and b are constants equal to 0.492 and 0.0177 for curing at 23 °C, type I cement and w/c ratio of 0.40. If the 3-day dynamic E modulus is considered from the measurements, the static E_s modulus can be predicted using (1) and compared to the experimentally measured E_S, as shown in Table 2. It can be seen that the dynamic modulus is constantly higher than the static modulus. This is expected as dynamic testing usually results in higher modulus values due to the higher strain rates involved compared to static testing. From the EWT method, the obtained dynamic modulus is 20% higher than the static modulus, while for the SAP concrete, the percentage rises to approximately 25%. These percentages are often found in literature, where for medium to high strength concretes, E_d is usually 20-30% higher than E_s [6]. The FreshCon measurements showed a 12.27% and 22.44% higher dynamic modulus for REF and SAP compositions compared to the static Young's modulus.

Table 2. Comparison of E_s to E_d and prediction of E_s based on E_d.

	REF	SAP	REF	SAP
E modulus	E (GPa)	E (GPa)	Deviation predicted from measured E_s (%)	
E_d – EWT	43.83	44.83	-	-
E_d – FreshCon	39.62	43.36	-	-
E_s – measured	**34.76**	**33.63**	**0.00**	**0.00**
E_s – predicted by EWT	33.90	34.85	2.52	3.51
E_s – predicted by FreshCon	29.95	33.46	16.05	0.52

The predicted values of static modulus based on dynamic measurements show varying levels of accuracy for the two methods. EWT seems to result in a more stable prediction accuracy of 2.52-3.51 %, while UPV measurements show a high deviation for the REF concrete, equal to 16.05 %, but quite an accurate prediction for the SAP concrete with an error of 0.52%. Nevertheless, EWT can provide a quite accurate representation of the 28-day static Young's modulus, with an error of less than 4%, as soon as 3 days of curing.

4. Conclusions

In this study, the stiffness development of normal concrete and concrete with SuperAbsorbent Polymers (SAPs) was assessed by means of Elastic Wave Tomography (EWT) and Ultrasonic Pulse Velocity (UPV). EWT was able to provide a successful 3D view of the elastic wave velocity evolution of the two compositions, starting at 7h after mixing. The various curing stages and the velocity evolution showed a relatively homogenous development of the velocity value along the volume. The Elastic Young's modulus evolution was calculated up to 3 days of curing, based on the velocity values obtained by the two methods. The static Young's modulus was calculated at 28 days of curing.

Predictions were made towards the final static Young's modulus using early-age dynamic measurements. The results showed that SAP concrete exhibited a slower development compared to the REF concrete, due to the overall higher amount of water present in the matrix. No significant inhomogeneities were found in the velocity evolution of SAP concrete, confirming that SAPs provide uniform curing. When compared to the conventional UPV technique, EWT provides a more sensitive measurement in monitoring the velocity evolution, showing a continuous increase in the velocity vs. time curve, as opposed to the UPV measurements, exhibiting high initial values and reaching a plateau relatively early. The 28-day static Young's modulus was predicted with a less than 4% error using the 3-day dynamic values of EWT, while the predictions made using the UPV values presented errors up to 16%.

The 3D stiffness evolution of SAP concrete is studied successfully for the first time in literature, starting as soon as 7h after mixing. However, this study of EWT is limited to only 2 specimens, due to the intense and time-consuming experimental procedure. A larger number of specimens, the use of more generating points on the surface of the material and a more refined computational mesh will upgrade the accuracy of the measurements.

Acknowledgments

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