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Short-term elastic characterization of an innovative non-cementitious bi-component grout by means of ultrasonic pulse velocity

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ABSTRACT: Backfilling is a crucial process when using a shielded machine for tunneling, and two-component grout (2CG) is undoubtedly the most common solution for backfilling. In response to environmental concerns, some novel 2CGs are gaining attention for their low carbon footprint. The mechanical characterization of these materials is fundamental to their applicability, although only their elastic properties can be measured soon after the casting. We focus on the elastic characterization of the product Mapequick CBS Active CF System, an innovative cement-free 2CG. The non-invasive geophysical technique called ultrasonic pulse velocity (UPV) was employed to measure the elastic properties of the grout at specific time intervals, ranging from 1 hour up to 24 hours and 28 days after the casting. After analyzing the UPV data, the Poisson's ratio, as well as the dynamic elastic, shear, and bulk moduli were determined. The obtained results were compared with those of a standard cement-based 2CG. The outcomes of this work prove the suitability of Mapequick CBS Active CF System as an effective backfilling material as well as the profitable use of the innovative system based on UPV to investigate the elastic properties of 2CGs.

1 INTRODUCTION

In modern tunneling, shielded tunnel boring machines (TBMs) are commonly used, particularly when excavating long tunnels through fractured rock and soil. An intrinsic characteristic of these machines is that they create an annular gap between the tunnel lining and the surrounding ground as they advance. This gap, known as annulus, is created due to several factors, i.e., overcutting tools, shield conicity, tail brushes, and the shield itself (Thewes & Budach 2009). Correctly filling this gap is crucial to minimize surface settlements and to ensure the structural integrity of the tunnel. One of the most widely adopted solutions for this purpose is the two-component grout (2CG) system, which is effective in both rock and soil conditions.

Traditional 2CG systems consist of a cementitious mortar (component A) and a sodium silicate-based accelerator (component B). This technology offers high stability, requires low pumping effort, and facilitates rapid gelation and hardening. These properties play an important role in reducing surface settlements and permitting to quickly stabilize the tunnel linings in the designed position (Dal Negro et al. 2017, Todaro et al. 2021). Once the two components are mixed, the grout begins to gel almost immediately, significantly increasing its mechanical strength in few hours after the gelation and providing an early load-bearing capacity (Oreste et al. 2021). However, despite the widespread use of 2CG systems, there is a growing interest in reducing their environmental impact, particularly by reducing the carbon footprint associated with cement-based products. In response, new cement-free 2CG systems have been developed and are currently being tested to assess their performance.

This study focuses on the elastic characterization of the Mapequick CBS Active CF System, an innovative 2CG without cement, hereafter referred to as cement-free 2CG or CF-2CG.

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The main objective is to evaluate the suitability of this grout for backfilling in tunneling projects, with particular attention to its elastic properties over time. To achieve this, a non-invasive geophysical technique, the ultrasonic pulse velocity (UPV) method, was utilized to assess the grout properties at various curing stages, ranging from 1 hour up to 28 days after the casting. The UPV method has been already applied for the elastic characterization of backfilling 2CGs (Todaro et al. 2020, Todaro & Pace 2022, Pace et al. 2024). Based on the UPV data, essential elastic parameters, including the Poisson's ratio, dynamic elastic modulus, shear modulus, and bulk modulus, were determined. These parameters are crucial for evaluating the grout ability to maintain the tunnel stability during the early curing stages.

The results of this study were compared to those of a standard cement-based 2CG, offering valuable insight into the performance differences between the traditional and innovative systems. The findings indicate that the Mapequick CBS Active CF System demonstrates promising elastic properties, positioning it as a viable and sustainable alternative for backfilling in tunneling projects.

2 MATERIAL

The tests were carried on CF-2CG samples produced according to the mix design reported in Table 1. The mixing phase has been carried out according to Todaro et al. (2019). The casting phase has been performed according to the procedure described in Todaro et al. (2020).

Table 1. The mix design for the cement-free 2CG. The mix design is referred to a cubic meter of two-component grout composed of components A and B.

	Ingredients	Dosage (kg/m^3)
Component A	Mapequick CBS Active CF	415
	Bentonite Mapebent CBS 4	20
	Water	713
	Mapequick Active ACF	66
Component B	Accelerator - Mapequick CBS System HEM SS 3	102

As pertaining to the characterization of component A, the assessment of the gel time and the characterization of the hardened grout at short and long curing times, the procedure specifically designed at Polytechnic of Turin was followed. It should be highlighted that the CF-2CG complies to the standard technical requirements of construction sites concerning the unit weight (ASTM D4380 2020), physical stability (UNI 11152-11 2005), workability and viscosity (UNI 11152-13 2005), as well as gel time (Todaro et al. 2019), surface compression strength (SCS) and uniaxial compression strength (UCS) (CEN 2016).

3 THE GEOPHYSICAL APPROACH: THE UPV METHOD

The dynamic elastic parameters of concrete-based or ceramic materials can be estimated by means of the UPV method (Sturrup et al. 1984, Todaro et al. 2020, Todaro & Pace 2022, Pace et al. 2024). It is a geophysical non-invasive method based on the propagation of longitudinal vibration pulses through materials and then on the measurement of the pulse velocities of the first-arrival elastic waves. These waves are the longitudinal and shear waves, also referred to as P-wave and S- wave, respectively.

At the laboratory scale, an ultrasonic pulse is forced to propagate through a specimen (usually with a cylindrical or prismatic shape) from an electro-acoustic transducer (the transmitter), which is placed in contact with one surface of the specimen, to another transducer (the receiver) placed on the opposite surface. The pair of transducers have usually a central frequency of 54 kHz and a natural frequency ranging from 100 to 250 kHz. Once the ultrasonic pulse is detected by the receiver, the travelling time is measured, and the ultrasonic velocity is easily calculated because the transmitter–receiver distance is known. The ultrasonic pulses depend on the density and elastic properties of the material (Aydin 2014).

The UPV method has been applied at a laboratory scale for the characterization of two-component grouts adopted in tunneling, and specifically, for the assessment of their elastic behavior (Todaro et al. 2020, Todaro & Pace 2022). The velocities of the first arrival of the longitudinal P-wave (V_p) and of the transverse S-wave (V_s) are calculated to finally retrieve the dynamic elastic properties of the investigated material. Given the sample length and recorded the first-arrival time, the velocities are calculated. Then, the dynamic Poisson's ratio (ν) can be calculated according to Equation 1 below. Given the material density (ρ), the dynamic shear modulus (G_d), elastic modulus (E_d) and bulk modulus (K_d) can be estimated using Equations 2,3,4, respectively:

$$\nu = \frac{V_p^2 - 2V_s^2}{2V_p^2 - 2V_s^2} \tag{1}$$

$$G_d = \rho V_s^2 \tag{2}$$

$$E_d = 2G_d(1+\nu) \tag{3}$$

$$K_d = \rho V_p^2 - \frac{4}{3}G_d \tag{4}$$

The UPV tests were carried out using the instrument Pundit PL200® (PROCEQ S.A. 2017). Pundit PL200® (Portable Ultrasonic Non-Destructive Digital Indicating Test) is a portable touchscreen device that has several functionalities. For example, it includes the automatic detection of the first arrival of the P and S waves so that V_p and V_s can be determined once the sample length is set in the device (acquisition in "pulse velocity" mode). This automatic picking can be further manually corrected for accurate data. Moreover, the acquisition in "data logging" mode allows automated test sequences for long term recordings of the pulse velocity, whose trend is shown graphically on screen. The device is connected to the power supply and has a small screen for the visualization and saving of the measurements. Pundit PL200® comprises a pulse generator, receiver amplifier and a time-measuring circuit. The acquisition settings of Pundit® PL-200 can be calibrated in real time depending on the case study. The receiver gain spans from 1x (0 dB) to 10000x (80 dB) with 11 different steps. The transmitter voltage spans from 100 V to 450 V. Other options that can be set by the user are the recording time, transducer type and frequency, sample size, file name.

4 THE UPV TEST CAMPAIGN

For our test campaign, the samples of the CF-2CG had a cylindrical shape, with a diameter of 52 mm and height of 130 mm. The mean density of the different samples used for the tests was 1317 kg/m^3.

To perform the UPV measurements, a pair of 250 kHz transducers were connected to the device via BNC cables. The transducer frequency was 250 kHz to be coherent with the small size of the samples and the known fine aggregate content. At the beginning of every UPV test, the transducers were zeroed by means of the calibration rod, whose transmission time was 25.4 µs. The UPV analysis was performed at specific time steps after the casting, from 1 hour to 24 hours and then up to 7 and 28 days. From 1 to 24 hours after the casting, the measurements were continuously recorded in "data logging" mode, every 30 minutes. Separate measurements in "pulse velocity" mode were recorded at 1 hour and 24 hours after the casting, that is, at the beginning and at the end of the data logging, and then at 7 and 28 days. In the meantime, the samples were stored in water, which is the common curing condition for the UPV tests on 2CGs (Todaro et al. 2020, Todaro & Pace 2022, Pace et al. 2024). To improve the quality of the recorded signals, the measurements recorded in "data logging" mode were carried out on two different instruments Pundit PL200®, one connected with the P-wave transducers and another one with the S-wave transducers. This way, three main advantages were ensured:

1) the P-wave and S-wave records were executed in parallel data logging and were perfectly synchronized;
2) the samples were not disturbed by the handling of the operator and kept on acquiring the signal for 24 consecutive hours;
3) the P-wave and S-wave signals were recorded by their respective transducers, thus ensuring no ambiguity in the interpretation of the waveforms.

The gain and voltage of the UPV acquisitions were set to record a clean signal without noise nor saturation and hence were changed at around every two hours. The receiver gain was set between 100x and 10000x at the beginning (1 hour of curing time) and between 20x and 50x at 28 days of curing time. The transmitter voltage was set between 50 V and 250 V, depending on the signal quality. The typical laboratory setup is represented in Figure 1.

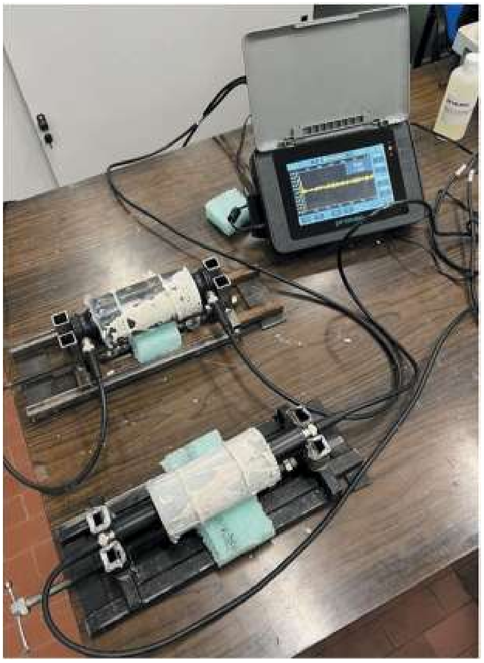

Figure 1. The samples of the CF-2CG for the UPV test with S-wave and P-wave transducers.

5 RESULTS

A preliminary analysis of the recorded signals was conducted on the software PL-Link (https://www.screeningeagle.com/en/download/). Then, the recorded waveforms were imported in Matlab® and the picking of the first arrival was accurately performed using a proprietary code. After that V_p and V_s were estimated, the dynamic E_d, G_d, K_d and ν were calculated for every sample at every time step.

The quality of the recorded signals was generally good, with this significant distinction. In the short term, that is, up to few hours after the casting, the signal quality was poor and specific care had to be devoted to the picking of the first arrival of the S-wave. In the long term, the signal quality was clear and unquestionable.

The S-wave signal at 1 hour after the casting was not detectable, since the signal was so noisy that it was not possible to understand a clear signature of the S-wave. This was not expected since the UPV signal was detected at 30 minutes after the casting for other 2CGs (Todaro & Pace 2022). However, the issue can be explained with the fact that the mix design of the investigated material has a large amount of water, where the S-waves do not travel. If the S-wave signal does not clearly propagate after the casting, then the dynamic elastic modulus may not be determined (see Equation 3). As soon as the material started hardening, it dried and leaked water, thus allowing the detection of the S-wave signal. It was observed that after two hours from the casting the signal had a good quality.

Table 2 lists the values of V_p, V_s, ν and the dynamic moduli (E_d, G_d, K_d) at specific time steps: 1, 2, 10, 12, 15 and 24 hours, and 7 and 28 days after the casting. It is worth mentioning that the material density did not change appreciably in the investigated time frame, as also demonstrated for other 2CGs (Todaro & Pace 2022, Pace et al. 2024).

Table 2. V_p, V_s, ν, E_d, G_d, K_d at different curing times for the CF-2CG.

Curing time	V_p (m/s)	V_s (m/s)	ν (-)	E_d (GPa)	G_d (GPa)	K_d (GPa)
1 h	1503.4	Undetectable	-	-	-	-
2 h	1524.4	243.0	0.4880	0.23	0.078	3.310
10 h	1547.6	289.5	0.4880	0.33	0.078	3.310
12 h	1547.6	486.9	0.4819	0.90	0.110	3.154
15 h	1547.6	528.5	0.4451	1.05	0.312	3.154
24 h	1460.7	610.3	0.4340	1.37	0.368	3.154
7 days	2016.1	1106.2	0.3942	4.14	0.491	2.810
28 days	2243.7	1131.6	0.2846	4.76	1.612	5.353

Figure 2 graphically shows the results listed in Table 2. Figure 2a represents V_p and V_s with solid and dotted lines, respectively. Only V_p was detectable at 1 hour after the casting. Figure 2b represents E_d, G_d and K_d with solid, dotted and dashed lines, respectively. Figure 2c represents the Poisson's ratio with a solid black line. In all cases, a slight parameter variation was observed within 10 hours of curing, while, after, a significant change appeared. From 2 hours to 28 days, the variation was little for V_p (+47%) and ν (-33%), moderate for V_s (+366%) and K_d (+111%), and drastic for E_d (+1956%) and G_d (+2209%). The bulk modulus K_d was almost constant for 24 hours, but then increased faster than E_d and G_d between 24 hours and 28 days. This can be explained by the contextual significant increase of both V_p and G_d after 24 hours of curing (see Equation 4). K_d can be interpreted as the volumetric compressibility of the material, which is high soon after the casting due to the large amount of free water that is not still bounded to the solid matrix of the grout. This parameter, never studied on the backfilling materials, is very important since it describes the possible volume variation due to the application of a certain pressure on the material caused by the advancement of the excavation at confined conditions (rings movements or backup advancements).

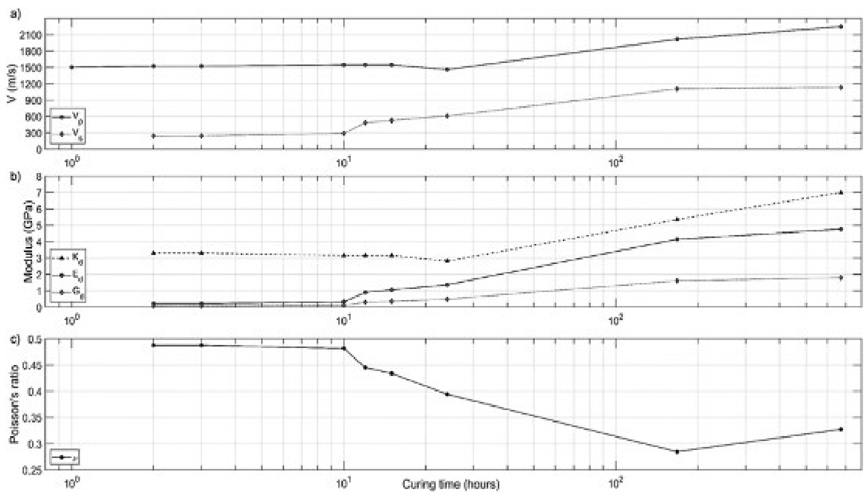

Figure 2. The geophysical parameters at different curing times: 1, 2, 10, 12, 15, 24 hours, and 7 and 28 days: a) V_p (solid line-blue circles), V_s (dotted line-red diamonds); b) E_d (solid line-blue circles), G_d (dotted line-red diamonds), K_d (dashed line-black triangles); c) Poisson's ratio ν (solid line-black circles).

6 DISCUSSION

The dynamic elastic modulus E_d from the geophysical test campaign can be compared with the static elastic modulus from the mechanical characterization of the CF-2CG. The static elastic modulus was measured with a specifically designed procedure in order to overcome some critical aspects caused by the peculiar behavior of the mix CF-2CG. The obtained results showed an average value of 27 MPa at 1 and 2 hours of curing. The measurements at 2 hours of curing had a lower standard deviation than that at 1 hour, probably due to the longer curing time. The geophysical data at 2 hours of curing put alight a value of 0.23 GPa for E_d, i.e., ten times higher than that obtained with the mechanical procedure.

The CF-2CG of this work can be compared with the cement-based 2CG mixes in Todaro & Pace (2022), where five different bentonites were tested by means of UPV tests in the short curing time (up to 24 hours after the casting). As regards the mix design, the main differences between the CF-2CG and the 2CGs in Todaro & Pace (2022) are that the CF-2CG has less water and bentonite and more accelerator than the 2CGs in Todaro & Pace (2022). The CF-2CG has not cement, but instead a special binder as reported in Table 1. The general variation of the geophysical parameters in the 24 hours was the same for the CF-2CG and cement-based 2CGs: ν decreased, while V_s, E_d and G_d increased. At 2 hours of curing, the mean V_s among the five 2CGs was 75.2 m/s, while it was 243 m/s for our CF-2CG. At 2 hours of curing, the mean E_d among the five 2CGs was 0.021 GPa, while it was 0.23 GPa for our CF-2CG. At 24 hours of curing, for the five 2CGs, the mean V_s was 258 m/s, while the mean E_d was 0.24 GPa. These values are similar to those of our CF-2CG at 2 hours. This means that our CF-2CG developed its mechanical properties far earlier than the cement-based 2CGs investigated in Todaro & Pace

Table 3. V_s, ν, E_d, G_d, K_d at 2 and 24 hours of curing for the CF-2CG (from this work) and for other cement-based 2CGs (mean value among five different mixes) from Todaro & Pace (2022).

Curing time	2CG	V_s (m/s)	ν (-)	E_d (GPa)	G_d (GPa)	K_d (GPa)
2 h	CF-2CG (this work)	243.0	0.4880	0.23	0.078	3.310
	Cement-based 2CGs (Todaro & Pace 2022)	75.2	0.4988	0.021	0.007	3.157
24 h	CF-2CG (this work)	610.3	0.4340	1.37	0.368	3.154
	Cement-based 2CGs (Todaro & Pace 2022)	257.8	0.4788	0.24	0.080	2.272

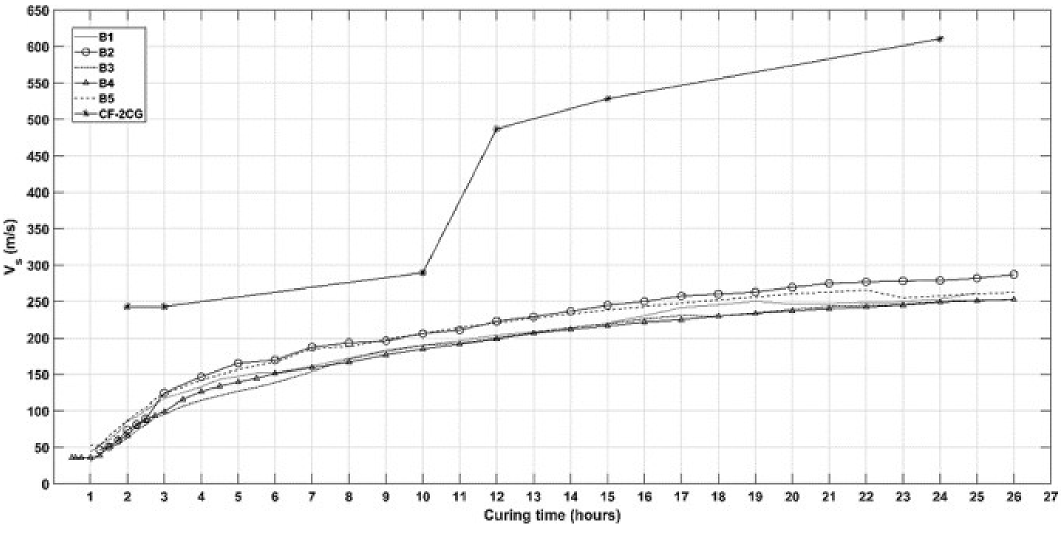

Figure 3. Comparison of the S-wave velocity (V_s) among the CF-2CG of this work (solid line-stars) and the five cement-based 2CGs from Todaro & Pace (2022): B1 (dotted line), B2 (circles and solid line), B3 (dash-dotted line), B4 (triangles and solid line) and B5 (dashed line).

(2022). The values of V_s, ν, E_d, G_d, K_d for the cement-based 2CGs in Todaro & Pace (2022) are listed in Table 3 at selected curing times, i.e., 2 and 24 hours after the casting. The corresponding values of the CF-2CG are listed to ease the comparison. V_p is not reported because it did not change for the cement-based 2CGs. For the CF-2CG, the values of V_s, ν, E_d, G_d, at 2 hours are similar to those of the cement-based 2CGs at 24 hours. The only exception for this behaviour applies to K_d which slowly decreases in 24 hours.

Figure 3 shows a graphical comparison between the V_s of the CF-2CG (solid line with stars) and the cement-based 2CGs from Todaro & Pace (2022) in the short curing time, from around 1 up to 24 hours. The five cement-based 2CGs are called B1, B2, B3, B4, B5. Figure 4 shows a similar plot for E_d. For CF-2CG, both V_s and E_d are much higher than those of B1-B5. This phenomenon can be due to the lack of cement and its replacement with another binder in our CF-2CG.

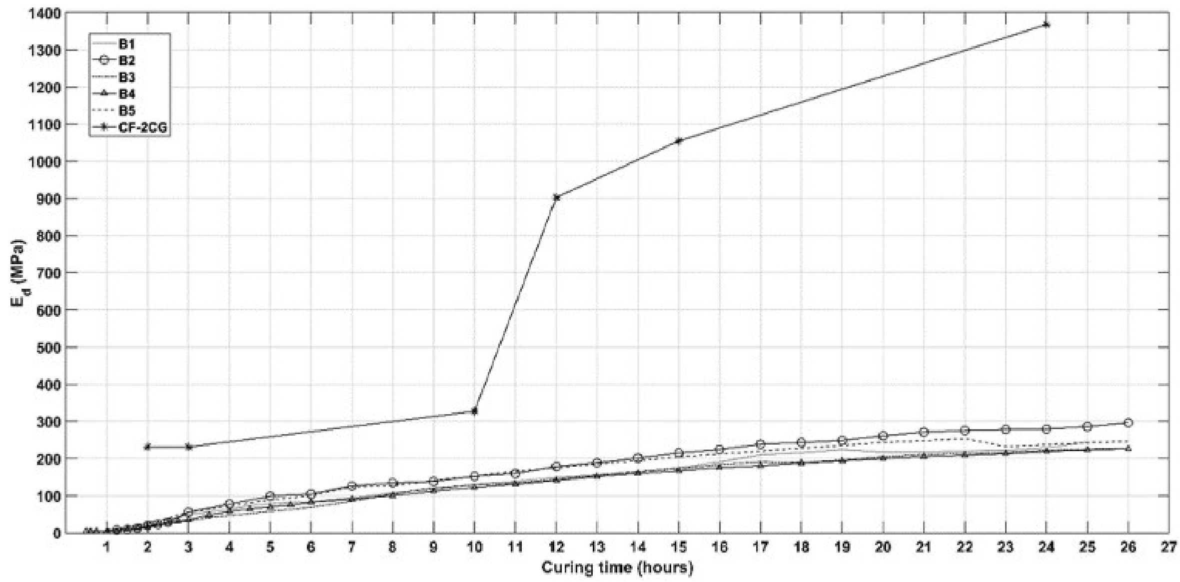

Figure 4. Comparison of the dynamic elastic modulus (E_d) in MPa among the CF-2CG of this work (solid line-stars) and the five cement-based 2CGs from Todaro & Pace (2022): B1 (dotted line), B2 (circles and solid line), B3 (dash-dotted line), B4 (triangles and solid line) and B5 (dashed line).

7 CONCLUSIONS

We examined the short-term elastic behavior of a two-component grout that is cement free, the Mapequick CBS Active CF System. We carried out a geophysical characterization by means of UPV measurements at different time steps after the casting, i.e., from 1 hour up to 24 hours in data logging mode, and then at 7 and 28 days of curing. The UPV data analysis allowed the estimation of the elastic wave velocities and then the calculation of the Poisson's ratio, the dynamic elastic, shear, and bulk moduli.

The results of our analysis demonstrated that there was a minimal parameter variation soon after the casting (i.e., within 10 hours of curing), while the most significant variation of the dynamic moduli (elastic, shear and bulk) happened between 10 hours and 28 days. The dynamic elastic and shear moduli significantly changed from 2 hours to 28 days of curing. From the comparison between the two different kinds of 2CGs tested, it is possible to conclude that the cement-free 2CG develops its elastic properties far earlier than and faster than the cement-based 2CG. Moreover, the elastic velocities and hence the moduli of the cement-free 2CG are higher than those of the cement-based 2CG.

This study confirms that the elastic properties of 2CGs can be determined in the earliest short term by means of UPV measurements. The findings indicate that the investigated cement-free 2CG ensures promising elastic properties that, combined with its low carbon footprint, make it a worthwhile and sustainable material for backfilling. Future work will be devoted to the long-term analysis of a similar cement-free 2CG.

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