

Durability performance of soil concretes: Role of cement and soil types under carbonation and wetting/drying cycles

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ABSTRACT

Soil concrete is a material obtained by mixing soil with cement. It is currently used for the construction of permanent structures such as dykes and retaining walls. The clay content in the soil requires a high-water content during preparation and placement, leading to increased porosity, which increases porosity and can negatively affect the long-term performance of soil concrete structures. In this context, it is essential to assess the durability of this material. Two durability indicators were studied in the laboratory: carbonation (mass loss (ζ), water-accessible porosity (η) and carbonation depth (X_c)) and wetting/drying (W/D) cycles (mass loss (ζ), P-wave velocity (V_p) and compressive strength (R_c)). The objective of this experimental study was to evaluate the role of cement and soil types on the durability performance of soil concretes under carbonation and W/D cycles. For the mixtures, two soils were selected: a clayey sand (SA5) and laterite (LA5), both with a grain size class of 0/5. Soil concretes were prepared at a constant spread of 32–33 cm (mini-slump test) using CEM I 52.5, CEM II 42.5, and CEM III 32.5 binders, with cement contents of 150 and 250 kg/m³. These durability tests were carried out on cylindrical specimens of dimensions ($\varnothing = 60$ mm and $h = 120$ mm) which were cured for 90 days in water prior to testing. The results indicate that mixtures containing CEM III 32.5 exhibited the highest carbonation depths due to the presence of blast-furnace slag, which reduces the availability of carbonatable products. LA5-based mixtures showed greater sensitivity to carbonation, mainly because of their higher porosity. While both soil and cement properties affect carbonation, the nature of the soil exerts a lesser influence on specimens containing Portland cements (CEM I 52.5 and CEM II 42.5) compared to those incorporating slag-based cement (CEM III 32.5). This can be explained by a soil-cement-water interaction. Unlike clinker, the main constituent of Portland cement, which hydrates faster, slag continues to hydrate over long periods. As our samples were cured for 90 days, this will lead to a more significant soil effect during carbonation in the case of formulations with CEM III 32.5 (blast furnace slag cement). Wetting/drying cycles led to higher mass losses and greater reductions in compressive strength in CEM III-based mixtures, particularly those prepared with LA5 soil. This behavior is attributed to the delayed hydraulic reactivity of slag, which causes mechanical instability during cyclic exposure. Overall, the study

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demonstrates that both cement composition and soil characteristics play a key role in controlling the durability of soil concrete under environmental actions.

1. Introduction

There are several methods available today for improving and strengthening soil, including deep soil mixing and Jet Grouting. These methods are applied in a variety of contexts, including the construction of retaining walls and watertight walls to soil reinforcement for foundations [1]. Soil concrete, a material produced using these methods, is obtained by mixing the on-site soil with a hydraulic binder. Using the on-site soil helps to limit soil movement and promotes the use of local materials. In this material, the soil acts as aggregate, reducing the need for large-scale extraction of natural aggregates from quarries. Given its advantages, soil concrete is an attractive alternative as a cost-effective solution with less environmental impact. In the past, soil concrete applications were reserved solely for temporary structures, but today these applications are gradually expanding to include semi-permanent and permanent structures [2]. A better understanding of the durability properties of this material would encourage the development of soil concrete for semi-permanent and even permanent structural purposes. However, the use of materials in construction is now systematically regulated by standards or technical documents. For example, Eurocode 2 provides rules for the design and calculation of concrete structures (reinforced and prestressed). In the case of soil concrete, however, there are no regulations that present in-depth, validated studies on the durability of this material. Little research has been carried out to date on understanding certain sustainability potentials such as carbonation and wetting/drying cycles (W/D). Civil engineering structures made of soil concrete are likely to be exposed for quite some time to atmospheric CO₂ present in the air, such as retaining walls, and even to fluctuations in groundwater levels (W/D), such as waterproofing screens.

Carbonation is caused by the reaction of CO₂ with the cement's hydration products: calcium silicate hydrate (CSH) and calcium hydroxide (CH) are converted into calcium carbonate CaCO₃ [3]. The formation of the carbonation reaction product CaCO₃ induces volume changes in the material. This can either lead to cracking, which increases permeability and results in a reduction of compressive strength, or conversely, act as a cementing agent, thereby reducing permeability and increasing strength [4]. Carbonation of a material can occur naturally due to the presence of CO₂ in the air, or in an accelerated manner in a laboratory carbonation chamber when the goal is to rapidly evaluate the long-term impact of carbonation on structures. In large cities, the natural CO₂ content in the air can reach an average concentration of approximately 0.3% to 1% [5], [6]. Thus, exposure to a 3% CO₂ concentration, for example, allows for accelerated modeling of the natural carbonation phenomenon, making it approximately 10 times faster. The carbonation rate depends on numerous factors such as CO₂ concentration, water content, permeability, binder type, humidity and temperature. It has been found that carbonation can have significant effects on the microstructure of stabilized soils [4]. According to Ref. [7], the carbonation depth of soils stabilized with CEM III/A 32.5 N binder follows an approximately logarithmic trend over time, remaining below 10 mm after 180 days for specimens with a cement content ranging from 200 to 300 kg/m³. The tests were conducted under standard atmospheric conditions (natural carbonation), at a relative humidity of 65% and a temperature of 20 °C, using specimens exposed on all sides. Studies carried out by Ref. [8] on soil concretes based on silty soil formulated with CEM III/C 32.5 N showed that higher relative humidity levels (40%, 65% and 100%) seem to slow down carbonation kinetics. He also showed that for low cement dosages, increasing the proportion of clay also seems to reduce carbonation kinetics. This was attributed to the fact that an increase in the clay content of the material leads to a reduction in the proportion of large pores, thus slowing down the kinetics of carbonation [9]. investigated the influence of CO₂ content through thermogravimetric analysis (TGA), X-ray diffraction (XRD), and mercury intrusion porosimeter (MIP) on mortars carbonated at various CO₂ levels (atmospheric concentration, 10%, 25%, and 50%). Three standardized mortars were prepared using purely siliceous sand and three distinct binders: CEM I 52.5 N, CEM II A-LL 52.5 N and CEM III A 42.5 N. This research demonstrates that higher CO₂ concentrations increase carbonation depth and confirms that the carbonation rate is strictly proportional to the square root of time [10]. investigated the influence of the water-to-cement (W/C) ratio on the evolution of carbonation depth in cement pastes exposed to a 10% CO₂ concentration. The results indicated that a higher W/C ratio leads to a greater carbonation depth (as measured on cement pastes subjected to natural carbonation for three years). This phenomenon is attributed to the fact that higher W/C ratios increase the amount of free water available for evaporation. The resulting evaporation creates voids, which facilitate CO₂ diffusion through the interconnected pore network.

Currently, there is very little data available in the literature describing how the nature of the binder impacts the W/D cycles of soil concretes. W/D cycles tests conducted in accordance with ASTM D559 on silty clay treated with Portland cement demonstrated that the water-cement ratio has a predominant influence on the test results [11]. Lower mass losses (indicating higher durability) were achieved for soil-cement mixtures with higher cement contents and lower water-cement ratios [12]. also state that compressive strength serves as an effective durability indicator, in addition to the conventional mass loss measurement [13]. worked on the use of weakly cemented sand as a material for the construction of dams and retaining walls in Korea. The results showed that the mechanical properties were improved during successive W/D cycles from 8% cement content by sand mass. The increase in strength was explained by the wetting phase, which extended the hydration process. However [13], observed a slight drop in strength after 3 cycles due to the washing of cement products and insufficient water to satisfy hydration. The work of [7] shows that in wetting/drying cycles, as long as drying periods do not induce microcracking, the compressive strength and stiffness of silt and sand soil concretes formulated with CEM III 32.5 N continue to increase before the cement hydration process is complete [14]. studied the durability of cement-treated compacted silty sands. The samples were immersed in saline water containing sulphates before being subjected to 12 W/D cycles, after different curing times. The authors observed that at an early age, compressive strength continued to increase despite exposure to salt

water [14]. However, after 90 days of curing in salt water, the W/D cycles induced a drop in compressive strength and the residual value stabilized at around 270 days.

Based on current data, no comprehensive study was carried out to assess the influence of the nature of the binder on the durability (carbonation and W/D cycles) of soil concretes. Furthermore, very few studies have addressed the impact of soil type on these two durability parameters. There is also a conspicuous lack of research regarding the combined effects of carbonation and W/D cycles, as well as an insufficient understanding of the interaction mechanisms within soil-cement systems related to both carbonation and W/D cycles. This article presents the results of experimental work carried out in the laboratory to gain a better understanding of the influence of the nature of the cement and the soil on the durability of soil concretes. The study first presents the properties of the materials used to make soil concrete. Secondly, the steps involved in formulating, preparing and storing soil concrete specimens are described. The experimental approach for carrying out carbonation tests and W/D cycles is also presented. Finally, key carbonation indicators such as mass loss, depth of carbonation and water-accessible porosity are analyzed, along with W/D cycles indicators such as mass loss, compressive strength and P-wave velocity.

2. Materials and methods

2.1. Material properties

In this study, the soil concretes were prepared using laterite (LA) and sandy clay (SA), which originated respectively from Yaoundé and Douala in Cameroon. The granular fraction (0/5) was used for laterite (LA5) and sandy clay (SA5). X-ray diffraction (XRD) was performed on powders obtained from both soils. The results obtained are presented in Fig. 1 and show that the clay present in these soils is essentially made up of dickite and kaolinite. These two clays have the same chemical formula ($\text{Al}_2\text{Si}_2\text{O}_5(\text{OH})_4$) but their crystallization mode and crystal lattice structure are different. Quantitative XRD analysis shows that the clay content of LA (89%) is higher than that of SA (54%). According to the XRD patterns presented in Fig. 1, laterite, which is richer in clay fines (notably dickite and kaolinite), is likely to exhibit greater pozzolanic reactivity, but may require adjustments in binder and water content. In contrast, sandy clay, with a significantly higher quartz content, may offer better dimensional stability but shows a lower potential for reactivity in cementitious environments [15].

analyzed the properties of earthen materials (including lateritic soils) used in construction. He highlights that soils with a high content of kaolinitic clays have a better aptitude for stabilization with hydraulic binders. However, their fine content requires precise dosages of cement and water to ensure the mechanical performance and durability of soil blocks or concretes.

The intrinsic and geotechnical properties of the LA and SA soils (Table 1) are detailed in a previous study by Ref. [16]. This study analyzed the specific gravity (NF EN ISO 17892-3 [17]), pH (NF EN ISO 10523 [18]), methylene blue value (NF EN 933-9 [19]), particle size distribution (NF EN ISO 17892-4 [20]) and elementary chemical composition (Table 2) as intrinsic soil properties. The results of this study showed that the elementary chemical composition of SA and LA is mainly composed of SiO_2 , Al_2O_3 , and Fe_2O_3 . As for pH, both soils are acidic with nearly similar pH values ($\text{pH} \approx 5.3$). The solid particles of LA have a specific gravity value (2688 kg/m^3) that is higher than that of SA (2487 kg/m^3). Despite a slightly finer particle size distribution for SA compared to LA, both soils exhibit a well-graded particle size distribution (Fig. 2). Regarding the geotechnical properties of the LA and SA soils [16], analyzed the Atterberg limits according to the NF EN ISO 17892 [21] standard. With a plasticity index for LA that is $20 \pm 2 \%$ greater than the plasticity index for SA, both LA and SA soils belong to the family of very plastic silty soils according to the GTR geotechnical soil classification.

In order to assess the influence of cement type, three types of cement were used for this study: CEM I 52.5 N CE CP2 NF and CEM III/C 32.5N CE PM-ES NF, manufactured in accordance with European classification [22], and CEM II B-P 42.5 R NC, manufactured in accordance with Cameroonian standard NC 234 [23]. Their densities are respectively 3150, 2900 and 3100 kg/m^3 [16]. For each cement, two contents, 150 and 250 kg/m^3 , were chosen for the design of the soil concrete. The chemical and physical properties of the cements were detailed also in a previous study [16]. The elementary chemical composition of the three cements is mainly composed of SiO_2 , Al_2O_3 , CaO , MgO , and Fe_2O_3 .

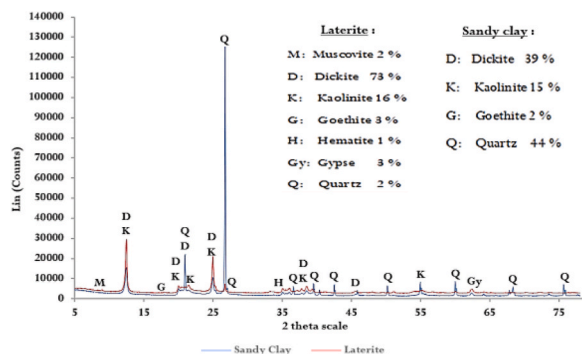


Fig. 1. XRD analysis of soils.

Table 1
Geotechnical properties of soils.

Soils	Wp (%)	WL (%)	Ip (%)	Specific Density (kg/m ³)
SA5	29.3	56.4	27.1	2487
LA5	42.6	76.5	33.8	2688

Table 2
X-ray fluorescence spectrometry of cement and soil samples.

	Elementary composition (%)								
	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	CaO	MgO	SO ₃	Na ₂ O	K ₂ O	P ₂ O ₅
Cements									
CEM I 52.5	20.70	4.60	3.30	64.40	1.30	3.40	0.07	1.33	0.50
CEM II 42.5	25.50	7.61	6.78	45.26	2.74	2.19	0.21	1.14	0.27
CEM III 32.5	32.80	10.20	0.70	46.0	5.50	2.90	nd	0.58	nd
Soils									
SA5	42.95	25.72	4.62	1.10	0.04	0.03	0.13	0.20	0.09
LA5	33.33	27.18	9.96	1.53	0.09	0.09	0.27	0.24	0.08

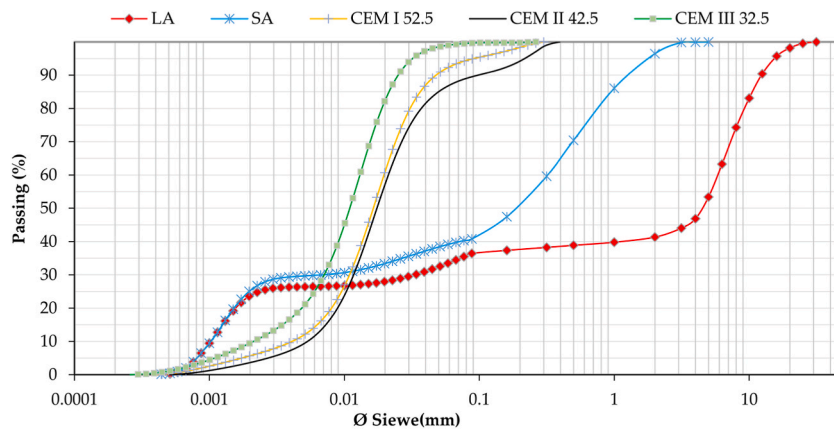


Fig. 2. Grains size distribution curves of soils and cements [16].

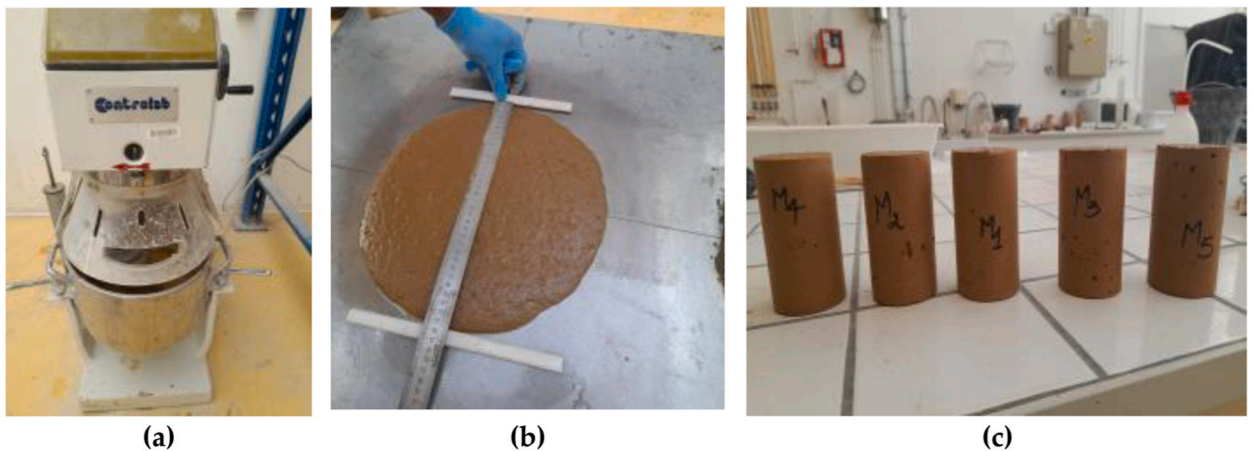


Fig. 3. a) CONTROLAB mortar mixer, b) Spread, c) Specimens after demolding.

2.2. Test specimens preparation

For this study, the formulation of the soil concrete samples was carried out in the laboratory. This approach guarantees the representativeness and repeatability of the samples and tests performed because the conditions are controlled. The mix design criterion is based on obtaining a self-compacting soil concrete with a slump flow between 32 and 33 cm using a mini-slump cone (Fig. 3b).

The nomenclature used for the different mix designs considers the type of soil, the particle size distribution, and the nature and content of the cement. For example, LA5C150_I will designate the soil concrete made from lateritic soil with a particle size of (0/5) and mixed with CEM I 52.5 cement at a content of 150 kg/m³. Table 3 presents the different mix designs obtained for 1 m³ of fresh soil concrete. The current mix design and modification scheme has been validated by relevant previous studies [24], [25], [26], [27] et [28].

Analysis of this table shows that for the same workability, i.e. between 32 and 33 cm, 1 m³ of fresh soil concrete requires more water in LA-based soil concrete (570 kg/m³) than in SA-based soil concrete (525 kg/m³). This can be explained by the higher clay content of LA5 obtained by XRD and Ip, which gives it greater plasticity than SA. This result is consistent with the work of [26], which shows that the water content of the mixture increases with the clay content of the soil to reach the target slump value. Finally, it is also important to note that for the same uses the same water contents, the type and content of cement have little effect on the workability of soil concretes, as reflected in the results of similar spread diameter values measured with the mini-cone for different formulations.

The first step in preparing the sample was to obtain a visually homogeneous mixture. To do this, the soil and cement were mixed together and then kneaded by hand for about 5 min. The resulting mixture was then mechanically mixed with water using a mixer (Fig. 3a) [27]. This mechanical mixing was carried out at a speed of 63 rpm for 10 min [29]. The moulds are filled in three layers using the tapping method, with 15 taps per layer. The moulds were filled no later than 45 min after the end of mechanical mixing, which limits the influence of the resting time on the properties of the material [30]. After manufacturing, the soil concrete samples are stored in sealed plastic bags to allow endogenous drying [31]. The soil concrete samples are demolded after 7 days of hardening (Fig. 3c). All samples were immersed in lime-saturated water [32].

2.3. Experimental procedures

2.3.1. Carbonation

In this study, the NF EN 13295 [33] standard was used to evaluate the carbonation resistance of soil concrete. Thus, accelerated carbonation tests were carried out at 0, 1 and 3 days on cylindrical specimens ($\varnothing = 60$ mm and $h = 40$ mm), and at 7, 14 and 28 days on cylindrical specimens ($\varnothing = 60$ mm and $h = 120$ mm), which are kept in a carbonation chamber with CO₂ content = 3%, relative humidity HR $\approx$ 60 to 70 % and temperature ranging from T $\approx$ 20 to 30 °C, (Fig. 4a). The specimens were exposed to CO₂ on one face to control unidirectional carbonation. Prior to this, the specimens were recovered after maturing for 90 days in water, weighed and pre-dried in an oven at a temperature of T = 60 °C for 24 and 48 h respectively for the cylindrical specimens ($\varnothing = 60$ mm and $h = 40$ mm) and ($\varnothing = 60$ mm and $h = 120$ mm). The objective here is to obtain a constant mass. After removal from the oven, the test specimens are weighed and then wrapped with self-adhesive aluminum foil. The sides and one of the bases are then sealed. Only one side is then exposed to the air and the CO₂ contained in the air (Fig. 4b). For each test analysis deadline, six soil concrete samples were tested.

2.3.1.1. Mass loss. The dry bulk density (ρ_d) is determined using equation (1).

$$\rho_d = \frac{M(\text{sec}) - M(\text{carb})}{M(\text{sec})} \quad (1)$$

where M(sec) is the mass of the sample (g) pre-dried for 24 or 48 h at a temperature of 60 °C after 90 days of curing in water, and M(carb) is the mass of the carbonated sample (g) on any given day j.

Table 3

Formulations per cubic meter of soil concrete and workability.

Materials	Type of cement	Nomenclature of specimens	Cement [kg/m ³]	Soil [kg/m ³]	Water [kg/m ³]	W/C [–]	Spread soil concrete diameter [cm]
SA5	CEM I 52.5	SA5C150_I	150	1063	525	3.5	30.8 $\pm$ 1.2
		SA5C250_I	250	984	525	2.1	31.1 $\pm$ 0.7
	CEM II 42.5	SA5C150_II	150	1061	525	3.5	33.0 $\pm$ 0.6
		SA5C250_II	250	981	525	2.1	33.2 $\pm$ 1.0
	CEM III 32.5	SA5C150_III	150	1053	525	3.5	34.1 $\pm$ 1.0
		SA5C250_III	250	967	525	2.1	33.3 $\pm$ 0.8
LA5	CEM I 52.5	LA5C150_I	150	1028	570	3.8	29.9 $\pm$ 1.1
		LA5C250_I	250	943	570	2.3	30.4 $\pm$ 0.8
	CEM II 42.5	LA5C150_II	150	1026	570	3.8	32.3 $\pm$ 0.8
		LA5C250_II	250	939	570	2.3	32.8 $\pm$ 0.9
	CEM III 32.5	LA5C150_III	150	1017	570	3.8	33.2 $\pm$ 1.2
		LA5C250_III	250	924	570	2.3	33.6 $\pm$ 0.7



Fig. 4. Experimental device for carbonation: a) carbonation chamber; b) sample with one side exposed.

2.3.1.2. Water porosity. After 28 days of carbonation, the samples (60 mm in diameter and 120 mm in height) are weighed and then placed under vacuum in a desiccator for 2 h (Fig. 5a). This process facilitates water saturation, ensuring that a maximum number of pores are filled as water rises by capillary action. Once submerged, the samples are kept in water for 3 days. Subsequently, hydrostatic weighing (Fig. 5b) and saturated surface-dry weighing are performed to determine the water-accessible porosity in accordance with standard NF P 18-459 [34], using Equation (2).

$$\eta = \frac{M(\text{air}) - M(\text{sec})}{M(\text{air}) - M(\text{eau})} \quad (2)$$

where $M(\text{air})$ is the mass of the saturated surface-dry sample (g), $M(\text{sec})$ is the mass of the dry sample (g) after removal from the carbonation chamber, and $M(\text{eau})$ is the mass of the sample obtained by hydrostatic weighing (g).

2.3.1.3. Scanning Electron Microscopy (SEM) analysis. Microscopic analysis is performed using a ZEISS scanning electron microscope (Fig. 6). After 90 days of carbonation, samples are taken from previously fractured soil-concrete specimens (60 mm in diameter, 120 mm in height). The objective is to analyse the microstructure of the material without any specific treatment that could alter the initial microstructure of the samples. Sampling was conducted from the center of the material to avoid artifacts that could occur at the edges. Microscopic observations were performed in VPSE (Variable Pressure Secondary Electron) mode at a magnification of 863 $\times$.

2.3.2. Wetting/drying cycles

To assess the strength of soil concretes subjected to wetting/drying cycles, ASTM D559 [35] was used. The W/D cycles began after 90 days of maturation in water. Soil concrete specimens of dimensions ($\varnothing = 60$ mm and $h = 120$ mm) are successively immersed in water and then dried, to generate accelerated ageing due to the resulting cycles of dimensional variations. For each test analysis deadline, six soil concrete samples were tested.

A phase of 2 days of immersion in water was adopted and corresponds, for the soil concretes tested, to an optimal degree of saturation (stabilized mass) [36]. However, the drying phase is more difficult to establish, as the rate of drying depends on the

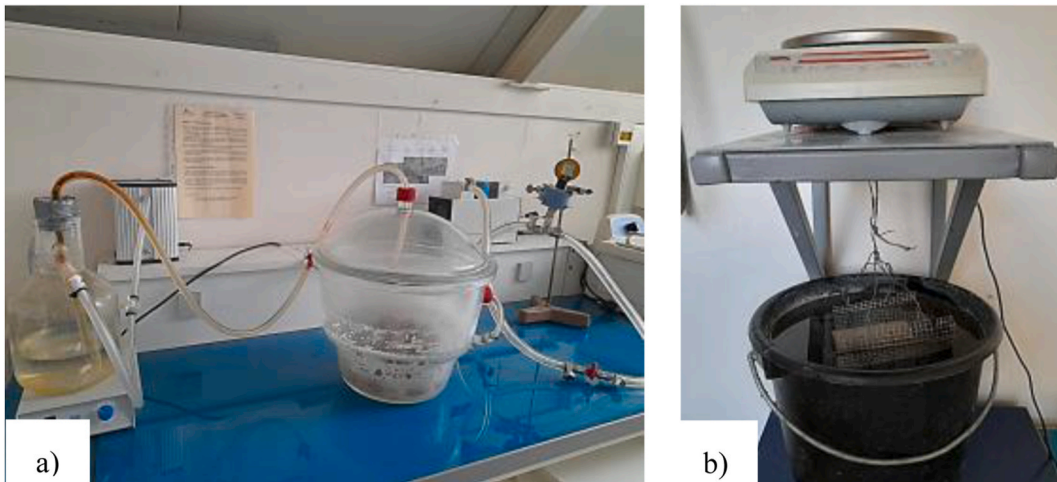


Fig. 5. Experimental Setup: a) Vacuum saturation, b) Hydrostatic weighing.



Fig. 6. Experimental Setup for Scanning Electron Microscopy (ZEISS brand).

formulation, the size of the specimen, the temperature, and the hygrometry [37]. In this study, drying consisted of storing cylindrical soil concrete specimens ($\varnothing = 60$ mm and $h = 120$ mm) in a room with controlled temperature and relative humidity (21 ± 2 °C and 69 ± 8 %) for 2 weeks (Fig. 7). The choice of this drying duration is motivated by the study conducted by Ref. [38]. These temperature and relative humidity ranges can be encountered under natural conditions. The aim was to approximate natural conditions as closely as possible.

The evolution of mass and compressive strength (R_c) was studied after 2, 4 and 6 cycles on three specimens of each formulation and cement content.

2.3.2.1. Uniaxial compression test. In accordance with standard NF EN 12390-3 [39], the samples tested in uniaxial compression have a slenderness ratio of 2, with a diameter of 60 mm and a height of 120 mm (Fig. 8). We opted for sulfur capping of the samples, according to standard [27]. The load is applied at a speed of 0.4 MPa/s, as recommended by standard [40]. The compressive strength (MPa) is calculated using Equation (3):

$$\sigma_c = \frac{F_c}{S} \quad (3)$$

where F_c is the ultimate load in uniaxial compression (MN), and S is the cross-sectional area of the sample (m^2).

2.3.2.2. P-wave velocity (V_p). The measurement of P-wave velocities (V_p) on soil-concrete samples in the laboratory was conducted using the Pundit device. It involves emitting an ultrasonic pulse signal and then analyzing its propagation through the sample (Fig. 9). The propagation velocity is the ratio between the distance traveled by the P-wave and its travel time. In this study, P-wave velocity (V_p) measurements were performed at cycles 2, 4, and 6 on cylindrical samples with a diameter of 60 mm and a height of 120 mm.

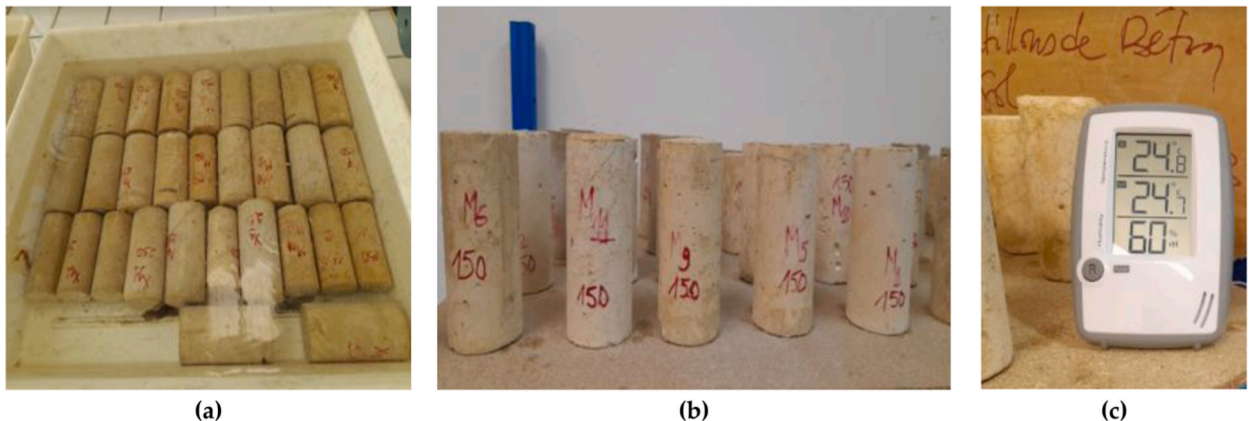


Fig. 7. Experimental device for W/D cycles: a) wetting of specimens, b) drying of specimens, c) temperature and humidity control device.

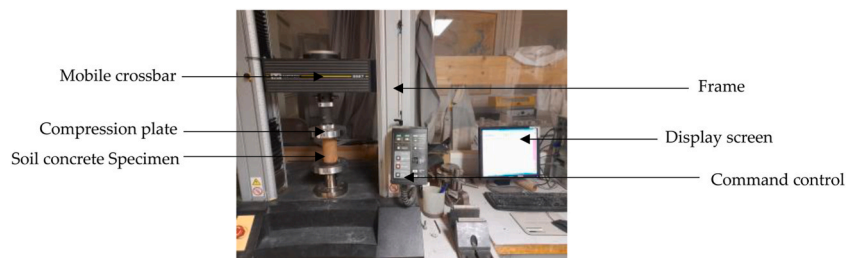


Fig. 8. INSTRON compression press.

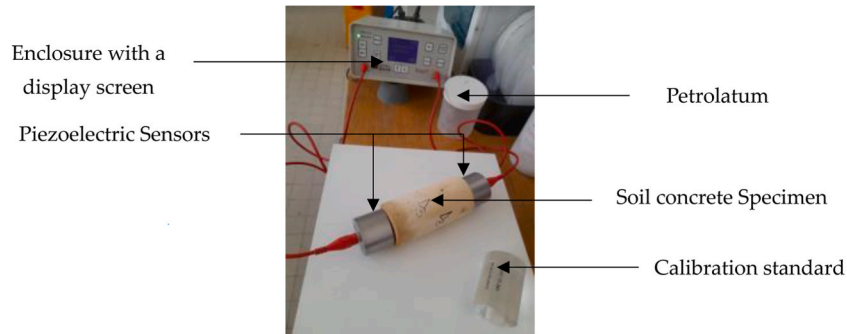


Fig. 9. Experimental setup for P-wave velocity (V_p).

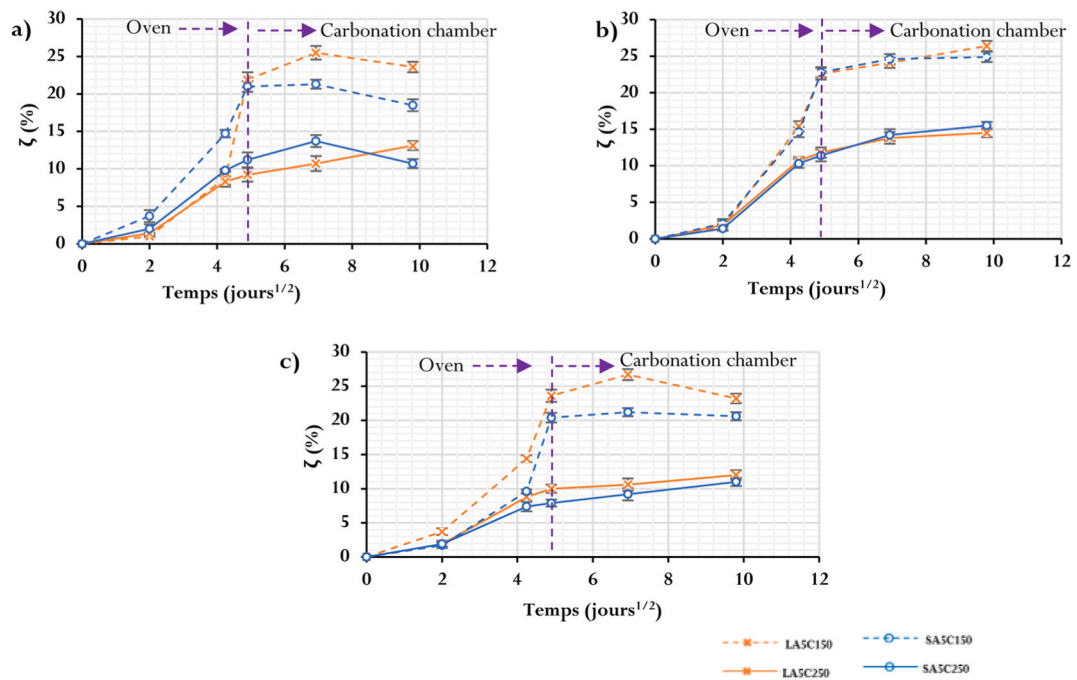


Fig. 10. Evolution of mass loss (ζ) of $4 \times 6 \text{ cm}^2$ soil concrete specimens based on SA5 and LA5, dosed at 150 kg/m^3 , as a function of square root of time and formulated with: a) CEM I 52.5, b) CEM II 42.5, c) CEM III 32.5.

3. Results and discussion

3.1. Carbonation

3.1.1. Mass loss

The evolution of mass loss (ζ) as a function of the square root of time on the specimens ($\varnothing = 60$ mm and $h = 40$ mm) and ($\varnothing = 60$ mm and $h = 120$ mm) is presented in Fig. 10(a and b and c) and Fig. 11(a and b and c) respectively. The results obtained on the different soil concretes show that the ζ varies overall between approximately 10 and 27%. The ζ is measured both in the oven and in the carbonation chamber.

The parameter ζ (%), representing the relative mass loss of the soil concrete specimens, reflects the departure of free water from the material's porous structure. This phenomenon is primarily driven by thermal drying in the oven, followed by carbonation, which can also induce further water loss through chemical reactions and continued drying in controlled environmental conditions. During the initial phase (up to $\sqrt{t} \approx 6$), corresponding to oven drying, all mix designs exhibit a rapid increase in ζ due to evaporation of free and weakly bound water. This increase is more pronounced in formulations with lower cement content (150 kg/m^3) than in those with higher cement content (250 kg/m^3). This difference is attributed to the lower density of the binder matrix in the 150 kg/m^3 mixes, which leads to a more open pore network and higher porosity, facilitating water evaporation. This result is in agreement with [26], which indicates that an increase in fine particles (clay and cement content) significantly reduces the number of large pores. After oven drying, a fairly slow change in ζ as a function of the square root of time is observed when the soil concrete samples are placed in the carbonation chamber. This loss of mass is influenced both by residual drying linked to parameters such as the temperature and relative humidity of the carbonation chamber and by the carbonation reactions that occur there. It can be seen that for all the sub-figures (a, b and c), ζ continues to increase slightly for some samples and seems to stabilise for others, and sometimes even decreases slightly, depending on the cement dosage and soil type. For all types of cement (CEM I, CEM II and CEM III) and content (150 and 250 kg/m^3), LA5-based soil concrete formulations have higher ζ values than SA5-based formulations. This is attributed to the higher water demand of LA5-based mixes (570 kg/m^3) compared to SA5-based ones (525 kg/m^3), which is consistent with the higher plasticity and finer particle size of LA5 (clayey silt) compared to SA5 (silty sand). This behavior is consistent with the findings of [37], who reported greater mass loss in clay-rich soils subjected to carbonation under 65% relative humidity and 3% CO_2 concentration, particularly when using CEM III 32.5. Interestingly, in contradiction with expectations from Ref. [18], which suggest that increasing cement and clay content reduces porosity due to particle packing effects, the experimental results in Fig. 11 show that lower cement content (150 kg/m^3) leads to higher ζ values, indicating more significant water loss. This apparent contradiction can be explained by the fact that the carbonation process is not limited to capillary pore water, but may also affect chemically bound water and microstructural changes that are more dynamic in mixes with lower cement content. Comparing the three cement types.

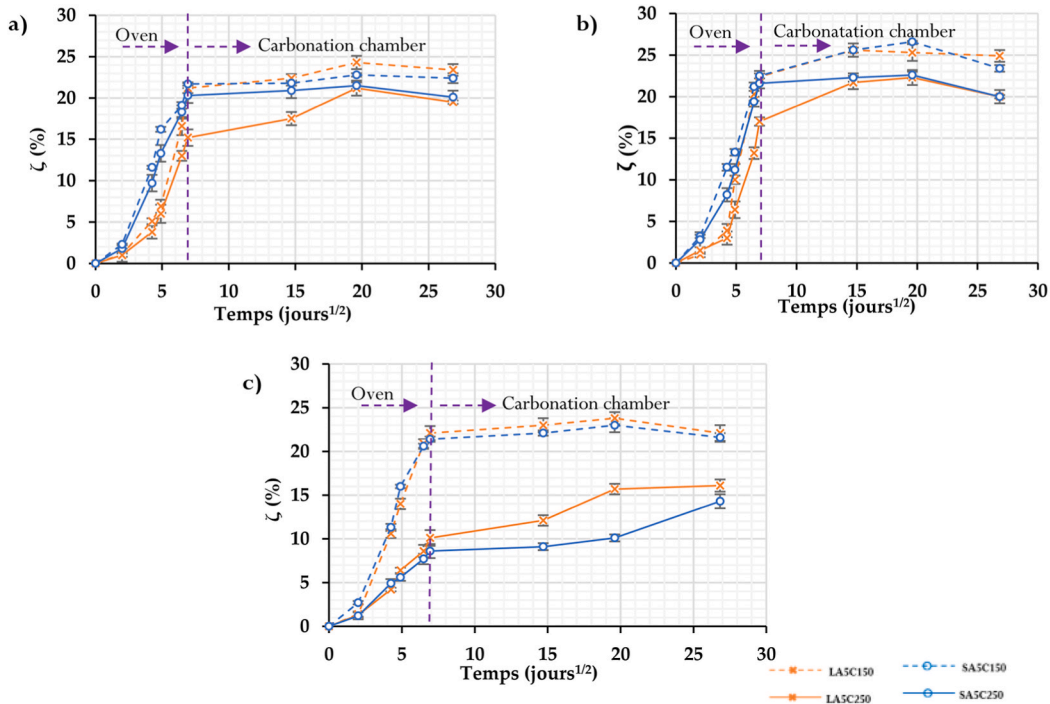


Fig. 11. Evolution of mass loss (ζ) of $6 \times 12 \text{ cm}^2$ soil concrete specimens based on SA5 and LA5, dosed at 150 and 250 kg/m^3 , as a function of square root of time and formulated with: a) CEM I 52.5, b) CEM II 42.5, c) CEM III 32.5.

- Fig. 11a (CEM I 52.5): shows a rapid and sustained increase in ζ for LA5C150 and SASC150, stabilizing beyond $\sqrt{t} = 10$. The LA5C150 formulation exhibits the highest water loss.
- Fig. 11b (CEM II 42.5): displays similar trends, but with slightly lower ζ values at 250 kg/m³ cement content, indicating improved matrix densification and reduced permeability.
- Fig. 11c (CEM III 32.5): demonstrates a more uniform behavior across the four formulations. Nevertheless, the difference between LA5 and SA5 remains noticeable, confirming the dominant influence of soil type over binder type.

3.1.2. Visual observation of the depth of carbonation

The carbonation depth of the soil concrete specimens was measured after 0, 1, 3, 7, 14, and 28 days of exposure. The temporal evolution of the carbonation depth is illustrated in Fig. 12.

Areas that remain colorless after spraying with the phenolphthalein indicator show carbonation, while non-carbonated areas appear pink [41]. When water leaves the voids, it facilitates the transport of free water deeper into the pore network, which favors the penetration and diffusion of CO₂ [3].

3.1.3. Carbonation depth

The carbonation depth X_c was measured for all formulations after 90 days of water curing. Figs. 13 and 14 show, respectively, the evolution of X_c as a function of the square root of time and the evolution of X_c as a function of the W/C ratio for the studied soil-concrete.

The evolution of carbonation depth X_c as a function of the square root of time clearly indicates that the carbonation process follows a diffusion-controlled mechanism, characterized by a linear relationship of the form X_c . This behavior is consistent with Fick's law of diffusion and with previous studies on conventional concretes [42], [43].

Across all three cement types (CEM I, CEM II, CEM III), increasing the cement content from 150 kg/m³ to 250 kg/m³ results in a systematic reduction in carbonation depth X_c . This trend confirms that a higher cement dosage enhances the material's resistance to carbonation. Two main mechanisms explain this behavior.

- The high clinker content in high-cement soil concrete formulations strengthens the chemical barrier against CO₂ penetration during carbonation.
- The increase in the fine particle content due to a higher cement content will lead to a reduction in the porosity and permeability of the matrix in the soil concrete test specimens, which will limit the diffusion of CO₂ in the material.

Regardless of the type and cement content, Fig. 13 shows that LA5-based formulations have significantly higher carbonation depths than SA5-based formulations. For instance, after 28 days.

- With CEM I 52.5, LA5C150 reaches 75 mm, versus approximately 40 mm for SA5C150.
- With CEM II 42.5, LA5C150 reaches 109.5 mm, and with CEM III 32.5, it reaches 110 mm.

This increase results from the higher clay content in LA5, which leads to a higher W/C ratio and therefore increased porosity, Fig. 14. Upon drying, the evaporation of excess water leaves behind a highly porous microstructure, enhancing the accessibility of CO₂ to the interior of the specimen. This is in agreement with the findings of [44], [45] which emphasize the role of W/C ratio in governing carbonation kinetics.

Among the three cement types, formulations based on CEM III 32.5 exhibit the highest carbonation depths, particularly at lower cement contents. This behavior is well-documented in literature [29] and is explained by.

- The lower clinker content in CEM III compared to CEM I and CEM II, which results in reduced portlandite (Ca(OH)₂) availability—this compound is primarily responsible for neutralizing CO₂ during carbonation.
- The incorporation of blast-furnace slag, which delays early hydration and weakens the buffering capacity of the pore solution.

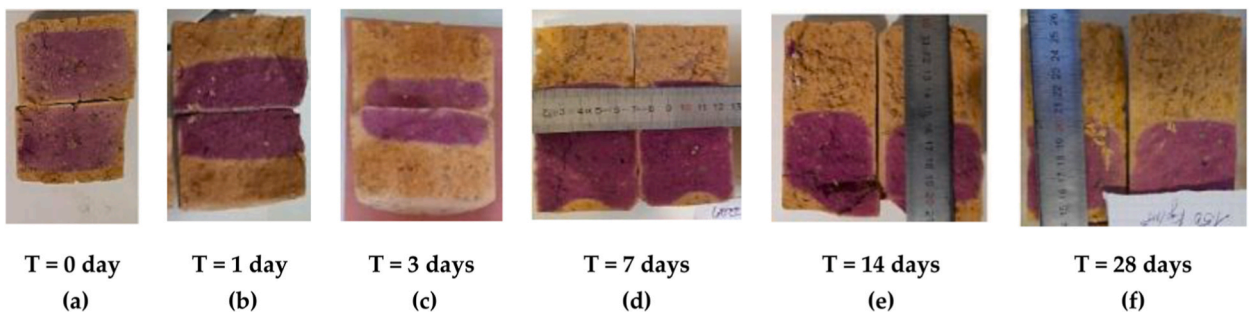


Fig. 12. Observation of the depth of carbonation in soil concrete specimens of dimensions: 4*6 cm² ((a), (b) and (c)) and 6*12 cm² ((d), (e) and (f)) based on LA5 dosed at 150 kg/m³, formulated with CEM I 52.5.

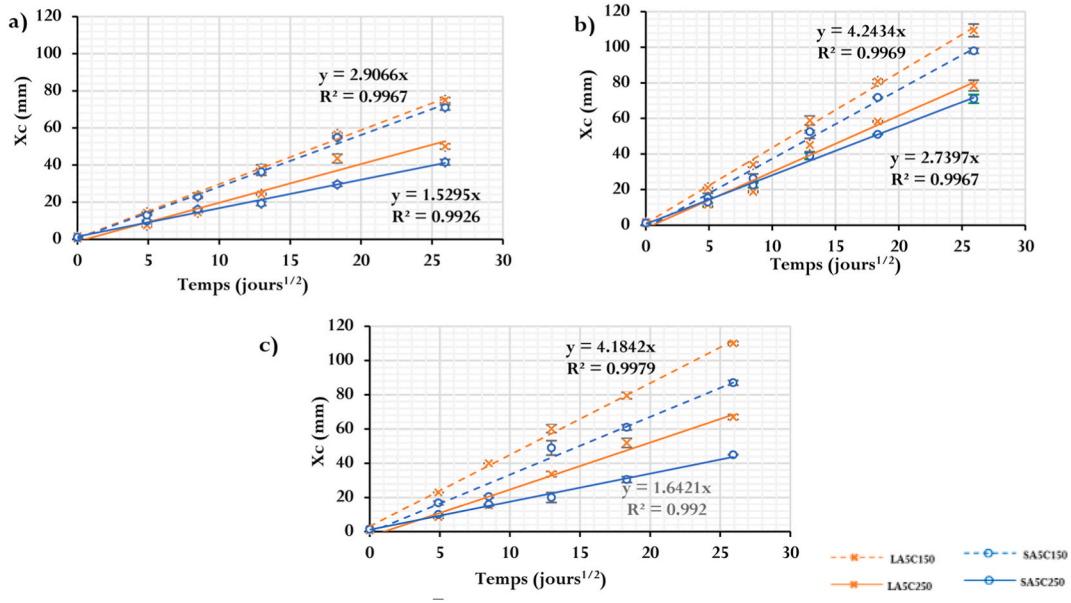


Fig. 13. Variation of X_c as a function of $\sqrt{t}$ for soil concrete test specimens based on SA5 and LA5 dosed at 150 and 250 kg/m³ and formulated with: a) CEM I 52.5, b) CEM II 42.5, c) CEM III 32.5.

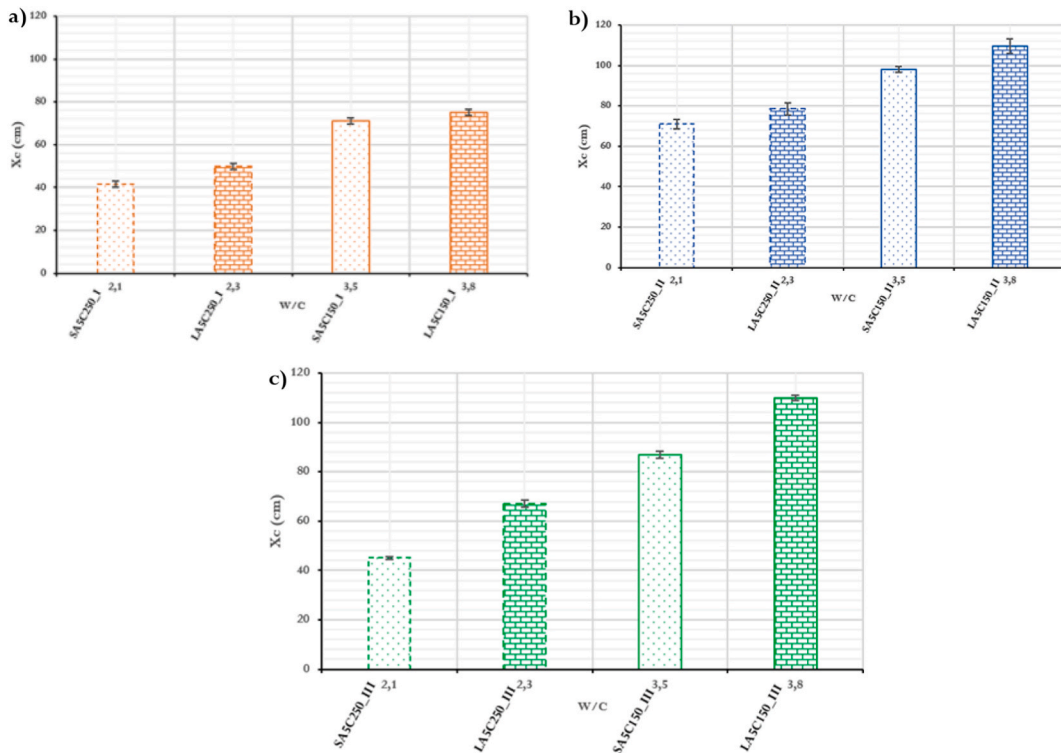


Fig. 14. Evolution of the carbonation depth of SA5 and LA5-based soil-concretes as a function of the W/C ratio: a) CEM I 52.5, b) CEM II 42.5, c) CEM III 32.5.

- A slower microstructural densification, especially in early stages, allowing greater CO₂ ingress.

In contrast, CEM I-based specimens show the lowest carbonation depths under identical exposure times, confirming its higher carbonation resistance, due to its high portlandite content and early-age hydration kinetics.

The consistently high R^2 values (all exceeding 0.99) across all subfigures confirm the excellent linear correlation between carbonation depth and the square root of time ($\sqrt{t}$), reinforcing the predominant role of diffusion processes. The slopes of the regression lines (carbonation coefficients) are systematically higher in the following cases.

- LA5-based formulations compared to SA5-based ones;
- Lower cement content formulations compared to those with higher cement content;
- Formulations with CEM III 32.5 compared to formulations with CEM I 52.5 and CEM II 42.5.

Ultimately, in Fig. 13, the evolution of the carbonation depth of soil concretes as a function of the square root of time is influenced by the nature of the soil and cement, as well as the cement content. Regardless of the cement content, soil concrete test specimens based on LA5 formulated with CEM III 32.5 are the most vulnerable to carbonation due to their high porosity and low chemical buffering capacity. These results are essential for optimising soil concrete formulations for durability in CO_2 -rich environments [46].

3.1.4. Porosity accessible to water

The water porosity was determined and is presented in Figs. 15 and 16. They show, respectively, the evolution of water porosity as a function of cement type and cement content for both sound and carbonated soil-concrete specimens, and the evolution of carbonation depth as a function of water porosity for the carbonated soil-concrete specimens.

The measurements at 28 days on the carbonated specimens show a reduction in the η on the soil concrete. The reduction is estimated at between 14.6 and 21.7% for formulations with CEM I 52.5, between 2.1 and 9.2% for CEM II 42.5 and between 4.9 and 18.4% for CEM III 32.5. This decrease in (η) can be explained by the filling of newformed pores in the material, with variation in the molar volumes of the portlandite. Indeed, the reaction relative to the transformation of 1 mol of $\text{Ca}(\text{OH})_2$ into 1 mol of CaCO_3 by the action of CO_2 , induces an increase in the volume of the solid phase, and therefore a decrease in the pore space [47]. The η is greater in LA5-based soil concrete than in SA5-based soil concrete. This is due to a greater quantity of water entering into its manufacture for the same workability, Fig. 16.

3.1.5. Influence of carbonation on the microstructure of soil concretes

Figs. 17 and 18 show the microscopic observations made on the different carbonated soil concretes based on SA5 and LA5 formulated with the three types of cement used.

The observations on SA5-and LA5-based formulations carbonated and formulated with the three types of cement show a microscopic structure different from that of normal formulations through the appearance of a new phase (N. Phase) which coats the surface of carbonated soil concrete samples in the shape of a mushroom. This can be explained by the fact that the precipitation of CaCO_3 , in response to the carbonation of the various hydrates, increases the volume of the solid phase and thus seals the porosity [48], [49], [50]. The visual consequence of this coating is the reduction of pores on the surface of soil concrete samples, which may explain the reduction in water porosity in these samples. In addition to the reduction in total porosity, carbonation impacts the pore size distribution, and consequently the morphology of sorption/desorption isotherms [46]. Regardless of the binder type, a comparison of the micrographs taken on the carbonated specimens shows a difference in the surface condition of LA5-based specimens, characterized by a less significant development of N. Phase than on SA5-based ones. The higher water content in LA5-based soil concrete specimens, which is linked to the amount of clay present in the soil, can explain this slow development of N. Phase, making it less pronounced in these samples. This helps to better understand why the obtained water porosity and X_c values are lower for SA5-based soil concrete specimens than for LA5-based ones. This aligns with the work of [51], which demonstrates that clay content (soil type) influences carbonation. Conversely, in the carbonated specimens, formulations with CEM III 32.5 appear to have developed a more significant N. P. on their surface than those formulated with CEM II 42.5 and CEM I 52.5. However, these are precisely the soil concrete specimens most affected by carbonation. This can be explained by a rapid consumption of portlandite due to a low clinker content in CEM III 32.5 compared to CEM II 42.5 and CEM I 52.5.

3.2. W/D cycles

3.2.1. Mass loss

Fig. 19 shows the evolution of ζ on soil concretes based on sandy clay and laterite formulated with the three types of cement used as a function of the number of W/D cycles.

After a 90-day water curing period, the specimens were subjected to six W/D cycles. The mass of each sample was recorded at the end of both the immersion and drying phases. Fig. 19 illustrates the evolution of mass loss (ζ) as a function of the number of W/D cycles for soil concretes formulated with SA5 (a) and LA5 (b), using CEM I 52.5, CEM II 42.5, and CEM III 32.5 and two cement contents (150 and 250 kg/m^3). Thus, there is an almost linear increase in mass loss as a function of the number of W/D cycles. In the medium and long term, this will have an impact on the material, resulting in progressive degradation of its microstructure and leading to the appearance of cracks on the surface and towards the core of the soil concrete samples. This result is consistent with the work carried out by Ref. [38], although some studies have sometimes found a slight decrease in mass loss in the long term as the number of W/D cycles increases. Regardless of the type of cement, LA5-based soil concrete formulations all have higher ζ values than those formulated with SA5. This is explained by the fact that for the same workability (32 to 33 cm), LA5-based soil concrete formulations require a greater amount of water (575 kg/m^3) than those formulated with SA5 (525 kg/m^3). In this regard, studies by Ref. [38] have shown that soil concrete samples with a high clay content tend to lose a significant amount of mass during the drying phase due to their higher initial

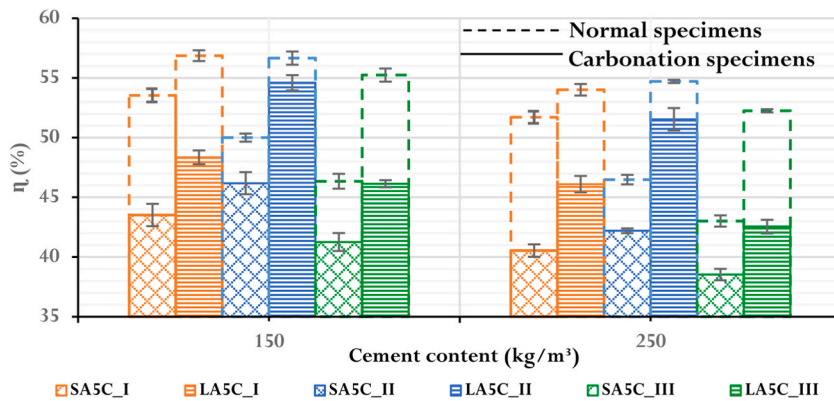


Fig. 15. Evolution of η on $6 \times 12 \text{ cm}^2$ soil concrete specimens based on SA5 and LA5 as a function of cement dosage.

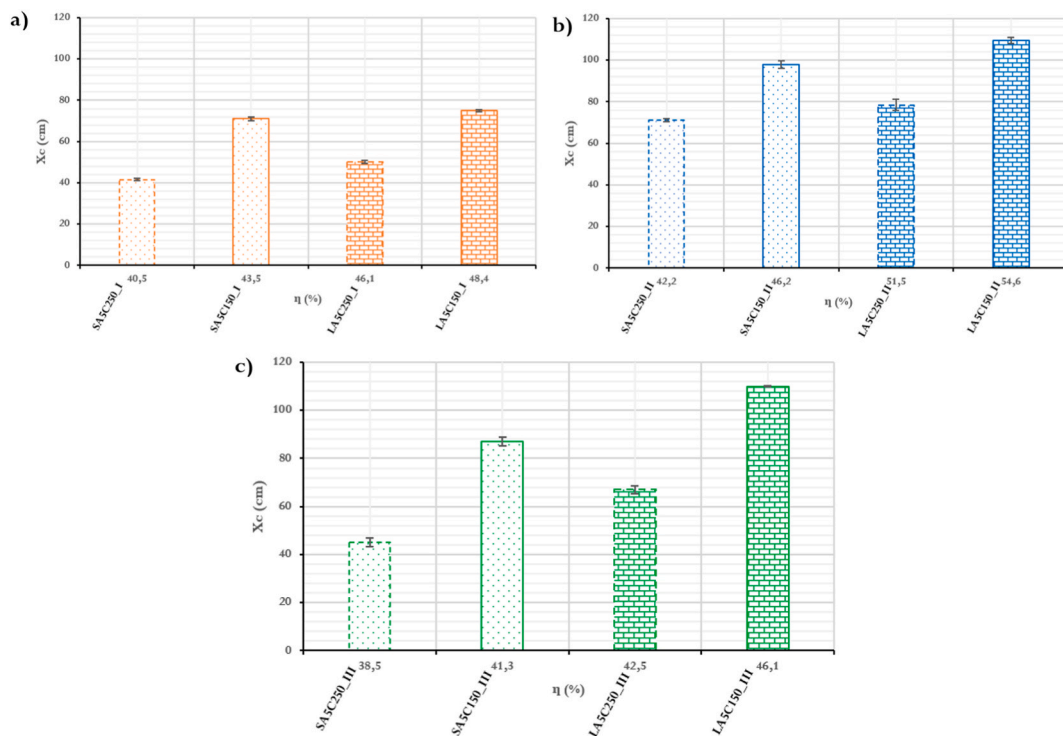


Fig. 16. Evolution of X_c as a function of the water porosity of carbonated soil-concrete specimens based on SA5 and LA5: a) CEM I 52.5, b) CEM II 42.5, c) CEM III 32.5.

water content and porosity. Regardless of the nature of the soil and cement, mass loss is more pronounced for lower cement content (150 kg/m^3). This means that an increase in cement content improves the compactness of the cement matrix and consequently reduces water penetration, thereby limiting the spread of cracks. However, no real influence of the type of cement (CEM I 52.5, CEM II 42.5 and CEM III 32.5) on the variation of mass loss as a result of the number of W/D cycles was observed. Thus, the cement content and soil type are the main influencing factors here, while the type of cement plays a secondary role.

3.2.2. Observation of specimens after W/D cycles

Fig. 20 shows an example of visual observation of soil concretes based on LA5 formulated with CEM I 52.5, dosed at 150 kg/m^3 .

When they are exposed to W/D cycles, soil concrete specimens show flaking, leaching, and cracking as damage to their surfaces. The cracks that appear on the samples result, among other things, from the shrinkage of the clay contained in the soil under the effect of the drying gradient, and from the incompatibility of deformations between the soil grains and the cement paste [2]. It was found that formulations dosed at 250 kg/m^3 were less degraded than those dosed at 150 kg/m^3 . This can be explained by the fact that the cement content influences the shrinkage in the floor concrete and consequently its state of degradation. Formulations based on LA5 are more

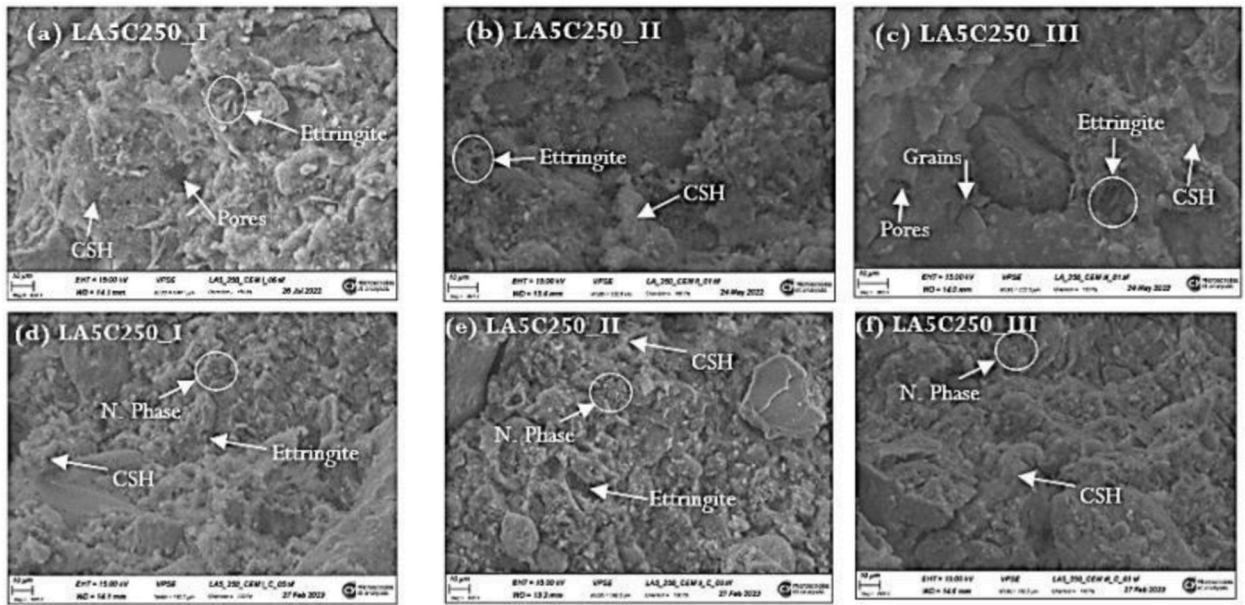


Fig. 17. SEM micrographs of non-carbonated LA5C (a, b and c) and carbonated LA5C after 28 days (d, e and f).

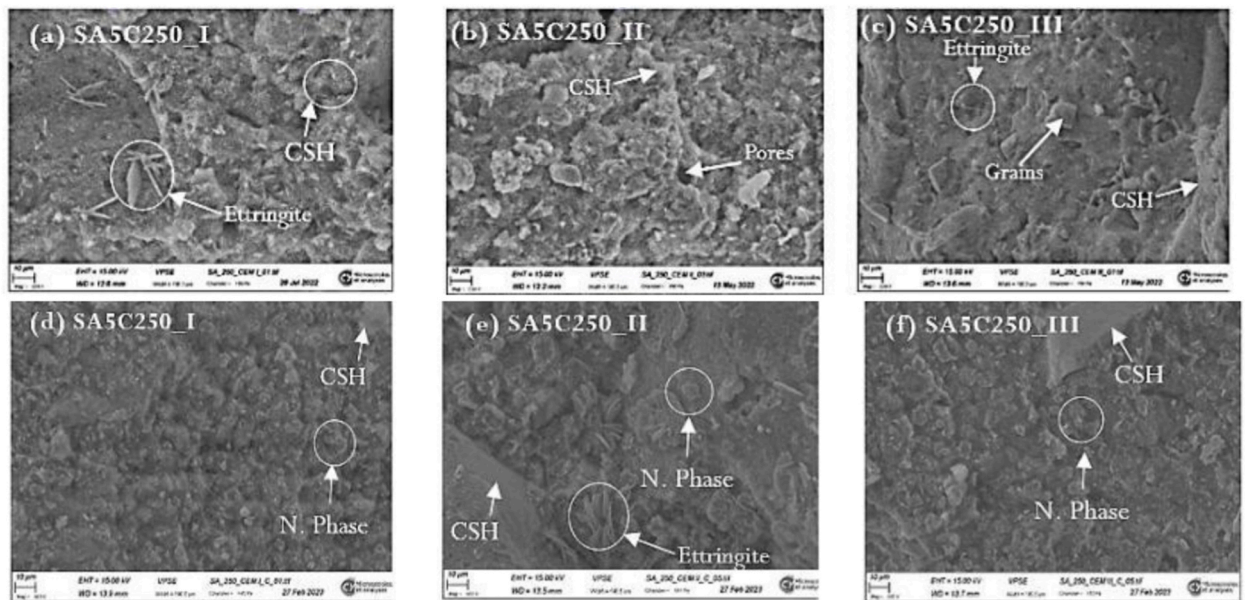


Fig. 18. SEM micrographs of non-carbonated SA5C (a, b and c) and carbonated SA5C after 28 days (d, e and f).

sensitive to W/D cycles than those based on SA5. This is due to the higher clay content (I_p) in LA5 than in SA5. Formulations with CEM III 32.5 are more sensitive to W/D cycles, followed by CEM II 42.5 and CEM I 52.5. This can be explained by the fact that CEM III 32.5, which is a blast furnace slag cement, is more sensitive to shrinkage than Portland cements.

3.2.3. Compressive strength

The evolution of R_c as a function of the number of W/D cycles and the evolution of moisture content as a function of the number of W/D cycles are illustrated in Figs. 21 and 22, respectively, for all soil-concrete formulations.

As illustrated in Fig. 21, after six W/D cycles, the most pronounced reduction in R_c is observed for specimens incorporating CEM III 32.5 cement at a dosage of 150 kg/m^3 , particularly with LA5-based formulations (panel b), where the relative R_c drops by 94%, compared to 79% for SA5-based formulations (panel a). However, regardless of the nature of the soil, soil concrete formulations with

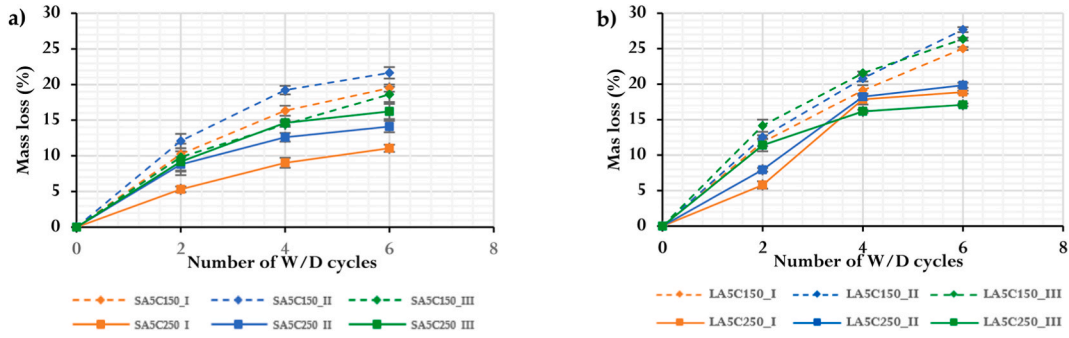


Fig. 19. Evolution of the ζ as a function of the number of W/D cycles. a) SA5 and b) LA5.

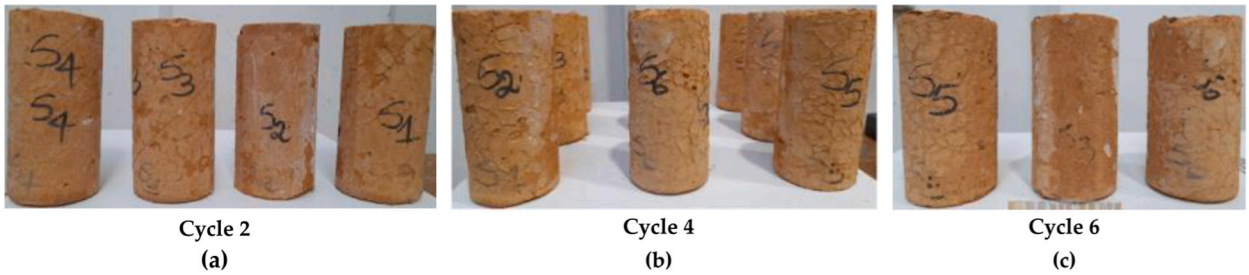


Fig. 20. Visual observations of LA5-based soil concrete specimens dosed at 150 kg/m³ and formulated with CEM I 52.5 and exposed to W/D cycles.

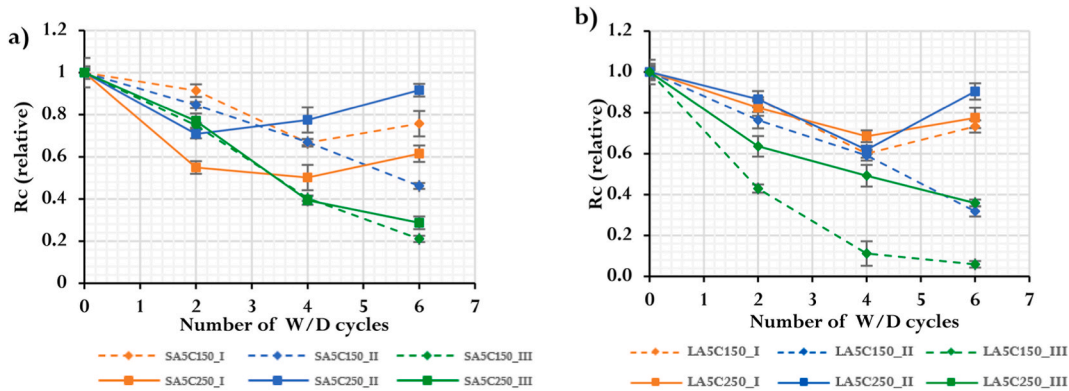


Fig. 21. Evolution of Rc as a function of the number of W/D cycles: a) SA5 and b) LA5.

CEM II 42.5 and especially with CEM I 52.5 offer better stability and therefore better resistance to freeze-thaw cycles.

Between the 4th and 6th cycles, formulations with CEM I 52.5 show strength gains of: +9% and +11% for SA5-based soil concretes at 150 and 250 kg/m³, respectively, +13% and +9% for LA5-based soil concretes at the same dosages. These results reveal a combined influence of cement type and soil nature on the variation in Rc.

The intermediate increase in Rc can be attributed to a reorganization of the clay matrix contained in the soil concrete induced by the wetting/drying mechanism. This can also be explained by the possibility of continuous hydration of previously unhydrated cement phases within the material, Fig. 22. The study conducted by Ref. [52] shows that Rc of concrete can increase by 9 to 14% under drying conditions due to the accumulation of internal capillary pressure.

Two behaviours appear to be observed towards the end of the W/D cycles (6th cycle) on the soil-concrete test specimens: a tendency towards Rc stabilization and a slight tendency towards an increase in Rc. This phenomenon is probably related to the nature and cement content of the material. During W/D cycles, the material is subjected to hydric gradients and capillary depression, initially causing microstructural instabilities. However, the presence of clay may facilitate structural rearrangement or densification, contributing to a partial recovery or stabilization of mechanical performance.

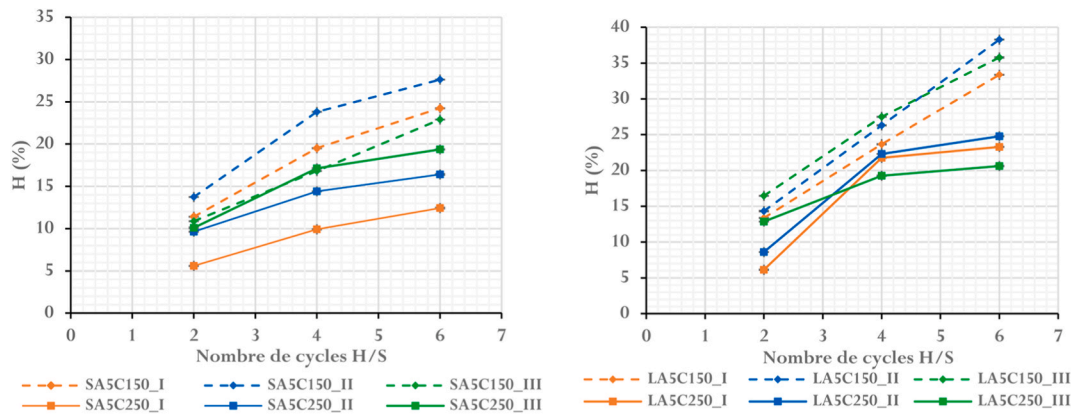


Fig. 22. Evolution of moisture content in soil-concretes formulated with CEM I 52.5, CEM II 42.5, and CEM III 32.5 as a function of the number of W/D cycles: a) SA5 and b) LA5.

3.2.4. Influence of the W/D cycles on elastic properties

Fig. 23 shows the evolution of the P-wave velocity (V_p) during the W/D cycles. The ultrasonic measurements were carried out at the same time as the mass readings. The results are normalized with a comparison to the initial values determined in the endogenous condition after 90 days of curing in water.

For all studied formulations, a decrease in P-wave velocity (V_p) was observed as the number of W/D cycles increased. This decline in V_p can be attributed to the formation and propagation of microcracks within the material, which result from the evaporation of free water during drying phases. The reduction in ultrasonic velocity is indicative of internal damage, in agreement with findings reported by Ref. [38] who also associated such decreases with microstructural deterioration due to W/D cycling.

In the case of SA5-based concretes, the most significant reduction in V_p was recorded in specimens with a cement dosage of 150 kg/m³, formulated with CEM I 52.5 and CEM II 42.5, showing a loss of 52% after six cycles. For LA5-based formulations, the greatest drop was noted in samples with the same low cement dosage but made with CEM III 32.5, reaching a 75% reduction after six cycles. The results obtained highlight the influence of the nature of the binder on the ability of soil concretes to undergo degradation during W/D cycles.

Significant decreases in V_p appear for most soil concrete specimens between the 2nd and 4th cycles. This shows that the structure of soil concrete is rapidly disrupted, resulting in the appearance of microcracks following the initial phases of the W/D cycles, but reorganises itself to stabilise during the subsequent cycles.

Similarly, for the two cement contents studied (150 and 250 kg/m³), a drop in V_p of the material is observed regardless of the type of cement. However, this drop in V_p on the soil concrete test specimens is less significant in formulations containing 250 kg/m³ of cement, which implies resistance to degradation when the cement content is lower.

Finally, the V_p reduction was more pronounced in LA5-based concretes than in SA5-based ones, confirming the influence of soil type. The higher clay content and water demand in LA5 likely promote higher porosity and greater microcracking, resulting in a more substantial loss of ultrasonic velocity.

4. Conclusion

Several parameters govern the durability performance of soil concretes, including soil mineralogy, cement type and dosage, mix

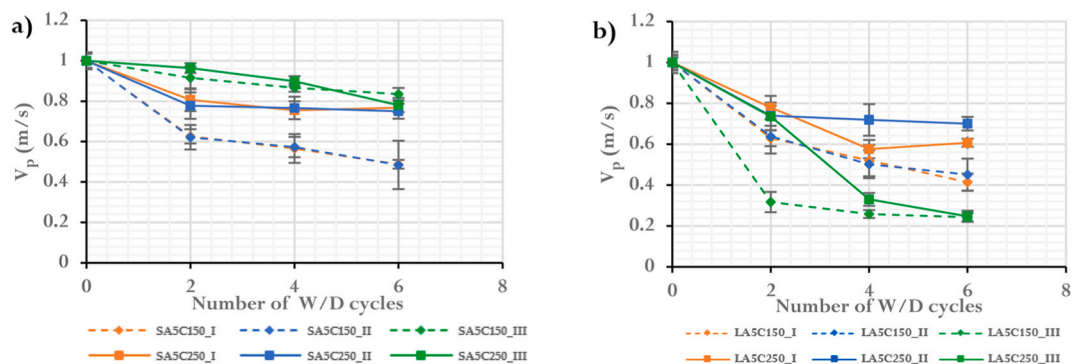


Fig. 23. Evolution of V_p as a function of the number of W/D cycles. a) SA5 and b) LA5.

proportioning, workability, curing conditions, and compaction procedures. In this study, the coupled effects of carbonation and wetting–drying (W/D) cycles on soil concretes were systematically investigated, with particular attention to the influence of soil type, cement type, and water-to-cement ratio.

The main findings of this study can be summarized as follows.

- Carbonation depth was strongly influenced by soil mineralogy and cement type. Mixtures incorporating soils with higher kaolinitic clay content exhibited reduced carbonation penetration, mainly due to their lower permeability and refined pore structure.
- The water-to-cement ratio, which varied to maintain constant workability, played a significant role in controlling porosity and carbonation resistance. An increase in W/C ratio led to higher porosity and accelerated carbonation, highlighting the need to consider mix proportioning effects when interpreting durability trends.
- Compressive strength (R_c) showed a moderate decrease under accelerated carbonation exposure. The magnitude of this reduction depended on cement composition and dosage, reflecting differences in carbonation-induced microstructural changes.
- Under wetting–drying cycles, two distinct behaviors were observed after six cycles: stabilization of R_c for certain mixtures and a slight strength increase for others. This behavior is attributed to combined effects of clay matrix reorganization, progressive densification, and possible continued hydration of unreacted cement phases.
- The evolution of mechanical performance during W/D cycles was closely related to moisture exchange, pore structure modification, and soil–cement interactions, confirming the importance of microstructural reorganization in long-term durability.
- Differences between mixtures demonstrated that both soil geotechnical properties (plasticity, particle size distribution) and cement characteristics govern the sensitivity of soil concrete to environmental degradation under combined carbonation and W/D actions.
- Microstructural observations revealed the formation of a new “Phase N” during carbonation. Preliminary SEM and XRD analyses suggest that this phase plays a significant role in pore structure evolution and strength development, although its precise chemical composition requires further investigation.

Overall, the results confirm that durability degradation of soil concrete results from complex interactions between mix design parameters, pore structure evolution, moisture transport, and chemical transformations induced by environmental actions.

To further strengthen the mechanistic interpretation of these findings, future work should include mercury intrusion porosimetry (MIP) to quantify pore size distribution and connectivity, and complementary XRD analyses to characterize the formation and evolution of Phase N. Additional investigations should also focus on the influence of curing conditions, compaction procedures, and specimen preparation methods on durability performance.

Moreover, systematic comparisons between accelerated and natural exposure conditions are required to improve the applicability of laboratory results to real field environments. Correlation analyses between carbonation depth, porosity, W/C ratio, and mechanical degradation would also contribute to establishing predictive durability models for soil concrete structures exposed to aggressive environments.

Such integrated experimental and analytical approaches will provide more robust guidelines for the design and long-term assessment of sustainable soil concrete materials.

CRediT authorship contribution statement

Alain Kamdem: Writing – original draft, Visualization, Software, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Emmanuel Elat:** Writing – review & editing, Visualization, Validation, Resources, Conceptualization. **Jean Chills Amba:** Writing – review & editing, Validation, Resources. **Albert Noumowé:** Writing – review & editing, Validation, Supervision, Project administration, Funding acquisition, Conceptualization. **Michel Mbessa:** Writing – review & editing, Validation, Funding acquisition. **Javad Eslami:** Writing – review & editing, Validation, Resources, Methodology, Funding acquisition.

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Declaration of competing interest

The authors declare that they have no conflict of interest.

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Data availability

Data will be made available on request.

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