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Experimental investigation of the UPV wavelength in compacted soil

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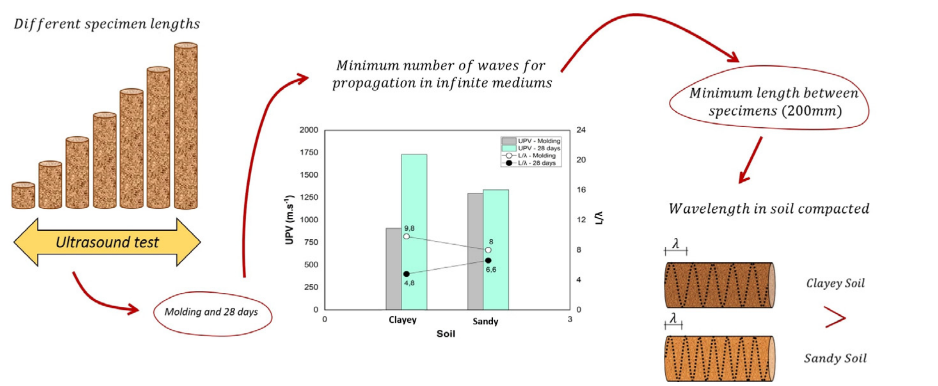
HIGHLIGHTS

- There was no great variation in wavelength sizes between sandy and clayey soil.
- For the frequency of 45 kHz, specimens of at least 200 mm are required.
- Between 5 and 7 waves are required to have flat waves.
- The smallest discontinuity detected by the ultrasound was between 8 and 19 mm.

GRAPHICAL ABSTRACT



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ABSTRACT

Considering this parameter, the minimum length of a soil test specimen to be compacted, to enable its characterization, was determined using ultrasonic testing. The experimental stage involved the production of specimens in different lengths for two types of soils (clayey and sandy) and three compaction energies (normal, intermediate, and modified). Ultrasound tests were performed after molding (0 days) and 28 days of compaction, using 45 kHz frequency longitudinal transducers and compression wave. The results indicated that the minimum length of the specimen should be 200 mm when the velocity stabilization occurred for the Clayey and Sandy soils. However, the factors considered (transducer frequency, compaction energy and apparent specific mass) may infer significant changes in wavelength.

1. Introduction

Soil is a versatile material that can be applied in various sectors of construction as supporting or construction material. The knowledge about the physical and mechanical properties of soils- microstructure and macro-structure - is essential to obtain the desired performance of constructions that use it as constructive or support material [1–3].

However, given that soil is a natural material- thus translating into significant heterogeneities between the types of soils and conditions of use (in natura or compacted)-, more advanced technologies are required to characterize soil samples. Given this context, ultrasound tests can be highlighted as a non-destructive method commonly used in the characterization and classification of other construction materials such as metal alloys, polymers, wood, concretes and mortars [4–8]. In addition to its validation in other materials, ultrasound is distinguished by the possibility of its “in situ” application, greater representatives results in relation to the structure or construction element analyzed, and velocity in obtaining the results.

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Regarding the use of this technique in compacted soils, the literature presents promising results on the determination of soil suction, elastic properties, estimation of mechanical strength, quality control and inspection of earth constructions [9–12,6,13,1,14].

However, some theoretical concepts that involve this technique must be respected to ensure that the results obtained are reliable. When performing an ultrasound test and considering the propagation of ultrasonic waves of compression (P) in relation to the sample's length, it is verified that the distance between the transducers (emitter and receiver) close to the wavelength (λ) results in a finite path. This condition contradicts the theoretical concepts about the propagation of acoustic waves (infinite path), causing an effect of reflection and refraction of the waves (dispersive path), which can result in the propagation of the wave across the material's surface [2,15–17]. Therefore, a minimum number of waves traversing the material during the ultrasound test is required to obtain a volume wave, thus ensuring its propagation in infinite paths. For such, the specimen's length (or dimension of the element under analysis) must conform to the frequency of the transducer used [18,16,19–21,15].

According to the Guidebook on non-destructive testing of concrete [22], there is a minimum dimension of the workpiece that must be respected according to the frequency of the transducer used for the test, and such dimension cannot be shorter than the wavelength. This concept was studied in wood specimens [18,21], having been observed that the ultrasound tests on this material should be carried out on samples that provide 3 minimum wavelengths in the material, which is related to the sample dimensions and frequency of the transducers.The results also indicated that there is a critical point between the L/λ ratio, from which the UPV becomes constant, corresponding to 3 λ as the minimum number [21].

There are few studies on the influence of the frequency of transducers on the UPV in cementitious materials (concrete, mortar, paste) and the distance between transducers; however, the approach on the wavelength was not direct [23,24].

Wavelength is approached in the geotechnical area in studies on seismic refractions and surface waves, methods that characterize land as a function of UPV in depth, using low frequencies ($\leqslant$ 10 Hz) to enable the achievement of results in great depths [25–29]. However, low frequency transducers do not meet the specifics of compacted soils due to low saturation and smaller dimensions of the construction elements and specimens.

Therefore, each material requires a minimum distance between the transducers, i.e., a minimum length of the specimen or construction element, to meet the condition of an infinite path considering the stabilization of UPV values and frequency of transducers available during testing. Therefore the aim of this study is to determine the minimum length that compacted soil specimens must be made to obey the infinite path condition.

2. Materials and experimental procedures

2.1. Materials and preparation of specimens

Two soil samples S1 (Clayey) and S2 (Sandy) were used in this study. The aim of selecting soils with different classifications was to verify if the UPV is sensitive to changes in the granulometric arrangement, since the size of the grains directly interferes with the physical indexes of the compacted material.

The materials used were collected and later prepared for the sample characterization tests. The preparation including the separation of clods using sieve of 4.8 mm in diameter and drying in an oven for 24 h at 105°C according to the procedures described in NBR 6457 [30]. The physical characterization of samples includes the respective granulometric curves [31], specific mass of solids [32] and plasticity indices [33,34].

The specimens used in this study were molded according to parameters determined in compaction tests (Proctor's method), i.e., maximum apparent dry mass (γ_{dmax}) and optimum moisture content (OMC), considering the three energies of compaction (normal, intermediate and modified) according to NBR 7182 [35].

To fulfill the aim of this study – minimum specimen length – cylindrical specimens sized 50 mm in diameter and 50, 100, 150, 200, 250, 300, 350 and 400 mm in length (Fig. 1a). The molds were made with PVC tubes which received a side cut in the direction of each preset length, required to extract the specimen from the molds after compaction- especially those larger than 200 mm. Stainless steel clamps (ø = 8 inches) were used to avoid the loss of material during the manufacture of the specimens, varying from two to five clamps according to the specimen's length (Fig. 1b).

The compaction was performed according to the parameters of γ_{dmax} and OMC, defined in the Proctor tests, according to three compaction energies (normal, intermediate and modified). Therefore, it was decided to fix the heights of the compaction layers according to each specimen length, ranging from 6.7 mm to 37.5 mm. When considering soil types (2), compaction energies (3), length of the molds (60) and 3 repetitions for each condition analyzed, 108 specimens were required (Fig. 2).

2.2. Ultrasound tests

Ultrasound tests were performed using UsLab equipment (Agricef, Brazil), with longitudinal wave transducers and 45 kHz frequency exponential transducers (Fig. 3a). These tests were performed after 0, 7 and 28 days of the compaction of the specimens, considering the perpendicular transmission of the ultrasonic pulse to the compacted layers (Fig. 3b). The adoption of the compaction ages was necessary to verify the effects of the variation in the moisture content (MC) at the ultrasonic pulse velocity (UPV) and, consequently, on the λ.

From the propagation time of the ultrasonic wave, the UPV values (Eq. 1) and the wavelength (Eq. 2) were calculated, considering the frequency of the transducers used (45 kHz). As there is no standard for compacted soil, the procedures described in the concrete and wood ultrasound standards were adapted [36–38].

$$V = \frac{L\ (cm)}{t\ (\mu s)} \times 10^6\ (m/s) \quad (1)$$

$$\lambda = \frac{V\ (m/s)}{f\ (Hz)}\ (m) \quad (2)$$

Based on the calculations of λ (Eq. 2) and of each condition established in the methodology, the minimum L required to stabilize

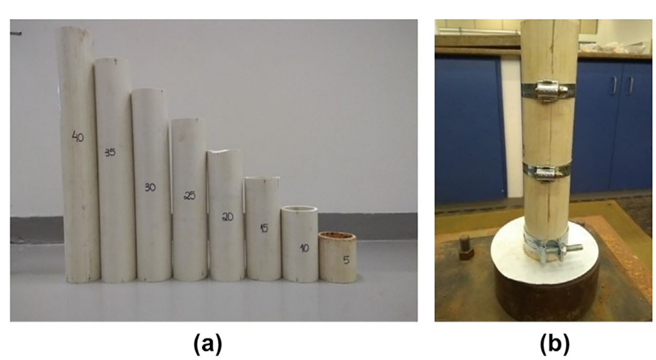

Fig. 1. PVC molds used for wavelength determination (λ) (a) and Adaptation of side-cut pipes and clamps (b).

Fig. 2. Test specimens exposed in the laboratory.

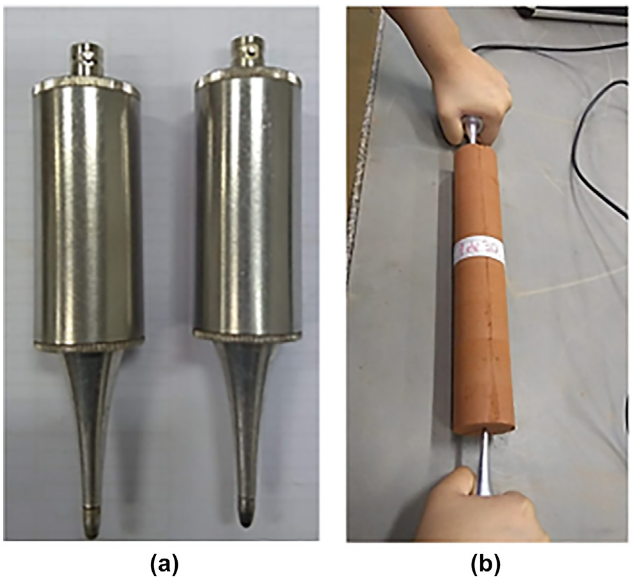

Fig. 3. (a) 45 kHz exponential transducers (b) Ultrasound test on specimens.

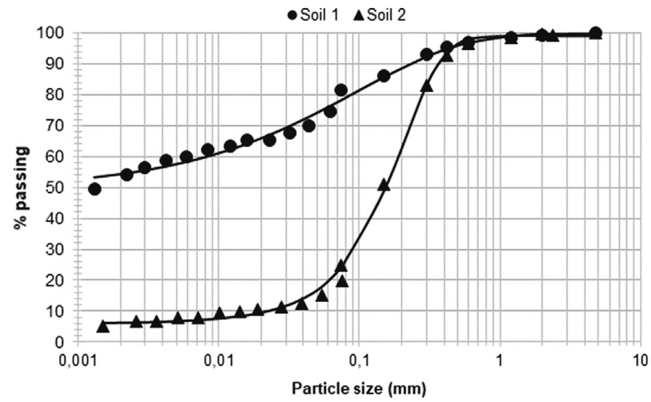

Fig. 4. Particle size distribution of soil samples S1 and S2.

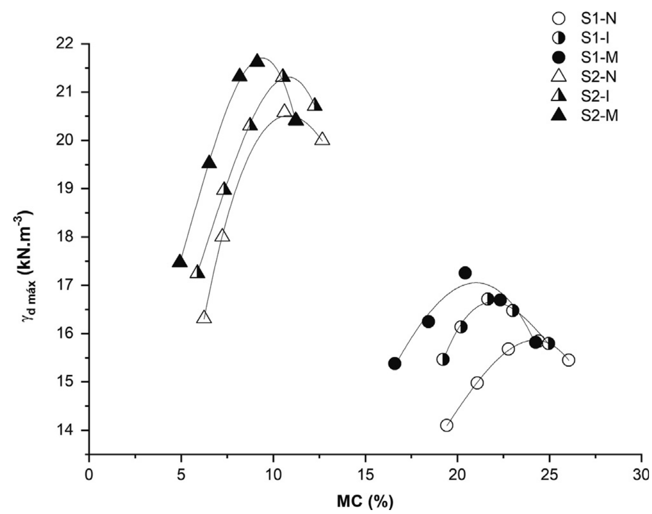

Fig. 5. Compaction curves of soil samples S1 and S2, according to compaction energy (Normal – N; Intermediate – I; Modified – M).

the UPV was determined, which indicates the propagation of the ultrasonic wave in infinite paths [22,21].

As identified in the literature [39,40,7,17,41], there are some factors that directly influence the UPV (MC and specific apparent mass). To verify whether these factors also influenced the λ values of compacted soil samples, statistical analyses were made between the soil types, compaction energy and MC. The hypothesis test method was used with the aid of the Origin software.

3. Results and discussions

From the granulometric curves obtained for the soil samples S1 and S2 (Fig. 4), it was possible to identify them as sandy-silt clay (55% clay, 23% sand and 22% silt) and clayey-silt sand (9% clay, 77% sand and 14% silt), with specific gravity of the grains equal to 27.9 $kN.m^{-3}$ and 26.5 $kN.m^{-3}$, respectively. The physical and plasticity parameters used for the classification two soil samples, according to the USCS (Unique Soil Classification System) and HRB (Highway Research Board) methods, indicated that samples S1 and S2 presented low plasticity, with a plasticity index equal to 10 and 13, respectively. The S1 sample was classified as A-5/ML [42] and the sample S2 as A-2-4/SC [43] according to the methods HRB and USCS, respectively. Clayey soils require higher MC than sandy soils to obtain the limits of plasticity and liquidity due to the greater surface area presented and minerals present of this soil.

Fig. 5 and Table 1 show the compaction curves and physical indexes of the two soil samples (S1 and S2), respectively. The increased density coincides with increasing compacting energy (N, I, M), which is justified for obtaining a higher grain content per unit volume. Furthermore, the shape of the curves (S1: open; S2: closed) are characteristic of behavior of clayey and sandy soil [43,44].

However, these parameters are changed when the samples are exposed to the environment, without controlling the loss of MC. Such modifications were considered in this research, being the specimens tested both after molding and after 28 days of exposure to the laboratory environment. The loss of water in this period changed the saturation conditions of the specimens, providing an increase in the void index for all the compaction energies (Table 1). The reduction in soil moisture content compacted unsaturated cause changes in its microstructure, both in the grain arrangement as in its rigidity. This is because the equivalent effective stress as a result of capillary forces, increases with decreasing saturation and the size of soil particles, which also affects the behavior of obtaining values UPV [45]. Therefore, in ultrasound tests, the size and shape of the particles and the moisture content must be account.

Based on the literature, specifically in the ultrasound test in compacted soil, the UPV is directly influenced by the moisture content [39,44,17,41,10]. In other studies, values UPV clay soil samples were stabilized after 3 days from compaction [40,46,17]. This was confirmed by statistical analysis (Paired-Samples T Test) considering the data obtained after 3, 30, 60 and 120 days after compaction, which were identified in the same homogeneous group.

Table 1
Physical properties of the soils by compaction energy and period.

Period	Soil	Identification	MC (%)	Yd (kN/m^3)	Voids	Porosity (%)	Saturation (%)
Molding	S1	S1-N	23,4	15,9	0,79	44,0	83,0
		S1-I	21,9	16,7	0,72	41,7	84,6
		S1-M	20,7	17,4	0,66	39,7	87,8
	S2	S2-N	10,6	20,6	0,36	26,7	73,0
		S2-I	9,6	21,2	0,34	25,5	72,1
		S2-M	8,7	21,7	0,31	23,9	55,4
28 days	S1	S1-N	19,2	13,5	1,1	52,4	48,7
		S1-I	18,4	14,0	0,99	49,8	51,7
		S1-M	17,1	14,7	0,95	48,6	50,4
	S2	S2-N	9,1	17,9	0,49	32,7	49,6
		S2-I	8,6	18,3	0,45	30,9	50,8
		S2-M	7,6	17,8	0,41	29,1	48,8

Table 2 presents the mean values of UPV, standard deviation (SD) and standard errors (SE), obtained in soil specimens S1 and S2, compacted in the three energies. The same statistical data are presented graphically in Fig. 6.

According to the hypothesis test- which allows us to reject or not a statistical hypothesis via the evidence provided by the sample (Paired Samples t-test)- the variation between 7 and 28 days was, on average, 15%, 9.5% and 13.5%, for normal, intermediate and modified energies, respectively. This behavior can be justified by the type of soil (clayey), which present OMC values above 20%, resulting in a moisture loss proportional to the MC when considering the same period (7 and 28 days). Moreover, according to the same hypotheses applied to the results of S1, there is no statistically significant difference between the periods of 7 and 28 days (p-value $\leqslant$0.05), except for the modified energy (p-value $\geqslant$0.05).

The S2 sample did not present significant UPV variation (p-value $\geqslant$0.05) after 7 and 28 days of specimens molding, considering the three compaction energies (N, I and M) (Fig. 6). This behavior is due to the type of soil (clayey-silt sand), which requires less OMC for compaction, resulting in a faster moisture stabilization. Other authors observed the same behavior when comparing the UPV values of the sandy soil sample after 2 and 7 days of molding, only obtaining a 5% UPV variation in this period [40].

Regarding the type of soil (S1 and S2), the UPVs were lower for S1 when obtained after molding. This is due to the greater attenuation of the compression wave, which is greater with a higher moisture content, since there are more capillary forces related to suction pressure [2,47,48]. However, after 7 and 28 days, the values were higher for the S1 sample, for the three compaction energies. Some studies that the ultrasonic velocities are lower for granular

Table 2
Analysis of variance (ANOVA) considering the UPV of molding and after 28 days.

Condition	Molding			28 days		
	Mean (m.s^{-1})	SD	SE	Mean (m.s^{-1})	SD	SE
S1 - N	680,6	41,3	16,9	1542,8	110,8	45,2
S1 - I	955,7	233,9	95,5	1641,9	185,9	83,1
S1 - M	1379,3	151,4	61,8	1283,9	120,5	49,2
S2 - N	835,0	125,6	51,3	1639,3	241,3	98,5
S2 - I	1090,2	257,2	105,0	1156,3	189,0	77,1
S2 - M	1384,4	105,9	43,2	1223,9	96,8	39,5

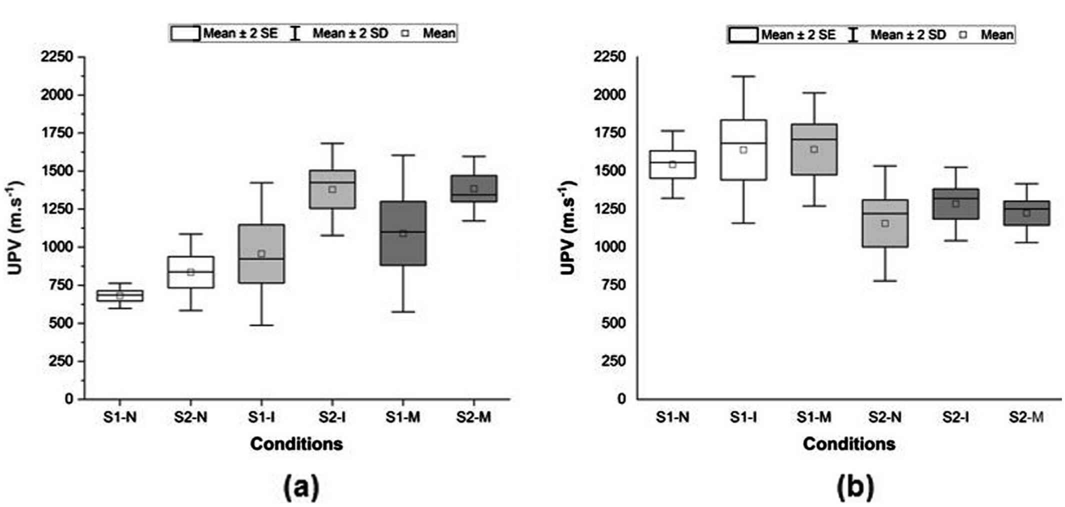

Fig. 6. UPV variation according to compaction energy (N; I; M), soil samples (S1 and S2) and time after molding (a) and 28 days (b).

soils [41,49], corroborating the results of this study. The discrepancy between the UPV values of the soils is due to the difference in specific surface between the two types of soil studied and, consequently, attenuation waves depends on interparticles contact area. The smaller the grain size, the greater the specific surface and consequently the greater the contact area between particles [45,2,50].

In heterogeneous material, dispersion and attenuation of the ultrasonic wave depends on the micro-structure of the medium, such as grains of different sizes and properties and the presence of water (adsorbed, capillary and, free). In this case, the higher the humidity, the greater the attenuation of the longitudinal waves [51,47]. Thus, the increase in UPV in compacted soils, after reducing the moisture content in relation to the optimum compaction humidity, occurs because the intergranular stresses that occur in unsaturated soils (suction pressure) increase the stiffness and facilitate the passage of ultrasonic wave in granular materials [45].

After 28 days, comparing the UPV value between both soils (S1 and S2), it was found that all molding conditions presented a statistically significant difference (Fig. 6b and Table 3). However, when comparing the different conditions (N, I and M) for the same soil, there was no difference (p-value $\leqslant$0.05). This behavior reinforces that there was stabilization of the UPV for both soils after the exposure period.

In unsaturated conditions, as analyzed in this study, one should take into consideration that the results are also influenced by stiffness increase caused during the period of exposure to the environment. The moisture loss process in which the test samples were subjected causes the increase inter-particle forces, due to pressure difference between air and water. This difference is related to the suction pressure, which is greater the lower the degree of saturation [45].

The specimens size must be bigger than λ to have the real velocity- similar to that which spreads in a free path (plane wave) [18,20,52]. Therefore, the UPV variation between the specimens of different dimensions, especially smaller, due to the fact that the surface wave is not a plane wave.

Considering the main objective of this research, it was determined how many wavelengths pass in each specimen dimension (50 mm to 300 mm) in order to identify from which dimension the wave becomes flat. UPV stability was not found in specimens with MC nearby to OMC, regardless of the λ and compaction energy. As reported by other authors, MC is the factor that influences UPV the values [46,41,39,17,44,49,41,53]. Performed a similar analysis on compacted soil panels for 14 days and also verified that the UPV increases according to the loss of moisture in the panels, despite the reduction of the apparent specific mass values [54].

Therefore, the lower the UPV, the shorter the λ and, consequently, the greater the number of waves traversing the material. This behavior was observed in the results of UPV obtained shortly after the molding of the specimens, a condition with MC nearby to OMC, resulting in 1.6 to 20.6 waves travelling through the specimen (Fig. 7).

After 28 days – and consequently a decrease in MC – there was an increase in UPV in S1, also reflecting the decrease in λ values. For S2, this same behavior was only observed the normal compaction energy, with intermediate and modified energies identified an increase in λ.

Another effect that the variation of the specimen's length may cause is the dissipation of part of the energy used during compaction due to the friction of the grains with mold's walls, which translates into non-linear variations of the physical indices, directly influencing the UPV. This relationship between voids, porosity and moisture content of compacted soils has already been evaluated using the propagation of ultrasonic waves, and the technique has identified the same nonlinear behavior of these variables, with velocity being sensitive to void variations [47,1].

This effect is more evident in the clayey soil (S1), which presents the intrinsic behavior of its properties in relation to UPV – cohesion; shape and size of the grains – thus changing the microstructure of this type of soil in a non-linear way. It can thus be concluded that the size of the specimens used during the characterization of the soil infers greater interference in clayey soils than in sandy soils. According to the literature, the difference between the behavior of both soils may be related to the amplitude of the ultrasonic wave, depends on the contact area between the particles, which is higher for samples with less amount of voids. As this contact area increases, the amplitude is also increased, which causes a decrease in the path taken by the wave and, consequently, an increase in velocity [47,2].

This behavior corroborates only for the specimens tested after 28 days, with the UPV being higher for the soil with less voids and porosity (S2). After 28 days, even with a higher void index, the UPV was higher for the S1 soil. This behavior indicates that the amount of voids, did not interfere as much in the results as the changes in MC.

The UPV values obtained in specimens tested stability after the passage of 6.2 and 5.4 waves for the normal and intermediate energies, respectively, for the S1 sample. Specimens molded in the modified energy for this soil did not present UPV values that identified some type of stabilization according to number of waves. The stabilization of the S2 specimens analyzed after molding occurred with 7.2 and 4.9 waves, also for normal and intermediate energies, respectively. In specimens tested after 28 days, for S1 it stabilized after the passage of 5.3; 3.9 and 5.0 waves, for normal, intermediate and modified energies, respectively. For S2, stabilization occurred after 7.3; 5.6 and 7.4 waves, for normal, intermediate and modified energies, respectively.

Table 3
Comparison between mean conducted using Tukey Test.

Comparation		Molding		28 days	
		P-value	Sig	P-value	Sig
S1-N	S2-N	0,6188	0	0,0042	1
S1-I	S2-I	0,0020	1	0,0097	1
S1-M	S2-M	0,0054	0	0,0030	1
S1-N	S1-I	0,0832	0	0,9100	0
S1-N	S1-M	0,0029	1	0,9170	0
S1-I	S1-M	0,7417	0	1,0000	0
S2-N	S2-I	0,0001	1	0,7606	0
S2-N	S2-M	0,0001	1	0,9792	0
S2-I	S2-M	1,0000	0	0,9878	0

Sig = 1: the difference of the means is significant at the 0,05 level.
Sig = 0: the difference of the means is not significant at the 0,05 level.

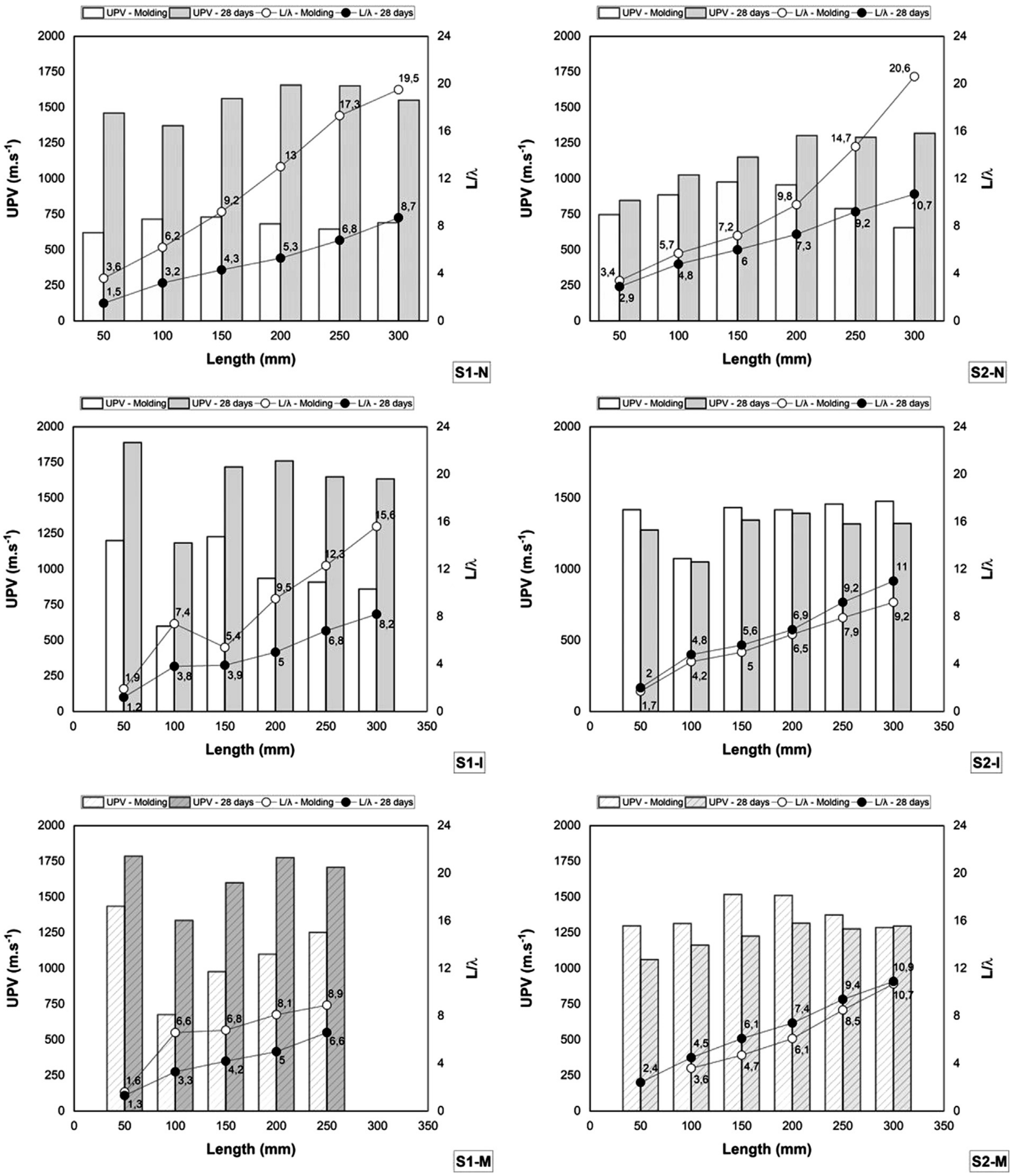

Fig. 7. UPV variation as a function of soil sample moisture content (S1 and S2) for each compaction energy (N, I and M) and specimen ages during tests (Molding and 28 days).

Although the intermediate energy showed a lower L/λ ratio, indicating the possibility of a smaller sample, this was also the condition that presented the highest standard deviation and standard error among the other energies considered, in S1 and S2 (Table 2).

In the case of this research, due to the frequency of the available transducers (45 kHz), the minimum length of 200 mm should be used, to guarantee at least 7 waves and, consequently, the propagation of waves in infinite media for all compaction energies, different from wood in which 3 waves must be guaranteed [18,21,19,20]. It should be noted that what will indicate the minimum length of the specimen will be the frequency of the transducer available to perform the test such must be increased if the use of smaller specimens is required for to obtain the real velocity in the material (infinite paths).

In addition to the actual UPV, knowledge of the wavelength is of significant importance, as it is directly related to the size of the defect to be detected. If the size of the discontinuities is much larger than λ, they may not be detected, and the data are inaccurate [18]. In general, the smallest diameter of a discontinuity to be detected in the material must be in the order of $\lambda/2$, that is, for a 200 mm specimen, with 7 passing waves, the minimum discontinuity to be detected will be approximately 8 and 19 mm, for tests after molding and 28 days, respectively.

4. Conclusions

Considering the proposed objective and the results obtained in this study, it is possible to conclude that:

- To ensure volume waves and infinite paths using a 45 kHz transducer, the compacted soil specimens must be at least 150 mm in length for the intermediate energy and 200 mm in length for the normal and modified energies, considering the S1 and S2 samples. Therefore, the soil type did not interfere with the minimum length required for the specimens to be used in ultrasound tests. When considering this behavior, it is concluded that the minimum length of the specimen must be 200 mm for both soil types;
- Among the physical indices, MC was considered the factor with the greatest influence on UPV variations, considering that ultrasound was able to identify the variations of MC between the period of exposure of the specimens to the environment laboratory;
- When comparing the values of UPV of the same soil, varying the compaction energy, it was found that the MC presents an inversely proportional influence, i.e., UPV increases as the MC decreases;
- Soil S1 (clayey) showed distinct behavior when correlating UPV values with the number of waves obtained for each length of the specimen. The fact occurred in 100 mm specimens, in which UPV sharply decreases in all 3 compaction energies. Further studies related to changes in the microstructure of this type of soil in relation to the type of compaction energy are required to explain such results.

These results indicate an advance regarding the procedures of the ultrasound test in compacted soil, indicating that there is interference in the sample dimensions, which must be considered in order to have the real UPV in the material. From this, it is necessary to investigate further the influence of variation of physical indexes in UPV, mainly related to MC and porosity/ voids. Such researches are necessary to make possible the use of ultrasound in different areas that have the soil as main building material, assisting in the characterization, technological control and inspection.

CRediT authorship contribution statement

W.S. Sarro: Conceptualization, Methodology, Formal analysis, Investigation, Writing - original draft, Writing - review & editing. **G.M. Assis:** Conceptualization, Methodology. **G.C.S. Ferreira:** Supervision, Writing - review & editing, Project administration, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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