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ORIGINAL ARTICLE

A new method for determining mortar shrinkage in the first 24 hours of hydration

Um novo método para a determinação da retração de argamassas nas primeiras 24 horas de hidratação

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Abstract: The shrinkage of cementitious materials is a complex phenomenon of volume reduction that can result in cracking, affecting the durability of these materials. The Brazilian standard ABNT NBR 15261 addresses long-term shrinkage without emphasis on the initial phase (< 24h) of hydration, which contains the plastic state of the cementitious material. Therefore, a method was proposed to measure the shrinkage in the first 24h of mortar hydration, on a laboratory scale, from prismatic samples, using molds from the Brazilian standard ABNT NBR 15261 (285x25x25mm) and rigid elements that transmit horizontal displacements of the sample to dial gauges. Cement mortar specimens were studied with the water/dry materials ratio fixed at 0.168 and varying the binder/aggregates ratio linearly: 33% (1:3); 25% (1:4); and 17% (1:6). Different exposures to the environment (sealed, open and wind) were applied. The analysis indicated that the proposed method was sensitive enough to indicate statistically significant relationships between the maximum initial shrinkages and the variation in the concentration of the binders, as well as indicating variations in the behavior of the initial shrinkage. The increase in cement concentration caused an increase in the average initial shrinkage of 76% in the samples exposed to air, 54% in those exposed to 5 m/s wind, and 22% in the sealed samples.

Keywords: early age shrinkage, mortar, measurement method, durability.

Resumo: A retração de materiais cimentícios é um fenômeno complexo de redução de volume que pode resultar em fissuras que afetam a durabilidade desses materiais. A norma brasileira ABNT NBR 15261 aborda a retração a longo prazo sem ênfase na fase inicial (< 24h) da hidratação, que contém o estado plástico do material cimentício. Portanto, foi proposto um método de mensuração da retração nas primeiras 24h de hidratação de argamassas, em escala laboratorial, a partir de amostras prismáticas, utilizando: o molde da norma brasileira ABNT NBR 15261 (285x25x25mm) e elementos rígidos que transmitem deslocamentos horizontais da amostra para relógios comparadores. Foram estudados traços de argamassa de cimento com a relação água/materiais secos fixa em 0,168 e variando a relação aglomerante/agregados linearmente: 33% (1:3); 25% (1:4); e 17% (1:6). Foram aplicadas diferentes exposições ao ambiente (selado, aberto e vento). As análises indicaram que o ensaio proposto foi sensível o suficiente para indicar relações estatisticamente significativas entre as retrações iniciais máximas e a variação da concentração dos aglomerantes, assim como indicar variações de comportamento da retração inicial. O aumento da concentração de cimento causou um aumento da retração inicial média de 76% nas amostras expostas ao ar, 54% nas expostas ao vento de 5 m/s e 22% nas seladas.

Palavras-chave: retração inicial, argamassa, método de medição, durabilidade.

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1 INTRODUCTION

After their first contact with water, cementitious materials undergo volumetric shrinkage changes. This is due to the smaller volume of hydration products compared to their anhydrous components, due to the loss of water to the environment, substrate, and hydration [1]. This volume contraction is called in the literature as shrinkage, Mehta and Monteiro [2] state that this volumetric reduction that cementitious materials undergo during hydration, whether plastic, drying, or autogenous, can be one of the causes of cracking of cementitious materials, thus compromising their service life and resistance, in addition to increasing the interference of aggressive agents. According to Maltese et al. [3, pp. 1], "shrinkage is one of the main reasons for failures in mortars, such curling, cracking and detachment", Kayondo et al. [4] found that the main mechanisms that promote plastic cracking are settlement of solid particles; exudation; evaporation; capillary movement; and surface finish. These mechanisms combined lead to a three-dimensional volume contraction of the cementitious material, which in its early hours has not yet developed the mechanical strength to support it. Therefore, if this movement is contained, cracks in the plastic state will occur as a result.

The shrinkage phenomenon can be divided into two stages: early and late (or "long-term") [5]. The initial stage is usually attributed to the first day of cement hydration, which is when the beginning and end of the setting of this material occurs, in addition to the initial hardening. The later age refers to those from 24 hours onwards. In the literature, in general, long-term shrinkage receives much more attention than the one that occurs in the initial stage [6]. Both stages should not be mistaken by the six main types of shrinkage recognized in the literature: plastic, chemical, autogenous, drying, thermal, and carbonation [7]. Except for plastic shrinkage – which refers to the volume reduction that occurs in the plastic state of the material [8] and occurs until the initial setting time [9] –, the types of shrinkage are categorized by their cause and not by the stage that they develop. Therefore, in each stage, early and long-term, multiple types of shrinkage contribute to the total volume reduction, also called total shrinkage.

There are several ways to interpret the dimensional variation caused by early shrinkage. One of them is to measure the autogenous shrinkage with a sealed flexible corrugated mold system (ASTM C1698-19 [10]) that prevents water loss, but it doesn't measure total early shrinkage since it ignores drying shrinkage.

Another standardized way is by the quantification of cracks on fresh restrained concrete surfaces (ASTM C1579-21 [11], specifically for restrained fiber reinforced concrete, and GBT 29417-2012 [12]), but it fails to measure the actual volume or length changes caused by total early shrinkage.

Other ways of interpretation, such as horizontal [13]-[23] or vertical linear displacements [16], [21], [24], were not developed in standardized methods yet. However, large research centers, excluding Brazilian research, have already explored these methods extensively (Silva [20]). In Brazil, the only standard that proposes to measure shrinkage in mortars is ABNT NBR 15261 [25], but it provides for measuring shrinkage only in the hardened state ignoring the early age.

In Brazil, there are few proposals for methods of measuring shrinkage at an early age. Bastos et al. [18], Silva [20] and Girotto et al. [26] are some examples.

Détriché's method [27], amplified by the conditions applied by Bastos et al. [18], is based on free shrinkage by horizontal displacements using LVDT (Linear Variable Differential Transformer) as measuring equipment. The same equipment was used by Silva [20] in his unilateral free-shrinkage adaptation for coating mortars, based on the study of fibers in concrete developed by Wongtanakitcharoen and Naaman [28]. Girotto et al. [26] proposed the adaptation of the method by Soroushian and Ravanbakhsh [29], who analyzed cracking in concrete for mortars. It is based on the same principle of differential mold depth to induce cracking as stated in ASTM C1579-21 [11].

Measuring the volumetric variation allows a better understanding of the mechanisms that govern the behavior of these materials under the influence of early shrinkage, in addition to predicting future durability complications. Greater knowledge about this phenomenon contributes to the study of how to avoid it. Hence the need for easily reproducible and accessible methods, thus with the potential to become standardized. Within this context, the objective of this article was to propose a new test method for determining total shrinkage in mortars in the first twenty-four hours of hydration, through the approach of horizontal linear displacements without making distinctions between different types of shrinkage, inspired by the study by Bastos et al. [18], expanding the study to simple cement mortars, adopting different exposures to air, opting for affordable instrumentation and facilitating ABNT NBR 15261's [25] long-term measurements.

2 MATERIALS AND EXPERIMENTAL PROGRAM

2.1 Materials

Natural river sand was used as fine aggregate. Table 1 shows its characteristics and the respective standard used in determining it. Particle size distribution was determined according to ABNT NBR NM 248 [30] (Figure 1).

Table 1. Fine aggregate characterization

Property	Result	Standard
Unit mass	1.45×10^{-3} kg/m^3	ABNT NBR 16972:2021 [31]
Specific gravity	2.49×10^{-3} kg /m^3	ABNT NBR 16972:2021 [31]
Pulverulent material content	4.09%	ABNT NBR 16973:2021 [32]
Water absorption	1.00%	ABNT NBR 16916:2021 [33]

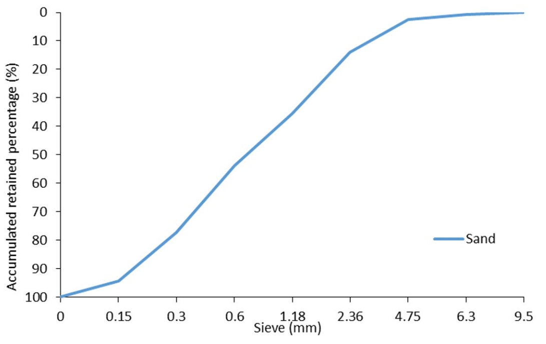

Figure 1. Sand's granulometric curve

A cement type CP-II-F, corresponding to American cement: IL Portland-limestone cement – ASTM C595/C595M - 21 [34], was used in the mortar (Tables 2-3). This cement was chosen because filler (limestone) is chemically inert, thus not conferring a chemical influence on the shrinkage behaviour.

Table 2. Chemical characterization of cement CP-II-F

Determination	Mass (%)
Loss on ignition	6.74
SiO_2	18.32
Al_2O_3	4.06
Fe_2O_3	2.77
CaO	61.58
MgO	2.47
SO_3	2.65
Na_2O	0.73
Insoluble Residue	1.20

Table 3. Physical characterization of cement CP-II-F

Property	Value
Hot expansibility (mm)	0
Setting time – beginning (min)	185
Setting time – end (min)	255
Blaine fineness (cm^2/g)	3,360
#200 sieve fineness (%)	2.30
#325 sieve fineness (%)	11.40
Unit mass (g/cm^3)	1.45
Specific gravity (g/cm^3)	3.11
Standard consistency (%)	29.50
Compressive strength – 1 day (MPa)	15
Compressive strength – 3 days (MPa)	27
Compressive strength – 7 days (MPa)	33
Compressive strength – 28 days (MPa)	40

2.2 Mortar formulation

According to Neville [35], the plastic shrinkage is greater as the cement content of the mixture increase. According to Silva [20], one of the main factors responsible for the restrictions to deformations in the fresh state of mortars is the aggregates.

Therefore, mortar mixture proportions with different aggregate/binder ratios were adopted to evaluate likely similar behaviors, but with different magnitudes of initial shrinkage (< 24 hours). Mortar mixture proportions were studied in a volume of cement mortar.

A constant water/dry materials ratio of 0.17 was adopted varying the binder/aggregates ratio by 8.33% by volume and 8.03% by mass. Table 4 shows the mortar mixtures proportions and their consistency index determined by ABNT NBR 13276 [36].

Table 4. Cement mortar mixtures characteristics

Composition/ Relation/ Index	Constituent/ Relation	Cement mortar mixtures		
		1:3	1:4	1:6
Composition by volume	Cement	1.00	1.00	1,00
	Sand	3.00	4.00	6.00
	Water	0.70	0.88	1.23
Composition by mass	Cement	1.00	1.00	1.00
	Sand	3.11	4.15	6.23
	Water	0.70	0.88	1.23
Water/Binder		0.70	0.88	1.23
Binders / Aggregates		0.32	0.24	0.16
Water/Dry Materials		0.17	0.17	0.17
Consistency Index (ABNT NBR 13276 [36])		259 mm	243 mm	223 mm

2.3 Mold and instrumentation

The proposed method used the same metallic prismatic mold of ABNT NBR 15261 [25], with dimensions of (285 x 25 x 25) mm. A rigid element was inserted in the fresh mortar during casting. This element was used to transfer material displacements, caused by shrinkage, to dial gauges. The rigid element consists of a metal plate (STEEL SAE 1006) with holes for better anchoring in the mortar (Figure 2).

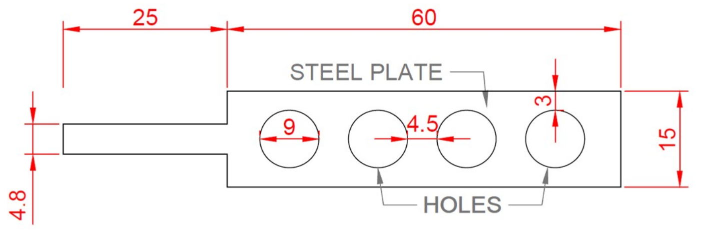

Figure 2. Rigid element vertical view (measurements in mm)

A rivet with a 2.5 mm thread was welded to the end of the rigid element (Figure 3) that allowed the connection between the metal plate with a connector.

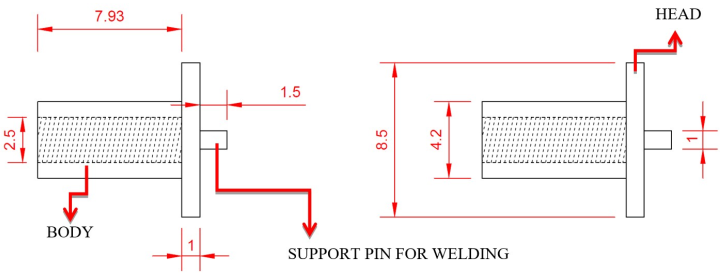

Figure 3. Rivet measurements in mm

The rivet dimensions were chosen according to the need to fit with the mold's block (Figure 4). The length was delimited by the thickness of the mold's block so that there would be no blocking during demolding. The rivet diameter was designed to be close to the diameter of the hole in the mold's block to avoid the eventual escape of water or material but still, allow its free movement. Moreover, the diameter of the rivet head is larger than the hole of the mold block to prevent water and material from coming out.

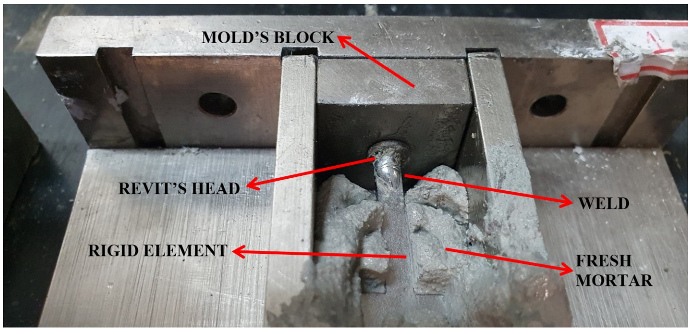

Figure 4. Rivet's head bigger than the mold's block hole

As the rivet and dial indicator have 2.5 mm threaded ends, a connector was developed from 2.5 mm headless screws and joined by a headless rivet through threading and instant glue, as exemplified in Figure 5. Figure 6 shows the projection of the rigid element on a mortar specimen, demonstrating how it is positioned internally.

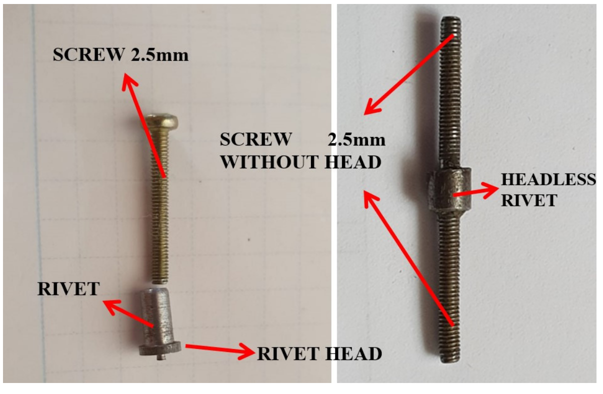

Figure 5. Connector assembly details. NOTE: on the left, screw and rivet before they are cut and connected; on the right, connector ready: two screws threaded and glued to a headless rivet.

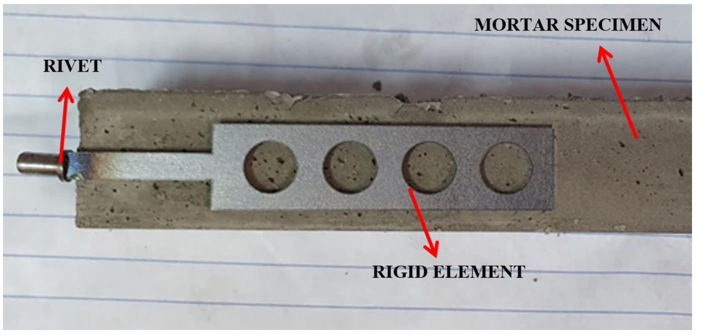

Figure 6. Overlay of the rigid element on the sample to demonstrate its position internally.

A digital indicator gauge was chosen as the measuring equipment. The equipment had 0.001 mm (10^{-6}m) accuracy – enough to capture the displacements of shrinkage and close to the reading accuracy provided by an LVDT. Two cameras were used to obtain the readings of the four dial gauges. These cameras filmed the specimens for 24 hours (Figure 7) in order to perform the readings without the need for operator to monitor the test during the 24 hours of the experiment. The final connection between the elements can be seen in Figure 8.

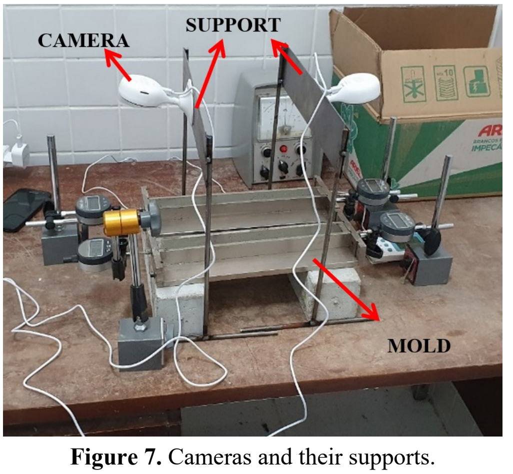

Figure 7. Cameras and their supports.

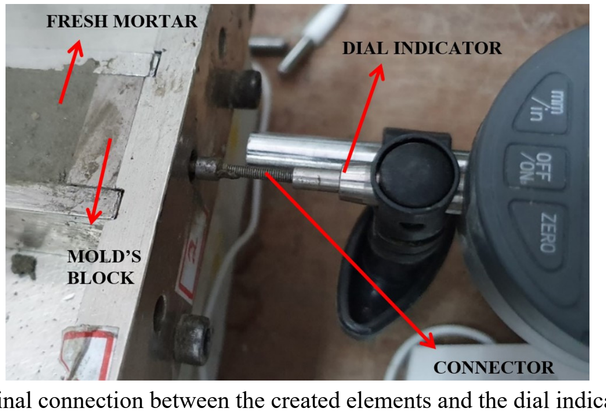

Figure 8. Final connection between the created elements and the dial indicator gauge.

2.4 Adopted air exposure conditions

ABNT NBR 15261 [25] requires that the samples remain during the first (48 ± 6) h in laboratory conditions, covered by PVC film and, after demolding, in a dry chamber (23 ± 2 ºC and 50 ± 5%). According to this standard, the shrinkage readings must be performed at 0, 1, 7, and 28 days after demolding the sample (therefore only in the hardened state). This article used three conditions of exposure to air in laboratory ambient conditions:

1. Sealed: covered by PVC film (according to ABNT NBR 15261 [25] guidelines);
2. Exposed to air: no PVC film or wind incidence on the surface, simply exposed to air;
3. Exposed to 5 m/s wind produced by a fixed fan, during the first 24h of hydration.

The relationship between water loss and shrinkage is quite direct. Therefore, those exposure conditions that induce different influences on water loss from the mixture were chosen to evaluate the proposed method and its sensitivity.

2.5 Step by step to run the proposed test

The new test proposed by this article was performed in the following sequence:

1. Two metallic molds (indicated in ABNT NBR 15261 [25]) are greased with mineral oil;
2. The hole of the mold's blocks and the outer surface of the rivet body receive a layer of vaseline paste to prevent the possible escape of water and material and to reduce possible friction between them;
3. With the materials already weighed and separated, the mortar mixture follows the procedure proposed by ABNT NBR 16541 [37] and the mixing start time is registered;
4. Two samples are then casted, one in each mold (each test is repeated twice, resulting in 4 samples per test). As guided by ABNT NBR 15261 [25], they are casted in two layers with 25 blows each and final flattening with a spatula;
5. After the blows of the first layer of the samples, the rigid elements are inserted in each of the mold's ends and threaded in their connectors. Then the second layer is executed;
6. The mass of each of the sets, mold, and fresh mortar specimens is recorded.
7. Then, the molds are taken to the dry chamber and positioned below the cameras. The connectors are threaded to the dial gauges that are already in a level position to receive them. Thus, the measurements begin.
8. Along with the displacements, the variation in temperature and humidity are recorded by the two cameras, one on each pair of dial gauges for 24 hours;
9. After 24 hours, in addition to the molds being weighed, the samples are demoulded, their first measurements on the ABNT NBR 15261 [25] are performed and then the samples are stored in the dry chamber, where the long-term shrinkage was registered in the following ages: 7, 14, 21 and 28 days.

The decision to demold the specimens after 24 hours, instead of 48 hours as prescribed by ABNT NBR 15261 [25], came from a need to keep the proposed schedule feasible. Therefore, the long-term shrinkage results obtained in this study cannot be directly compared with the results external to the research that follow the 48-hour demolding standard of ABNT NBR 15261 [25].

The readings of displacement, temperature, and humidity of the environment were performed by watching the recordings and noting the variations recorded every 5 minutes for 24 hours. To obtain the total linear displacement (mm) of a specimen, the readings obtained from the two clocks connected to it were added. Finally, to obtain the total shrinkage that occurred in each reading (mm/m), the sum of the readings was divided by the distance from the center of the rigid elements.

A recurring fact in the measuring of early shrinkage was the absence of displacement in one or more of the dial gauges. The event was observed at all points of all molds, and at least once in each dial. When one or both ends of a mold did not register any displacement, the reading was discarded, and the test was repeated until there were at least four specimens for the test. In 86.46% of the tests, the movement was registered, and they were not discarded. It is suspected that thread wear between the connector and the dial gauge could have been one of the causes. Also, despite the efforts, there may have been percolation of cementitious material into the hole of the mold's block, with consequent blocking of the rivet's movement.

3 RESULTS AND DISCUSSIONS

A one-way ANOVA analysis of variance with a 5% level of significance was adopted. This evaluation seeks to statistically discover the validity of two hypotheses: H0 (null hypothesis), in which there are no significant differences between groups (groups being the results of a sample influenced by a factor); H1 (alternative hypothesis), there is a significant difference between the groups caused by the controllable factor investigated [38]. H0 can be ruled out, that is, there are significant differences between the groups caused by the controllable factor under study, when the calculated F-value is greater than F-critical (tabulated value), concomitantly, the P-value is less than 0.05, according to a significance level of 5% [38].

3.1 Early shrinkage

3.1.1 Exposed to air

Figure 9 demonstrates early shrinkage curves recorded for the samples exposed to air. The binder/aggregate variation resulted in different shrinkage magnitudes. The dotted lines represent individual tests for each mixture and the thicker continuous ones represent the mixture's average curve.

To statistically understand whether there was a significant influence on the shrinkage achieved between the adopted mixtures, an analysis of variance (ANOVA) was performed (F-value: 40.870; F-critical: 4.270; P-value: 0). According to the ANOVA results, the variation of the binder/aggregates ratio had a significant impact on early shrinkage's magnitude.

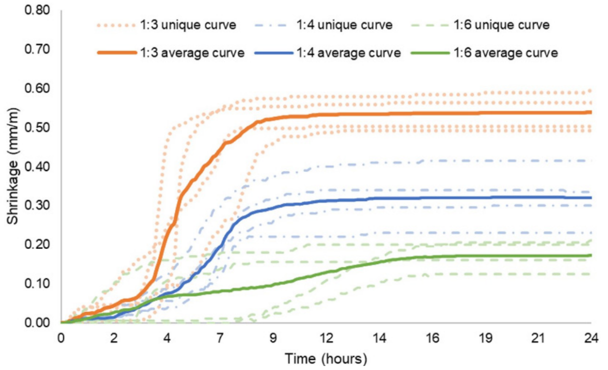

Figure 9. Early shrinkage curves of exposed to air samples. NOTE: dotted lines indicate individual tests, and continuous ones are their respective average curves.

In order to better characterize the difference in behaviour between the average shrinkage curves, the series of each data curve was selected, within the intermediate stage (when retraction progresses faster), which obtained the highest linear correlation (R). This series selection was made from all data within the intermediate stage and excluding the extremes simultaneously, thus increasing the linear correlation of the series until it decreased.

For each mixture, a linear function ($f(x) = ax + b$) was found, using a time x_0 and x that resulted, respectively, in a shrinkage y_0 and y. From it, the rate of change of the average shrinkage concerning the analysed time was calculated, which can be interpreted as a shrinkage speed. Considering the proposed period, the speed found would be the highest shrinkage speed for each average analysed.

The average shrinkage speed of the 1:3 mixture was 2.89E-5 mm/m/s, 75% higher than the 1:4 mixture (1.65E-5 mm/m/s), and 835% higher than the 1:6 mixture (3.09E-6 mm/m/s). Figure 10 shows the series selected for each mixture used to find the maximum speed.

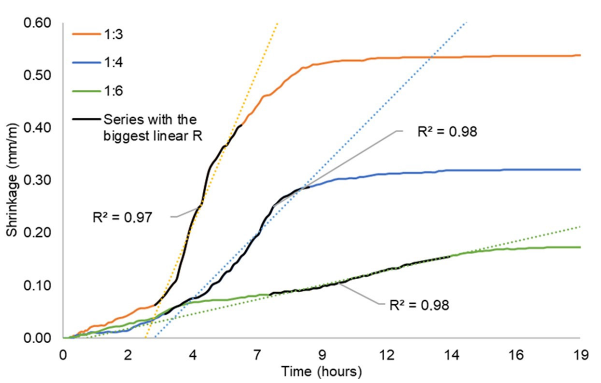

Figure 10. Average early shrinkage curves of exposed to air samples and their selected series for shrinkage speed calculation. NOTE: time scale of the graph used in 19 hours to improve the visualization of the selected series for calculating the intermediate stage's slope. The dotted lines represent the linear trend line taken from the series with the highest linear R within the intermediate stage.

The lowest mass loss (14.47%) after 24 hours was observed in the mixture with the highest cement/aggregate ratio (mixture 1:3), while the mass loss of mixture 1:6 had the highest value (19.23%). The 1:4 mixture showed an intermediate value (16.19%).

Analysis of variance (F-value: 16.366; F-critical: 4.256; P-value: 0.001) confirmed an inversely proportional influence between cement content and mass loss. This suggests that a greater amount of cement consumes more available water from the mixture, indicating greater hydration, and consequently greater chemical shrinkage. At the same time, water exits from thinner channels when the binder content is higher, which also causes greater shrinkage. Thus, the new test proposed in this article showed sufficient sensitivity to identify the effect of different cement contents in shrinkage mortars.

3.1.2 Sealed with PVC film

The sealed samples showed low-magnitude early shrinkage (maximum of 0.085 mm/m) and low dispersion curve behavior between mixtures (Figure 11).

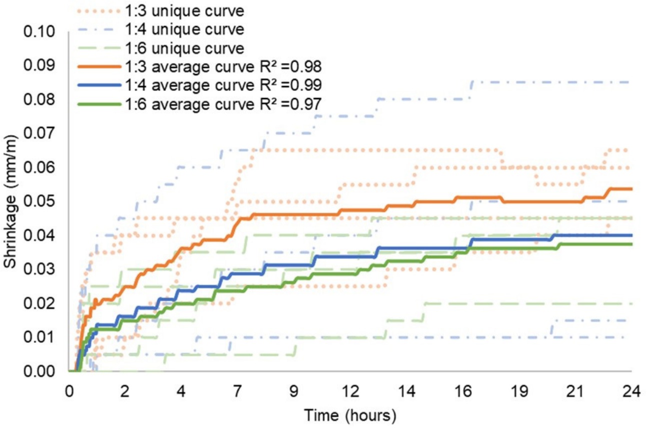

Figure 11. Early shrinkage curves of cement mortars sealed with PVC film. NOTE: dotted lines indicate individual tests, continuous ones are their respective average curves and their legend contains their linear R used to find shrinkage speed.

Visual analysis of Figure 11 does not provide a clear differentiation between mixture behaviour and this observation is confirmed by analysis of variance, which resulted in non-significant for the sealed specimens (F-value: 0.701; F- critical: 4.267; P-value: 0.521). Despite the statistical insignificance, a small difference can be visually observed between the average curves.

The high dispersion of data can be attributed to the fact that 64% of the sealed samples did not show any displacement in one of the dial gauges, and 14% did not show any displacement. This may indicate a failure in the ability of the proposed method to detect low-magnitude shrinkage. The behaviour of the average shrinkage curves for the sealed condition showed a pattern that differs from that found in the other exposure conditions. Therefore, the shrinkage speed study did not use the same linear correlation method, but a logarithmic correlation with the entire data series of the average shrinkage curve of each mixture (Figure 11 shows de R found for each average). An average maximum shrinkage speed of 8,98E-06 mm/m/s was observed for the 1:3 mixture, 47% higher than the 1:4 mixture (6.12E-06 mm/m/s), and 94% higher than the 1:6 mixture (4.63E-06 mm /m/s).

The analysis of variance in the relationship between mixture and mass loss (F-value: 13.229; F-critical: 4.256; P-value: 0.002) remained consistent with what was found in samples exposed to air. The mass loss after 24 hours decreased as the cement content increased. The 1:3, 1:4, and 1:6 mortar mixture had mass loss equal to 3.05%, 3.89%, and 5.09%, respectively. This would correspond to a 76.16% lower mass loss, on average, compared to measurements performed in the mixture exposed to air, which indicates that the PVC film drastically reduces evaporation during the first 24 hours of hydration.

3.1.3 Exposed to wind (5 m/s)

The shrinkage curves of the cement mortar mixtures exposed to 5 m/s wind were marked by an initial abrupt growth followed by an abrupt stagnation (Figure 12). As well as the mortars exposed to the air, the mortars exposed to the wind also showed a significant response in the maximum shrinkage caused by the variation of the mortar mixture (F-value: 10.790; F-critical: 4.103; P-value: 0.003), that is, by the cement content. The average shrinkage speed within the intermediate stage, for the mixtures exposed to 5 m/s wind, resulted in 1.08E-4 mm/m/s for the 1:3 mixture, 46% higher than the 1:4 mixture (7.41E-5 mm/m/s), and 113% greater than the 1:6 mixture (5.09E-5 mm/m/s). Besides showing all test results from the exposed to wind samples, Figure 12 shows the R linear for each mixture average curve used to find the shrinkage speed.

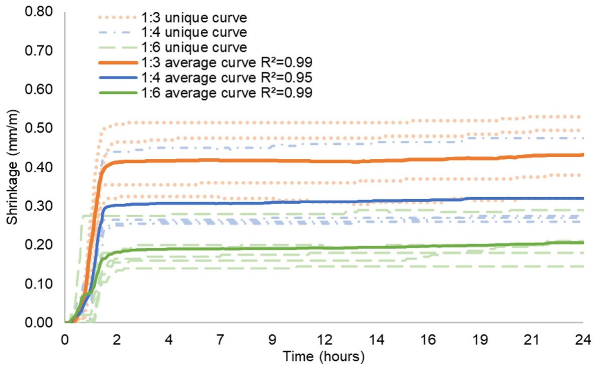

Figure 12. Early shrinkage curves of cement mortars exposed to 5 m/s wind. NOTE: dotted lines indicate individual tests, continuous ones are their respective average curves and their legend contains their linear R used to find shrinkage speed.

The mass loss recorded after the first 24 hours for the samples exposed to wind also resulted in significant variation as a function of the binder concentration (F-value: 72.070; F-critical: 4.102; P-value: 0). Again, the highest mass loss found was in the 1:6 mixture (24.68% on average), the intermediate value in the 1:4 mixture (19.71%), and the lowest value in the mixture with the highest cement concentration, 1:3 (16.7%). Therefore, the proposed new method had sufficient sensitivity for this curing condition.

3.1.4 Comparison between exposures for each mixture

Figure 13 shows the comparison between the average shrinkage speeds of cement mortars in the intermediate period, separated by the different exposures used in the tests and the different binder/aggregate ratios.

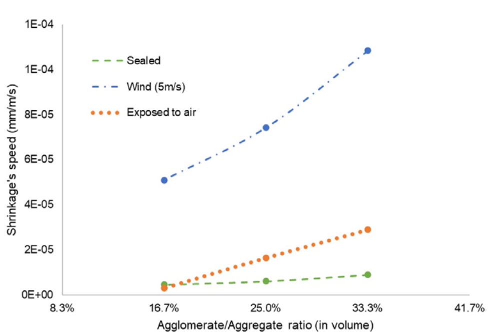

Figure 13. Average early shrinkage speeds of cement mortars under different air exposure conditions

A trend can be observed concerning the increase in the shrinkage speed to a more intense condition of exposure to air. It is also noted that the difference in speed magnitude between the mixtures with different binder/aggregate ratios is intensified by the greater intensity of exposure to air since the curves become steeper as a function of this exposure.

The analysis of variance for the effect of different exposures on the maximum shrinkage recorded in cement mortars was significant for all mortar mixtures. Figure 14 shows the shrinkage results for the 1:3 mixture under different exposure conditions. Mixtures 1:4 and 1:6 had similar behaviours to 1:3.

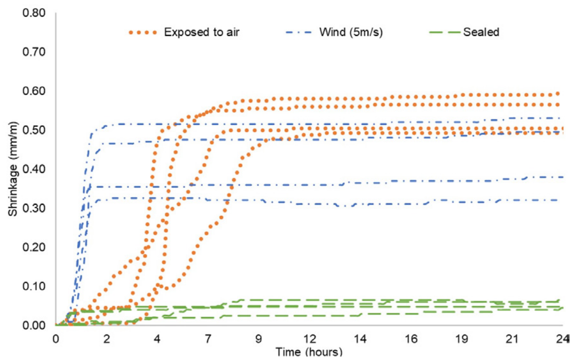

Figure 14. Early shrinkage curves of the individual specimens from the 1:3 mixture and the variation of different exposures to air.

According to Figure 14, the magnitude of the maximum shrinkage is smaller for the tests sealed with PVC film when compared to those exposed to air. This indicates that the lower loss of water by evaporation drastically reduces early shrinkage – which shows the large contribution of drying shrinkage (by evaporation) to early shrinkage. However, the shrinkage recorded in the sealed condition was not null, possibly accusing the test's ability to record the contribution of other types of shrinkage in addition to drying, like chemical shrinkage. Also, there is an expressive difference between the behaviour of shrinkage curves of exposed to wind samples when compared with the behaviour of exposed to air samples. It is visually evident that the wind causes the increase in shrinkage to start earlier and faster, hence the "steepest" appearance of the curve in the early stage.

The maximum shrinkage of the mortar exposed to the wind was smaller or only marginally larger than that exposed to the air. This is justified by the early water loss. As the wind accelerates the loss of water by evaporation, it is likely that later, within the first 24 hours, the mortars exposed to wind will have less water for hydration than those exposed to air, which could minimize the impact of the hydration contribution for total shrinkages, such as chemical shrinkage. Other lower wind speeds would possibly slope the shrinkage curves less and produce different magnitudes of early shrinkage.

3.2 Long term shrinkage

The results for the long-term shrinkage were obtained by the method proposed by ABNT NBR 15261 [25] with the variation of two aspects: demolding of the specimens after 24 hours instead of 48 hours due to schedule and adoption of alternative initial cure conditions.

Although in all exposures the average maximum long-term shrinkage was greater for the 1:3 mixture (0.722 mm/m), intermediate for the 1:4 mixture (0.661 mm/m), and smaller for the 1:6 mixture (0.550 mm/m), the variation of the concentration of binder/aggregates in the cement mortar mixtures was significantly influential on the maximum long-term shrinkage only in the case of specimens exposed to air.

According to Table 5, the maximum long-term average shrinkage was higher for sealed specimens (0.770 mm/m), intermediate for those exposed to air (0.648 mm/m), and lower for those exposed to wind (0.516 mm/m).

Table 5. Comparison of the magnitude of average long-term maximum shrinkage for the different exposures adopted (mm/m)

Exposition	Mixture		
	1:3	1:4	1:6
Sealed	0.848	0.800	0.661
Exposed to air	0.768	0.656	0.520
Wind (5m/s)	0.550	0.528	0.469

The statistically significant influence of exposure on the long-term mean maximum shrinkage was not found only for the 1:6 mixture. It is believed that this occurs due to the 1:6 mixture's smaller magnitude shrinkage, which reduces the dispersion (smaller shrinkage results are closer to each other) and makes it difficult to verify the accuracy with the sample size. Figure 15 illustrates the observed long-term shrinkage behavior for the 1:3 mixture. The other mortar mixtures had similar behavior.

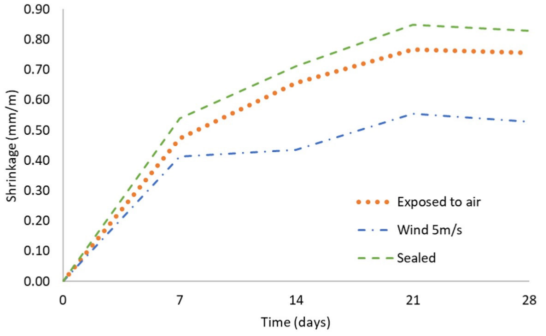

Figure 15. 1:3 mixture's long-term average shrinkage at different air exposures.

As discussed in the 24-hour shrinkage results, the PVC film minimized evaporation on the first day of hydration. Therefore, the sealed specimens would have more water available at long-term ages than those exposed to air and wind, making them more susceptible to drying shrinkage, resulting in greater long-term shrinkage.

The long-term shrinkage behaviour found was reaffirmed by the long-term average maximum mass loss results, with the sealed specimens showing the highest percentage (7.76% on average for all mixtures). The air and wind conditions showed mass loss of 3.37% and 1.18%, respectively. Therefore, within the comparative analysis between the exposures, the specimens that showed the greatest long-term shrinkage were also those that lost more mass in the long term, possibly highlighting the role of drying shrinkage.

3.3 Comparison between early age and long-term shrinkage

Assuming that the total shrinkage consists of the sum of the initial and the long-term values, Table 6 shows the contribution of the initial and long-term shrinkages to the total (represented by the blue bars).

Table 6. Comparison between initial and long-term shrinkage and their contributions to total shrinkage

Exposure	Mixture	Total shrinkage (mm/m)	Percentage of contribution to total shrinkage	
			Early age	Long term
Exposed to air	1:3	1.31	41.20%	58.80%
	1:4	0.98	32.90%	67.10%
	1:6	0.69	25.00%	74.90%
Sealed	1:3	0.90	6.00%	94.00%
	1:4	0.84	4.80%	95.20%
	1:6	0.70	5.30%	94.70%
Wind 5 m/s	1:3	0.99	44.00%	56.00%
	1:4	0.85	37.80%	62.20%
	1:6	0.65	28.30%	71.70%

According to Table 6, specimens tend to shrink and lose more water in the long term when sealed in the first 24 hours of hydration than specimens under other conditions. However, the sealed ones shrink in total on average 15% less than those exposed to air and 1% less than those exposed to wind.

Excluding sealed specimens, the cement mortar specimens' long-term shrinkage was 98% greater than their early shrinkage. However, considering that early shrinkage refers to one day of hydration and long-term shrinkage refers to the first 28 days, the initial stage's importance to total shrinkage becomes significant.

The method proposed by the ABNT NBR 15261 [25] standard is similar to the PVC film-sealed condition adopted in the present study and in this condition the total shrinkage occurs mostly in the long-term period (Table 6), which points to the fact that the standard is not losing so much of the total shrinkage reading in this condition by disregarding the initial shrinkage.

However, the condition of exposure of mortars within the practice of civil engineering is much closer to the conditions exposed to air and wind and, as demonstrated, the behavior of total shrinkage observed in these conditions is quite different. Therefore, if the purpose is to study coating mortars and their day-to-day behavior, the standard is lacking in precision because it ignores the early shrinkage, and the newly proposed method of this paper is the beginning of an attempt to fill this gap.

4 CONCLUSIONS

A method of measuring the early shrinkage in mortars was proposed using the horizontal displacement approach. The test is interesting in terms of low cost, considering that dial gauges were used, and this instrument is cheaper than the LVDT, which is generally adopted in tests that use the same approach. Also, the reading did not depend on data collectors (digital, instruments used to connect watches to computers) since cameras were used in this study. Thus, this article demonstrates the experimental technical feasibility of the proposed method to measure the early shrinkage in mortars.

The test proved to be sensitive to evaluate the effect of cement content on shrinkage, despite the test showing difficulties for low shrinkage values (sealed condition). It was shown that it can detect not only different magnitudes of early shrinkage, but different speeds influenced by cement content and early curing conditions. Also, the test developed by this paper enables the study of early age conditions on long-term shrinkage and the correlation between these ages.

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