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Evaluation of the Shrinkage Produced with the Use of Cements with Pozzolanic Additions in the Production of Concrete

Maria Betania Diaz-Garcia [1,*], Yosvany Diaz-Cardenas [1,*], Juan Ribalta-Quesada [2] and Fernando Martirena-Hernandez [1]

[1] Research Center for Structures and Materials (CIDEM), Universidad Central Marta Abreu de las Villas, Carretera de Camajuni km 51/2, Santa Clara 50100, Villa Clara, Cuba
[2] Faculty of Chemistry (FQ), Universidad Central Marta Abreu de las Villas, Carretera de Camajuni km 51/2, Santa Clara 50100, Villa Clara, Cuba
* Correspondence: mbetania@uclv.cu (M.B.D.-G.); yosvanyd@uclv.edu.cu (Y.D.-C.)

Abstract: Early age cracking in concrete is caused by a combination of the chemical and autogenous shrinkage caused by the exhaustion of the water in the pores during the hydration of cement phases. Generally, this process takes place in the first 72 h of concrete casting. The use of supplementary cementitious materials (SCMs) can mitigate cracking due to several factors, among them: dilution effect, provision of extra nucleation sites due to the high specific surface of the SCMs, and the increased water retention associated with the presence of fine SCMs. This paper compares the impact of two SCMs systems on early age cracking of the following concretes: (i) pozzolanic cement with natural pozzolan (zeolite) and (ii) a ternary binder limestone-calcined clay cement (LC3). The study was Carried out on cement paste and concrete. The addition of calcined clay and limestone decreases early age cracking better than in any other system, including the Portland-pozzolan system. It is related to a lower clinker factor and improved hydration of the system, and a better-developed microstructure at early ages due to the energetic reaction of the alumina phase C_3A, enhanced by the extra alumina (Al_2O_3) provided by the calcined clay.

Keywords: cement; concrete; early age cracking; chemical shrinkage; autogenous shrinkage

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1. Introduction

New materials technologies in different fields such as chemistry, nanotechnology, and material science have enabled applications that project concrete even more strongly into the future [1]. Its high performance compared to its low cost make it an indispensable material in construction and civil works [2–4].

Cracks, disaggregation, disintegration, change of color and efflorescence are the main deteriorations that are recorded as the most difficult to repair [5]. Existing cracks and fissures in concrete are the main problems associated with durability deterioration, allowing corrosion of the steel to occur over a period of time [6]. In all constructions in which concrete is used, cracks may appear, which may be due to multiple causes, firstly, due to the intrinsic phenomena of concrete such as shrinkage (setting process), and in other cases, due to defects during placement. Shrinkage is manifested by a decrease in the volume of the concrete during the setting process in its first hours, or when it is already hardened days or months later, and is caused by a very simple fact—the loss of water [4,7]. When water is lost and volume is lost, internal tensile stresses are produced that give rise to shrinkage cracks, although they depend on the amount of fines, the amount of cement, the type of cement, the water–cement ratio, the thickness of the structural element, whether it is reinforced concrete or not, and the ambient temperature. As water is lost either by evaporation (drying shrinkage) or by internal reactions (autogenous shrinkage), tensile stresses are generated [5,8].

Shrinkage in concrete at an early age can be caused by different mechanisms. The main justification is that the hydration products formed by the hydration of Portland cement occupy less space than the reacting water and cement [8,9]. This phenomenon, chemical shrinkage, causes a successive emptying of the pore structure and leads to tensile stresses in the pore water through the formation of menisci [10]. Meniscus formation causes the relative humidity to drop and self-drying of the cement paste (autogenous shrinkage) [9]. These phenomena are closely linked and act as the main effects of volume changes associated with early age cracking [8,11,12].

To ensure shrinkage reduction at an early age it is important to produce concrete with reduced permeability to achieve a low water/cement ratio, suitable compaction, adequate cement weight, a sufficient cement hydration, and efficient curing [5,8,11,12]. This results in as few pores as possible and a poorly communicating internal capillary network, thus reducing attacks on the concrete. Among the new materials being studied as a shrinkage mitigation measure are shrinkage control admixtures or SRAs, which are designed to act on the material by reducing the tendency of concrete to shrink during hydration [10]. They base their action on the reduction of the surface tension of the water in the mix, which favors its use for hydration by the cementitious materials present in the mix, helping to reduce the reduction of the interior relative humidity [10].

Another mitigation measure is the use of supplementary cementitious materials, such as tuffs, fly ash, silica fume, and calcined clays [13–16]. These materials reduce chemical shrinkage due to better filling in the hydration process of the gel pores, but they interfere with autogenous shrinkage by increasing the specific surface tension, which is higher in these materials and the capillary pressure between these solid particles [16,17]. One of the reasons given is the lower amount of C_3A or reactive Al_2O_3 in Portland cement with additions which makes it effective for use as a measure [18].

The blend of fly ash, superpoze, silica fume, blast furnace slag, and natural pozzolan with Portland cement has been reported to not only outperform control samples prepared with the 100% Portland cement system in terms of strength, but also to mitigate shrinkage characteristics when exposed to aggressive environmental conditions [19,20].

Calcined clays together with limestone form an admixture that not only improves the matrix of the cementitious system but is much less sensitive to a decrease in relative humidity than the hydration products of cement clinker [21–23]. The degree of hydration of the clinker and the content of metakaolin, which can consume part of the available portlandite in the system, have an effect on the pore structure and the reduction of internal stresses within the pores [24–26]. These SCMs inhibit the hydration reaction at an early age and decrease the autogenous shrinkage of concrete caused by the hydration reaction. In addition, the refining effects and pozzolanic reaction of SCMSs improve the pore structure and shrinkage resistance of concrete [27,28].

The current paper presents a study on the evaluation of shrinkage in pastes and concretes admixed with the LC3 cement with 30% clinker substitution, with the aim of finding out the influence of this cement on the volume changes in paste and concrete and its relationship with the hydration process. The paper also aims to compare the volume changes that take place at cement pastes with the shrinkage behavior of concrete and link it with hydration kinetics. A comparison was made with concrete produced with pozzolanic cement with natural pozzolana and pure Portland cement.

2. Materials and Methods

The research includes assessing the volume change and its relationship with hydration in cement pastes made with different binders. Parameters such as the water–cement ratio (0.40 and 0.45) and the impact of a PC-based chemical admixture were assessed. The series includes cement pastes made with Portland cement (OPC), Portland-pozzolan cement (PPC), and a combination of OPC and a mineral addition consisting of 60% calcined clay, 35% limestone, and 5% gypsum (LC2).

The studies include the use of chemical shrinkage facilities to assess volume changes in the first 3 days, coupled with measuring the heat of hydration under isothermal conditions.

This study was carried out on concrete specimens cast with cement binders, where short-term volume change will be assessed aided by a shrinkage drain, and the long-term volume changes was assessed on prisms.

2.1. Materials

Cement: Table 1 shows the main characteristics of the cements tested. OPC cement and pozzolanic Portland with 15% of zeolite tuffs (PPC) are produced at the Carlos Marx factory in Cienfuegos, Cuba. The LC3 cement was produced as a blend of the OPC (70%) and the mineral addition LC2 (30%) for a total clinker content of 65%. This latter was produced at an industrial trial in Cuba in 2018. With regard to the parameters shown, the binders also comply with the requirements of the specification standards NC 1340 2020 [29]. It is worth highlighting the values obtained for specific weight, Blaine, consistency, and setting time, which can reasonably explain the differences between the two cements.

Table 1. Main characteristics of the cements and additions.

Type of Cement	OPC	PPC	LC2
Pe: NC 1340 (%): 2020 [29]	3.08	3	2.83
Blaine: NC 980 (cm^2/g): 2013 [30]	3166	3520	6000
CN: NC 524:2015 [31]	24.6	27.2	-
Volume stability (mm): NC 504:2013 [32]	0.39	1	-
Retention 90-micron sieve (%): NC 980:2013 [30]	2.6	4.1	5
Setting time NC 524: 2015 [31]			
Initial (min)	102	140	-
Final (h)	3.17	3.5	-

Aggregates: All the aggregates used in the elaboration of the concretes came from the quarry "El Purio", Villa Clara province. They are the product of the crushing of limestone rocks, with a grain size between 19.0–9.50 mm for the coarse aggregate (gravel) and 4.76–0.147 mm for the fine aggregate (sand). Lithology is pure limestone, hard, compact, white to cream. They all comply with the required standards.

Chemical admixture: Sika Plast 9100: A product of the SIKA industry, it is used in the manufacture of concrete for a wide variety of structures, specifically where one of the objectives pursued is to optimize the quantity f cement and the maintenance of workability over time is required. Condition: Liquid additive Colour: Dark Carmelite Density: 1.13 kg/L.

2.2. Experimental Program

Cement pastes will be cast with all binder systems described (OPC as a pure OPC, PPC as a pozzolanic cement with 15% natural pozzolan, and the blend of OPC and LC2). Water–cement ratio will be varied from 0.4 to 0.45. Table 2 presents the sample in cement pastes.

A certified mix design 35 MPa for flowable concrete was used as a reference for the preparation of concrete specimens (See Table 3).

The minimum slump required by the 16 cm Abrams cone test was checked and then the samples were placed in the 100 mm × 20 mm cylindrical specimen molds for strength, in the 75 mm × 75 mm × 285 mm prismatic specimen molds for ASTM C-157 and in the shrinkage drain. The hardened concrete cylinders were tested for compressive strength in batches of three at 7 and 28 days after curing begins, and the ASTM 157C test to measure shrinkage in the prismatic specimens for 28 days.

Table 2. Samples in the cement paste.

Samples	Composition
P (0.4)	OPC, w/c = 0.40
PA (0.4)	OPC, w/c = 0.40, 0.5% SP
P (0.45)	OPC, w/c = 0.45
PA (0.45)	OPC, w/c = 0.45, 0.5% SP
PP (0.4)	PPC, w/c = 0.40
PPA (0.4)	PPC, w/c = 0.40, 0.5% SP
PP (0.45)	PPC, w/c = 0.45
PPA (0.45)	PPC, w/c = 0.45, 0.5% SP
LC3-65 (0.4)	70%OPC + 30% LC2, w/c =0.40
LC3-65A (0.4)	70%OPC + 30% LC2, w/c = 0.40, 0.5% SP
LC3-65 (0.45)	70%OPC + 30% LC2, w/c = 0.45
LC3-65A (0.45)	70%OPC + 30% LC2, w/c = 0.45, 0.5% SP

Table 3. Samples in concrete.

Samples	Composition
PA (0.4)	OPC, w/c = 0.40, 0.65% SP
PPA (0.4)	PPC, w/c = 0.40, 0.65% SP
PPA (0.45)	PPC, w/c = 0.45, 0.65% SP
LC3-65A (0.45)	70%OPC + 30% LC2, w/c = 0.45, 1% SP
LC3-65A (0.4)	70%OPC + 30% LC2, w/c = 0.40, 1% SP

2.3. Methods and Techniques

2.3.1. Cement Paste

Isothermal calorimetry: To define the entire research process, as reflected in the stages, tests were carried out on Portland cement pastes and cement pastes with the active mineral addition LC2, in order to evaluate the best water–cement ratio to be used in subsequent tests on concrete. This test is established according to NC: 525 2014 [33] Hydraulic cement. Test methods. Determination of the heat of hydration. A whole protocol was defined to evaluate the samples and to be able to obtain the different values of heat release and accumulated heat. An isothermal calorimeter, model TAM Air, connected to a computer where the data was recorded every minute, mechanical stirrer, vials for the placement of representative samples of cement paste and pipettes were used.

Chemical shrinkage: The volume stability of this test was defined to determine the deformation of the cement paste with respect to the volume of the sample, which infers how much the concrete can shrink or expand according to the measurement criteria. For this purpose, a correlation was defined between the chemical shrinkage produced in the pastes and the heat released in the cement hydration process. For this test, a shrinkage set, vials with graduated pipettes for placing the paste, mechanical stirrer, and pipettes were used.

2.3.2. Concrete

Shrinkage drain: The shrinkage drain was a 1.00 m long U-shaped stainless steel profile. A neoprene sheet is used to prevent friction between the concrete and the walls of the channel. The channel had a fixed anchor at each end and a mobile anchor that moves on three wheels. This movement was recorded by a highly sensitive LVDT probe. As a displacement sensor, a digital probe was used, which was connected to an electronic interface probe that converts the analogue signal to digital format.

A datalogger with the reference system recorded the retraction channel information and stored it as standard ASCII files. Optionally, a synchronized recording of temperature and humidity was possible. For better data processing and results analysis, Microsoft Excel was used. This test was used for concretes, with the same profile in order not to have variations between the results.

Shrinkage according to ASTM C-157: The shrinkage test was carried out according to the standard (ASTM-C-157, 2006) [34] Standard Method for Calculation of Changes in Length of Mortar and Concrete. It was established to use three samples for each condition to be tested. The inserts are placed on the upper and lower face of the specimens, which are references for subsequent measurements.

After 24 h of concreting, the specimens must be stripped and the first measurement is carried out. The specimens were measured for 28 days, where length and weight were checked daily. The measurements were made with a defrometer.

Consistency (Abrams Cone): This test is defined to determine the consistency of the samples, which according to the research protocol must be greater than 160 mm, which classifies it as a fluid concrete. This test was performed according to (NC.ISO1920-2, 2010) Concrete testing. Properties of fresh concrete.

Compressive strength: Cylindrical molds made of steel of 100 mm × 200 mm that do not react with the alkalis in the cement were used for the compression test. The molds were watertight and retain their dimensions, which gives the specimens admissible dimensions and tolerances for the test. The specimens to be tested had ages of 7 and 28 days. Based on the provisions of (NC:724, 2015) Tests on concrete. Strength of concrete in a hardened state, in an Ibertest Press. Once the specimens have been cured in water, excess moisture was removed from the surface before being placed in the testing machine.

Porosity (capillary water absorption): According to NC 345:2011 [35] "Hardened concrete. Determination of water absorption by capillary action", s cylindrical specimen or core is taken and sawn as a thin sheet of concrete or mortar of 20 mm to 30 mm thickness which is preconditioned to moisture equilibrium. This equilibrium is achieved by drying at 50 °C for 48 h (to constant weight) and subsequent cooling in a desiccator. The suction surface shall be the sawn part of the specimen that is free of carbonation and other impurities, it is recommended to pre-coat the curved side areas of the specimen with epoxy resin or paraffin. The specimens were weighed before being placed in water and reweighed at ages 1/12, 1/6, $\frac{1}{4}$, $\frac{1}{2}$, 1, 2, 3, 4 h; 6 h; 1; 3; 5 and 7 days from the start of the test or their contact with water. Before each weighing, the surface of the test specimen is cleaned so that no sand particles remain adhered to it and the surface water is wiped off with a cloth. With the weights obtained at the different ages indicated, a curve is obtained.

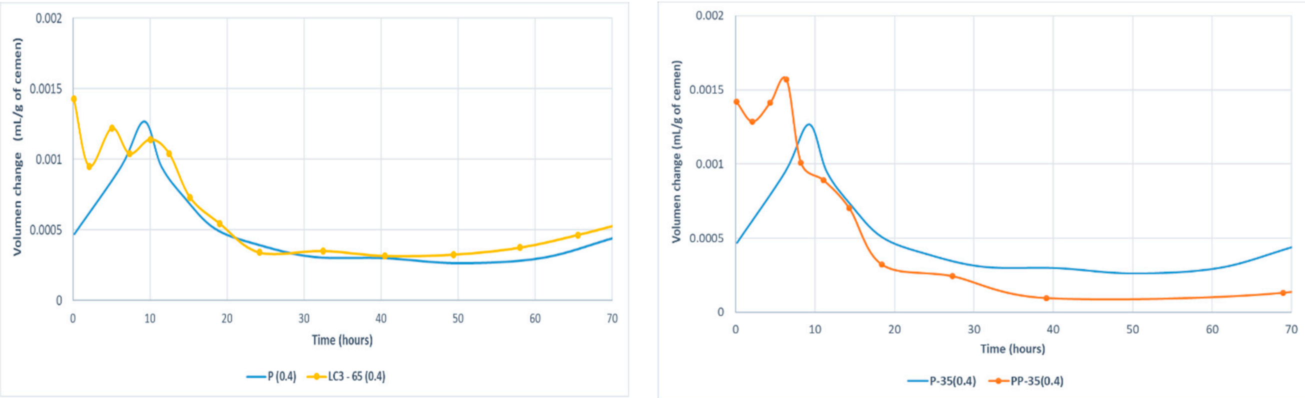
3. Results and Discussion

3.1. Cement Pastes

3.1.1. Impact of the Binder

Previous studies show that in the finer cements or cements with a high C_3A and C_4AF content, the autogenous shrinkage values tend to increase and the hydration process will be accelerated [9,36]. With regard to mineral additions, the higher the percentage added and the higher the fineness, the higher the autogenous shrinkage. These materials have an effect that reduces chemical shrinkage due to better filling in the hydration process, but they interfere with autogenous shrinkage and increase the tension between solid particles and capillary pressure due to the high specific surface area of this material. It is therefore very important to analyze both phenomena and the influence of the type of binder in the systems [22,37].

Figure 1 presents the results of measuring volume changes in cement pastes with similar water–cement ratio. The reference OPC is compared with the pozzolanic cement PPC and the blend of OPC and LC2. In both PPC and OPC + LC2 the expansion associated with the hydration of the clinker products begins earlier. This can be explained by the dilution rate [38,39]. The series with Pozzolanic cement containing 15% of natural pozzolan cement shows a greater expansion in the period of time of the formation of the silicates, and the series with combinations of OPC and LC2 has two peaks of greater change, associated with the silicate and aluminates reaction [40].



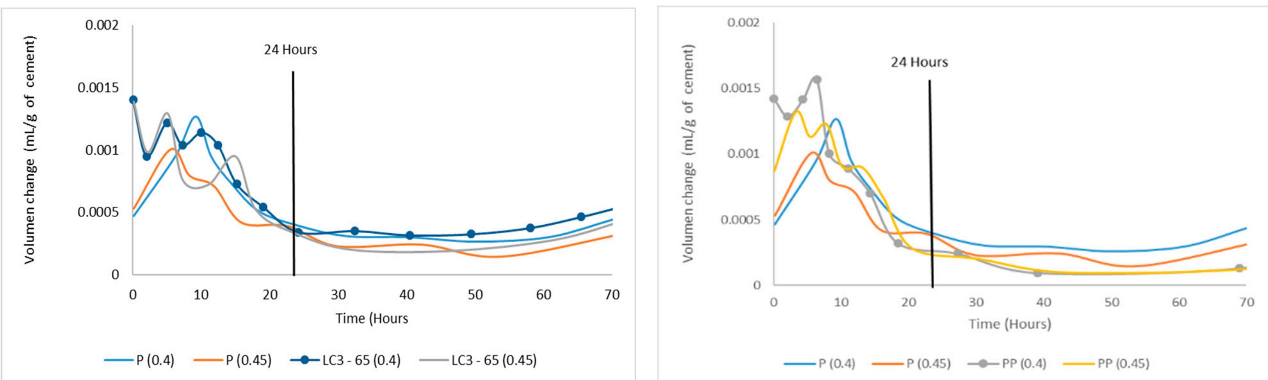
(**a**) (**b**)

Figure 1. Effect of type of binder on volume changes in paste: (**a**) LC3 binder, (**b**) Pozzolanic cement containing 15% of natural pozzolan binder.

3.1.2. Impact of the Water–Cement Ratio

A higher w/c ratio translates into more water available for hydration; its increase tends to reduce shrinkage and, at the same time, reduce the strength of the concrete. Since it changes the kinetics of hydration, it also changes the moment when the expansion associated with the hydration of clinker products takes place. Increasing the amount of water in the system impacts a higher porosity, especially for systems where clinker content is reduced through the addition of pozzolans [9].

Figure 2 shows the series with OPC and PPC cement for two water–cement ratios (0.4 and 0.45). Increasing water–cement ratio in the OPC series reduces the volume change at all ages and the peaks associated with the formation of reaction products become wider, probably associated with the precipitation of more reaction products since more space is available. A similar impact is caused in the series with PPC, for similar reasons. In systems containing calcined clay and limestone the trend is different; the increase in water–cement ratio delays the expansion peak associated with aluminates and increases expansion associated with the reaction of the aluminates. This could indicate that the high specific surface of the calcined clay is enhancing the hydration and increasing water content will improve the hydration of the clinker phases [41–43].



(**a**) (**b**)

Figure 2. Effect of water/cement ratio on volume changes in paste: (**a**) combinations of OPC and LC2 binder, (**b**) pozzolanic cement containing 15% of natural pozzolan binder (PPC).

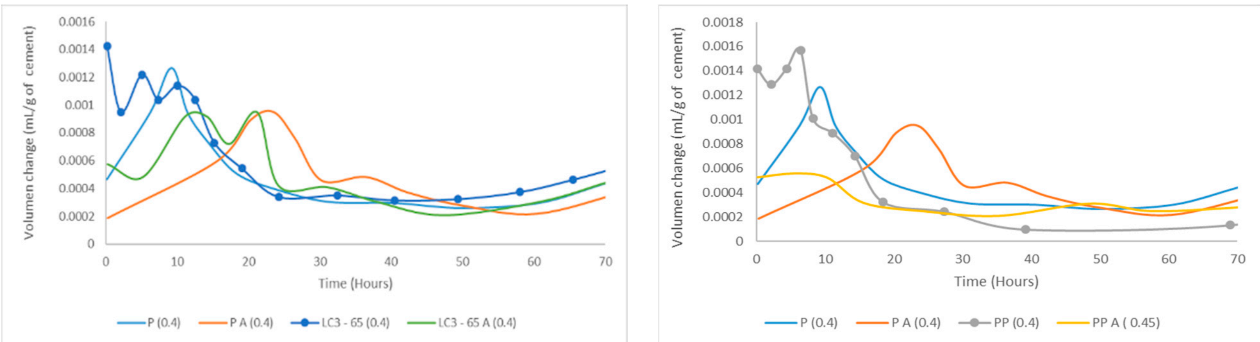
As the water–cement ratio increases, these stages move in time around 5 or 6 h, and tend, as in the case of sample 65%OPC + 35%LC2 (0.45), to present greater variation. It was observed that although the samples with combinations of OPC and LC2 have greater accumulated volume changes over time, the variations that these exert on the hydration process were smaller in the sample with water–cement ratio of 0.4 (65%OPC + 35%LC2 (0.4)) than with the OPC cement with the same ratio [10]. This increase could be associated with the enhancement of the hydration of clinker products due to the high specific surface of the calcined clay [44,45].

The volume change peaks occurred very close to the heat of hydration peaks associated with the hydration of clinker products. The higher the heat released, the higher the expansion. It should be noted that all these volume changes occurred in the samples with pozzolanic additions (OPC/LC2 and pozzolanic cement containing 15% of natural pozzolan), and their maximum variations occurred before 24 h, after which time they remained constant without variations.

3.1.3. Impact of the Use of Superplasticizers

The use of the PC-based superplasticizer SikaPlast delays the initial setting of the cement, thus prolonging the formation of the phases of a hydrated paste. Therefore, a comparison was made between series with and without the additive to assess the impact of the additive on the hydration of the cement pastes.

Figure 3a presents the curves of the first derivative of the volume variation versus time variation in the series PPC and the blend of OPC and LC2. The expansion associated with the formation of the silicates was defined in the 65%OPC + 35%LC2 (0.4) sample at 6 h; adding SP brought about a delay, and the process took place between 8 and 10 h, similar to results obtained in the heat of hydration. A third peak of expansion can be seen at the OPC and LC2 series with SP at around 30 h corresponding to the secondary aluminate reaction.



(**a**) (**b**)

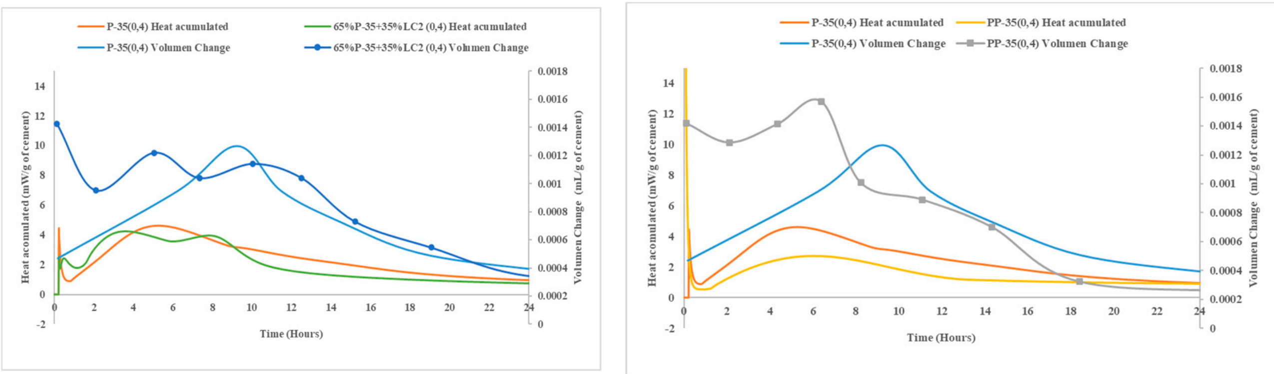
Figure 3. Effect of chemical admixtures on volume changes in paste: (**a**) combinations of OPC and LC2 binder, (**b**) pozzolanic cement containing 15% of natural pozzolan (PPC) binder.

The sample 65%OPC + 35%LC2 (0.4) showed the best behavior. This sample is defined as having less heat released during the hydration process and better formation of the components of the hydrated cement paste. It is also observed how the sample with combinations of OPC and LC2 presents all the variations of the volume before 24 h, which enhances the formation of the microstructure at early ages.

Figure 3b shows the curves of the first derivative of the volume variation versus time variation for the series with PPC. There is also a delay in the expansion peak with the addition of SP. After 24 h, it can be seen that the volume of the PPC cement samples with additive does not vary, while the Portland cement sample has a greater volume variation between 30 and 40 h. This is probably caused by the retarding effect of the SikaPlast admixture.

3.1.4. Impact of Cement Hydration for Each Cementitious System

Figure 4a,b presents a correlation between volume change and heat of hydration. It can help explain the expansion peaks and the shrinkage with time. There is a good match between the volume changes measured in cement pastes and the heat of hydration for all series.



(**a**) (**b**)

Figure 4. Impact of cement type on hydration in cementitious systems. (**a**) LC3 binder, (**b**) Pozzolanic cement containing 15% of natural pozzolan binder.

The samples with combinations of OPC and LC2 have two peaks of volume change, the first when the C-S-H gel is formed and the second with the formation of ettringite. Each peak of volume change is preceded by a peak in the heat of hydration. The sum of the volume change in the two peaks is higher than in Portland cement.

3.2. Investigation in Concrete

The investigation of volume change is made in concrete. Shrinkage is measured in an open system in contact with the environment, so the shrinkage measured consists of a combination of chemical, autogenous and drying shrinkage. With each binder series a set of concrete specimens were prepared.

3.2.1. Impact of Calcined Clay Addition on Slump of Concrete

The presence of pozzolanic materials with high specific surface implies an increase in water demand. In this study, water demand was assessed by measuring the slump in concrete [46,47]. SP was added until reaching the target consistency for concrete (fluid). Figure 5 presents the slump of concrete produced.

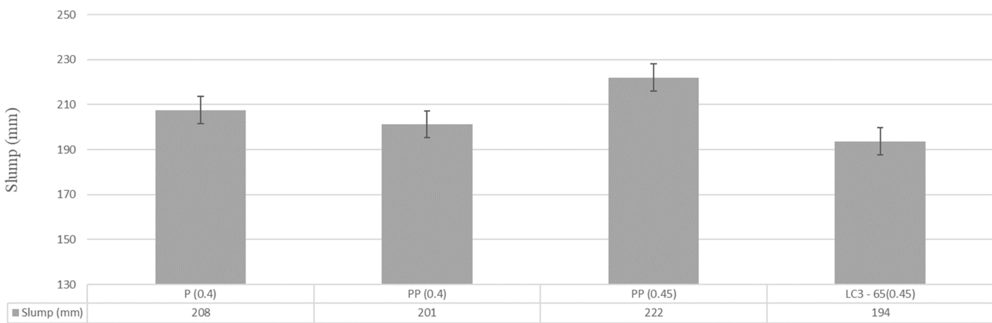


Figure 5. Effect of calcined clay addition on Slump.

A comparison was made between concrete made with OPC and pozzolanic cement containing 15% of natural pozzolan and the series with combinations of OPC and LC2. The dosage of chemical admixture was dictated by the desired slump, with a maximum of 1% related to cement content.

3.2.2. Impact of Calcined Clay Addition on Compressive Strength

Figure 6 presents the results for compressive strength in concrete made with OPC, PPC and OPC + LC2. The strength of concrete made with blended cements is slightly lower than that of concrete made with OPC. Despite the higher water–cement ratio, the combination of OPC and LC2 yields higher strength compared to PPC. The strength evolution is strongly related to the amount of clinker in the system. Cements with calcined clay are less sensitive to changes in water–cement ratio.

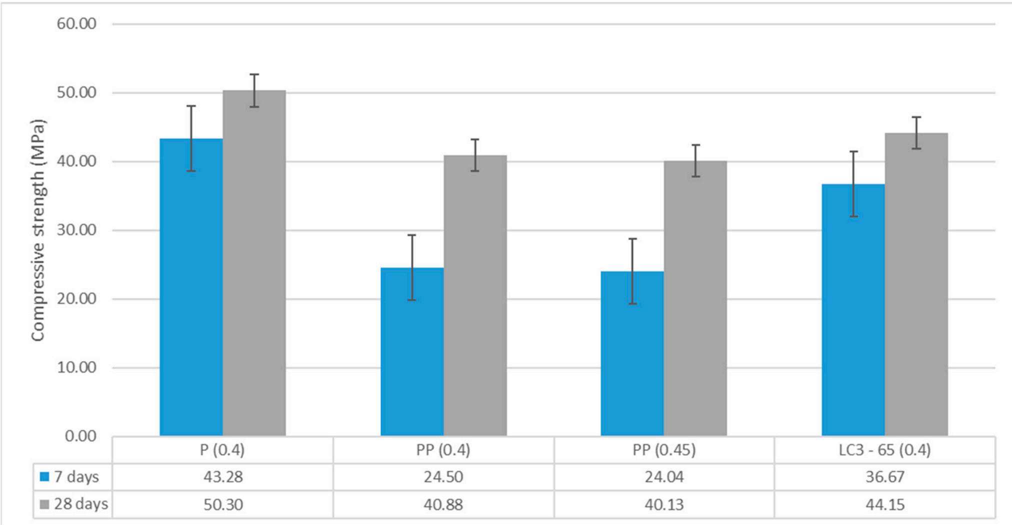


Figure 6. Effect of calcined clay addition on compressive strength.

3.2.3. Impact of the Binder

The shrinkage drain was used for the evaluation of volume changes in concrete up to 1 day. The equipment begins measuring shrinkage as the final setting time is reached, and the microstructure is formed. This technique provides information on the expansion associated with the hydration of clinker products when the microstructure is not completely formed. The specimen is in contact with the environment, so variations of relative humidity could influence the measurement because of drying the pore system.

Figure 7 shows the volume changes at early ages of concrete with different binders. The highest values of expansion are reached with LC3-65, most likely associated with the enhancement of the hydration of the clinker products produced by the lower clinker rate and the high specific surface of calcined clays, which creates extra spaces for heterogenous nucleation [45].

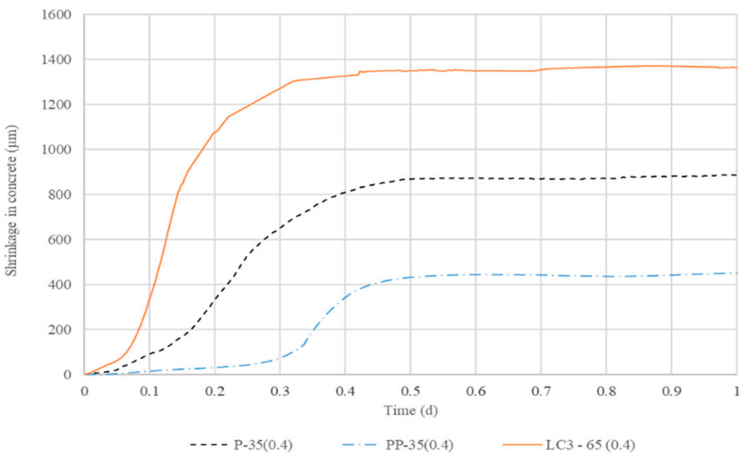
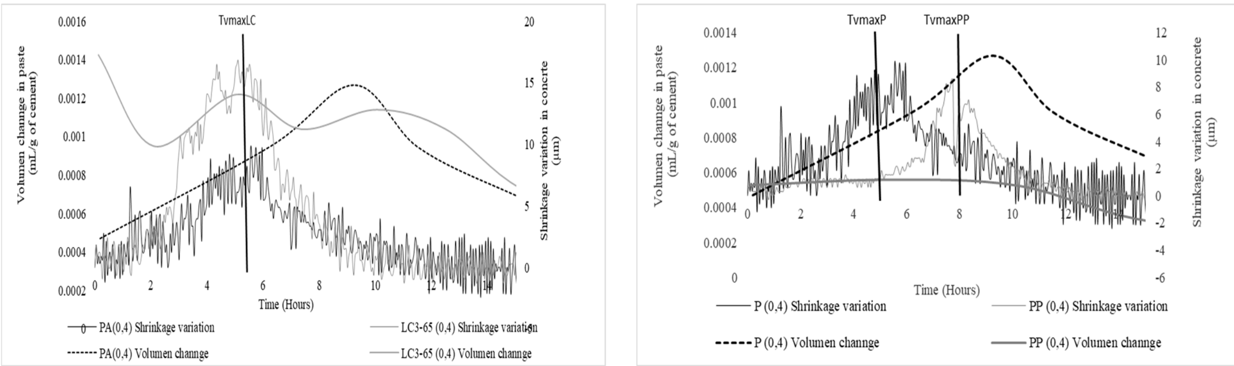


Figure 7. Effect of binder type on concrete shrinkage 24 h.

The lowest expansion was associated with the PPC series, most likely caused by the poor reactivity of the pozzolan used in this cement. Most of the volume change took place in the first 24 h of curing.

This research aims to compare the behavior in cement pastes with the behavior in concrete. The shrinkage phenomenon in concrete occurs from the moment the water comes into contact with the cement, so the shrinkage that occurs in the paste is fundamental to defining which factor affects it. Figure 8 presents a comparison between the volume change in cement pastes, measured by a chemical shrinkage device and the volume change in concrete with the same binder and water to cement, measured by the shrinkage drain.



(**a**) (**b**)

Figure 8. Relationship between shrinkage in concrete and hydration of cement: (**a**) combinations of OPC and LC2, and (**b**) pozzolanic cement containing 15% of natural pozzolan binder (PPC).

Concrete with LC3-65 expands and contracts in a period of 3 h, approximately 5 h after the contact of water with cement and corresponding to the first hydration curve, which is the reaction of tricalcium aluminate, a reaction in which tobermorite gel and portlandite (CH) are formed. The highest values of heat release and the greatest contractions are observed in this period.

In concrete made with Pozzolanic cement containing 15% of natural pozzolan cement, the shrinkage values in the concrete coincide with the same stage of formation of portlandite and tobermorite during hydration, which takes place 8 h after mixing. The delay is probably caused by the dilution effect caused by the presence of pozzolan.

3.2.4. Impact of the Water–Cement Ratio

Figure 9 presents the volume changes in concrete made with two different water–cement ratios (0.4 and 0.45). Increasing of the water–cement ratio increased the volume change in the short term, mainly associated with better hydration of the clinker products. This effect is more pronounced in the systems containing calcined clay.

The moment where the maximum value of volume change is reached indicates the point where the microstructure of the cement matrix is formed. From that point on, the reaction products begin to fill the empty pores, and shrinkage begins to take place. The series with the combination OPC and LC2 reached the expansion point much earlier than the other two series [10,48].

The long-term shrinkage will be assessed aided by the protocol of the ASTM C157 in concrete prisms. The starting point was marked at 2 days to avoid the noise of early hydration. Figure 10 presents the results for the concrete series OPC, PPC, and OPC + LC2. The shrinkage in the blended systems was less than in pure systems due to the dilution effect of clinker.

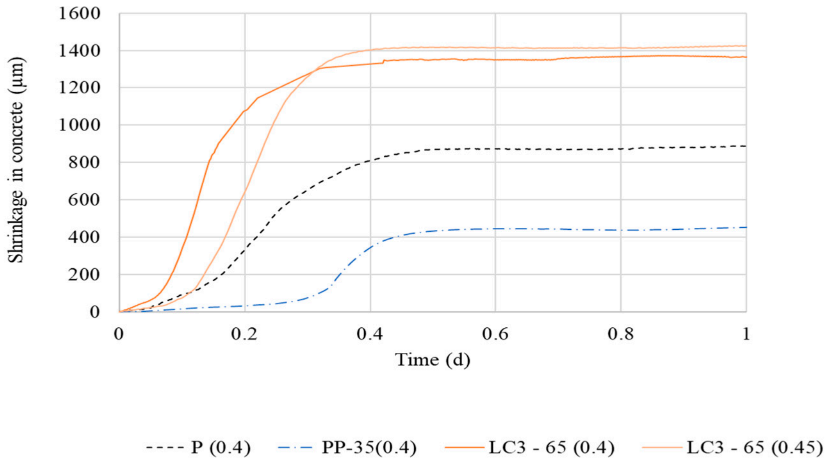


Figure 9. Impact of the water–cement ratio on volume change in concrete.

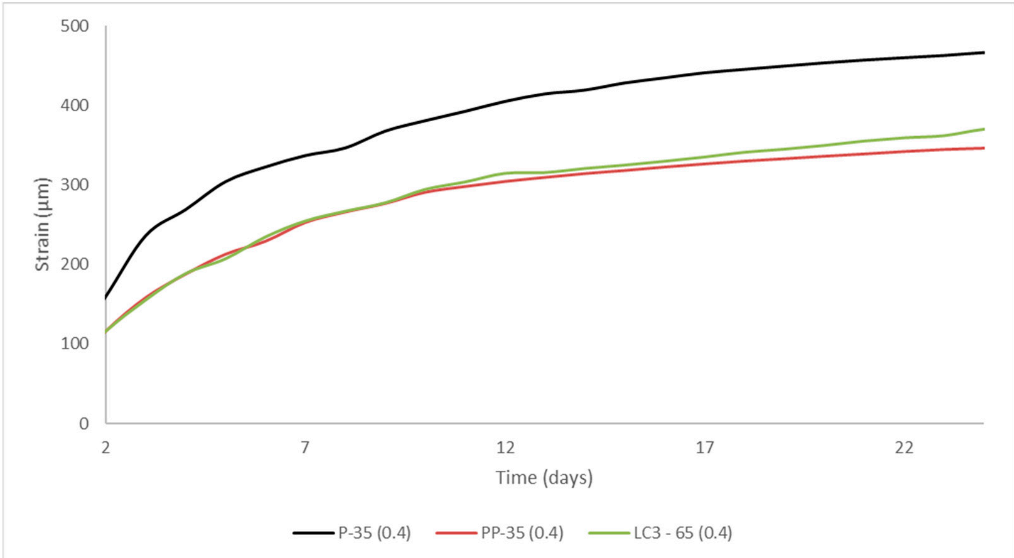


Figure 10. Long term shrinkage in concrete prisms.

In the long term, the series of concrete made with OPC shows the highest volume change at 28 days, while PPC had a much lower shrinkage, as expected. The lowest shrinkage values at 28 days were for the concrete series with OPC + LC2.

3.2.5. Strength vs. Strain in Concrete (28 Days)

The changes in volume after setting, called the autogenous shrinkage process, is relevant in high-strength concrete with low water–cement ratios and consists of shrinkage due to the loss of water from the capillary pores due to cement hydration (diffusion stage) [36]. On the contrary, in high-strength concrete, autogenous drying acts rapidly to increase capillary pressures and, therefore, compress the solids, which increases the probability of early age cracks in the concrete. Therefore, it is important to analyze the relationship between strengths and deformations over time [4,38,49].

Figure 11 presents the values of compressive strength versus the strain from T = 0 to T = 28 days in all concrete series. The series with OPC has a much larger strain compared to PPC and 65%OPC + 35%LC2 concrete. The best results are obtained with the combination of OPC + LC2, where high strength values and lower strain are experienced. This result is mainly due to the use of mineral additions such as calcined clays (LC2), which favor an increase in compressive strength and contribute to mitigating deformations over time.

Further, the impermeability of the matrix can mitigate the occurrence of drying shrinkage in concrete made with OPC + LC2.

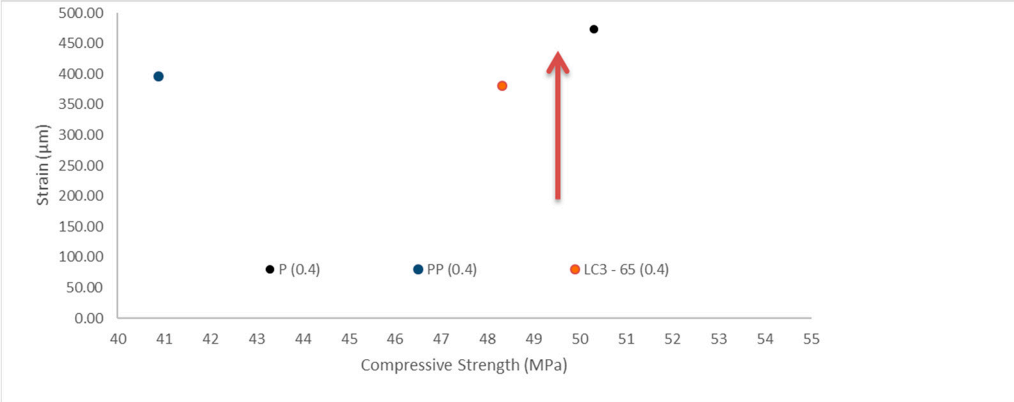


Figure 11. Strength vs. strain.

3.2.6. Concrete Porosity vs. Strain (28 Days)

The porosity of concrete depends on the ratio of the solid volumes generated to occupy the available space left by the excess mixing water. In the case of concrete with a low water–cement ratio, cement grains may remain anhydrate and, therefore, the properties of the concrete may vary. Porosity depends primarily on the initial water/solid ratio and the volume of hydrate products.

Figure 12 shows the relationship between the effective porosity of the concretes with the deformation they undergo in 28 days, where it is observed that concretes with mineral additions have a lower porosity. The effective porosity is represented as the interconnected pores in the concrete mass, which, depending on the type of cement, has an effect on durability. The best combination is the concrete series with OPC + LC2, with the lowest porosity for a similar strength. This concrete is less prone to cracking in comparison with the other two.

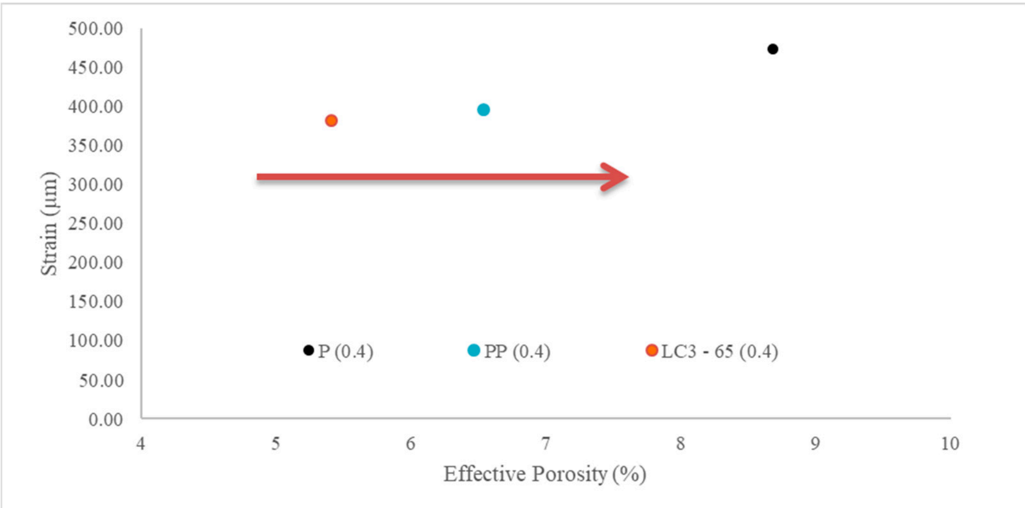


Figure 12. Effective Porosity vs. strain.

4. Conclusions

1. Blended cements reduce volume changes occurring during cement hydration. The reason is the decrease in clinker content, which dilutes the impact of hydration of clinker phases.

2. Systems containing a combination of calcined clay and limestone have different characteristics compared to pozzolanic cement. At early ages, the microstructure develops very rapidly and the expansions associated with hydration of the clinker phases are greater. At late ages, this is reversed, probably due to the less connected pore system, which prevents significant shrinkage from occurring. The is a coherent relationship between volume changes taking place in cement pastes, the heat of hydration, and the corresponding volume changes in concrete.
3. Concrete porosity has a strong relationship with long-term shrinkage, probably associated with drying shrinkage. The combination of calcined clay and limestone produces a very dense pore network, which mitigates shrinkage in the long term. Its performance is much better than concrete made with pozzolanic cement.

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