Durability behaviour of sustainable concrete produced with seawater and recycled aggregates

Maria Carolina De Andrade dos Anjos Galrão Caracol

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Extended Abstract

Supervisors:

Professor Doutor Jorge Manuel Caliço Lopes de Brito

Doutor Miguel Nuno Caneiras Bravo

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Abstract

This dissertation was developed with the objective of analysing the behaviour in terms of durability of sustainable concrete produced with seawater and with different percentages of substitution of natural aggregates with recycled aggregates. Due to the problem of potable water's scarcity in the world and the high use of potable water in concrete production, seawater is seen as a sustainable alternative due to its abundant availability.

In this dissertation, the effect of using seawater in the composition and curing of concrete with natural aggregates and recycled aggregates was evaluated. The concrete mixes with recycled aggregates were produced with different percentages of replacement of natural aggregates with recycled aggregates (0%, 50% and 100%). Simultaneously, the effect of curing with seawater was analysed on the performance of concrete submitted to a curing process similar to concrete watering.

To evaluate in terms of durability, tests of water absorption by immersion and capillarity, resistance to carbonation and chloride penetration, and shrinkage were performed. It was found that the use of seawater in the composition worsened the performance of concrete produced with and without recycled aggregates. Regarding the performance of seawater curing, it was found that it worsened the behaviour of concrete in terms of water absorption. However, it was found that seawater curing improved the carbonation resistance of concrete.

Keywords: Concrete; seawater; recycled aggregates; construction and demolition waste; durability.

1. Introduction

Water scarcity is currently a worldwide problem. According to the United Nations, this problem is expected to worsen by 2050 due to the growing demand from the industrial sector and domestic consumption, the increase in the world population and the climate changes that have been noticed over time (UN, 2022). Therefore, it is necessary to implement strategies to achieve a good management of the use of freshwater, but it is also beneficial to find alternatives to the use of freshwater.

Annually, the construction sector produces thirty billion tonnes of concrete (Monteiro *et al*., 2017), leading the consumption of freshwater in concrete production to very high values. Thus, finding an alternative type of water for concrete production could bring a lot of benefits at several levels.

Seawater shows to be a sustainable alternative material to freshwater to produce concrete due to its abundant availability. Although this is a controversial topic, as the use of seawater has been avoided due to the presence of chlorides, it is believed that in some situations the application of concrete with seawater may be feasible, such as structures in marine environments (Hamada *et al*., 2021).

In order to boost the use of seawater in the construction industry, it is important to study and understand its effect on concrete behaviour. Because it is an innovative and recent issue, there are still few investigations on the subject. Thus, this research intended to extend the knowledge on the topic, evaluating the feasibility of using seawater in concrete with natural aggregates (NA) and recycled aggregates (RA) from CDW.

2. Methods

2.1. Materials

Table 1 presents the characteristics defined for the reference concrete.

Table 1 - Characteristics of the reference concrete

Strength class	C30/37
Environmental exposure class	XC3
Consistency class	S3 (100 mm to 150 mm)
Maximum aggregate	22.4 mm

Two types of water were used in the composition of concrete: freshwater, from the public network, and seawater, collected at the beach of Ericeira. The fine natural aggregates used were fine sand (0.125/1 mm) and coarse sand (0.125/4 mm). The natural coarse aggregates used were gravel 1 (9.5/19 mm) and gravel 2 (19/25 mm). The recycled coarse aggregates used are from CDW, collected from a CDW recycling plant (4/22.4 mm). The main constituents of the RA are concrete waste (70.8%) and ceramic materials (28.6%). To keep the workability constant in all mixes, the water absorption of the RA after 10 minutes (5.1%) was determined in order to adjust the water/cement ratio of the mixes with RA. Table 2 presents the physical characteristics of the aggregates. The binder used was Portland cement type CEM I 42.5 R from SECIL, and a superplasticizer SikaPlast 717 from SIKA was used.

Table 2 - Physical characteristics of the aggregates

Physical properties	Fine sand	Coarse sand	Gravel 1	Gravel 2	Recycled aggregates
Oven-dry particles density (kg/m^3)	2583	2581	2609	2599	2274
Water absorption (%)	0.3	0.7	1.3	1.5	6.0
Bulk density (kg/m^3)	1530	1540	1350	1360	1261
Los Angeles wear (%)	-	-	26.5	27.8	46.0

2.2. Mixes' composition and curing process

Six concrete mixes were produced with different percentages of RA (0%, 50% and 100%) and with replacement of freshwater with seawater. It was defined that the mixes would have a constant workability, with a slump value between 100 mm and 150 mm. The mixes with freshwater and with seawater were produced with an effective water/cement ratio of 0.55 and 0.58, respectively. Due to the higher water absorption of the RA, the total water/cement ratio of the mixes with RA was adjusted to have an effective water/cement ratio identical to that of the reference concrete (0.55 if produced with freshwater or 0.58 if produced with seawater).

Each of the six concrete mixes was subjected to a curing process, similar to concrete watering, where freshwater and seawater were used. This curing process consisted in immersing the specimens in water for 30 minutes per day, during the first 7 days after demoulding.

2.3. Test methods

Table 3 shows the tests performed on concrete in the fresh and hardened states, with the respective standards, to evaluate the effect of using seawater in the composition and curing of concrete, in terms of durability.

Table 3 - Tests performed on concrete

Aggregate tests	
Size distribution analysis	NP EN 933-2 (1999)
Particles density and water absorption	NP EN 1097-6 (2003)
Bulk density	NP EN 1097-3 (2003)
Los Angeles wear	LNEC E-237 (1970)
Composition analysis	-
Fresh concrete tests	
Abrams cone slump	NP EN 12350-2 (2002)
Density	NP EN 12350-6 (2002)
Hardened concrete tests	
Water absorption by immersion	LNEC E394 (1993)
Water absorption by capillarity	LNEC E393 (1993)
Carbonation resistance	LNEC E391 (1993)
Chloride ions penetration resistance	LNEC E463 (2004)
Shrinkage	LNEC E398 (1993)

3. Results and discussion

3.1. Fresh concrete properties

The Abrams cone slump test allowed checking the workability, so that it remained between 100 mm and

150 mm. It was observed that all concrete mixes had slump values within the desired range. However, even keeping the effective water/cement ratio between mixes with and without RA, a slight decrease of the slump was observed as the percentage of RA in concrete increased.

The density in the fresh state varied between 2173 kg/m^3 and 2335 kg/m^3. It was found that the increase of RA in concrete slightly decreased the density. Younis *et al.* (2018) and Khatibmasjedi *et al*. (2020) concluded that the densities of concrete with seawater and with freshwater are close, due to the slight difference in densities of freshwater and seawater. In this research, despite having increased the effective water/cement ratio of concrete with seawater, compared to concrete with freshwater, there was only a slight decrease in density between these two types of concrete.

3.2. Hardened concrete properties

3.2.1. Compressive strength

Table 4 shows the results obtained in the compressive strength test at 28 days. Although the study of concrete produced with seawater is in terms of durability, the determination of the compressive strength was important to characterize the quality of the mixes. In parallel with this research, an investigation was carried out by Lena Kravchanka to study the mechanical behaviour of concrete produced with seawater.

Table 4 - Compressive strength at 7, 28 and 91 days

Concretes	$f_{cm\ 7\ days}$ (MPa)	Δ (%)	$f_{cm\ 28\ days}$ (MPa)	Δ (%)	$f_{cm\ 91\ days}$ (MPa)	Δ (%)
P-CP-0	37.7	-	44.3 ± 0.6	-	51.0 ± 1.8	-
P-CS-0	37.2 ± 1.3	-1.3	42.8 ± 1.2	-3.4	52.3 ± 1.5	2.5
S-CP-0	36.2 ± 0.2	-4.0	42.7 ± 0.6	-3.6	49.4 ± 0.3	-3.1
S-CS-0	34.2 ± 3.2	-9.3	41.7 ± 2.0	-5.9	47.9 ± 0.3	-6.1
P-CP-50	30.5 ± 0.7	-19.1	40.6 ± 0.0	-8.4	46.3 ± 1.3	-9.2
P-CS-50	29.6 ± 0.6	-21.5	39.5 ± 0.4	-10.8	45.4 ± 1.2	-11.0
S-CP-50	31.3 ± 0.9	-17.0	39.9 ± 1.4	-9.9	42.3 ± 0.7	-17.1
S-CS-50	31.8 ± 1.5	-15.6	40.0 ± 0.3	-9.7	44.0 ± 0.6	-13.7
P-CP-100	24.9 ± 1.8	-34.0	29.0 ± 0.7	-34.5	41.3 ± 1.2	-19.0
P-CS-100	23.9 ± 0.6	-36.6	30.7 ± 1.1	-30.7	37.8 ± 0.1	-25.9
S-CP-100	25.8 ± 1.1	-31.6	32.6 ± 0.9	-26.4	38.6 ± 0.9	-24.3
S-CS-100	22.6 ± 0.0	-40.1	29.3 ± 0.2	-33.9	38.2 ± 1.1	-25.1

From Table 4, it was found that the replacement of freshwater with seawater in the composition caused a slight decrease in the compressive strength of concrete. Younis *et al*. (2018) and Liu *et al*. (2022) concluded that, in the first days, compressive strength tends to be higher in concrete with seawater relative to concrete with freshwater and, in the long term, the compressive strength of concrete with freshwater tends to become higher than that of concrete with seawater. In the present investigation, this phenomenon was not observed. Instead, a slight worsening of the compressive strength results obtained at 7 days was found.

The fact that the use of seawater in the composition decreases the compressive strength of concrete can be attributed to the increase in the effective water/cement ratio of the mixes produced with seawater, relative those produced with freshwater. The higher the water/cement ratio, the lower the compactness, hence the lower the mechanical strength of concrete.

Regarding the use of seawater in concrete curing, there was also a tendency for the seawater curing to cause a slight decrease in the compressive strength of concrete.

3.2.2. Water absorption by immersion

Figure 1 shows the results obtained in the water absorption by immersion test at 28 days, which allowed evaluating the concrete porosity. From Figure 1, it can be concluded that the use of seawater in the composition caused an increase in water absorption by immersion, compared to concrete with freshwater. In mixes with 0% of RA, this increase was approximately 10%, while in those with 50% and 100% of RA, this increase was about 7% and 3%, respectively. The mixes with RA were shown to be slightly less affected than those without RA. Khatibmasjedi *et al*. (2019) found an improvement in water absorption in mortars produced with seawater and with the same water/cement ratio. However, in this research, the effective water/cement ratio of concrete with seawater was higher than that of concrete with freshwater, which may justify the higher water absorption by immersion of the mixes with seawater, compared to those with freshwater.

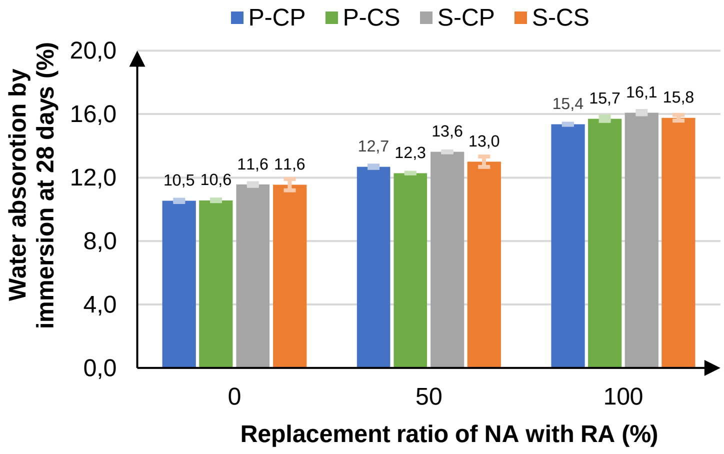

Figure 1 - Water absorption by immersion at 28 days

Figure 1 also allows analysing the effect of seawater on concrete curing. Compared to curing with freshwater, no clear effect of the effect of seawater on concrete curing was observed. In mixes with 0% of RA, no variation was observed, while in those with 50% and 100% of RA no clear trend was observed. A possible justification for this phenomenon may be related to the test method followed, where all mixes were immersed in freshwater. After 7 days of curing, the mixes cured with seawater developed a layer of crystallized salts on their surface. This layer may have been dissolved during the test, destroying a possible protective barrier to the entry of water into concrete.

It was observed that the water absorption by immersion increased with the increase of the replacement ratio of NA with RA, and it was found that this increase occurs in a linear way (R^2 between 0.96 and 1.00). Ferreira (2000) found a linear relationship between water absorption by immersion and compressive strength, and this relationship was also detected in mixes with seawater, with and without RA ($y = -2.59x + 72.08$ with $R^2 = 0.89$).

3.2.3. Water absorption by capillarity

Figure 2 shows the results obtained in the capillary water absorption test at 28 days. From Figure 2, it can be concluded that the use of seawater in the composition caused an increase in water absorption by capillarity, compared with the mixes with freshwater. Although in mixes with 0% RA no clear trend was observed, in those with 50% and 100% of RA, this increase was 7% in mixes cured with freshwater and considerably lower in those cured with seawater. Liu *et al.* (2022) observed an improvement in water absorption by capillarity in mixes with seawater and sea sand compared to those with freshwater and river sand, with the same water/cement ratio. However, in this investigation, the effective water/cement ratio of concrete with seawater was higher than that of concrete with freshwater, which may justify the higher water absorption by capillarity of the former compared to the latter.

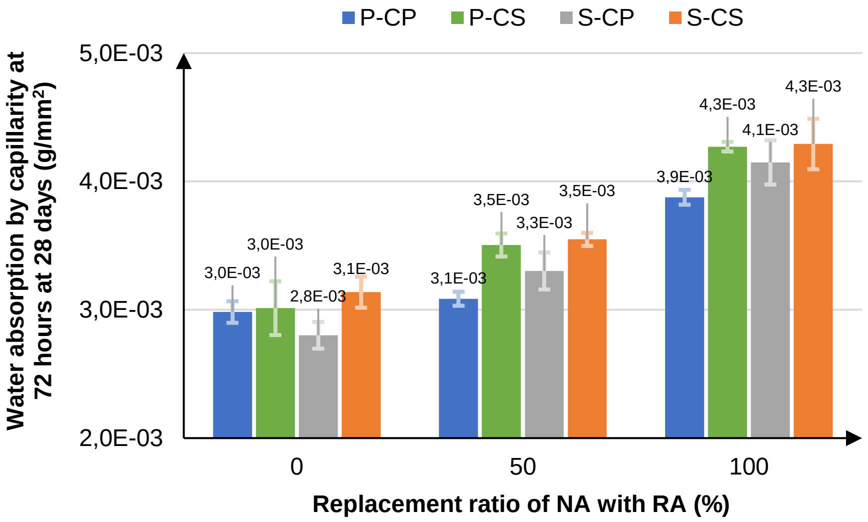

Figure 2 - Water absorption by capillarity at 28 days

In Figure 3, it is possible to compare the water absorption by capillarity of concrete at 72 hours at 28 days with that at 56 days. At 56 days, it can be seen that seawater caused a decrease in water absorption by capillarity, compared to concrete with freshwater. In mixes with 0% RA, this decrease was on average 13%, while in those with 50%, this decrease was on average 11% and, in mixes with 100% of RA, no clear trend was observed. The mixes without RA showed a better performance than those without RA. This decrease in water absorption by capillarity may be related to the densification of the microstructure of concrete with seawater, caused by the formation of Friedel's salt (Li *et al*., 2020).

The use of seawater in concrete curing caused an increase in water absorption by capillarity at 28 and 56 days, compared to concrete cured with freshwater. At 28 days, this increase was on average 7% and, at 56 days, it decreased to 4%. In mixes with 50% and 100% of RA, this increase was on average 11% and 7%, respectively, and at 56 days, this increase tends to decrease in mixes with 50% of RA and to increase slightly in those with 100% of RA. The mixes with RA were shown to be more affected than those without RA. Montanari *et al*. (2019) concluded that seawater causes a slight refinement of the porous structure in mortars, so the increase in capillary water absorption in seawater cured concrete mixes can be justified by the refinement of the porous structure of concrete with seawater.

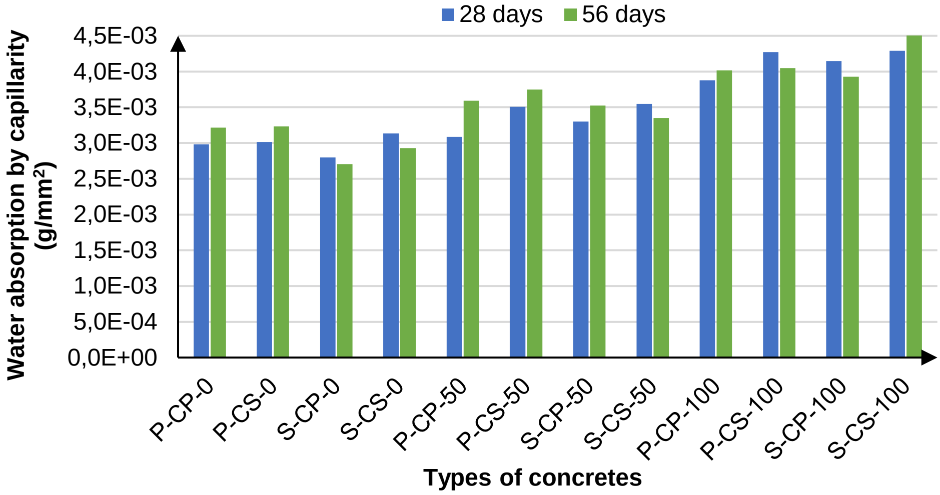

Figure 3 - Comparison between water absorption by capillarity at 72 hours at 28 and 56 days

It was observed that water absorption by capillarity increased with the increase in the replacement ratio of NA with RA, and it was found that this increase occurs in a linear way (R^2 between 0.84 and 0.98). Ferreira (2000) found an exponential relationship between water absorption by capillarity and water absorption by immersion, and this relationship was also detected in mixes with seawater, with and without RA ($y = 0.0014e^{0.0673x}$ with $R^2 = 0.87$).

3.2.4. Carbonation resistance

Figure 4 shows the results obtained in the carbonation resistance test at 28 days. From Figure 4, it can be concluded that the use of seawater in the composition caused an increase in the carbonation depth, compared with the mixes with freshwater. In mixes with 0% of RA, this increase was on average 44%, while in those with 50% and 100% of RA, it was found that this property's increase decreased to 11% and 15%, respectively. Liu *et al*. (2021) concluded that the presence of chlorides in concrete promotes an improvement in the carbonation resistance of concrete, compared to concrete with freshwater, for the same water/cement ratio. However, in this research, the water/cement ratio of concrete with seawater was higher than that of concrete with freshwater, which may justify the increased depth of carbonation of the former, compared to the latter.

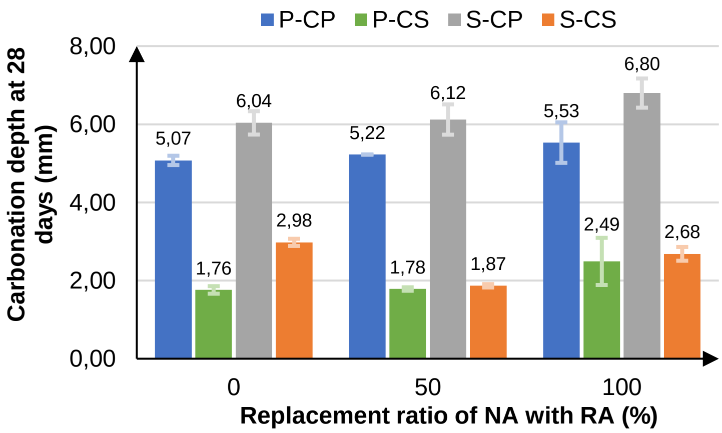

Figure 4 - Carbonation depth at 28 days

However, curing with seawater revealed better resistance to carbonation of concrete, compared to that cured with freshwater. In mixes with 0% of RA, this decrease was on average 58%, while in those with 50% of RA, this decrease was increased to 68%, and with 100% of RA in the mix, it decreased. This decrease in the carbonation depth of concrete cured with seawater, compared to concrete cured with freshwater, may be associated with the formation of a layer of crystallised salts, due to seawater curing, making it difficult for CO_2 to enter concrete. Noor and Asali (2019) concluded the same effect of seawater on concrete curing.

3.2.5. Chloride ions penetration resistance

Figure 5 presents the results obtained in the chloride migration test at 28 days only for mixes with freshwater. This test was inconclusive in terms of the effect of seawater in the composition. The silver nitrate solution may have reacted with the chlorides, derived from the seawater in the composition, and with the chlorides introduced by the migration test, which made it impossible to measure the depth of chlorides in the mixes with seawater. Therefore, it was only possible to analyse the effect of seawater curing on the mixes with freshwater. From Figure 5, it can be concluded that the seawater curing increased the chloride migration coefficient, compared with the mixes cured with freshwater. This increase may be related to the higher water absorption by capillarity of the concrete cured with seawater, compared to the one cured with freshwater. In mixes with 0% of RA, this increase was 10%. However, in those with 50% and 100% of RA, this increase was 4% and 31%, showing a substantial increase of variation with the increase of RA in concrete. Due to this inconsistency, it was not possible to conclude which of the mixes, with or without RA, was more affected by seawater curing.

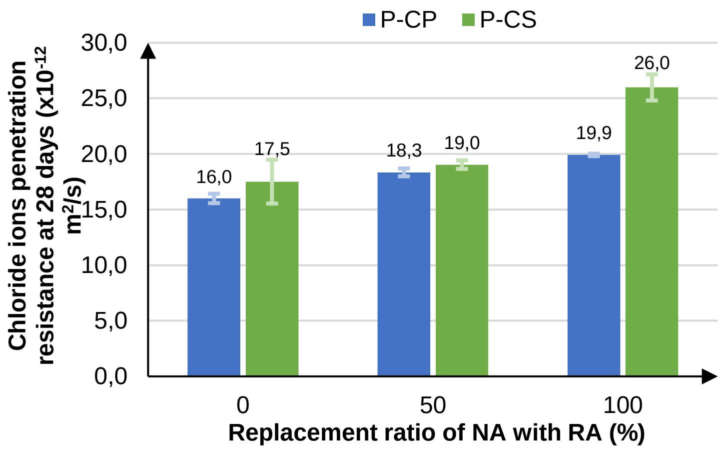

Figure 5 - Chloride migration coefficient at 28 days for concretes with freshwater

It was observed that the chloride migration coefficient increased with the increase in the replacement ratio of NA with RA, and it was found that this increase was linear (R^2 between 0.88 and 0.99). This increase may be associated with the higher water absorption by capillarity in the mixes cured with seawater, compared to those cured with freshwater. Ferreira (2000) found a linear relationship between water absorption by capillarity and chloride ion coefficient, and this relationship was also detected in mixes cured with seawater, with and without RA ($y = 5996.68x – 1.25$ with $R^2 = 0.84$).

3.2.6. Shrinkage

Figure 6 presents the results obtained in the shrinkage test over time and Table 5 shows the variations between the values for concrete with freshwater and with seawater. The effect of seawater on concrete curing was not studied for concrete shrinkage, because the curing process designated for this investigation was not compatible with the test procedure adopted.

Table 5 - Shrinkage at 91 days

Concretes	Shrinkage at 91 days (μm/m)	Effect of seawater (%)
P-0	-343.8 ± 5.0	-
S-0	-465.7 ± 16.7	35.4
P-50	-434.0 ± 21.7	-
S-50	-612.6 ± 16.7	41.1
P-100	-604.3 ± 83.5	-
S-100	-780.4 ± 72.5	29.1

From Table 5, it can be concluded that the use of seawater in the composition caused an increase in concrete shrinkage, compared to concrete with freshwater. In mixes with 0% of RA, this increase was on average 35%, while in those with 50% and 100% of RA, this increase decreased to 41% and 29%, respectively. The increase in shrinkage seems to influence in the same way concrete with and without RA. Khatibmasjedi *et al.* (2019) and Younis *et al.* (2018) also concluded that the shrinkage of concrete with seawater is higher than that of concrete with freshwater, for equal water/cement ratio. This increase can be justified by an early acceleration of cement and a refinement of the microstructure of concrete. However, in this research, the effective water/cement ratio of concrete with seawater was higher than that of concrete with freshwater, which may justify the higher shrinkage of the former compared to the latter.

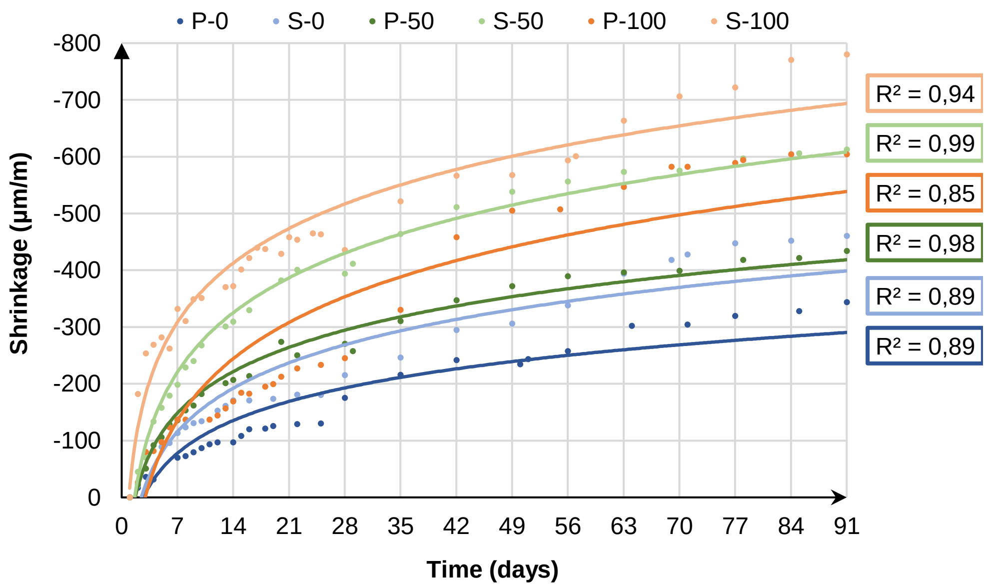

Figure 6 - Shrinkage over 91 days

It was observed that concrete shrinkage increased with the increase in the replacement ratio of NA with RA, and it was found that this increase is linear (R^2 between 0.97 and 1.00). This increase in shrinkage due to RA may be associated with the lower stiffness of RA, compared to NA, causing a decrease in concrete stiffness and, consequently, increasing deformations in it (Bravo *et al.,* 2018).

4. Conclusions

This study intended to analyse the effect of seawater in the composition and curing of concrete produced with different ratios of incorporation of RA (0%, 50% and 100%). Thus, it was possible to draw some conclusions from the study carried out of the behaviour of concrete in terms of durability.

It was concluded that the use of seawater in the composition of concrete caused a worsening of concrete behaviour in terms of water absorption, carbonation resistance and shrinkage. On the other hand, it was concluded that the use of seawater in the curing process worsened the performance of concrete in terms of water absorption and chloride penetration resistance. However, in terms of carbonation resistance, seawater curing promoted a decrease in carbonation depth, thus promoting an improvement in carbonation resistance of concrete cured with seawater. The use of seawater in concrete composition had a more pronounced effect on mixes without RA than on those with RA, while the use of seawater in curing of concrete had a more pronounced effect on mixes with RA than on those without RA.

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