Extended Abstract

Mechanical characterization of concrete produced with recycled cement

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1. Introduction

The construction industry puts a high pressure on the environment, covering various polluting activities, such as the extraction and processing of raw materials or the transport of materials [1]. In this industry, concrete is the most used material, resulting from its versatility, low cost and ease of production.

In fact, among the main constituents of concrete, cement production has the greatest impact on the environment, accounting for about 25 to 27% of total industrial carbon dioxide (CO_2) emissions or 5 to 7% of global emissions [2], as well as the consumption of 12 to 15% of industrial energy worldwide [3]. In addition to these aspects, concrete also has a high environmental impact associated with its deconstruction and waste generation phase, being the main component of construction waste. In Europe, around 180 million tons of concrete demolition waste are produced annually, corresponding to around 500 kg per capita [4].

For various decades, concrete recycling studies have mainly addressed its use as coarse and fine aggregates as well as low-activity filler additions [5 – 7]. On the other hand, through the past decade, several studies have been published on the incorporation of recycled cement (RC) as a substitute for Portland cement in both mortars and concrete [8 - 11]. This work intends to study the viability of the production and incorporation of RC and to ensure the workability and mechanical resistance of mixtures produced with it.

2. Experimental campaign

In a first phase, the production of RC from origin paste or concrete with at least 120 days of age was carried out. Then, concrete of different water/binder ratios (w/b) was produced with the incorporation of different percentages of RC. In parallel, recycled concrete aggregates were also considered, manufactured from origin concrete directly from just crushing (ARB) or, alternatively, from crushing, followed by heat treatment and grinding (ART). In this work, the incorporation of other mineral additions was also considered, namely fly ash and limestone filler, in order to evaluate its relative efficiency compared to RC and to analyze the possible synergy between RC and these additions.

2.1. Recycled cement production

To obtain RC, an origin paste with a water/cement ratio (w/c) of 0.55 was initially produced. In the production of these concretes, cement type CEM I 42.5 R (designation “OPC”) was used. Its main properties are shown in Table 1.

Table 1 - Properties of ordinary Portland cement (OPC)

Property	CEM I 42.5R
Density (kg/m^3)	3070
Blaine Surface Area (cm^2/g)	4437
Fraction < 45 μm (%)	6.8
Compressive strength of the reference mortar at 28 days (MPa)	57
SiO_2+Al_2O_3+Fe_2O_3 (%)	19.64+5.34+3.05
CaO+MgO (%)	62.80+1.80
Free CaO+MgO (%)	0.7+0.9
Setting Time initial/final (min)	170 / 280

The origin paste was produced with the aid of an electric mixer, to achieve an adequate homogenization. After 24 hours, the specimens used for RC production were demolded and stored in atmospheric conditions. During the first 7 days, the specimens were sprayed with water, and then left under these conditions for at least 3 months, in order to obtain a well hydrated paste. After this period, and with the aim of producing powders with the desired fineness (<250 μm), the specimens were subjected to a size reduction process with several stages, followed by a final screening. Two jaw crushers, a roller mill and a ball mill were used for this.

Finally, the ground material was subjected to thermoactivation to obtain RC. The heat treatment was carried out in a rotating electric oven, aiming at obtaining a more homogeneous dehydration of the material. Based on the optimization study carried out under the *EcoHyb* project [8], a treatment temperature of 650ºC was selected. The adopted heating curve consisted of heating up to 150 ºC, where it stayed for 1 hour, heating up to the level of 650 ºC, where it stayed for 3 hours. Between levels, a heating rate of 10 ºC/min was stipulated. Cooling was carried out slowly inside the oven, until room temperature.

2.2. Recycled aggregate production

As with RC, it was necessary to first produce an origin concrete (OC) that later allowed to produce construction waste representative of an old concrete. The cement used in this concrete was the same used to produce the origin paste. For the OC, a w/c of 0.55 was also considered, as performed for the origin pastes, to represent cementitious matrixes of similar compactness. The OC was produced with the aid of a vertical axis mixer and then molded into 300x150x150 mm specimens. After demolding at 24 hours, the specimens were stored outside the laboratory for 18 months, subject to varying atmospheric conditions, as occurred in a real environment.

The crushed recycled aggregates (ARB) were obtained by crushing the concrete using a jaw crusher, which were then sieved in different granulometric fractions, between 2 and 12.5 mm. For the production of the thermally treated recycled aggregate (ART), the analysis for the optimal treatment temperature within the scope of the *EcoHyb* project [9] showed that, for treatment temperatures between 300ºC and 500ºC, the highest aggregate-paste separation yield, without changing the characteristics of the aggregates, occurred for temperatures around 400ºC. However, contrary to what was intended, it was not possible to make a prior optimization of the oven's heating curve, and the aggregates ended up being treated at just 300ºC, at which the separation efficiency is significantly lower. After the thermal treatment, the aggregates were subjected to autogenous grinding for 10 minutes, using the Los Angeles machine. At the end of this process, and through a sieving process, the various fractions of ART were finally obtained.

2.3. Materials and compositions

In the production of concrete, natural aggregates as well as ARB and ART were used. In the production of concrete, additions of fly ash (CZ) and limestone filler (FC) were also incorporated, in order to analyze a possible synergy of these materials with recycled cement. Following a previous study within the scope of the project in which this work is included [8], concrete filler (FB) was also used as an addition resulting from the process of separating the paste from aggregates from construction and demolition waste.

All the works involved in this experimental campaign were carried out with the same type of cement, CEM I 42.5 R (Table 1). Within the scope of this investigation, the RC produced according to what was indicated in 2.1, from residues of origin paste with a w/b of 0.55 (designation "P") was adopted. Before proceeding with the thermoactivation of recycled cement, the material is in an untreated form (designation "NT"). NT was also considered in the work, to confirm its reactive inactivity as an addition. RC obtained from origin pastes with a w/b of 0.35 (designation "S") was also used, following the same production method of recycled cement described in 2.1. Finally, a recycled cement produced from the OC, introduced in 2.2, and subject to a new separation process [8,10], designated "C", was used. This recycled cement has about 76% and 24% by mass, of cementitious matrix and natural aggregates, respectively [8]. Subsequently, this material was sieved through a 250 μm sieve and subjected to the same thermoactivation treatment, according to the methodologies described in 2.1.

2.4. Compositions

In this study, concrete with w/b of 0.35, 0.55 and 0.65 was produced. Accordingly, the mass substitution of OPC by 5%, 15%, 30% and 40% and 100% of P was analyzed. Concrete was also produced with cements S and C, up to 30% of incorporation. The performance of CZ and FC as a partial substitute for recycled cement was also evaluated. The cementitious materials NT and FB were also considered and analyzed as additions. For the analysis of concrete with cement and recycled aggregates, the ARB and ART were also considered. Due to the smaller dimension of these aggregates (< 12.5mm), it was necessary to provide a complementary series of reference concrete. Finally, a concrete was also produced with 15% P and w/b of 0.62 (15P62), in order to achieve the same workability as the R55 control concrete. All concretes were formulated based on the Faury method. The compositions adopted in this work are summarized in Table 2, with the various concretes designated based on the nomenclatures presented for each type of binder or addition (P, C, S, CZ, FC, FB, NT), type of aggregate (AN, ARB, ART), dimension of the aggregate (D for D_{max} of 12.5 mm) and w/b of the mixture (0.35 to 0.65).

Table 2 - Compositions of binders used in concrete production

Designation	w/b	RC	Addition
R35	0.35	-	-
R55	0.55	-	-
R65	0.65	-	-
15NT55	0.55	-	15% NT
15P35	0.35	15% P	-
5P55	0.55	5% P	-
15P55	0.55	15% P	-
30P55	0.55	30% P	-
40P55	0.55	40% P	-
100P65	0.65	100% P	-
15P65	0.65	15% P	-
15P62	0.62	15% P	-
30S55	0.55	30% S	-
15C55	0.55	15% C	-
30C55	0.55	15% C	-
15CZ55	0.55	-	15% CZ
15FC55	0.55	-	15% FC
15FB55	0.55	-	15% FB
30CZ55	0.55	-	30% CZ
30FC55	0.55	-	30% FC
30FB55	0.55	-	30% FB
15P15CZ55	0.55	15% P	15% CZ
15P15FC55	0.55	15% P	15% FC
R55D	0.55	-	-
ARBR55D	0.55	-	-
ARTR55D	0.55	-	-
ART15P55D	0.55	15% P	-
ART30P55D	0.55	15% P	-

2.5. Concrete production

As part of this experimental campaign, the specimens were produced according to the same procedure described in 3.1. Depending on the type of test, cubic molds with 150 mm and 100 mm, cylinders with com 150x300 mm and prisms with 100x100x350 mm were produced. The specimens subjected to mechanical and density tests were cured in water until the testing age. The shrinkage specimens were placed in a controlled environment chamber after demolding.

2.6. Fresh concrete properties

The workability of the concrete was measured based on the slump test (Abrams cone), as specified in the standard NP EN 12350-2 [16]. This test was carried out right after mixing. The fresh density tests were performed according to NP EN 12350-6 [17]. The fresh concrete was compacted inside a rigid and watertight container, of known volume and mass, registering its mass.

2.7. Hardened concrete properties

The dry density tests were performed according to the standard NP EN 12390-7 [18]. In this test, 2 cubic specimens of 100mm of edge with 28 days of age were used per mixture. The measurement of the ultrasonic pulse velocity, according to the standard NP EN 12504-4 [19], was carried out on cubic specimens with side of 150 mm at 28 days of age, having been performed immediately before the compressive strength test. The compressive strength tests were performed according to the standard NP EN 12390-3 [20]. These tests were performed on cubic specimens with 150 mm of side, at 3, 7, 28 and 90 days of age. Three specimens were tested per composition. The tensile splitting strength test was performed according to the standard NP EN 12390-6 [21], using 3 cylindrical specimens of Φ150x300mm, at 28 days of age. The modulus of elasticity test was performed according to the LNEC specification E 397 [22]. For this purpose, for each mixture, 3 cylinders of Φ150x300mm with 28 days of age were tested. The drying shrinkage test was carried out according to the LNEC specification E 398 [23]. For each composition, 2 specimens were tested.

3. Analysis and discussion of results

3.1. Workability and density

As expected, the loss of workability with increasing the percentage of RC incorporation was confirmed, as documented in the literature

[10–12]. Without the incorporation of SP, the mixture with 15% P showed a reduction of 40% compared to the reference concrete with the same w/b of 0.55.

The polycarboxylate based superplasticizer (SP) proved to be effective in improving the workability of concrete with P. The partial replacement of OPC by C led to greater slump decreases than those obtained for the same incorporation of OPC by P. Since the cement C has a concrete origin, it is contaminated with non-porous aggregates, corresponding to a higher water/RC ratio for the same w/b, leading to a significant reduction in the water required for normal consistency. The cement S had a lower water demand than the cement P, due to its lower porosity associated with a lower specific surface.

The use of CZ promoted an increase in workability in the mixtures. In the ternary mixture with 15% CZ and 15% P, it was possible to compensate for the high workability reduction of mixtures with the same RC content, allowing to achieve a slump level very similar to that of the reference concrete (R55). For the same w/b, mixtures with the incorporation of 15% NT or 15% FB revealed greater workability than mixtures with 15% P, but lower than mixtures with FC. Compared to P, NT has less porosity, an almost inert nature and the absence of free CaO, which reduces its water requirement. On the other hand, FC contains only non-porous aggregate particles, contributing to better behavior in terms of workability. Finally, the FB consists of a mixture of porous and aggregate paste, presenting an intermediate water requirement between the NT and the FC.

The use of ARB had little influence on workability, with just a slight reduction justified by the fact that they have a similar shape index and lower density. Alternatively, the use of ART led to an increase in workability compared to the R55D. In fact, the ART production process promoted a decrease in the shape index which can promote an increase in workability [13]. The addition of P reduced the workability of ART concrete in a similar way as showed in natural aggregate concrete.

Both fresh and dry concrete density were more affected by the w/b than by the incorporation of P, which has a density slightly lower than that of OPC. In addition, as mentioned, due to the RC greater water requirement compared to OPC, concrete produced with RC tends to have lower workability, which may justify the lower degree of compactness and, as such, greater void content. This explains the marked reduction of fresh density in concrete produced with up to 15% P and without using SP. For 40% replacement of P, there is an inversion in the tendency to reduce density. This can be explained by the compactness gain achieved using high dosage of SP, with consequent benefit for the better dispersion of the particles of P and OPC.

3.2. Compressive strength and tensile splitting strength

In general, the compressive strength was not significantly influenced by the incorporation of P, even considering the high incorporation percentages (up to 100%).

Table 3 – Experimental campaign results

Designation	w/b	Flow. (mm)	ρ_{fresh} (kg/m^3)	ρ_{dry} (kg/m^3)	V_{voids} (L/m^3)	fcm_{3d} (MPa)	CV $_{fcm,3d}$ (%)	fcm_{7d} (MPa)	CV $_{fcm,7d}$ (%)	fcm_{28d} (MPa)	CV $_{fcm,28d}$ (%)	fcm_{90d} (MPa)	CV $_{fcm,90d}$ (%)	VUS,$_{28d}$ (m/s)	CV,$_{VUS}$ (%)	$fctm_{28d}$ (MPa)	CV $_{fctm,28d}$ (%)	Ecm_{28d} (GPa)	$CV_{Ecm,28d}$ (%)
R35	0.35	150	2360	2330	34	63.6	3	72.1	3	84.4	1	93.5	4	5180	0	5.54	12	-	1
R55	0.55	150	2330	2290	13	33.7	1	42.0	3	52.2	1	59.2	0	4716	0	3.59	6	40.0	1
R65	0.65	Fluid	2280	2170	8	27.9	1	33.4	2	39.8	3	-	-	4620	0	2.71	2	-	-
15NT55	0.55	110	2270	2200	38	29.0	2	35.8	3	43.1	3	-	-	4520	1	3.23	11	-	-
15P35	0.35	100	2340	2310	35	76.3	3	86.1	1	90.0	4	-	-	5268	0	5.50	-	-	-
5P55	0.55	130	2320	2290	17	35.8	1	44.5	1	53.2	3	-	-	4762	0	3.98	7	-	-
15P55	0.55	90	2290	2260	27	34.7	1	42.9	3	52.4	1	57.9	2	4771	1	4.14	2	38.8	3
30P55	0.55	105	2280	2240	30	33.7	2	40.1	0	47.8	2	50.7	5	4646	0	3.30	3	36.4	2
40P55	0.55	185	2290	2230	19	37.4	1	44.4	1	52.5	2	-	-	4663	0	3.55	9	-	-
100P65	0.65	100	2220	2150	24	28.5	0	30.2	1	33.2	2	-	-	4415	0	2.19	6	-	-
15P65	0.65	190	2230	2150	26	27.9	1	33.5	1	40.1	1	-	-	4586	0	3.48	1	-	-
15P62	0.62	140	2260	2180	28	31.1	2	35.8	1	44.6	2	-	-	4650	1	3.48	11	-	-
30P75	0.75	210	2200	2060	14	18.3	1	21.2	2	27.1	3	-	-	4330	1	2.02	15	-	-
30S55	0.55	165	2260	2240	38	29.4	2	35.8	5	46.8	1	53.7	3	4699	1	3.11	9	35.6	3
15C55	0.55	120	2290	2260	28	30.0	1	42.2	2	52.0	1	-	-	4745	0	3.82	0	-	-
30C55	0.55	130	2270	2230	33	24.2	1	36.5	1	45.0	0	-	-	4626	1	3.33	0	-	-
15CZ55	0.55	190	2280	2260	26	27.2	1	33.3	2	44.2	0	56.5	2	4640	1	3.41	16	37.0	2
15FC55	0.55	170	2310	2260	17	27.5	1	35.2	1	42.9	1	47.3	1	4581	1	2.78	5	36.2	1
15FB55	0.55	130	2300	2220	21	29.5	2	35.6	3	43.1	3	-	-	4618	0	2.66	10	-	-
30CZ55	0.55	180	2310	2240	11	20.8	2	24.9	1	38.4	1	50.1	1	4644	0	2.54	11	37.5	1
30FC55	0.55	150	2300	2220	19	23.5	1	27.4	2	33.8	5	36.1	4	4457	0	2.55	14	35.3	1
30FB55	0.55	140	2300	2200	21	22.3	1	26.8	3	32.8	0	-	-	4524	0	2.41	14	-	-
15P15CZ55	0.55	160	2300	2230	14	28.2	2	34.7	1	44.3	3	56.7	1	4648	0	2.60	6	35.9	2
15P15FC55	0.55	150	2300	2240	17	27.7	1	34.3	2	40.9	2	46.1	1	4630	0	2.71	5	-	-
R55D	0.55	140	2290	2210	14	37.4	2	-	-	50.3	2	-	-	4823	0	-	-	-	-
ARBR55D	0.55	130	2210	2080	7	33.9	2	-	-	46.7	2	-	-	4447	0	-	-	-	-
ARTR55D	0.55	170	2220	2120	15	36.0	1	-	-	49.3	1	-	-	4451	0	-	-	-	-
ART15P55D	0.55	110	2190	2100	23	35.0	4	-	-	48.3	2	-	-	4444	0	-	-	-	-
ART30P55D	0.55	130	2160	2080	38	33.0	3	-	-	44.2	4	-	-	4372	0	-	-	-	-

For the same w/b, the compressive strength tended to increase slightly for percentages of P up to 15%. It is possible that the finer P particles have promoted a filler effect, improving the refinement of the microstructure, due to its high specific surface [11,12].

In fact, for P incorporations above 15%, the compressive strength tended to decrease. This can be attributed to the effect of diluting the quantity of OPC, but also to the reduction of workability and consequent increase of concrete's voids content with incorporation of high amounts of P. However, for 40% of P incorporation, an inverse trend was observed, with increased compressive strength. The incorporation of high amounts of SP dispersed more effectively, not only the agglomerated particles of P, but also the OPC, allowing to counteract the lower workability, compensating for the previously mentioned negative effects. As for the same workability analysis, with the increase in the w/b by about 13%, the 28 days compressive strength of 15P62 concrete decreased by 13.5% compared to R55.

Similarly to P, the incorporation of up to 15% C did not significantly affect compressive strength. However, the incorporation of 30% C led to a reduction of about 14% compared to the reference concrete. As mentioned, concrete with this cement, being contaminated with about 26% of aggregate, has a water/cement fraction (w/cf) higher than that of P, namely 0.57 and 0.6 to 15% and 30% C, respectively. As for the incorporation of 30% S, this resulted in a decrease of about 10% of the compressive strength, having been slightly lower than that of 30% P concrete. The slightly higher air content in these concretes, combined with the lower porosity and surface area of the S, which increases the intraparticle w/b, should be the main reasons for this additional resistance reduction.

Compared to R55 at 28 days of age, concretes with 30% incorporation of CZ and FC showed a decrease of around 26% and 35% of the compressive strength, respectively. This confirms that these mineral additions showed significantly lower reactivity than any of the RC considered in this study. However, more hydration products could be expected to develop at older ages, due to the development of pozzolanic reactions of CZ. Correspondingly, the ternary mixtures 15CZ+15P and 15FC+15P displayed an increase the compressive strength of 15% and 21% compared to mixtures with 30% CZ and FC, respectively. Due to their almost inert nature, the incorporation of FB and NT fillers only contributed through their physical filler and nucleation effect, which justifies their low contribution to mechanical resistance, showing minor differences between the two different types of filler.

As for the use of ARB aggregates, the compressive strength was about 7% lower than that of the reference concrete. In fact, the ARBs are composed of paste and aggregate, and although the w/c of the paste in this aggregate is identical to that of the concrete matrix in which it is incorporated, its production process (crushing) may have reduced the quality of the paste. On the other hand, ARTR55D concrete showed a less significant reduction, reaching about 98% of the strength of R55D concrete. As analyzed for concrete with natural aggregates, the compressive strength of concrete with ART was not significantly influenced by the incorporation of up to 15%P. However, for 30% P, there was a reduction of about 10% of the compressive strength.

In general, the tensile splitting strength followed a similar trend to that observed for the compressive strength. In fact, given that these properties are essentially influenced by the quality of the matrix, the same compressive strength result justifications can also explain the tensile splitting strength results.

3.3. Modulus of elasticity

The modulus of elasticity decreased with increasing percentage of incorporation of RC. There was a more significant non-proportional reduction in the modulus of elasticity for the incorporation of 30% P, about 3 times greater than that observed for 15% P, since this concrete presented lower compressive strength. In addition, the concrete produced with cement P was produced with a slightly higher paste volume than the reference concrete with the same w/b, which also contributed to the reduction of the modulus of elasticity.

As with mechanical strength, CZ contributed to a lower reduction in the elasticity modulus of concrete than FC, which has an almost inert nature and low capacity to develop additional hydration products, capable of densifying the cement matrix and increasing its stiffness. As expected and similarly verified in the remaining mechanical properties analyzed, the P was much more efficient than these mineral additions currently used in the construction industry, leading to insignificant variations in the modulus of elasticity compared to the reference concrete R55, at least for P contents up to 15%.

3.4. Ultrasonic pulse velocity

The ultrasonic pulse velocity (VUS) with the incorporation of P followed a similar trend as that of the compressive strength. Nonetheless, it can be concluded that the incorporation of P had little influence on the variation of the VUS, with maximum variations of 2% between concretes. Furthermore, in concretes of identical workability, the VUS of the reference concrete (w/b of 0.55) was only 1.4% higher than that of concrete with 15% P and a w/b of 0.62.

Concretes with C showed similar values to those achieved in concretes with an equal percentage of incorporation of P. The slightly lower equivalent w/RC ratio of these concretes was partially offset by the increase in density of the binder, due to its contamination with aggregate, which resulted in similar VUS values between the different mixtures. Contrary to what was observed in the mechanical strength, concrete with 30% S presented a slightly higher VUS than mixtures with 30% P, which can be justified by the greater rigidity of the S particles from waste paste of higher compactness, and therefore, associated with lower porosity and greater density, which compensated for the eventual lower reactivity and less development of hydration products of this binder.

The VUS of FC concrete was naturally lower than that of concrete with an equal percentage of incorporation of P. In this case, the cementitious matrix has less rigidity, resulting from the non-development of hydration products. In this case, concrete with FC and FB showed a slightly higher VUS than that of concrete with NT, since FC and FB contain aggregate in their constitution, increasing their density. Furthermore, in concrete with an equal percentage of OPC substitution with CZ, VUS was higher than that of concrete with filler, since these have a greater reactivity and contribute more to the increase of rigidity of the cementitious matrix. However, the VUS value for 30% CZ was not expected, having been similar to that of concrete with 30% P. This may be explained by the greater compactness achieved, associated with a lower accidental voids content and a higher dry density. The ternary mixtures with P and CZ or P and FC led to intermediate values of those obtained in concrete with the same content of CZ, P, or FC.

There was a very sharp decrease in VUS in recycled aggregate concrete compared to the R55D with natural aggregates, due to the higher porosity and lower density of the recycled aggregates. In ART concretes, no change was observed with the incorporation percentages of up to 15% P. However, with 30% incorporation of P, the VUS decreased, due to the increase in void content and to the decrease in the stiffness of the cementitious matrix. In general, the type of aggregate assumes greater relevance in VUS than the incorporation of RC.

3.5. Drying shrinkage

In general, the long-term retraction, up to 120 days, followed the same trend as compressive strength. The shrinkage decreased slightly with the incorporation of up to 15% P, but above this percentage it increased with the P content, except for concrete with 40% P, which was produced with a high dosage of SP. Thus, and taking into account some variability of the test, it can be concluded that the retraction over time is similar in both types of concrete, without prejudice to the incorporation of small percentages of P. However, as observed in compressive strength, there was an inverse trend after the incorporation of 40% P. Although it is necessary to continue testing for older ages, as it is being carried out within the framework of the research project EcoHydb that is being developed at IST, there still seems to be a greater stabilization of the long-term shrinkage in concrete with P.

The incorporation of 15 and 30% P, C and S led to similar shrinkages. This can be explained by the similarity of the modulus of elasticity for mixtures with S and P. On the other hand, C cement presented a higher w/c than the other RCs, and consequently, less rigidity and a greater volume of evaporable water, which should have been counterbalanced by the lower volume of cement paste in relation to the others. The incorporation of CZ or FC and P caused an expected increase in shrinkage, justified by the greater porosity and less rigidity of the P particles.

ARB mixture showed an increase of shrinkage of almost 90% compared to R55D, justified by the adherence of the cement paste to the natural aggregate and consequent high permeability, high porosity and the presence of less dense particles. Based on the experimental analysis carried out, it is possible to conclude that the ART used in this study has a high quality, with no significant differences in shrinkage behavior, in comparison with equivalent mixtures with natural aggregates. Both the mixture produced with only OPC and the mixture of 30% P showed an increase lower than 20%.

4. Conclusions

For the same workability, concrete with P required more mixing water or SP than concrete with OPC. However, up to 15% of P incorporation, the workability was not significantly affected, and the RC mixture could be produced without correcting the composition of the mixture. The fresh density and the dry density followed similar trends, decreasing with the increase in the percentage of incorporation of P. This is essentially attributed to the increased demand for water by the RC in relation to OCP, which reduces the workability of the mixtures, leading to greater difficulty in compaction, and consequently, greater amounts of voids.

For the same w/b, the compressive and tensile splitting strength were not significantly influenced by the replacement of OPC with P, even for high incorporation percentages. Unlike NT and FB, non-thermoactivated products, the RC showed a high capacity for rehydration and effectively contributed to improving the mechanical strength of concrete, reaching an optimum incorporation percentage at 15%P. The performance of the RC was significantly affected by its effective dispersion and by the workability of the concrete in the fresh state. On the other hand, the incorporation of CZ allowed to increase the workability of the mixtures with RC, without significantly influencing their resistance and modulus of elasticity. Contrarily, the ternary mixture of FC and RC resulted in the reduction of the mechanical resistance when compared with the reference OPC concrete.

The modulus of elasticity showed a decrease with the increase in the incorporation percentage of P, due to the lower hardness and stiffness compared with the OPC. This reduction was not proportional, having been more significant for incorporations greater than 15%P.

The VUS followed the same trend as that observed for compressive strength, increasing up to 15% substitution percentages of OPC with P, and above this percentage decreasing due to its void content, decreased stiffness of the cement matrix and the porous nature of the P particles. However, the incorporation of RC had little influence on the variation of VUS, with a maximum variation of 2% between concretes.

For the same w/b, the shrinkage of mixtures produced with P followed the same trend as the compressive strength. In concrete with up to 15% incorporation, the lower stiffness of the P particles and the slightly higher volume of paste were compensated by the development of denser microstructures, with the trend being reversed for higher incorporation amounts of P.

The use of ART and ARB showed a high decrease in the density of mixtures and a reduction in mechanical strength and ultrasound speed, as well as a significant increase in retraction. However, the influence of RC incorporation followed the same trend for density and mechanical strength, comparing to AN.

References

Written Publications

[1] H. Yan, Q. Shen, L. C. H. Fan, Y. Wang, and L. Zhang, "Greenhouse gas emissions in building construction : A case study of One Peking in Hong Kong," *Build. Environ.*, vol. 45, no. 4, pp. 949–955, 2010, doi: 10.1016/j.buildenv.2009.09.014.

[2] F. A. Rodrigues and I. Joekes, "Cement industry: sustainability, challenges and perspectives," pp. 151–166, 2011, doi: 10.1007/s10311-010-0302-2.

[3] M. B. Ali, R. Saidur, and M. S. Hossain, "A review on emission analysis in cement industries," *Renew. Sustain. Energy Rev.*, vol. 15, no. 5, pp. 2252–2261, 2011, doi: 10.1016/j.rser.2011.02.014.

[4] D. Gastaldi, F. Canonico, L. Capelli, L. Buzzi, E. Boccaleri, and S. Irico, "An investigation on the recycling of hydrated cement from concrete demolition waste," *Cem. Concr. Compos.*, vol. 61, pp. 29–35, 2015, doi: 10.1016/j.cemconcomp.2015.04.010.

[5] H. Le and Q. Bui, "Recycled aggregate concretes – A state-of-the-art from the microstructure to the structural performance," *Constr. Build. Mater.*, vol. 257, p. 119522, 2020, doi: 10.1016/j.conbuildmat.2020.119522.

[6] B. Cantero, I. F. S. Bosque, A. Matías, and C. Medina, "Statistically significant effects of mixed recycled aggregate on the physical-mechanical properties of structural concretes," *Constr. Build. Mater.*, vol. 185, pp. 93–101, 2018, doi: 10.1016/j.conbuildmat.2018.07.060.

[7] C. Medina, W. Zhu, T. Howind, M. Isabel, and S. De Rojas, "Influence of mixed recycled aggregate on the physical e mechanical properties of recycled concrete," *J. Clean. Prod.*, vol. 68, pp. 216–225, 2014, doi: 10.1016/j.jclepro.2014.01.002.

[8] S. Real, A. Carriço, J. A. Bogas, and M. Guedes, "Influence of the treatment temperature on the microstructure and hydration behavior of thermoactivated recycled cement," *Materials (Basel).*, vol. 13, no. 18, 2020, doi: 10.3390/ma13183937.

[9] S. Hu, "Separação de constituintes do betão visando a obtenção de cimentos reciclados," Instituto Superior Técnico, 2019.

[10] J. A. Bogas, A. Carriço, and M. F. C. Pereira, "Mechanical characterization of thermal activated low-carbon recycled cement mortars," *J. Clean. Prod.*, vol. 218, pp. 377–389, 2019, doi: 10.1016/j.jclepro.2019.01.325.

[11] Z. Shui, D. Xuan, W. Chen, R. Yu, and R. Zhang, "Cementitious characteristics of hydrated cement paste subjected to various dehydration temperatures," *Constr. Build. Mater.*, vol. 23, no. 1, pp. 531–537, 2009, doi: 10.1016/j.conbuildmat.2007.10.016.

[12] R. Serpell and F. Zunino, "Recycling of

hydrated cement pastes by synthesis of α′H-C2S," *Cem. Concr. Res.*, vol. 100, no. January, pp. 398–412, 2017, doi: 10.1016/j.cemconres.2017.08.001.

[13] J. H. Kim, N. Noemi, and S. P. Shah, "Effect of powder materials on the rheology and formwork pressure of self-consolidating concrete," *Cem. Concr. Compos.*, vol. 34, no. 6, pp. 746–753, 2012, doi: 10.1016/j.cemconcomp.2012.02.016.

[14] D. Qian *et al.*, "A novel development of green ultra-high performance concrete (UHPC) based on appropriate application of recycled cementitious material," *J. Clean. Prod.*, vol. 261, p. 121231, 2020, doi: 10.1016/j.jclepro.2020.121231.

[15] R. Yu and Z. Shui, "Influence of agglomeration of a recycled cement additive on the hydration and microstructure development of cement based materials," *Constr. Build. Mater.*, vol. 49, pp. 841–851, 2013, doi: 10.1016/j.conbuildmat.2013.09.004.

[16] NP EN 12350-2 (2009): Ensaios do betão fresco – Ensaio de abaixamento. Instituto Português da Qualidade (IPQ)

[17] NP EN 12350-6 (2009): Ensaios do betão fresco – Massa volúmica. Instituto Português da Qualidade (IPQ)

[18] NP EN 12390-7 (2009): Ensaios do betão endurecido – Massa volúmica do betão endurecido. Instituto Português da Qualidade (IPQ)

[19] NP EN 12504-4 (2007): Ensaio do betão nas estruturas – Determinação da velocidade de propagação dos ultra-sons. Instituto Português da Qualidade (IPQ)

[20] NP EN 12390-3 (2011): Ensaios do betão endurecido – Resistência à compressão de provetes. Instituto Português da Qualidade (IPQ)

[21] NP EN 12390-6 (2011): Ensaios do betão endurecido – Resistência à tração por compressão de provetes. Instituto Português da Qualidade (IPQ)

[22] LNEC E 397 (1993): Módulo de elasticidade em compressão.

[23] LNEC E 398 (1993): Betões – Determinação da retração e da expansão