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Thermal Performance of Concrete with Recycled Aggregates from CDW Plants

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Abstract: This investigation intends to analyse the thermal performance of concrete with recycled aggregates (RA) from construction and demolition waste (CDW) collected from several locations in Portugal. A total of 17 concrete mixes were analysed by means of thermal conductivity tests. Firstly, the composition and characteristics of the aggregates (natural and recycled) used in the production of the concrete mixes were analysed thoroughly, by means of several physical and chemical tests. Later, in order to evaluate the thermal behaviour of the mixes, several tests were performed and their results analysed, both on the fresh-state (slump with the Abrams cone test, density and air content) and the hardened state (compressive strength and thermal conductivity). The analysis of the thermal behaviour showed that the use of RA improves the thermal performance of the concrete mixes. The extent of this change was shown to be quite variable depending on the origin of the RA used.

Keywords: recycled aggregates; construction and demolition waste; thermal performance; thermal conductivity

1. Introduction

According to data presented by the United Nations, in 2015 the world population was about 7.3 billion, and was expected to reach 9.7 billion by 2050 [1]. The same report also indicates that in 2015, for the first time, the majority of the world's population was living in cities. Migration of populations to urban areas has benefited global development, but the urban pressure in these areas implies a significant increase in built-up area, with an increase in the production of construction and demolition waste (CDW), whose environmental impact is extremely negative.

The constitution of the CDW depends, for instance, on the origin of the waste, on the time it was collected and on the type of construction which gave rise to it. According to Zordan [2], CDW is the most heterogeneous of industrial wastes. Taking into account that a building consists of dozens of distinct elements, it is not surprising that the waste resulting from the demolition of a given construction will have a heterogeneous composition. Oliveira et al. [3] further highlighted other factors that explain the heterogeneity of CDW coming from a given construction site: the level of technical development of the construction industry, the quality of labour available, the construction and demolition techniques used, the recycling and reuse processes defined and the materials available.

The European Union has set some targets for the reduction, reuse and recycling of CDW by means of Directive 2008/98/EC, which defines that, by the year 2020, 70% of the CDW produced annually must be recycled [4]. In 2010, according to Soniego et al. [5], the percentage of CDW sent for recycling in the European Union was only 47%.

Today, despite all technological developments, reinforced concrete still remains the most widely used structural material in the world. However, if it is generally agreed that this material has several advantages, it is also true that concrete carries with it a serious problem: a high ecological footprint. This problem has to be solved/minimized urgently so that the construction sector can become sustainable. The production of concrete involves the use of natural aggregates (sand and crushed stone), which, since they are non-renewable materials, give rise to significant environmental impacts. The geological impacts caused by the extraction of sand, such as the alteration of the ground and coastlines and the visual impact, are some of the most significant [6]. It should also be noted that the production of aggregates, due to the energy required for their generation, accounts for about 15% of the total CO_2 emissions resulting from the production of concrete [2]. Hence, one of the environmental improvements that has been studied is the incorporation of several waste products in the production of concrete. This measure results in a decrease of the natural resources consumed by the concrete industry and reduces the amount of waste deposited in landfill, both of which have beneficial effects for the environment.

It should be highlighted that the European Commission identified CDW as a priority waste stream for treatment and recycling since high quantities are produced and due to its high potential for reuse as a raw material [4]. Thus, it is not surprising that, in recent years, several investigations have been carried out to evaluate the use of CDW in concrete [4].

The properties of concrete with recycled aggregates made of concrete, ceramic materials, glass or plastics, among others, have been analysed in order to understand their potential and limitations. However, research on the use of CDW from recycling plants in concrete is still limited [7]. Most previous studies dealt with the use of a single type of recycled aggregates (RA) from CDW, overlooking the need for comparing different CDW with distinct compositions. On the other hand, there are also few studies that exhaustively analyse the RA used in concrete, by means of composition analysis and physical and chemical tests.

The study presented herein intends to fill some of the existing gaps in the knowledge on the incorporation of RA from CDW in concrete. It should be noted that there is currently a low confidence of the construction sector in the use of concrete with RA from CDW, due to the lack of technical knowledge and low experience in its use, compared to those on conventional concrete. Therefore, the thermal characterization of concrete with RA from CDW made in this study intends to increase the existing knowledge on its possible uses in the construction industry, whether as structural or non-structural concrete. This paper is part of an extensive research in which the evaluation of the mechanical [7], durability [8], rheological [9], microscopic [10] and thermal behaviour of concrete with RA sourced from different CDW (coarse RA from Valnor (Avis, Portugal) and Retria (Porto, Portugal) and fine RA from Vimajas (Algueirão–Mem Martins, Portugal) and Ambilei (Leiria, Portugal)) was carried out.

To date, investigations that analyse the thermal behaviour of concrete with RA from CDW are scarce. Xiao et al. [11] and Díez Ramírez et al. [12] indicate that the thermal conductivity of concrete decreases as the percentage of replacement of natural aggregates (NA) with coarse recycled aggregates (CRA) increases. Díez Ramírez et al. studied the thermal behaviour of concrete made with CRA from CDW and found that the thermal conductivity of the concrete mixes with 100% CRA and 100% NA was of 1.58 and 2.00 W/m.K, respectively.

Marie [13] carried out an investigation in which the influence of the simultaneous incorporation, in several percentages, of RA made of concrete and of rubber on the thermal behaviour of concrete was assessed. Three 150 × 150 × 150 mm specimens were prepared from each mix. The specimens were cured in the laboratory in water at a temperature of 20 ± 2 °C for 28 days. This author found that the use of 10% of concrete RA and 10% rubber RA reduces the thermal conductivity of the recycled aggregate concrete (RAC) by 32% in comparison with that of natural aggregate concrete (NAC). Hence, this author concluded that it is feasible to use this hybrid concrete as a non-structural thermal insulation material. In the case of concrete RA, the decrease in thermal conductivity of the RAC mix is related to the increase in the air content of the cement paste, which is responsible for a lower density [14].

Zhu et al. [15] studied the thermal behaviour of RAC with concrete RA and ceramic RA. Two 200 × 200 × 30 mm specimens were produced for each mix, totalling 18 specimens. The specimens were cured in the standard condition of temperature and relative humidity for 28 days (20 ± 2 °C and 95%, respectively). Regarding the former, the study showed that the thermal conductivity of RAC decreases with the increase of aggregate replacement ratio. The authors also concluded that the use of CRA was the one that most influenced the thermal conductivity of concrete. Through this investigation, it was also observed that the use of 70% ceramic RA caused a decrease of the thermal conductivity of RAC. One of the explanations suggested by the authors for this trend is that the high water absorption of the ceramic RA can cause a greater evaporation of the water present in the cement paste, causing a decrease in the density of the RAC.

The analysis of the thermal behaviour of concrete is important, since this property influences the behaviour of concrete in several domains, among which is the onset of cracks with thermal origin, due to the heat of hydration. Cement hydration is an exothermic chemical process, during which significant volumetric variations occur in the concrete, which, if partially or totally restrained, can lead to the appearance of tensile stresses and, consequently, to the onset of cracks. This type of cracks can lead to serious durability problems, due to the increased permeability of concrete to the entrance of external aggressive agents [16].

For the present study, an investigation of the thermal behaviour of concrete with RA from CDW was performed by analysing the results yielded by the thermal conductivity test. The coefficient of thermal conductivity of a material corresponds to the amount of heat transmitted due to a unitary temperature variation between its longitudinal edges, per unit of time, through a unitary thickness and in a direction orthogonal to the unit surface area considered.

In this way, thermal conductivity quantifies the ability of materials to conduct heat. Materials with high thermal conductivity conduct heat faster than materials with low thermal conductivity. Hence, materials with high thermal conductivity are used as heat sinks and materials of low thermal conductivity are used in thermal insulation [17]. The study of the thermal conductivity of concrete, as well as other thermal properties, is important for the analysis of temperature gradients (difference between maximum and minimum temperatures), thermal deformations, the chances of cracking, and thermal insulation capacity.

High values of thermal conductivity correspond to a high heat dissipation capacity, thus leading to a low thermal gradient. In other words, the higher the thermal conductivity of concrete, the lower the temperature it can reach, since it will be easier to dissipate the heat internally generated.

Considering that the lower the thermal gradient, the lower the probability of thermal stresses, some investigations concluded that a high thermal conductivity reduces the appearance of cracks [17]. However, a structural solution with a reduced thermal conductivity decreases the environmental impact by improving the energy performance of the building [18].

2. Experimental Programme

2.1. Tests and Methodology

Throughout this investigation several tests were carried out on the aggregates used and the concrete mixes produced, the latter in both the fresh and hardened states.

The "Aggregates for concrete" standard (EN 12620 [19]) specifies the required properties of natural aggregates, mechanically processed, recycled aggregates or aggregate mixes to be used in concrete. It covers aggregates with dry density above 2000 kg/m^3, for use in all types of concrete mixes, including those conforming to the EN 206-1 [20] standard.

The characteristics of the aggregates were determined according to the requirements of the standards and specifications given in Table 1. In addition to the tests mentioned in this table, the composition of the various recycled aggregates was also evaluated according to the procedure of EN 933-11 [21], as imposed in the LNEC E-471 [22] specification. The latter serves as a guide for the use of coarse recycled aggregates in concrete with hydraulic binders.

Table 1. Tests performed in the determination of the properties of aggregates.

Properties	Standard
Physical Characterization	
Determination of particle density and water absorption	EN 1097-6 [23] and patent by de Rodrigues et al. [24]
Determination of loose bulk density and voids	EN 1097-3 [25]
Shape index	EN 933-4 [26]
Methods for the determination of resistance to fragmentation (Los Angeles)	EN 1097-2 [27]
Chemical Characterization	
Determination of water-soluble chloride salts	1744-1 Section 7 [28]
Determination of water-soluble sulphates	1744-1 Section 10 [28]
Determination of acid soluble sulphates	1744-1 Section 12 [28]
Determination of total sulphur content	1744-1 Section 11 [28]
Determination of lightweight contaminators	1744-1 Section 14.2 [28]
Determination of potential presence of humus	1744-1 Section 15.1 [28]
Determination of water solubility	1744-1 Section 16 [28]

The fresh-state properties of the concrete mixes evaluated were: slump through Abrams cone (EN 12350-2 [29]), density in the fresh-state (EN 12350-6 [30]) and air content (EN 12350-7 [31]).

In order to complement the analysis of the thermal behaviour of concrete mixes with RA from CDW, the compressive strength at 28 days was also determined according to EN 12390-3 [32].

The thermal conductivity test was carried out by means of the ISOMET 2114 device (Applied Precision, Bratislava, Slovakia) which directly measures, among other thermal characteristics, the thermal conductivity coefficient through surface probes. The results are obtained by evaluating the thermal response of the analysed material to the heat flux impulses. These flows are generated by the electrical energy dissipated through a probe that is in direct contact with the material.

For this test, two specimens per type of concrete were used and each specimen was analysed at least twice. The size of the specimens tested was 10 × 10 × 50 cm and they were cured in a dry chamber (20 °C and 50% relative humidity) for 28 days until testing.

2.2. Mix Design and Materials

A total of 17 concrete mixes were produced: a NAC, eight concrete mixes with replacements of 10%, 25%, 50% and 100% of the total volume of coarse NA with coarse RA (from Valnor and Retria) and eight with replacements of 10%, 25%, 50% and 100% of the total volume of fine NA with fine RA (from Vimajas and Ambilei).

Particles passing and particles retained by the 4-mm mesh sieve were considered, respectively, as fine and coarse aggregates. The maximum particle size used was 22.4 mm. The replacement of NA with RA was made by volume, fraction by fraction, in order to maintain, for all the concrete mixes with RA, the particle size distribution of the NA used in the NAC mix design. In this investigation, no admixtures or additions were used.

All mixes were produced with a required slump of 125 ± 25 mm measured in the Abrams cone test [29], in order allow a correct comparison between them. For this, a preliminary experimental phase was carried out, in which the amount of water used in the production of each concrete mix was adjusted, whenever necessary, in order to comply with this requirement.

The composition of the NAC mix was determined by the Faury's curve method [33], in order to obtain a concrete mix included in the C30/37 strength class. The mixing proportions, in volume, of the materials used can be seen in Table 2.

Table 2. Materials and mixing proportions of the natural aggregate concrete (NAC).

Cement		**0.115 L/L**	**351 kg/m³**
Fine Aggregates	0–0.063	0.000 L/L	0 kg/m³
	0.063–0.125	0.016 L/L	42 kg/m³
	0.125–0.25	0.044 L/L	114 kg/m³
	0.25–0.5	0.050 L/L	130 kg/m³
	0.5–1	0.057 L/L	148 kg/m³
	1–2	0.066 L/L	172 kg/m³
Coarse Aggregates	2–4	0.076 L/L	198 kg/m³
	4–5.6	0.041 L/L	111 kg/m³
	5.6–8	0.046 L/L	124 kg/m³
	8–11.2	0.047 L/L	127 kg/m³
	11.2–16	0.121 L/L	327 kg/m³
	16–22.4	0.122 L/L	329 kg/m³
Water		0.182 L/L	182 kg/m³
Voids		0.017 L/L	-
Total		1.000 L/L	2354 kg/m³

In this investigation, type I 42.5R cement was used, which has a minimum clinker content of 95% and contains up to 5% of additions.

With respect to the RA source, four Portuguese recycling plants (Ambilei in Leiria, Vimajas in Algueirão–Mem Martins, Valnor in Avis and Retria in Porto) were considered. The recycling plants were chosen according to their geographical location, in order to collect RA from areas with different construction types and technologies. Regarding NA, crushed limestone (limestone 1 and 2—coarse aggregates) and rolled river sand (fine and coarse sand—fine aggregates) were used.

2.3. Recycled Aggregate Properties

In this experimental campaign, RA were randomly withdrawn from each recycling plant that produces several types of CDW. To better understand the composition of the RA used in the production of concrete mixes, a visual analysis was carried out.

Table 3 shows the composition of the four types of RA. The RA used have a high percentage of "concrete, mortar and natural stone", which is estimated to be between 69% and 84% of their total content (by mass). The percentages of "masonry—clay materials" are quite variable (between 1% and 29%). Mália et al. [34] analysed several sources on the composition of CDW and also concluded that concrete and ceramic materials are the main sources of inert materials.

RA from Ambilei have a large amount of glass, which reaches 15.4% of their composition. In turn, RA from Vimajas stands out in terms of the amount of bituminous materials found, which corresponds to 10.5% of these RA.

Table 3. Composition of recycled aggregates.

Composition (%)	FRA Ambilei	FRA Vimajas	CRA Valnor	CRA Retria
Concrete, mortar and natural stone	83.7	75.2	70.8	69.1
Masonry—clay materials	0.9	11.6	28.6	28.6
Glass	15.4	1.0	0.5	2.1
Bituminous materials	0.0	10.5	0.0	0.0
Others	0.0	1.7	0.1	0.2
Total	100.0	100.0	100.0	100.0

Abbreviations: FRA, fine recycled aggregates; CRA, coarse recycled aggregates.

In Tables 4 and 5, it is possible to observe the results of the physical characterization carried out on several aggregates used. When compared to the NA, the RA exhibit a lower density and higher water absorption, which derives from their nature and higher porosity.

Table 4. Results of the physical characterization of coarse aggregates.

Physical Characterization	Limestone 2	Limestone 1	CRA Valnor	CRA Retria
Particle dry density (kg/m^3)	2599	2609	2091	2137
Water absorption (%)	1.5	1.3	8.6	8.4
Loose bulk density (kg/m^3)	1360	1350	1095	1236
Shape index (%)	15	17	24	24
Los Angeles wear (%)	26	28	52	46

Table 5. Results of the physical characterization of fine aggregates.

Physical Characterization	Fine Sand	Coarse Sand	FRA Ambilei	FRA Vimajas
Particle dry density (kg/m^3)	2583	2581	2112	2070
Water absorption (%)	0.3	0.7	12.9	10.1
Loose bulk density (kg/m^3)	1530	1540	1435	1332

It is found that all RA have a higher shape index than the NA, which can lead to a lower workability of the concrete mixes with RA, compared to that of NAC.

It was also observed that the RA present a higher level of fragmentation than the NA, possibly due to their composition.

Table 6 shows the results obtained in the chemical tests carried out on the different recycled aggregates. By performing these tests, the aim is to know which chemical components in these aggregates can be detrimental to the concrete mixes. These components will influence how curing takes place, as well as the protection of the steel rebars, among other aspects.

There are compounds that significantly alter the curing rate and the quality of the hardening of concrete, one of them being humus [35]. The humus test, carried out according to EN 1744-1 [28], only performs a qualitative analysis, signalling the existence or absence of organic matter. Regarding the RA analysed, a negative result for the presence of hummus was obtained for the RA from all the recycling plants.

Table 6 shows that the biggest concern regarding the results of the chemical tests is the amount of lightweight contaminants existing in the various RA. As seen in this table, the maximum allowable value of these contaminants is 0.5%, according to EN 12620 [19]. Furthermore, if there is special concern with the final finish of the concrete, this value should not exceed 0.25%. Most of the RA analysed in this investigation have values higher than the limits mentioned (of up to 1.7%). Rodrigues et al. [24] performed a chemical analysis of eight types of RA from CDW and also obtained high amounts of light contaminants (between 0.3% and 17.1%).

Table 6. Results of the chemical characterization of the recycled aggregates.

Chemical Characterization	CRA Valnor	CRA Retria	FRA Ambilei	FRA Vimajas	Maximum limit
Water-soluble chloride salts	<0.010	<0.010	<0.010	0.016	0.010 [1]
Water-soluble sulphates	0.04	0.04	0.11	0.18	0.20 [1]
Acid soluble sulphates	0.2	0.3	0.2	0.8	0.8 [1]
Sulphur content	0.1	0.1	0.1	0.3	1.0 [1]
Lightweight contaminators	1.5	<0.1	1.8	1.7	0.5 [1]
Potential presence of humus	Neg.	Neg.	Neg.	Neg.	Neg.
Water solubility	1.0	1.2	0.5	2.1	10.0 [2]

[1] According to EN 12620 (2008) standard; [2] According to BS EN 1744 standard.

The chemical tests carried out also indicate that RA from Vimajas have a percentage of water-soluble chloride salts higher than the limit imposed. The alkaline salts, namely sodium chloride and potassium chloride, are the ones that mostly contribute to the chlorides present in the aggregates and that most affect concrete [35]. Limiting the amount of chlorides is necessary to minimize the risk of corrosion of the steel rebars in reinforced concrete elements. In addition to that present in the aggregates, it is also important to consider the chloride content of the other materials used in the composition of concrete. According to APEB [36], the chloride content of a concrete is expressed as a percentage of chloride ions per mass of cement, which means that a high chloride content present in the aggregates may not be decisive if a high mass of cement is also used.

It should be noted that the results obtained in the remaining chemical tests performed on the RA are within the upper boundaries imposed, except for the sulphur content of the fine RA from Vimajas, which is equal to the maximum limit. Internal sulphates are a potential risk source for the chemical attack of concrete [37]. Some of the other chemical tests have also shown that RA from Vimajas have a number of harmful elements which lie above those found in the remaining RA, even though they are within the maximum limits. Hence, one of the possible solutions for the use of these RA in concrete is to previously wash them.

2.4. Fresh-State Concrete Properties

In this investigation, it was intended that all concrete mixes had a similar slump, in the range of 125 ± 25 mm, in order to belong to the S3 consistency class. Therefore, prior to the first phase of the experimental campaign, several concrete mixes were produced with the objective of assessing the effective water/cement (w/c) ratio to be used. It should be clarified that the effective w/c ratio only considers the amount of water available for the hydration of cement at the time of mixing of the materials. In other words, when calculating the effective w/c ratio, contrary to what happens with the total w/c ratio, the water that will be absorbed by the aggregates during the concrete production is not considered.

Figure 1 depicts all the values of slump obtained from the Abrams cone test, allowing us to conclude that the workability of the various mixes remained within the range of the S3 consistency class (100 mm to 150 mm). This is considered essential for a valid comparative analysis of all the remaining properties of the mixes.

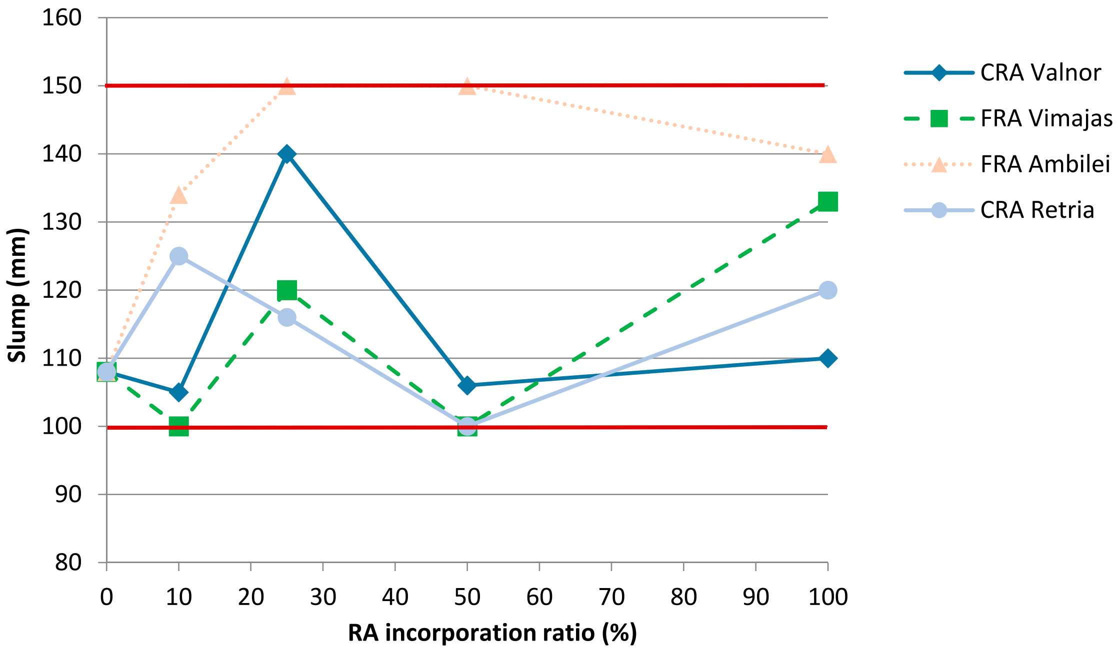

Figure 1. Slump measured using the Abrams cone. Abbreviations: RA, recycled aggregates; CRA, coarse recycled aggregates; FRA, fine recycled aggregates.

Table 7 shows the values of the effective w/c ratio used in the production of the various concrete mixes. For two types of RA (from Valnor and from Ambilei), it was not necessary to increase the effective w/c ratio as the ratio of aggregates replacement increased.

Table 7. Effective water/cement (w/c) ratio of the concrete mixes at different percentages of replacement of NA with RA.

Type of Aggregate (Recycling Plant)	Percentage of Replacement of NA with RA				
	0%	10%	25%	50%	100%
CRA (Valnor)	0.53	0.53	0.53	0.53	0.53
CRA (Retria)	0.53	0.53	0.54	0.54	0.55
FRA (Vimajas)	0.53	0.54	0.56	0.59	0.64
FRA (Ambilei)	0.53	0.53	0.53	0.53	0.53

However, the significant increase in the effective w/c ratio with the increase of fine RA from Vimajas should be highlighted. This is due to the high content of clay of these RA [23]. These fine particles adsorb a high amount of water, resulting in the need of a higher effective w/c ratio in the mixes made with these RA, to maintain the target workability.

The variation of the effective w/c ratio was not identical for all families of RA. Hence, in addition to the differences caused by the composition of the RA, the workability of the various mixes may have also been influenced by the different shape of the RA, as shown by the results of the shape index test. As reported by de Brito and Robles [38], the rougher shape of the RA, compared to that of the NA, may contribute to the variability of the workability observed.

In Table 8, the fresh-state density values determined for the different concrete mixes are shown, as well as the variation of this property in each concrete mix when compared to that of the NAC mix. It is found that, with the use of 100% coarse RA and 100% fine RA, maximum decreases of 7.1% and 6.1% are obtained, respectively.

Table 8. Fresh-state density of the concrete mixes.

Type of Aggregate (Recycling Plant)	Percentage of Aggregate Replacement								
	0%	10%		25%		50%		100%	
	Density (kg/m³)	Density (kg/m³)	Variation (%)	Density (kg/m³)	Variation (%)	Density (kg/m³)	Variation (%)	Density (kg/m³)	Variation (%)
CRA (Valnor)	2361.0	2360.2	0.0	2340.7	−0.9	2289.7	−3.0	2241.0	−5.1
CRA (Retria)	2361.0	2339.0	−0.9	2310.8	−2.1	2269.2	−3.9	2193.1	−7.1
FRA (Vimajas)	2361.0	2339.4	−0.9	2314.1	−2.0	2306.1	−2.3	2216.2	−6.1
FRA (Ambilei)	2361.0	2364.9	0.2	2358.5	−0.1	2342.3	−0.8	2310.4	−2.1

Figure 2 compares the results obtained in this investigation with those established by other authors. The results obtained here are within the scatter of results yielded by the literature.

One other test performed on fresh-state concrete was the determination of its air content, whose percentage should be limited in order to not affect the mechanical strength of concrete. According to the recommendations of ACI (specifications for structural concrete) [39], concrete with a maximum aggregate dimension of 22.4 mm, after compaction, must not have an air content above 4.7% (47 L/m³). Table 9 shows that the air content of the concrete mixes produced with RA reached a maximum of 26.5 L/m³. On the other hand, for NAC an air content of 15 L/m³ was obtained. It is recalled that when the design concrete composition was determined, an air content of 17.4 L/m³ was predicted. According to Lessard et al. [40], a 4% to 5% decrease in the compressive strength of concrete may be expected for each percent (10 L/m³) of air content.

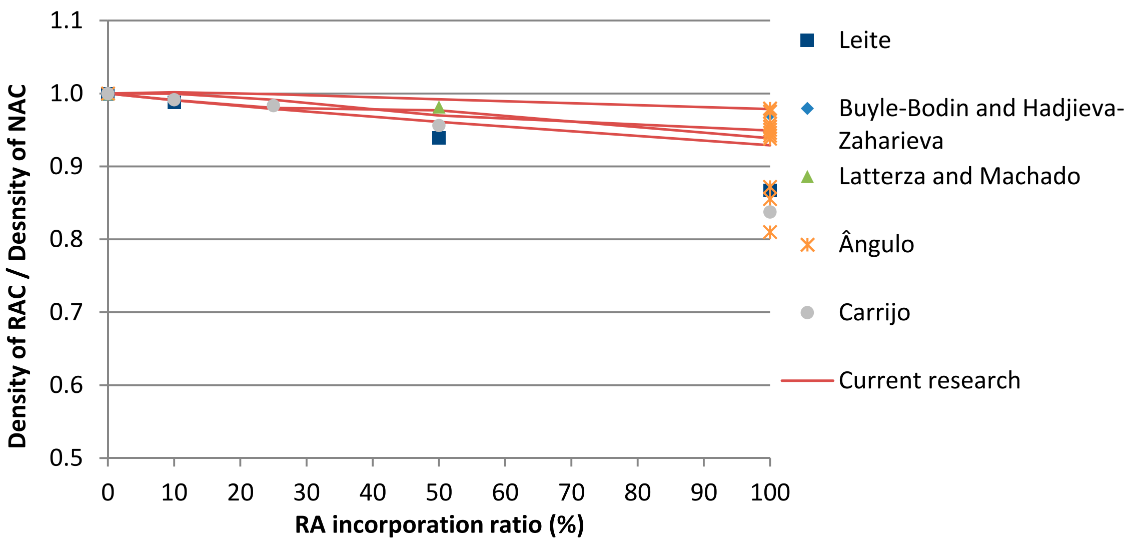

Figure 2. Comparison of the measured fresh-state density of the concrete mixes with the literature, reported by Leite [41], Buyle-Bodin and Hadjieva-Zaharieva [42], Latterza and Machado [43], Ângulo [44], and Carrijo [45].

Table 9. Air content determined in concretes in the fresh-state.

	CRA Valnor		CRA Retria		FRA Vimajas		FRA Ambilei	
	Air Content (L/m³)	Variation (%)	Air Content (L/m³)	Variation (%)	Air Content (L/m³)	Variation (%)	Air Content (L/m³)	Variation (%)
0% RA	15.0	-	15.0	-	15.0	-	15.0	-
10% RA	19.5	30.0	19.0	26.7	20.5	36.7	20.0	33.3
25% RA	20.5	36.7	20.0	33.3	24.5	63.3	22.5	50.0
50% RA	22.5	50.0	22.5	50.0	26.0	73.3	23.5	56.7
100% RA	23.5	56.7	23.0	53.3	26.5	76.7	25.0	66.7

Table 9 shows that the replacement of NA with RA causes an increase in the air content of the mixes. Evangelista and de Brito [46] evaluated the air content in concrete mixes with RCA, and observed an increase from 12 L/m^3 to 17 L/m^3 from the NAC mix to the RAC with 30% fine RA. This result was explained by the higher porosity of the RA, when compared to that of the NA, and by the more angular shape of the RA, which reduces the compactness of concrete. Katz [47] evaluated the air content of concrete made with coarse RCA and obtained a similar conclusion. Juan and Gutiérrez [48] also indicate that the air content of concrete with RA is higher than that of conventional concrete. However, the authors also note that, when using RA pre-saturated with water in the production of concrete, the difference in air content fades. The conclusion was obtained by these authors when testing concrete mixes with coarse RA from CDW.

With the execution of this test, it was concluded that concrete mixes made with fine RA possess a higher air content compared to those made with coarse RA. This result may be justified by the higher porosity of the fine RA.

3. Analysis and Discussion of Results

3.1. Compressive Strength

The compressive strength of concrete is one of the most important properties in the evaluation of the performance of a structure, since it corresponds to the capacity of its elements to withstand stresses without collapsing. The determination of the compressive strength is especially important since it is usually strongly correlated with the majority of the other mechanical properties, as well as with the stiffness, durability and thermal performance of concrete. Hence, the compressive strength allows an overall assessment of the quality of a given concrete mix.

Table 10 shows the average compressive strength values of the concrete mixes at 28 days ($f_{cm,28}$), and the variation of strength values (Δ) relative to the NAC. The measured compressive strength at 28 days of the NAC mix was 47.8 MPa. Thus, it can be concluded that, according to the compressive strength test carried out on cubic specimens, the NAC mix produced belongs to strength class C35/45, which is higher than that expected since this concrete mix was designed for the target strength class C30/37.

Generally, it can be seen that, regardless of whether the replacement is made in the fine or coarse fraction of aggregates, the compressive strength decreases with the increase of RA content. These results stem from the composition of the RA and, in most cases, from the increase of the effective w/c ratio needed with the increase of RA in concrete. However, the results show that the percentages of the decreases in compressive strength vary with several factors, as discussed hereafter.

One of the factors that most influenced the results was the source of the RA. Since these aggregates were collected from different companies, located in different parts of Portugal, their composition greatly varied. This was shown in the analysis made to the composition of the RA. Hence, as expected, the results of concrete with different RA are quite different.

Table 10. Compressive strength at 28 days.

	$f_{cm,28}$ (MPa)	Δ (%)
NAC	47.8 ± 0.4	-
C10C-Valnor	47.7 ± 1.1	−0.2
C25C-Valnor	44.1 ± 4.0	−7.7
C50C-Valnor	43.2 ± 0.1	−9.6
C100C-Valnor	39.3 ± 1.9	−17.9
C10F-Vimajas	47.5 ± 1.5	−0.6
C25F-Vimajas	43.2 ± 1.2	−9.7
C50F-Vimajas	37.6 ± 0.6	−21.4
C100F-Vimajas	27.1 ± 0.3	−43.4
C10F-Ambilei	48.4 ± 1.2	1.2
C25F-Ambilei	43.3 ± 1.4	−9.5
C50F-Ambilei	41.8 ± 0.7	−12.5
C100F-Ambilei	36.4 ± 0.4	−23.9

C10C-Retria	47.1 ± 1.2	−1.6
C25C-Retria	43.1 ± 0.3	−9.9
C50C-Retria	42.3 ± 1.3	−11.6
C100C-Retria	37.7 ± 0.8	−21.2

Abbreviations: C10C-Valnor, concrete with 10% of coarse RA from Valnor; $f_{cm,28}$, average compressive strength values of the concrete mixes at 28 days; Δ, variation of strength values.

With respect to the concrete mixes in which fine recycled aggregates (FRA) were used, a much higher decrease in the compressive strength at 28 days of mixes with the use of FRA from Vimajas (43.4%) was obtained when compared to that yielded by the use of FRA from Ambilei (23.9%), for 100% replacement. The lower compressive strength of concrete mixes with FRA from Vimajas can be attributed to the high increase in the effective w/c ratio of these mixes, due to the presence of clay in the aggregates (Rodrigues et al. [24]). The fine particles of clay coat the RA particles and adsorb part of the mixing water. In addition, they prevent the proper bonding between the RA and the cement paste, thus leading to a concrete with lower strength.

The scanning electron microscope (SEM) images show that these phenomena caused a porosity increase in these mixes, which resulted in a decrease of their compressive strength [10]. For instance, Figures 3–6 show that mixes made with FRA from Vimajas have micro and macro porosities that are higher than that of concretes made with FRA from Ambilei. This was visible both in concrete mixes with 50% (Figures 3 and 4) and 100% (Figures 5 and 6) FRA.

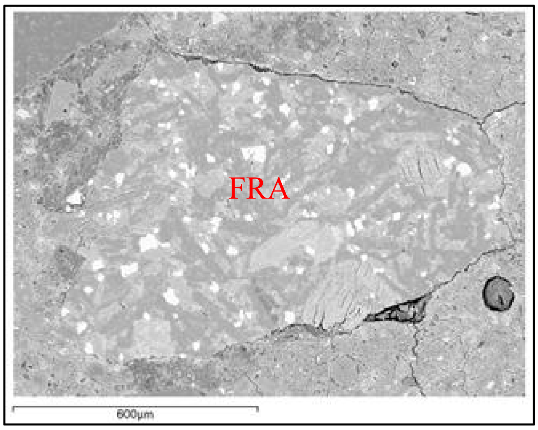

Figure 3. Comparison of the macro-porosity of concrete mixes with 50% FRA: detail of the interfacial transition zone of a FRA of a concrete mix made with 50% Vimajas's FRA. Bravo, M.; Santos Silva, A.; de Brito, J. and Evangelista, L. Microstructure of Concrete with Aggregates from Construction and Demolition Waste Recycling Plants, *Microsc. Microanal.* 22, 149–167, reproduced with permission [10].

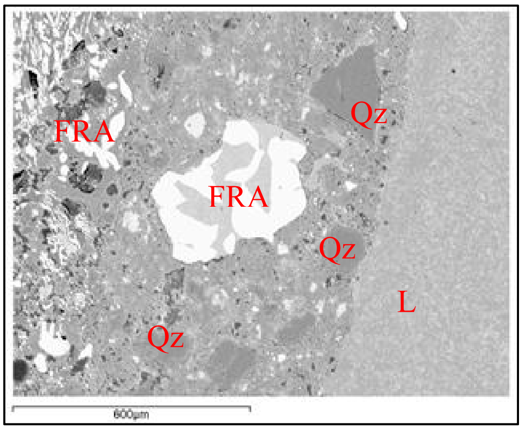

Figure 4. Comparison of the macro-porosity of concrete mixes with 50% FRA**:** detail of the interfacial transition zone of a FRA of a concrete mix made with 50% Ambilei's FRA (L—limestone, Qz—quartz). Bravo, M.; Santos Silva, A.; de Brito, J.; Evangelista, L. Microstructure of Concrete with Aggregates

from Construction and Demolition Waste Recycling Plants, *Microsc. Microanal.* 22, 149–167, reproduced with permission [10].

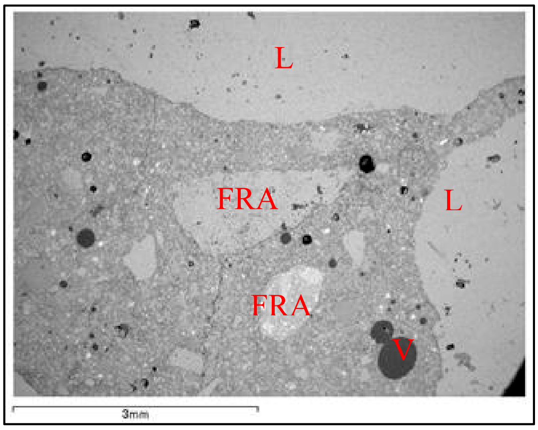

Figure 5. Comparison of the macro-porosity of concrete mixes with 100% FRA: detail of the interfacial transition zone of a FRA of a concrete mix made with 100% Vimajas's FRA (L—limestone, V—voids). Bravo, M.; Santos Silva, A.; de Brito, J.; Evangelista, L., Microstructure of Concrete with Aggregates from Construction and Demolition Waste Recycling Plants, *Microsc. Microanal.* 22, 149–167, reproduced with permission [10].

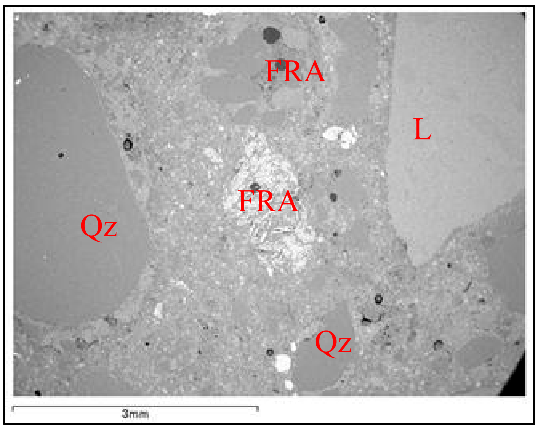

Figure 6. Comparison of the macro-porosity of concrete mixes with 100% FRA**:** detail of the interfacial transition zone of a FRA of a concrete mix made with 100% Ambilei's FRA (L—limestone, Qz—quartz). Bravo, M.; Santos Silva, A.; de Brito, J.; Evangelista, L. Microstructure of Concrete with Aggregates from Construction and Demolition Waste Recycling Plants, *Microscopy and Microanalysis*, 22, 149–167, reproduced with permission [10].

The size of the RA used was another factor that influenced the results obtained. The decrease in compressive strength of the concrete mixes with FRA was higher than that of their counterparts with CRA. Table 3 shows that CRA have a lower amount of "concrete, mortar and natural stone" and a higher amount of "masonry–clayey materials" in their composition, when compared to FRA. Therefore, CRA were expected to result in a higher decrease in compressive strength than FRA. However, the apparently contradicting results obtained are justified by the amount of clay that FRA tend to possess. As mentioned earlier, the presence of clay resulted in a need to increase the effective w/c ratio used in the composition of the mixes with these FRA, in order to obtain a similar workability in all mixes. This increase in the effective w/c ratio resulted in a decrease in compressive strength.

Silva et al. [49] gathered the results available in 65 publications on the compressive strength of concrete mixes made with RA from CDW. Compressive strength test results of 787 concrete mixes with FRA and CRA from different types and origins were analysed.

Figure 7 shows that, as found in this investigation, concrete mixes with CRA present, on average, a compressive strength higher than those with FRA. The straight lines in Figure 7 define the upper and lower limits of the results analysed for a 95% confidence interval. Hence, it is interesting to compare the slopes (m) of the straight lines of the study made by Silva et al. [49] with those obtained in our investigation. The results from CRA (m = −0.0015) indicate that the RA used in our study are of medium quality, when compared to the CRA evaluated in the study of Silva et al. [49]. Conversely, the slope of the line defining the linear regression of the evolution of the compressive strength with the increase of FRA (m = −0.0028) proves that the FRA used in our work are of poor quality. This is due to the obtained slope being closer to that of the lower limit line defined in the Silva et al. study [49], for a 95% confidence interval.

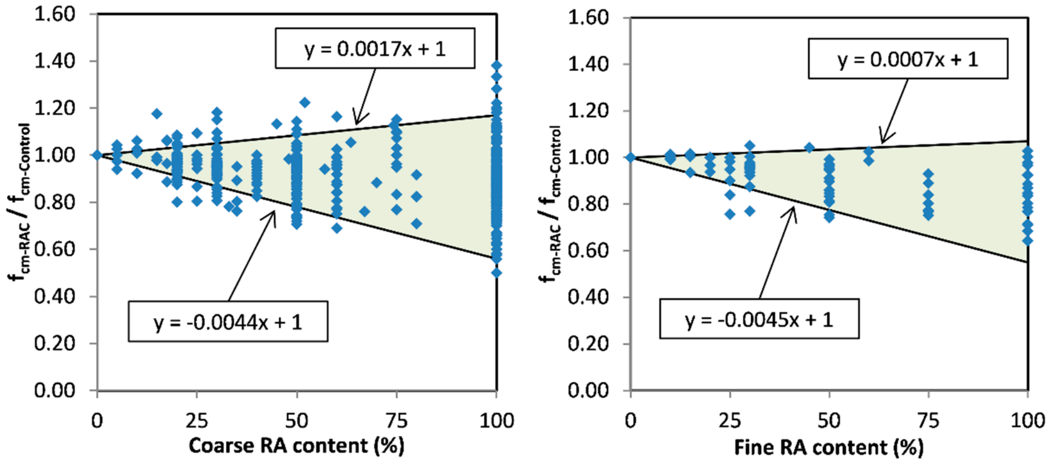

Figure 7. Variation of the compressive strength at 28 days in concrete mixes with FRA or CRA from different studies. Reproduced with permission from http://www.tandfonline.com/doi/abs/10.1080/19648189.2014.974831 [49]. Abbreviations: $f_{cm\text{-}RAC}$, average compressive strength values of the concrete mixes with recycled aggregates; $f_{cm\text{-}Control}$, average compressive strength values of the concrete mixes with natural aggregates.

3.2. *Thermal Conductivity*

The thermal conductivity is a specific characteristic of each material, and strongly depends on the temperature of the material. Eurocode 2 proposes two equations that estimate the thermal conductivity (λ), as a function of temperature (θ), for standard density concrete. They define an upper and lower limit of λ (Equations (1) and (2), respectively).

$$\lambda = 2 - 0.2451 \times (\theta/100) + 0.0107 \times (\theta/100)^2\ (\mathrm{W/m.K}),\ \text{for } 20\ ^\circ\mathrm{C} \le \theta < 1200\ ^\circ\mathrm{C} \quad (1)$$

$$\lambda = 1.36 - 0.136 \times (\theta/100) + 0.0057 \times (\theta/100)^2\ (\mathrm{W/m.K}),\ \text{for } 20\ ^\circ\mathrm{C} \le \theta < 1200\ ^\circ\mathrm{C} \quad (2)$$

Hence, according to Eurocode 2, the λ of a standard density concrete, for θ = 20 °C, varies between λ = 1.33 W/m.K and λ =1.95 W/m.K.

According to Gambale et al. [50], the λ of concrete mixes varies between λ = 1.4 W/m.K and λ = 3.6 W/m.K. In this investigation, a value of λ = 2.08 W/m.K was obtained for NAC. This value is similar to the upper limit computed by means of the Eurocode 2 equation.

Table 11 and Figure 8 show the results yielded by the various mixes with respect to this property. As was mentioned, each result presented in Table 11 was obtained by averaging at least four results. There, it is found that the replacement of NA with RA reduces the λ-values of the concrete mixes, therefore improving their thermal and energetic performance for use in building applications where insulation is important. This improvement is quite significant in concrete mixes in which 100% of the coarse and fine NA are replaced, reaching decreases in λ of 42% and 23%, respectively. The extent of this decrease varies significantly depending on the constitution of the RA used. The different types of RA have quite varied compositions, with different contents of concrete, ceramics, glass, wood, among other materials. Considering that these wastes have different thermal conductivity, concrete mixes with different thermal behaviour were expected.

Table 11. Variation of the thermal conductibility (λ).

	CRA - Valnor		FRA -Vimajas		FRA - Ambilei		CRA - Retria	
	λ (W/m.K)	Variation (%)	λ (W/m.K)	Variation (%)	λ (W/m.K)	Variation (%)	λ (W/m.K)	Variation (%)
0% of RA	2.08 ± 0.02	-	2.08 ± 0.02	-	2.08 ± 0.02	-	2.08 ± 0.02	-
10% of RA	2.10 ± 0.00	1.2	2.06 ± 0.02	−0.9	2.07 ± 0.01	−0.4	2.02 ± 0.18	−2.6
25% of RA	2.05 ± 0.00	−1.2	1.94 ± 0.02	−6.8	2.02 ± 0.03	−2.8	2.01 ± 0.00	−3.3
50% of RA	1.96 ± 0.00	−5.5	1.68 ± 0.00	−18.9	1.90 ± 0.03	−8.3	1.82 ± 0.01	−12.2
100% of RA	1.72 ± 0.00	−16.7	1.21 ± 0.02	−41.9	1.63 ± 0.00	−21.7	1.60 ± 0.14	−22.8

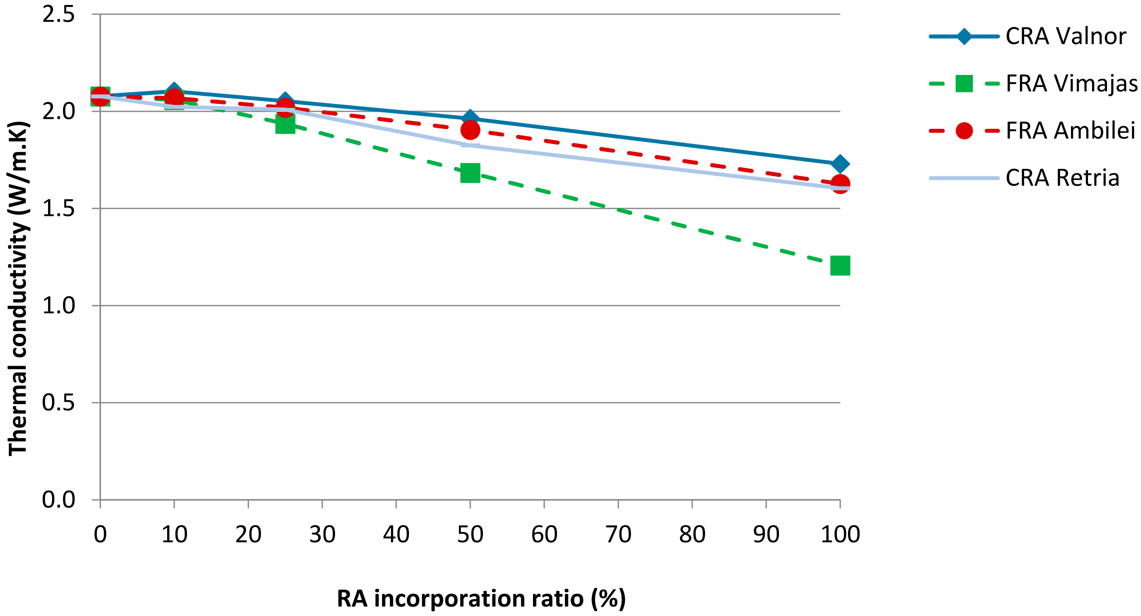

Figure 8. Thermal conductivity of the concrete mixes studied.

Table 11 also shows that the concrete mixes with FRA from Vimajas displayed the best results, i.e., the lowest values of λ, obtaining a decrease of 42%, relatively to the NAC. Díez Ramírez et al. [12] evaluated the thermal performance of concrete mixes made with CRA consisting mainly of natural stone and mortar in equal proportions. The authors obtained decreases in λ-values of up to 9% with the integral replacement of the coarse NA with CRA. The difference between these values and the results obtained in our study are probably due to the significant variation of the composition of the RA used in the two investigations.

Figure 9 shows the values of R^2 obtained in the linear regressions (black lines shown in the Figure) made to the variation of the thermal conductivity with the increase of CRA and FRA in the concrete mixes ($R^2 = 0.97$ in both cases). The high values of R^2 obtained show that the reduction of λ with the replacement of NA with RA is linear.

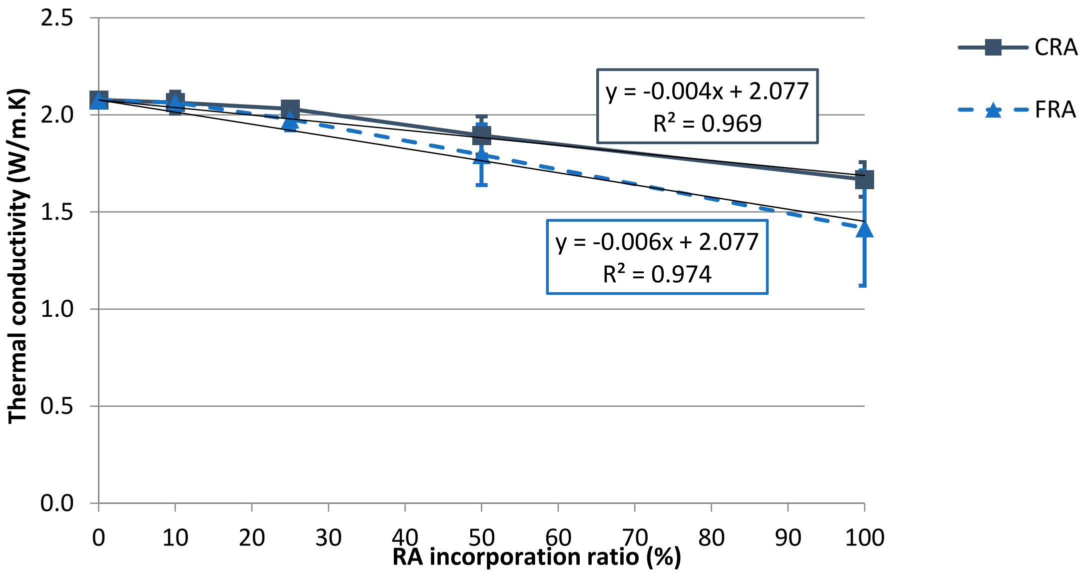

Figure 9. Variation of the thermal conductivity with the recycled aggregate replacement percentage.

The thermal conductivity of concrete depends on several parameters: density, porosity, temperature, degree of hydration, water content and type of aggregates. Several works suggest that the thermal conductivity is directly proportional to the material's density [51]. Figure 10 shows the correlation between these two properties for the concrete mixes produced. The R^2 value obtained for the linear regression ($R^2 = 0.70$) shows that these two properties have a significant linear correlation. This comparative analysis allows concluding that the λ-values of concrete mixes with RA increases with increasing density. Zhu et al. [15] obtained a similar conclusion when evaluating the thermal conductivity of concrete mixes with RA (fine and coarse). These authors justify the results with the porosity increase stemming from rising RA contents in the concrete mixes.

ACI 213R-03 [52] recommends an empirical equation (Equation (3)) that allows obtaining λ from the value of dry density (d) for lightweight concrete. Considering that the density of concrete with recycled aggregates, depending on the nature of the RA, can be approximated to the density of lightweight concrete, the exponential expression defined by ACI 213R-03 [52] is tested herein to evaluate whether it can be used in RAC.

$$\lambda = 0.0864e^{0.00125d} \tag{3}$$

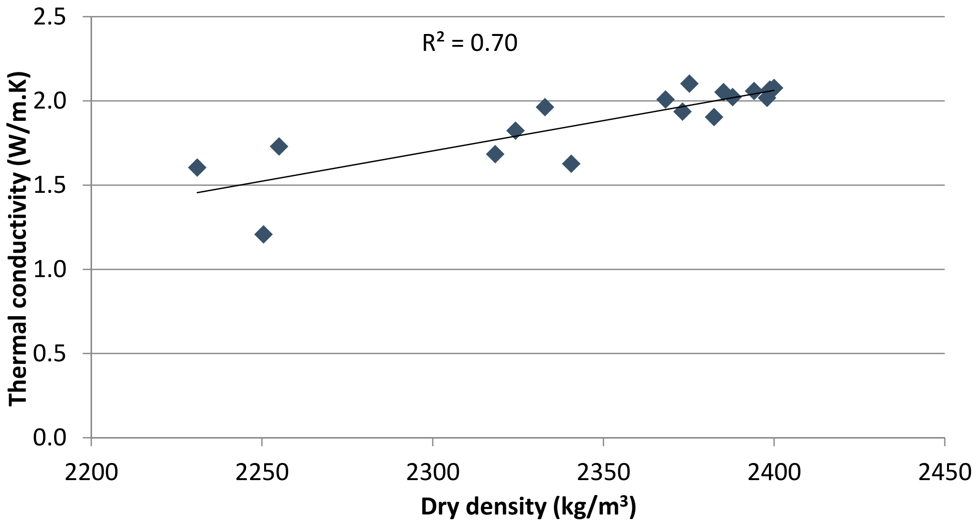

Figure 10. Variation of the thermal conductivity with the dry density.

The values obtained in our study and represented in Figure 11 do not seem to fit well with the ACI 213R-03 [52] proposed equation, displaying an R^2 value of 0.57.

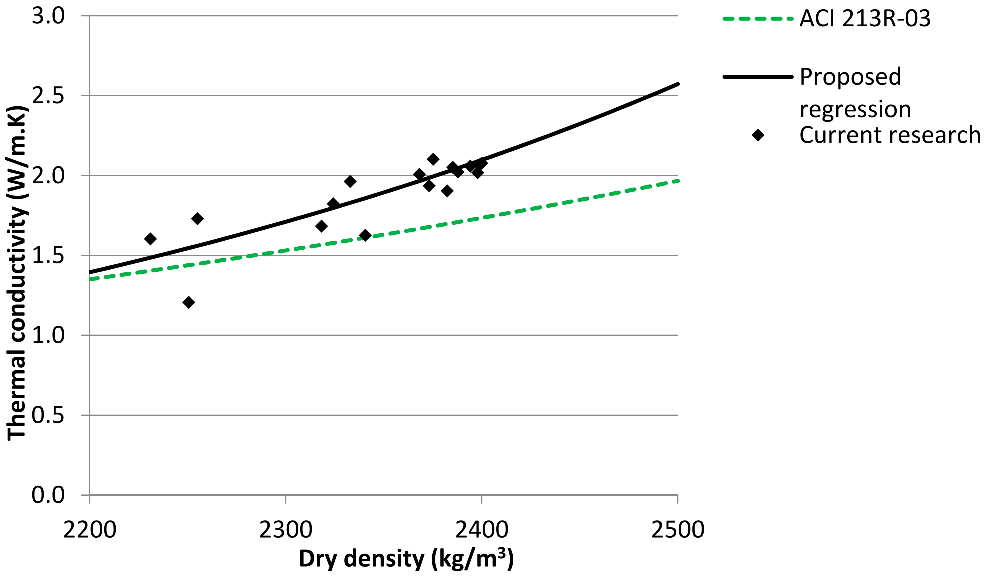

Figure 11. Variation of the thermal conductivity with the dry density—proposal of regression. ACl 213R-03 was reported in the literature [52].

In order to better adapt the model established for lightweight concrete to the results obtained for RAC, a non-linear regression was performed. For this purpose, a model similar to that presented by ACI 213R-03 [52] was used, in which the thermal conductivity has an exponential relationship with the dry concrete mass ($\lambda = ae^{bd}$). The nonlinear regression performed has a R^2 = 0.71 and corresponds to Equation (4):

$$\lambda = 0.0157e^{0.00204d}. \quad (4)$$

The other parameter that affects the thermal conductivity of concrete is porosity. In order to confirm this, the correlation between thermal conductivity and air content determined for fresh concrete was evaluated. Figure 12 shows that a relatively weak linear regression between these two properties is obtained (R^2 = 0.57).

In turn, Figure 13 shows, as reported by several authors, that there is a reasonable linear association between the thermal conductivity and the amount of water present in the concrete mixes (R^2 = 0.60). These results are in agreement with the observations made by Zhu et al. [15]. These authors also observed a moderate linear relation between these two properties, concluding that, compared with other factors, the influence of the effective w/c ratio on thermal conductivity is not significant.

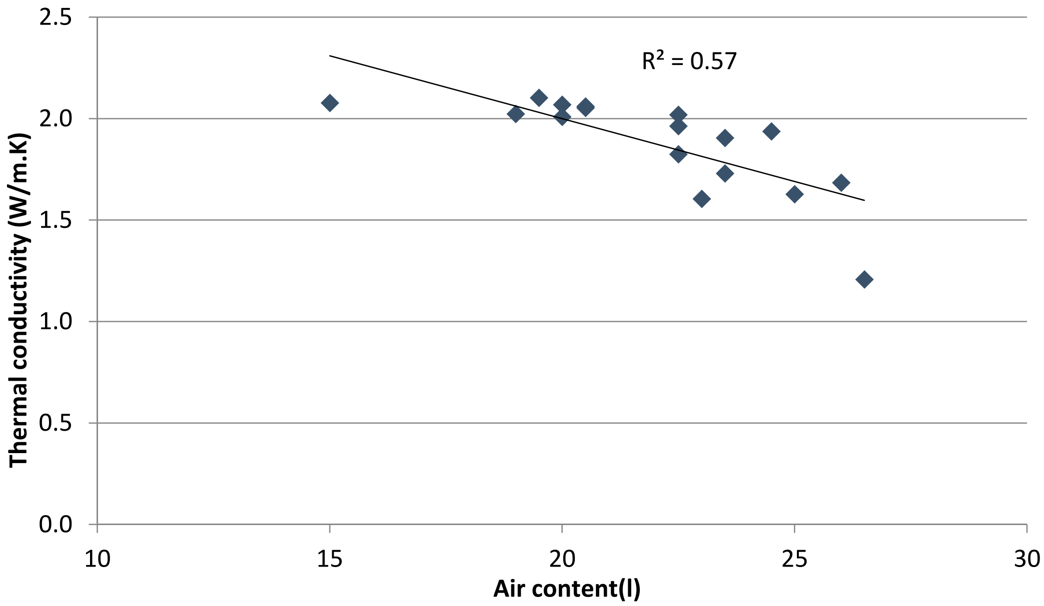

Figure 12. Variation of the thermal conductivity with the air content.

Figure 14 shows that there is a clearly linear relationship between the thermal conductivity and the compressive strength at 28 days, as evidenced by the high value of $R^2 = 0.94$. The strong correlation that exists between these two properties is justified by the fact that they are influenced by the same factors. As previously stated, the nature of the various RA and the quality of the interfacial transition zone (ITZ) between the RA and the cement paste were the factors that most influenced the compressive strength. On the other hand, the thermal conductivity is also strongly influenced by the above mentioned factors, since the composition of the RA and the ITZ between the aggregates and the cement paste are the main aspects that influence the porosity of concrete, which, in turn, is a fundamental parameter for thermal conductivity [15].

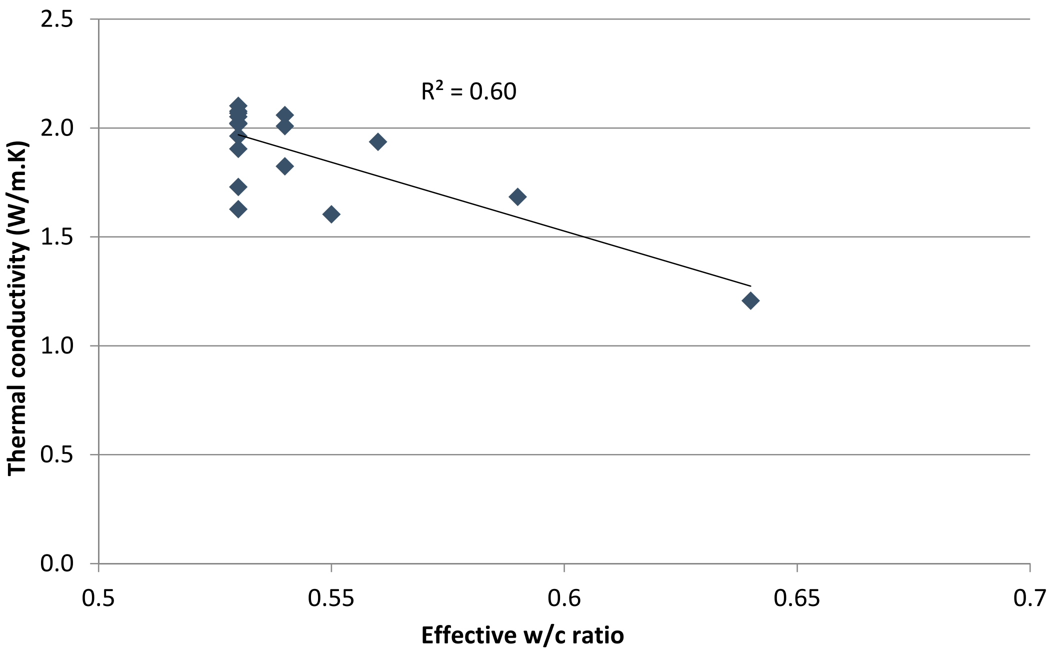

Figure 13. Variation of the thermal conductivity with the effective w/c ratio.

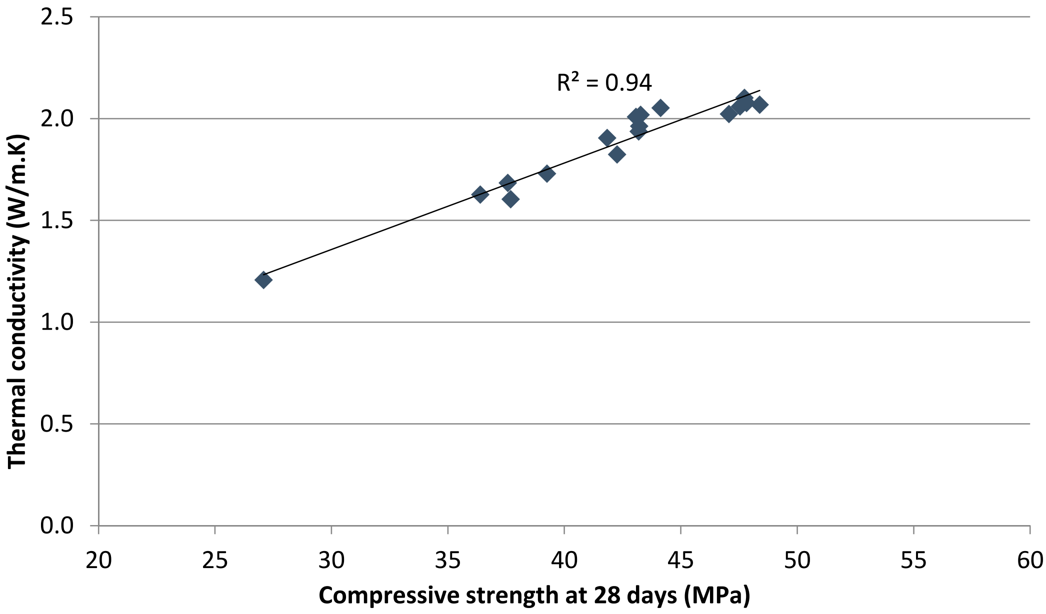

Figure 14. Variation of the thermal conductivity with the compressive strength.

4. Conclusions

This research intended to analyse the thermal behaviour of concrete mixes with recycled aggregates (RA) from four construction and demolition waste (CDW) plants in Portugal.

With respect to the thermal conductivity test, a value of 2.08 W/m.K was obtained for the reference concrete (RC), made with natural aggregates only. According to Eurocode 2, the thermal conductivity of a standard density concrete, at a temperature of 20 °C, has a value between 1.33 and 1.95 W/m.K. Hence, it was concluded that the value obtained in the present study for the RC mix is similar to the maximum limit suggested by the Eurocode 2.

In this investigation, the thermal conductivity coefficients of the concrete mixes with RA from CDW were also evaluated, and it was concluded that the use of RA causes a decrease of the thermal conductivity coefficients of the concrete mixes. This decrease was quite significant (between 17% and 42%) when all the NA were replaced with fine or coarse RA. As in the analysis performed regarding the compressive strength of the concrete mixes, a high variation of the thermal conductivity with the RA used in concrete production was also observed. The different types of RA have quite different compositions, with the incorporation of distinct percentages of concrete, ceramics, glass, wood, and other materials. Hence, considering that these wastes have different thermal conductivity, the concrete mixes were expected to have different thermal behaviour. The concrete mixes produced with fine RA from Vimajas displayed the best results, with a 42% decrease in their thermal conductivity coefficients when compared to the RC. The lower thermal conductivity of concrete with RA is due to the lower density and thermal conductivity of these aggregates. On the other hand, the change of the thermal behaviour it is also due to the higher porosity of these RA and of the corresponding concrete itself. The results obtained in the compressive strength test carried out at 28 days also confirm that the different composition of the RA used strongly influences the strength and durability of the concrete mixes produced with these aggregates.

The use of RA from Vimajas resulted in a much higher reduction of compressive strength at 28 days (43.4%), when compared to the RC, than that observed with the use of RA from Ambilei (23.9%). This variation, together with the analyses carried out through Scanning Electron Microscopy, shows that the concrete mixes with RA from Vimajas have the highest porosity.

Finally, it was concluded that the choice of the size of the RA used does not seem to significantly influence the quality of the concrete mixes regarding their thermal performance.

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Author Contributions: J.d.B., L.E. and M.B. conceived and designed the experiments; M.B. performed the experiments; M.B. and J.d.B. analyzed the data; L.E. contributed analysis tools; M.B. wrote the paper.

Conflicts of Interest: The authors declare no conflict of interest. The founding sponsors had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, and in the decision to publish the results.

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