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Thermal Performance of Concrete with Recycled Concrete Powder as Partial Cement Replacement and Recycled CDW Aggregate

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Abstract: This novel study was triggered by a lack in the international literature of the simultaneous use of ground recycled concrete (GRC) as a cement replacement and mixed recycled aggregate as part of the granular skeleton in recycled concrete. It explores the thermal behaviour of concrete mixes bearing 10 wt% or 25 wt% GRC as a cement replacement and 25 wt% or 50 wt% mixed recycled aggregate (MRA) sourced from construction and demolition waste (CDW). The experimental programme conducted assessed concrete's dry density, open porosity, electrical and thermal conductivity and specific heat capacity. The findings showed that the use of 10% and 25% GRC, in conjunction with 50% MRA, reduced thermal conductivity by 7.9% to 11.8% and raised specific heat capacity by 6.0% to 9.1% relative to concrete with 100% natural aggregate (NA). A cross-property analysis revealed that improved thermal performance was linearly related to lower density and higher porosity. The results also support the conclusion that these new recycled aggregate concrete mixes are more energy-efficient construction materials than conventional concrete.

Keywords: recycled aggregate; ground recycled concrete; recycled materials concrete; construction and demolition waste; thermal properties

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1. Introduction

Concrete production is responsible for serious environmental impacts worldwide. These impacts can be divided into two main problems: use of natural aggregates, and Portland cement production, which leads to an average consumption of 125 kW/h of electricity and results in an emission to the atmosphere of 800 kg of CO_2. Furthermore, the latter also leads to the consumption of a vast number of natural resources [1,2].

In addition to these two problems, the construction industry is also faced with the challenge of adequately disposing the large amount of waste that the industry itself generates. It is recalled that construction and demolition waste (CDW) represents more than 30% of solid waste generated among all economic sectors [3].

It is essential to find, on the one hand, solutions for the use of these CDW, in addition to their use as recycled aggregates (RA), and, on the other hand, sustainable binders that can replace cement. Hence, a hypothesis to solve these environmental problems is the use, in concrete, of binders formed by these CDW.

The use of CDW in concrete as RA has already been proven to be environmentally friendly and cost-efficient [4,5]. However, its evaluation as a substitute material for cement has just begun.

Some studies started by analysing the performance of concrete with different types of ceramic material powders as the replacement of cement. Subaşi et al. [6] found that the use of waste ceramic powders in self-consolidating concrete causes a slight increase in viscosity and a decrease in the mechanical performance of concrete. For example, the use of 20% ceramic powder resulted in a 15% reduction in compressive strength at 28 days.

Ge et al. [7], Kannan et al. [8] and Vejmelková et al. [9] also investigated the durability of concrete with the use of ceramic powders as binders instead of cement, having studied maximum replacement ratios of 30%, 40% and 60%, respectively. These investigations came to the conclusion that the use of ceramic powders can maintain or even slightly improve the durability and shrinkage of the concrete. Kannan et al. [8] states that ceramic powders will provide a relatively high silica environment that might be able to convert calcium hydroxide (CH) into strong calcium silicate hydrate C-S-H. However, it is important to highlight that in all these studies, the ceramic powder used does not have precisely the same particle size of the replaced cement. Therefore, the finer particle size distribution of the ceramic powder, compared to that of the cement, may have caused a greater compactness of concrete and may be the cause of the improved durability of concrete with ceramic powder.

In turn, Cantero et al. [10] analysed the use in concrete of binder and aggregates from CDW. To this end, these authors produced concrete mixes with RA from CDW (0%, 25% and 50%) and recycled cement with CDW (0% and 25%) mixed with Portland cement. The authors found maximum decreases in compressive strength at 28 days of 10% and 20%, when using, respectively, recycled cement alone and recycled cement and RA simultaneously.

Liu et al. [11] evaluated the use of hybrid recycled powder from demolished concrete solids and clay bricks as supplement for cement. This investigation also obtained a decrease in the mechanical performance of these cementitious materials. These authors state that the use of this recycled binder affects the microstructure of the cement paste, changing the size and morphology of C-S-H gels. The nanoindentation test showed that a weaker interfacial transition zone (ITZ) was produced to form the cement paste-recycled particle interface.

It is agreed that the incorporation of CDW powder as replacement of cement in concrete results in worse mechanical properties. However, this decrease appears to vary widely with the nature of the CDW used. Nevertheless, as mentioned, the results obtained in the existing investigations to date on the durability performance of these concrete mixes seem to be even more variable.

To date, there are nearly no studies that analyse the thermal behaviour of concrete with recycled cement from CDW. Only Vejmelková et al. [9] studied the thermal properties of high-performance concrete with ceramic powders, having analysed the thermal conductivity and specific heat capacity. According to the authors, thermal conductivity decreased from 1.69 $Wm^{-1}.K^{-1}$ (reference concrete) to 1.41 $Wm^{-1}.K^{-1}$ (concrete with 60% ceramic powder), due to an increase in open porosity from 11.2% to 15.5%. Additionally, with the replacement of cement, the specific heat capacity increased by about 13%.

Several studies have been published on the thermal performance of concrete containing RA processed from CDW. Bravo et al. [12] evaluated the thermal behaviour of concrete with RA from CDW. The authors produced mixes with 0%, 10%, 25%, 50% and 100% of RA from four different recycling plants where for two mixes the authors only studied coarse RA and two mixes with only fine RA. It should be noted that all mixes were produced with the same workability (100 mm to 150 mm). The authors concluded that the total replacement of fine and coarse aggregates decreased thermal conductivity, respectively, between 22% and 42% and between 17% and 23%. The lower thermal conductivity of concrete with RA was explained by the lower density and thermal conductivity and the higher porosity of these aggregates. Hence, the authors concluded that the effect of using RA is quite variable depending on their nature.

Despite this variation, several other investigations [13–17] also point to decreases in thermal conductivity higher than 20% in mixes with the replacement of natural aggregates with RA from concrete or glass.

This work aims at analysing the thermal behaviour of concrete with recycled concrete powder, as partial cement replacement and RA from CDW, in order to fill the complete lack of information in the literature on this subject. This study started with the collection of CDW from a recycling plant, to be used as RA, and with the production of concrete powder, to be used instead of cement as a binder. In order to carry out this investigation, concrete was produced with RA from CDW (0% and 50%) and recycled cement with recycled concrete powder (0%, 10% and 25%) mixed with Portland cement. The analysis of the thermal behaviour of concrete was carried out through thermal conductivity and specific heat capacity tests, as well as by confronting these properties with the air content, the compressive strength, the open porosity and the electrical resistivity of these mixes. The joint analysis of these concrete properties and the physical and chemical properties of recycled concrete powder allowed a detailed analysis and understanding of the thermal performance of these mixes. The main innovation of this investigation is the analysis of the thermal behaviour of concrete with recycled concrete powder as partial cement replacement, which, as mentioned above, is totally innovative. Furthermore, the present study also evaluates the thermal behaviour of concrete that simultaneously contains recycled cement and recycled aggregates from CDW.

2. Materials and Methods

2.1. Materials

2.1.1. Binders

The three binders used, all European standard EN 197-1-compliant (Table 1), were: a type 1 42.5 R (CEM I 42.5 R) ordinary Portland cement (OPC); a blend of 90% OPC and 10% ground recycled concrete (GRC), labelled RB_{10}; and a blend of 75% OPC and 25% GRC, labelled RB_{25}.

Table 1. Fresh properties in binders.

Property		OPC	RB_{10}	RB_{25}	EN 197-1 [1]
Setting time (min)	**Initial**	84	90	91	≥60
	Final	136	138	141	-
Water content (g)		143	144	147	-
Normal consistency (mm)		36	35	35	34 ± 2
28 d compressive strength (MPa)		67.5 ± 1.0	62.6 ± 1.0	51.39 ± 2.2	≥42.5

[1] Values referred to strength class 42.5 R.

The GRC was obtained by crushing and grinding (to a maximum size of 147 µm) laboratory-prepared concrete specimens, batched as per the Faury method [18]. The composition and fresh and hardened 28-day characteristics of that concrete mix are given in Table 2.

Table 2. Characteristics of the source concrete.

Parameter	Value	Property	Value
Cement type	CEM II/A-L 42.5 R	Slump class [2]	S3
Cement content	300 kg/m^3	Compressive strength [3]	39.8 MPa
w/c$_{eff}$ [1]	0.55	Splitting tensile strength [3]	2.75 MPa
Coarse aggregate	1020 kg/m^3 (crushed limestone)	Modulus of elasticity [3]	38.9 GPa
Fine aggregate	910 kg/m^3 (natural river sand)		

[1] w/c$_{eff}$: effective water cement ratio; [2] as per European standard EN 206-1 [19]; [3] 28 days.

Further to the X-ray fluorescence (XRF)-determined chemical composition of the GRC and OPC shown in Figure 1a, the major oxides were SiO_2 (46.10 wt%) and CaO (40.0 wt%). The figure also presents graphically the minimum and maximum ground concrete replacement ratios used in earlier studies [20–26] on pastes, mortars and concrete.

The large, irregularly shaped particles visible in the micrograph in Figure 1b were identified as aggregate with bound mortar, and the small clusters with a rough surface as the paste. GRC's density was 2.54 g/cm^3, a value lower than 3.11 g/cm^3 observed in OPC.

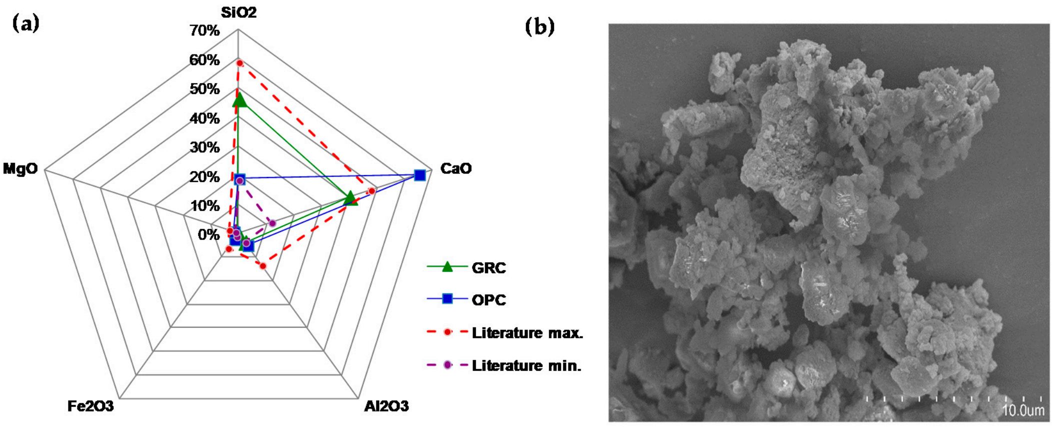

Figure 1. (**a**) Chemical composition of ground recycled concrete (GRC) and ordinary Portland cement (OPC); and (**b**) GRC morphology.

2.1.2. Aggregates

The crushed limestone coarse natural aggregate used was graded in two particle sizes, 4 mm to 12 mm (NG-M) and 12 mm to 22 mm (NG-G). The fines consisted of two siliceous river sands, graded to 0 mm to 2 mm (NS-F) and 2 mm to 4 mm (NS-C).

The mixed recycled aggregates (MRA) supplied by a CDW recycling plant in Lisbon, Portugal, were sieved and classified at the laboratory, where sizes <4 mm and >22 mm were rejected. The composition of the coarse (4 mm to 22 mm) MRA aggregate used, complying with European standard EN 933-11 [27], is given in Table 3. On the grounds of those data and Spain's structural concrete code (EHE-08) [28], the MRA is designated a mixed recycled aggregate for its R_{cu} (R_{cu} = R + Ru) content was ≤95 wt% and its Rb content >5 wt%. It would also be classified under that category in the Agrela et al. [29] proposal, with R_{cu} >70 wt% and Rb <20 wt%.

Table 3. Composition of the source concrete.

Constituent	Label	Content (wt%)
Concrete and mortar	Rc	47.1
Natural stone	Ru	25.2
Clay materials	Rb	22.6
Bituminous materials	Ra	0.2
Glass	Rg	1.7
Floating particles	FL	1
Gypsum	X1	1.8
Metals	X2	0.4

The physical and mechanical properties of the aggregates given in Table 4 show that the MRA was less dense and less abrasion-resistant than the NA (NC-M and NC-G). This was attributed to the higher water absorption of the bound mortar and fired clay materials comprising the MRA. The Los Angeles coefficient (LA), a measure of abrasion fragility, was higher in the MRA (LA = 46 wt%) than in the NA

(LA = 26 wt% to 28 wt%), due to the greater hardness of NA relative to the MRA components such as concrete, brick and tile. The MRA also exhibited a higher flakiness index (FA), 20 wt%, than that of the NA, 13 wt%, likewise attributable to its components, particularly brick and tile, which are flakier than NA.

Table 4. Physical and mechanical properties of aggregates.

Property	NS-F	NS-C	NC-M	NC-G	MRA	EHE 08
Dry density (kg/m^3) [30]	2581	2583	2600	2620	2069	-
SSD [1] density (kg/m^3) [30]	2601	2609	2630	2670	2256	-
24 h water absorption (wt%) [30]	0.4	0.5	1.3	1.3	9.1	≤5
10 min water absorption (wt%) [31]	0.2	0.3	0.5	0.6	8.1	-
Los Angeles coefficient (wt%) [32]	-	-	28	26	46	≤40
Flakiness index (wt%) [33].	-	-	13	16	20	<35

[1] SSD: saturated surface dry.

2.2. Testing and methodology

Table 5 lists the fresh state and 28-day properties of the concrete mixes analysed and the standards followed to determine them. All the mixes were batched with the same volume to ensure non-interference by parameters irrelevant to the study. The specimens were prepared and cured as per European standard EN 12390-2 [34]. After moulding, performed with particular care to minimise pouring and consolidation times, the specimens were wrapped in plastic and stored for 24 h. The demoulded specimens were subsequently stored in a humidity chamber at 20 ± 2 °C and 95 ± 5% humidity until tested.

Thermal testing was conducted on an Applied Precision Ltd. ISOMET 2114 analyser. Two 100 × 100 × 500 mm prismatic specimens of each mix cured 28 days in a dry chamber (20 ± 2 °C, 50% RH) were analysed in these tests, taking at least three readings per sample.

Table 5. Properties of the concrete mixes analysed.

Parameter Tested	Standard	Specimen Dimensions
	Fresh properties	
Slump	EN 12350:2 [35]	-
Fresh density	EN 12350-6 [36]	
Air content	EN 12350-7 [37]	
	Mechanical properties	
Compressive strength	EN 12390-3 [38]	150 mm Ø × 300 mm
Tensile strength		
	Physical properties	
Open porosity	UNE 83,980 [39]	100 × 100 × 100 mm
Dry density		
Electrical resistivity	UNE 83988-2 [40]	100 mm Ø × 200 mm
	Thermal properties	
Thermal conductivity	ISOMET 2114 [41]	100 × 100 × 500 mm
Volume heat capacity		

2.3. Concrete Design

The six concrete mixes batched for the tests were divided into two groups: mixes containing 100% NA and GRC as OPC replacement at ratios of 0% (labelled NAC), 10% (labelled N10/0) or 25% GRC (labelled N25/0); and mixes with 50% MRA and GRC as an OPC replacement at ratios of 0% (labelled R0/50), 10% GRC (labelled R10/50) or 25% (labelled R25/50). The mixes with 100% NA were designed to study the effect of GRC on conventional concrete prepared with NA, and those with 50% to determine the joint effect of the two recycled materials. No plasticizers were used in any of the mixes.

All the mixes were batched as set out in European standard EN 206-1 [19] to durability class X2 and strength class C25/30, although using 300 kg/m^3 of binder (OPC + GRC), slightly more than the standard minimum of 280 kg/m^3 for that exposure class. All were also prepared for a target workability of S2, as defined in EN-206-1 [19], equivalent to a 70 ± 20 mm slump [32].

The particle size distribution of the (fine + coarse) aggregate, irrespective of whether it was natural or recycled, fit the theoretical curve defined by Faury [18] for a maximum size of 22 mm. The batching for the six materials used in the study is given in Table 6. The total amount of water used in each mix was defined as the effective water plus the water needed to offset the amount absorbed by aggregate when soaked for 10 min (approximately the mixing time) [42]. All the aggregates were used moist, subtracting the water required from the total in the mix.

Table 6. Concrete mix design.

Component	Amount (kg/m^3)					
	NAC	**N10/0**	**N25/0**	**R0/50**	**R10/50**	**R25/50**
Cement	300.0	270.0	225.0	300.0	270.0	225.0
GRC	-	30.0	75.0	-	30.0	75.0
Total water	171.3	177.1	183.3	205.2	211.2	217.2
NS-F	154.0	150.0	154.0	154.0	154.0	154.0
NS-C	754.5	754.5	754.5	754.5	754.5	754.5
NG-M	367.0	367.0	367.0	183.6	183.6	183.6
NG-G	653.0	653.0	653.0	326.5	326.5	326.5
MRA	-	-	-	449.0	449.0	449.0

3. Results

3.1. Fresh Properties

The fresh-state properties of the mixes are given in Table 7, according to which they all fall in the same workability class, S2 (70 ± 20 mm), defined in European standard EN 206-1 [19].

Table 7. Fresh-state concrete properties (±: standard deviation).

Agg. Group	Mix	w/b$_{eff}$	Slump (mm)	Density (kg/m^3)	Air Content (vol%)
	NAC	0.56	65 ± 2.8	2367 ± 8	2.6 ± 0.2
NA	N10/0	0.58	74 ± 2.5	2340 ± 9	2.7 ± 0.2
	N25/0	0.60	65 ± 3.7	2309 ± 10	2.9 ± 0.1
	R0/50	0.59	75 ± 3.1	2251 ± 11	3.2 ± 0.1
MRA	R10/50	0.61	61 ± 3.7	2244 ± 12	3.4 ± 0.2
	R25/50	0.63	63 ± 4.2	2219 ± 10	3.8 ± 0.2

Figure 2 shows that fresh-state density ($R^2 > 0.848$) and air content ($R^2 > 0.779$) varied linearly with the w/b$_{eff}$ ratio. Both the rise in air content and the decline in density with rising w/b$_{eff}$ were induced by the use of GRC and MRA, which are respectively less dense than OPC and NA. That behaviour was consistent with the findings reported by Cantero et al. [10] in a study of concrete mixes prepared with both 25% ground recycled CDW (RC-CDW) as a cement replacement and 50% MRA. The authors found a linear rise in fresh-state air content ($R^2 > 0.842$) and a linear decline in density ($R^2 > 0.921$) as a result of using the two recycled materials.

The air content in all the mixes studied here was lower than the 4.5 vol% recommended by ACI [43] for concrete mixes prepared with a maximum aggregate size of 22.4 mm.

3.2. Mechanical Properties

The 28-day mean compressive (f_{cm}), mean splitting tensile (f_{st}), relative compressive (Δf_{cm}) and relative splitting tensile (Δf_{st}) strengths are plotted in Figure 3. In terms of compressive strength, four of the recycled material mixes (R10/0, R25/0, R0/50 and R10/50), which exhibited $f_{cm} > 25$ MPa, would be apt for structural applications in building construction. A value under 25 MPa was found only in the mix with 25% GRC and 50% MRA (R25/50), whose use would be restricted to non-structural purposes.

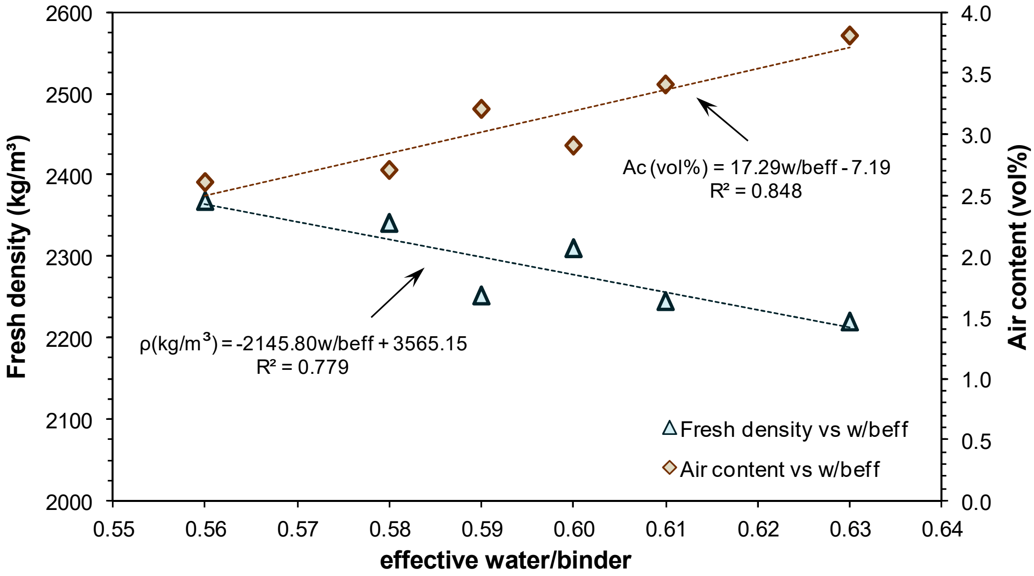

Figure 2. Fresh-state density and air content as a function of the w/b$_{eff}$ ratio.

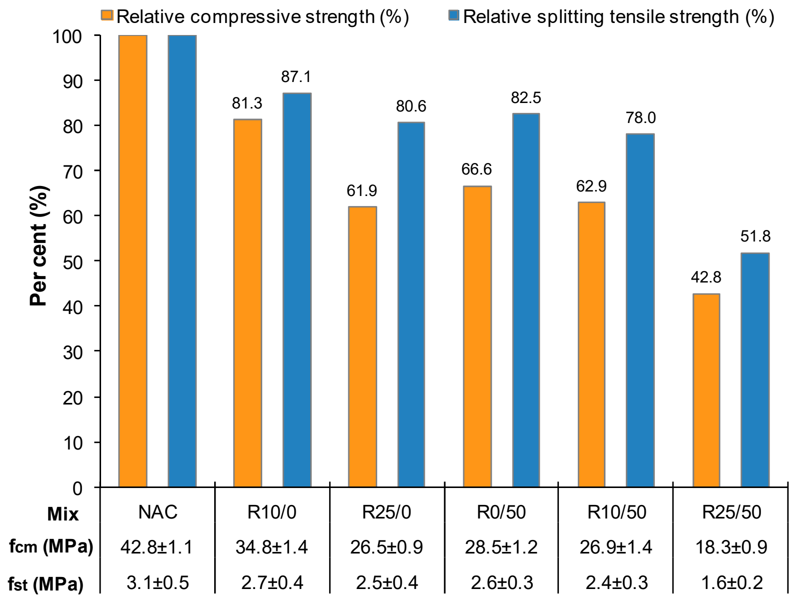

Figure 3. Relative compressive strength (Δf_{cm}), calculated as $\Delta f_{cm_i} = \frac{f_{cm_i}}{f_{cm_{NAC}}} \times 100$, and relative splitting tensile strength (Δf_{st}), as $\Delta f_{st_i} = \frac{f_{cm_i}}{f_{cm_{NAC}}} \times 100$, where subscript *i* denotes the type of recycled materials mix.

Figure 3 also shows that, irrespective of the GRC replacement ratio and the presence or absence of MRA, the experimental materials had lower compressive and splitting tensile strengths than those of the reference mix. Letelier et al. [44], studying concrete mixes with 10% or 15% ground brick and 30% RCA, found the incorporation of ground brick at both replacement ratios induced declines in 28-day compressive and flexural strength in the mixes, whether made with 100% NA or 30% RCA.

Adding 10% GRC to the NA mix (R10/0) lowered compressive strength by 18.7% and tensile strength by 12.9%, whilst at a replacement ratio of 25% (R25/0) the decline was 38.1% in compressive and 19.4% in tensile strength relative to NAC, due to the lower reactivity of GRC relative to cement and the smaller amount of the latter in the mixes. In a study of the effect of replacing OPC with 15%, 30% or 45% ground crushed concrete, Kim [22] attributed the declines in compressive and flexural strength observed to the lower reactivity of the addition.

With the combined use of GRC and MRA, compressive strength was 33.4% and splitting tensile strength was 17.5% lower in R10/50 than in NAC, whilst in R25/50 compressive strength was 57.2% and splitting tensile strength was 48.2% lower. Those findings were the result of two factors: low GRC reactivity [22] and the lesser density and hardness of MRA than NA [45–47]. The declines recorded were steeper than the up to 20% reported for compressive strength and up to 24% for splitting tensile strength in a study [10] of concrete mixes with ground fired clay-based materials recycled from CDW, which were more reactive than the present GRC, and 50% of a harder MRA (LA < 36 wt%) than the one used here (LA = 46 wt%).

3.3. Physical Properties

Table 8 lists the 28-day dry density (ρ_{dry}), open porosity (P_o) and electrical conductivity (EC) values for all the mixes, as well as the effects of using GRC, MRA and the two jointly.

Table 8. Physical properties of the concrete mixes.

	NA mix			MRA mix		
Parameter/Differential	**NAC**	**N10/0**	**N25/0**	**R0/50**	**R10/50**	**R25/50**
ρ_{dry} (kg/m^3)	2290 ± 35	2227 ± 20	2158 ± 25	2101 ± 40	2052 ± 38	1990 ± 42
Δ with GRC (%)	-	−2.8	−5.8	-	−2.3	−5.3
Δ with MRA (%)				-8.3	−7.9	−7.8
Δ with GRC (%) × MRA (%)					−10.4	−13.1
P_o (vol%)	12.1 ± 0.2	12.7 ± 0.3	13.7 ± 0.3	15.2 ± 0.4	15.9 ± 0.5	16.9 ± 0.3
Δ with GRC (%)	-	5.0	13.2	-	4.6	11.2
Δ with MRA (%)				26.5	25.2	23.4
Δ with GRC (%) × MRA (%)					31.4	39.7
EC (10^{-3} Ω·m^{-1})	8.8 ± 0.5	9.5 ± 0.3	10.6 ± 0.3	9.9 ± 0.3	10.2 ± 0.2	11.1 ± 0.4
Δ with GRC (%)	-	−7.1	−16.8	–	−3.0	−10.9
Δ with MRA (%)				−10.6	−6.7	−4.3
Δ with GRC (%) × MRA (%)					−13.3	−20.4

Notes: Δ with GRC (%) compares NAC to N10/0 and to N25/0 in mixes with NA; and R0/50 to R10/50 and to R25/50 in mixes with MRA; Δ with MRA (%) compares NAC to R0/50, N10/0 to R10/50 and N25/0 to N25/50; Δ with GRC × MRA (%): compares NAC to R10/50 and to R25/50.

3.3.1. Dry Density

Analysing the data from Table 8, dry density (ρ_{dry}) was lower in all the mixes containing GRC and MRA than in the NAC reference. Figure 4a shows that replacing OPC with GRC lowered ρ_{dry} linearly ($R^2 \geq 0.998$) in the mixes with NA and MRA due to the lower density of the recycled materials (see Section 2.1.1), which also yielded less hydration product (low reactivity) [5,6]. Dry density was 2.8% lower in N10/0 and 5.8% lower in N25/0 than in NAC and 2.3% lower in R10/50 and 5.3% lower in R25/50 than in R0/50. The vertical distance between the two trend lines in Figure 4a, labelled the 'MRA effect', measures the effect of replacing 50% NA with MRA. The mean 8.0% decline in ρ_{dry} in the MRA mixes (R0/50, R10/50 and R25/50) relative to the NA mixes (NAC, N10/0 and N25/0) was attributable to the lower mean dry density of MRA (ρ_{dry} = 2069 kg/m^3) relative to that of NA (ρ_{dry} = 2591 kg/m^3). The joint use of GRC+MRA, in turn, induced declines in dry density relative to NAC of 10.4% in R10/50 and 13.1% in R25/50, findings consistent with earlier observations in concrete made with recycled (coarse and fine) aggregate consisting of crushed waste clay brick [48].

3.3.2. Open Porosity

The open porosity (P_o) data in Table 8 show greater pore volume in all the mixes containing GRC and MRA than in the reference NAC. This was attributed to two factors: the larger w/b_{eff} ratio in the new cementitious matrices associated with the greater water demand in the new binders (RB_{10} and

RB_{25}); and higher water absorption MRA (9.1%) than NA (1.3%) (higher open porosity) primarily due to the presence of bound mortar and fired clay-based material in MRA [49]. Those results are consistent with earlier studies on concrete batched with up to 100% MRA [50], up to 100% RCA [51] and concrete with up to 100% RCA fine and 100% RCA coarse aggregate [52].

The use of GRC raised P_o by 5.0% in N10/0 and 13.2% in N25/0 relative to NAC and by 4.6% in R10/50 and 11.2% in R25/50 relative to R0/50, an indication that the joint use of CDW as additions and aggregates had no adverse effect on open porosity. As Figure 4b shows, a direct linear relationship ($R^2 \geq 0.997$) was observed between open porosity and GRC replacement ratio in all the mixes, whether containing NA or MRA, where it was added. The vertical distance between the two trend lines depicts the impact of replacing 50% NA with MRA, which induced a maximum rise in the mean P_o of up to 25% in the MRA (R0/50, R10/50, R25/50) relative to the NA mixes (NAC, N10/0, N25/0).

All the P_o values lay within the 12.5% to 17% range reported in the literature for concrete made with 50% MRA [52–54] and concrete made jointly with 30% ground granulated blast furnace slag and 50% RCA [55].

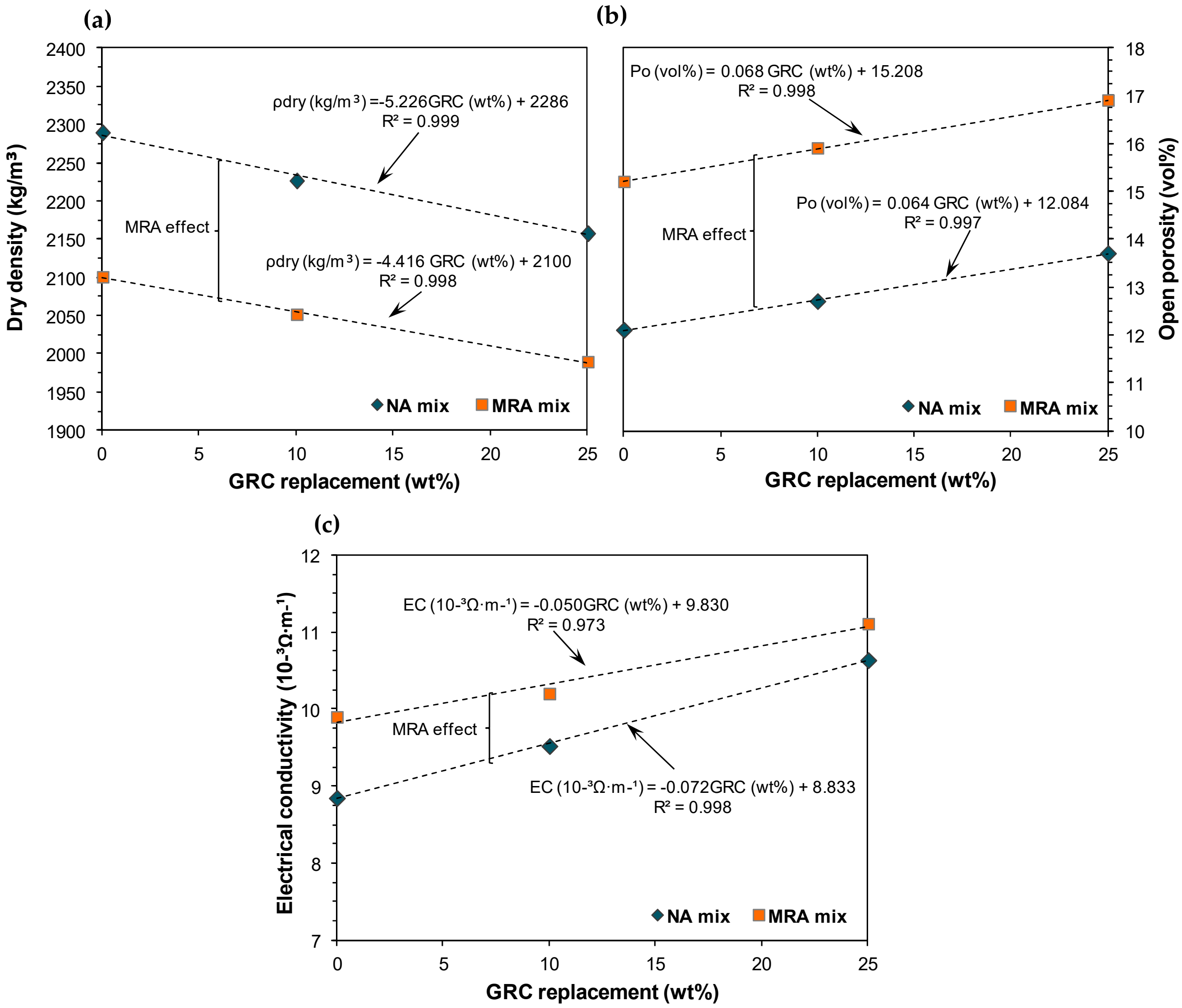

Figure 4. (**a**) Open porosity; (**b**) dry density; and (**c**) electrical conductivity as a function of the GRC replacement ratio.

3.3.3. Electrical Conductivity

The electrical conductivity (EC) values in Table 8 show that the parameter rose with the inclusion of GRC in both the NA and MRA mixes. That observation is related to the greater ion mobility resulting from a more inter-connected saturated pore structure induced by the addition, which in turn raises electrical conductivity [56]. The graph in Figure 5 shows a direct linear relationship ($R^2 \geq 0.978$) between EC and P_o or the volume of permeable pores in the NA and MRA mixes. The use of GRC raised EC linearly ($R^2 \geq 0.980$) (Figure 4c)) by 7.1% in N10/0 and 16.8% in N25/0 relative to NAC and by 3.0% in R10/50 and 10.9% in R25/50 relative to R0/50. Using 50% MRA raised EC by a mean of 7.2% relative to the mixes with 100% NA.

All the increases in EC observed lie within the 7% to 24% range reported in the literature for concrete mixes with 25% or 50% coarse fired clay aggregate [53] and mixes with 25% or 50% RCA fines [57].

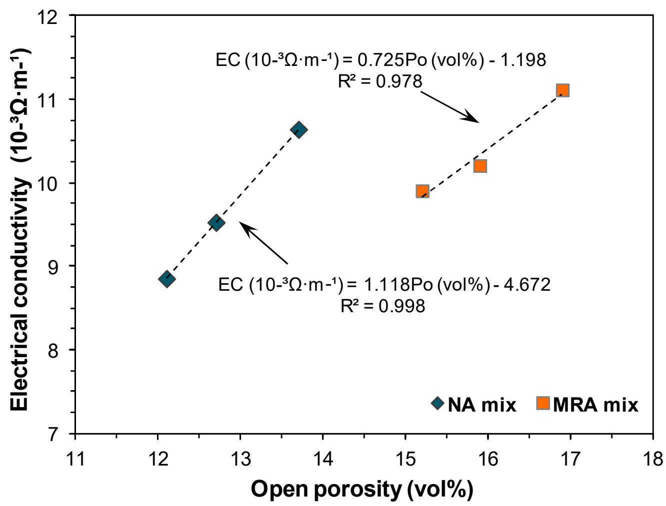

Figure 5. Open porosity versus electrical conductivity.

3.4. Thermal Properties

Twenty-eight-day thermal conductivity (λ) and specific heat capacity (c_p) are given for all the mixes in Table 9, which also lists the effects of including GRC, MRA and the two jointly.

Table 9. Thermal properties of the concrete mixes.

	NA mix			MRA mix		
Parameter/Differential	**NAC**	**N10/0**	**N25/0**	**R0/50**	**R10/50**	**R25/50**
λ (W/m·K) [1]	2.064	2.013	1.922	1.963	1.901	1.821
Δ with GRC (%)	-	−2.5	−6.9	-	−3.1	−7.2
Δ with MRA (%)				−4.9	−5.6	−5.3
Δ with GRC (%) × MRA (%)					−7.9	−11.8
Volume heat capacity (MJ/m³·K) [1]	1.864	1.839	1.828	1.781	1.771	1.768
c_p (kJ/m³·K)	0.814	0.826	0.847	0.848	0.863	0.888
Δ with GRC (%)	-	1.4	4.1	-	1.8	4.8
Δ with MRA (%)				4.1	4.5	4.9
Δ with GRC (%) × MRA (%)					6.0	9.1

[1] Standard deviation was <0.003 for all parameter values. Notes: Δ with GRC (%) compares NAC to N10/0 and to N25/0 in mixes with NA; and R0/50 to R10/50 and to R25/50 in mixes with MRA; Δ with MRA (%) compares NAC to R0/50, N10/0 to R10/50 and N25/0 to N25/50; Δ with GRC × MRA (%): compares NAC to R10/50 and to R25/50.

3.4.1. Thermal Conductivity

Figure 6 shows that mixes N10/0 and N25/0 exhibited lower thermal conductivity (λ) than NAC and mixes R10/50 and R25/50 lower λ than R0/50, inferring that the recycled material concrete would afford more effective thermal insulation than conventional materials. The use of GRC lowered λ by 2.5% in N10/0 and 6.9% in N25/0 relative to NAC and by 3.1% in R10/50 and 7.2% in R25/50 relative to R0/50. Those values lay in the 2.8% to 6.8% range observed for concrete made with up to 25% RA to replace NA fines [9] and concrete prepared with 10% ground granulated blast furnace slag as an OPC substitute [58].

The inverse linear relationship ($R^2 \geq 0.997$) between λ and GRC in NA and MRA mixes is plotted in Figure 6a. The mean decline of 5.3% in λ (determined as the vertical distance between the two trend lines: the MRA effect) attributed to the use of 50% MRA was very close to the 5.5% decline reported for concrete with 50% RA of a type similar to the RA used in this study [12]. The joint use of GRC and MRA lowered thermal conductivity by 7.9% in R10/50 and by 11.8% in R25/50 relative to the reference NAC.

All the recycled material mixes exhibited λ in the 2.01 W/m·K to 1.60 W/m·K range found for concrete with up to 50% RA fines and up to 50% RA coarse recycled CDW aggregate [12], as well as within the range recommended by Eurocode 2 [59]: 1.95 W/m·K to 1.33 W/m·K.

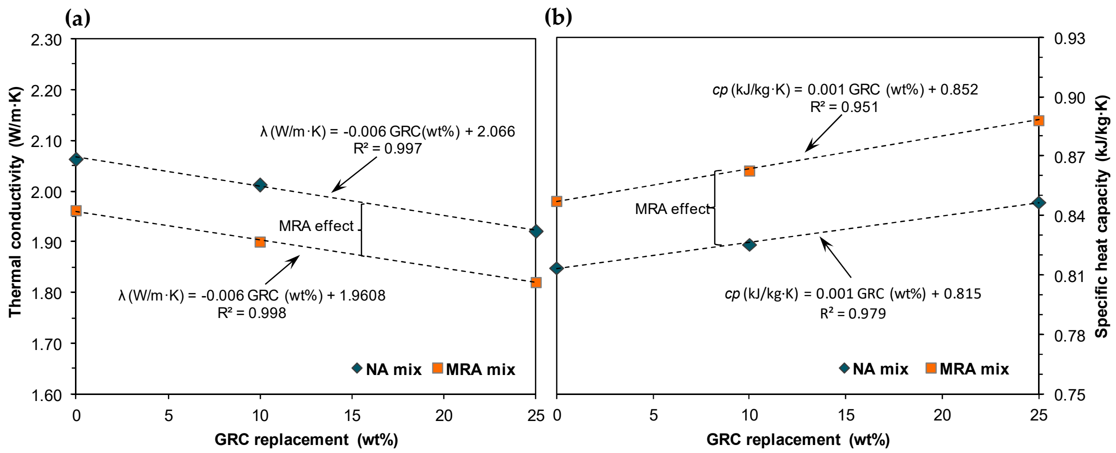

Figure 6. (**a**) Thermal conductivity and (**b**) specific heat capacity as a function of the GRC replacement ratio.

3.4.2. Specific Heat Capacity

Specific heat capacity (c_p in J/kgK) is calculated as $c_p = \frac{c}{\rho_{dry}}$, where c is volumetric heat capacity in J/m^{3}K and ρ_{dry} is concrete dry density in kg/m^3. Further to the data in Table 9, the use of GRC raised c_p by 1.4% in N10/0 and 4.1% in N25/0 relative to NAC and by 1.8% in R10/50 and 4.8% in R25/50 relative to R0/50, an indication that the new mixes would be less affected by abrupt temperature changes than NAC [60]. Figure 6b plots the direct linear relationship ($R^2 \geq 0.950$) between c_p and GRC in NA and MRA mixes and shows that the use, in addition, of 50% MRA (MRA effect) raised c_p by a mean 4.5% in the MRA mixes relative to the NA mixes, a value similar to the mean 5.3% decline observed for λ.

The joint use of GRC and MRA induced a rise in c_p of 6.0% in R10/50 and 9.1% in R25/50 relative to the reference NAC. Those increases with the use of GRC and MRA infer greater thermal inertia in the new recycled material mixes than in the reference concrete and, consequently, greater thermal stability when exposed to changing outdoor temperatures.

All the c_p values lay within the normal range (0.790 kJ/m^3·K to 0.960 kJ/m^3·K) for concrete used in residential building construction [13].

3.5. Cross-Property Relationships

3.5.1. Thermal Properties and Air Content

Thermal conductivity and specific heat capacity are plotted against fresh-state air content in Figure 7. The linear relationships denote a good correlation between these properties with determination coefficients R^2 of over 0.84, a value higher than $R^2 = 0.57$ reported by Bravo et al. [12] for a study on the thermal behaviour of concrete in which NA was replaced with 10% to 100% (coarse and fine) recycled aggregate from several CDW management plants.

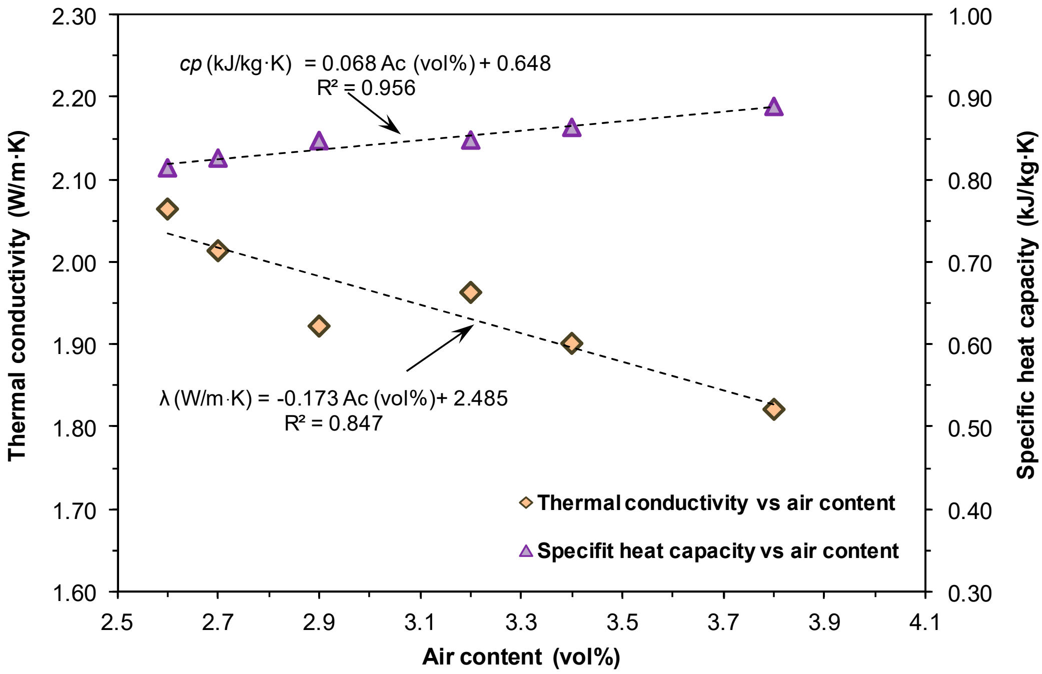

Figure 7. Air content/thermal conductivity and air content/specific heat capacity relationships for all concrete mixes.

3.5.2. Thermal Properties and Compressive Strength

Analysing Figure 8, both thermal conductivity and specific heat capacity were linearly related to compressive strength with determination coefficients R^2 above 0.92, the former inversely and the latter directly, i.e., the lower the thermal conductivity or the higher the specific heat capacity, the higher the compressive strength. Those findings were consistent with the results reported by Bravo et al. [12] and Pavlu et al. [61] for concrete with up to 100% RMA fine and coarse aggregate.

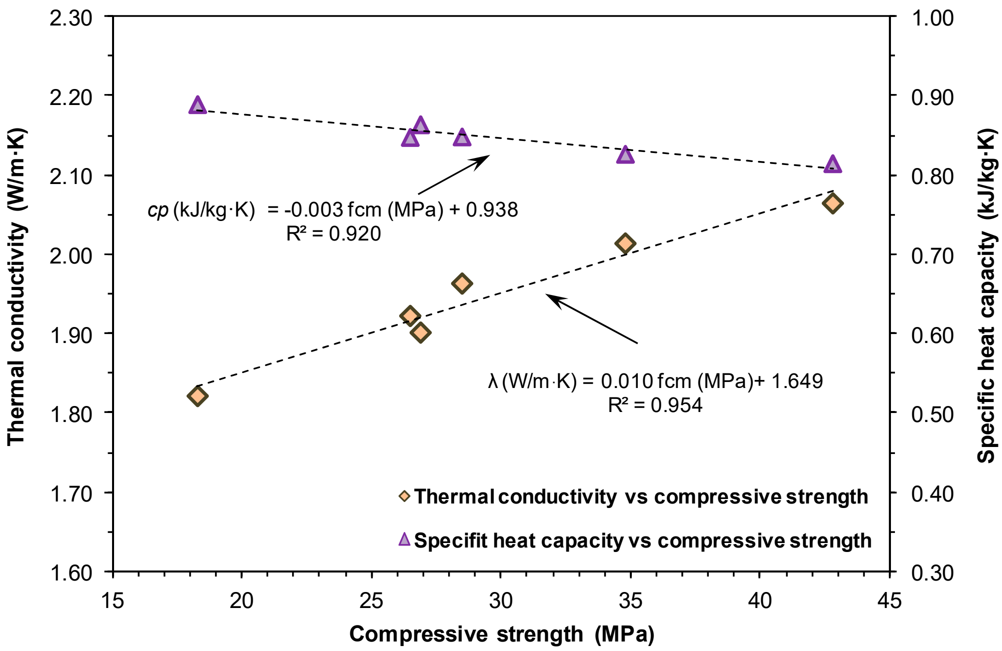

Figure 8. Compressive strength/thermal conductivity and compressive strength/specific heat capacity relationships for all concrete mixes.

3.5.3. Thermal Properties and Open Porosity

Conversely to compressive strength, open porosity was inversely related to thermal conductivity and directly to specific heat capacity (Figure 9) with determination coefficients R^2 for the respective linear relationships above 0.823. According to these data, the larger the pore volume, the more effective the thermal insulation (lower conductivity) is and the greater the thermal stability (higher specific heat capacity) when exposed to abrupt outdoor temperature changes. Earlier studies also related lower concrete thermal conductivity to higher pore volumes [41,44,45,47,48].

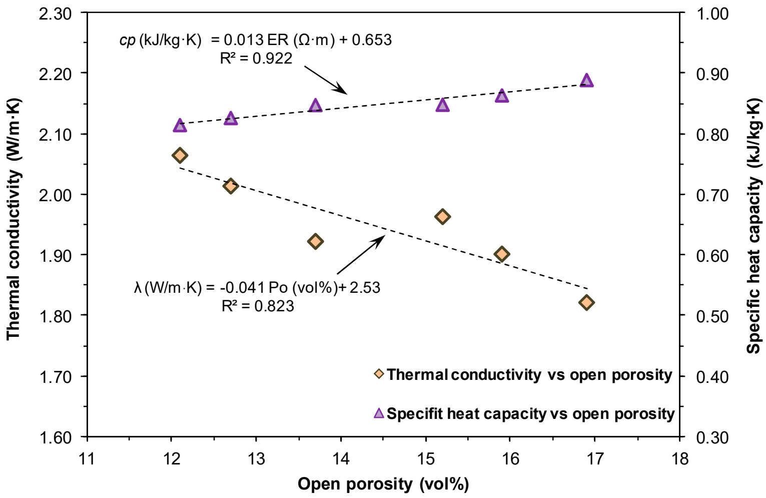

Figure 9. Open porosity/thermal conductivity and open porosity/specific heat capacity relationships for all concrete mixes.

The thermal conductivity of the solid matrix (λs) in concrete mixes is given in Table 10. This parameter separates the effect of the volume of open pores from the effect of adding both recycled materials (GRC and MRA) to the mixes. It exhibited higher values than overall thermal conductivity (Table 9). With GRC, λ_s was 1.8% lower in N10/0 and 5.2% lower in N25/0 than in NAC and, in the mixes with MRA, 2.4% lower in R10/50 and 5.4% lower in R25/50 than in R0/50. The combined use of GRC and MRA lowered the mean λ_s value by 1.7% in (R0/50, R10/50 and R25/50) relative to the reference NAC. In other words, the use of 25% GRC had a greater impact than the use of 50% MRA.

Table 10. Thermal conductivity of the concrete matrices.

Parameter/Differential	NA mix			MRA mix		
	NAC	N10/0	N25/0	R0/50	R10/50	R25/50
λ_s (W/m·K) [1]	2.345	2.303	2.223	2.310	2.256	2.186
Δ with GRC (%)	-	−1.8	−5.2	-	−2.4	−5.4
Δ with MRA (%)				−1.5	−2.0	−1.7
Δ with GRC (%) × MRA (%)					−3.8	−6.8

[1] λ_s = ((λ − (P_0i × λ_air)))/V_s, where: λ is overall concrete thermal conductivity; Po is open porosity (expressed as a decimal); λair is the thermal conductivity of air, equal to 0.024 W/m·K; Vi is the volume of the solid matrix for a given total volume defined as Vi = (1 − Poi), where the subscript i denotes the type of concrete mix.

3.5.4. Thermal Properties and Electrical Conductivity

As Figure 10 shows, electrical conductivity, like open porosity, was inversely related to thermal conductivity and directly to specific heat capacity with determination coefficients R^2 for linearity above 0.830. The explanation for these findings lies in the greater electrical conductivity of the recycled materials mixes than the reference mix, resulting from the greater volume of saturated pores in the former (see item 3.3.3). Earlier authors also mentioned a rise in electrical conductivity (reported as a decline in electrical resistivity) with the higher porosity attributed to using MRA coarse aggregate [50], RCA coarse aggregate [62], RCA fines [57] or RCA coarse and fine aggregate jointly [63].

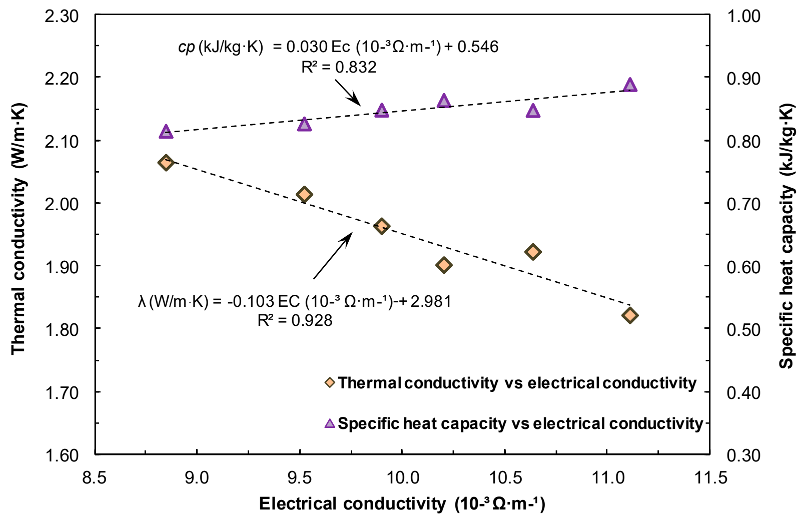

Figure 10. Variation in electrical conductivity/thermal conductivity and electrical conductivity/specific heat capacity relationships for all concrete mixes.

4. Conclusions

The conclusions that may be drawn from this study are set out below:

- The use of GRC to replace 25% of OPC and MRA to replace 50% of NA lowered concrete fresh-state density by 6.2% and raised its air content by 30%. All the recycled material concrete mixes studied had an air content under 4.5%, the upper limit recommended by the ACI committee for structural concrete;
- Porosity rose by 39.7% in the mixes with 25% GRC and 50% MRA and by 13.2% in the mixes with 25% GRC and 100% NA relative to the reference mix made with 100% OPC and 100% NA;
- The decline in dry density and the rise in electrical conductivity were associated with the incorporation of GRC in mixes with 100% NA as well as those with 50% MRA due to the higher porosity in the recycled materials;
- The use of 25% GRC in conjunction with 50% MRA reduced thermal conductivity by 11.8% and raised specific heat capacity by 9.1%, whilst the values for 25% GRC with 100% NA were a 6.9% reduction in thermal conductivity and a 4.1% rise in specific heat capacity, both relative to concrete with 100% natural aggregate (NA);
- Due to their greater porosity, the new recycled materials concrete may provide better thermal insulation and greater thermal inertia than conventional concrete;
- Cross-referencing concrete properties showed that, whereas using GRC and MRA as replacement materials had an adverse effect on concrete's compressive strength, it improved its thermal properties;
- Mixes with 25% GRC and 100% NA and those with 10% GRC and 50% MRA, with compressive strength values of >25 MPa, are not only apt for use in building construction, but afford greater energy efficiency than conventional concrete.

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