Freeze-thaw durability of recycled concrete from construction and demolition wastes

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Abstract. Road engineering is one of the most accepted applications for concrete including recycled aggregates from construction and demolition wastes as a partial replacement of the natural coarse aggregates. Amongst the durability concerns of such application, the deterioration due to freeze-thaw cycles is one of the most important causes decreasing the life span of concrete in countries with a continental climate. Moreover, the use of de-icing salts, which is a common practice to prevent ice formation on roadways and walkways, increases the superficial degradation of concrete due to frost-salt scaling. Thus, this paper aims to assess the resistance to frost salt with de-icing salts of two recycled concrete mixtures containing a 50% replacement of the conventional gravel by recycled aggregates both of mixed and ceramic nature, i.e. containing ceramic percentages of 34% and 100%, in comparison to a conventional concrete made with siliceous gravel. Therefore, the surface scaling was evaluated based on EN 1339 (2004) on 28 days cured cylinders, exposed to 7, 14, 21 and 28 freeze-thaw cycles in the presence of sodium chloride solution. Given that no air-entraining admixture was used in any of the mixtures, the scaling of both conventional and recycled concretes exceeded the 1 kg/m^2 limit established by the European standard. Nonetheless, for the casting surface, the recycled concrete with low ceramic content exhibited a similar behaviour to the conventional concrete, whereas the performance of the recycled concrete with high ceramic content was better. However, as expected, trowelled surfaces showed a worse performance and both recycled concretes had a lower freeze-thaw durability than the conventional mixture. In any case, the results suggested that the composition of the recycled aggregates could be used as a factor to limit the differences in performance between recycled and conventional mixtures.

Introduction

Among construction materials, estimates indicate that concrete is the most employed material worldwide with around 1 tonne per inhabitant and year [1]. As thus, it is one major player in the current environmental problems. However, in the last decades, it has also been regarded as a possible solution to environmental issues such as the natural resource depletion and the generation of construction and demolition wastes (CDW). Under the circular economy principles, constructions at the end of their life span may transform into secondary resources for new constructions in order to close the production loop [2]. In Spain, the reutilizing scenario is characterized by a 68% recycling rate [3], but 90% of the commercialized recycled aggregates are employed as unbound aggregates [4]. This situation is caused in great part by the lack of standardization regarding the use of mixed and ceramic recycled aggregates in the concrete manufacture, despite these recycled aggregates constitute 70% of the total production at CDW management plants [4].

Road engineering is one of the most accepted applications for concrete including recycled aggregates from CDW as a partial replacement of the natural coarse aggregates. Amongst the durability concerns of such application, the deterioration of concrete due to freeze-thaw cycles is one of the most important causes decreasing its life span in countries with a continental climate. For instance, the Spanish Code on Structural Concrete [5], namely the EHE-08, establishes that all elements located in frequent contact with water, or areas with an average relative environmental humidity over 75%, and which have an annual probability of over 50% of reaching temperatures below 5ºC at least once a year are liable to freeze-thaw damage.

Concrete exposed to low temperatures may suffer from surface scaling resulting in a progressive loss of mortar or even coarse aggregates. Since the use of de-icing salts is a common practice used to de-ice concrete roadways and walkways, the superficial degradation is increased due to frost-salt scaling. Although it is agreed that the deterioration is mostly physical as the chemical reactions between the salt and the hydration products play a secondary role in the damage [6], the scaling of the concrete surface enable the penetration of water and secondary aggressive substances, such as chlorides, that can lead to an eventual corrosion of the rebar.

Although the phenomenology that characterizes this damage is well known, some possible underlying mechanisms (hydraulic pressure, crystallization pressure, thermal shock, precipitation and growth of salt, salt concentration, reduction in vapour pressure and osmotic pressure) have been discussed at length. Nowadays, the glue-spall theory proposed by Valenza II and Scherer [7] seems to give the more plausible explanation to the surface scaling phenomenon in presence of de-icer salts. The glue-spall theory postulates that the ice layer is mechanically bonded to the concrete surface. Hence, the magnitude differences between the coefficients of thermal expansion of each material produce a tensile stress that may cause the cracking of the external ice layer and the penetration of that crack in the concrete surface causing the removal of some flakes.

Previous investigations. Since most countries have already specifications allowing and regulating their use, a vast number of investigations have paid attention to the freeze-thaw durability of concrete made with recycled concrete aggregates. Several researches [8–11] have observed a lower freeze-thaw performance, which has been attributed to the adhered mortar (specifically its origin from non-air entraining parent concrete [12]) or the aggregate saturation [13]. Nonetheless, Yildirim et al. [14] and de Oliveira and Vazquez [15] observed improvements in the frost performance when semi-saturated recycled aggregates were incorporated. Other treatments have also shown an improvement in the recycled concrete durability, such as the selection of air entrained parent concrete [12,16], the equivalent mortar volume (EMV) proportioning method [17], the mortar removal and the two mixing stage approach (TMSA) [18] and the elimination of impurities [19]. Finally, a similar behaviour between conventional and recycled concretes with different replacement ratios has also been reported [20–23].

A lower number of studies have been focused on the effect of ceramic recycled aggregates. Marginal deterioration has been reported when using brick aggregates by Topçu and Sengel [24] and Bazaz and Khayati [25], provided that lower water/cement ratios were used in the latter. Medina et al. [26] registered a similar mass loss for ceramic sanitary replacements (20% and 25%). Meanwhile, Topçu and Canbaz [27] and Adamson et al. [28] noticed an increase in the freeze-thaw resistance when using crushed tiles (50% and 100% replacements) and bricks (25% and 50% replacements) respectively.

Conflicting results have been reported regarding the use of mixed recycled aggregates. Dhir and Paine [29] observed that concrete made with mixed recycled aggregates containing 80% ceramic materials exhibited lower frost resistance, whereas Richardson et al. [30] observed a better performance of the recycled concrete incorporating mixed recycled aggregates containing 25% concrete rubble and 75% of ceramic bricks.

In conclusion, the performance discrepancies may be attributed to the different nature, composition and quality (water absorption and fragmentation resistance particularly [31]) of the CDW.

Materials

For all concrete mixtures, raw materials included potable water, type III slag blended cement (CEM III/B 42.5 N SR LH LA) and siliceous sand and gravel. Moreover, two recycled aggregates from CDW were used in this investigation to represent typical mixed and ceramic recycled aggregates commercially available in Spain. The RA-L sample, which was collected in TEC-REC (Madrid), presented a 44.11% of cement based materials, 33.56% of ceramic materials, 17.51% of unbound natural aggregates and a remaining 4.82% of varied impurities (asphalt, glass, metal, plastic, wood…); meanwhile the RA-H sample, which was collected in Bierzo Recicla (Castile and Leon), was 100% comprised by ceramic materials. Table 1 shows the physical and mechanical characteristics of recycled aggregates according to the requirements set in the Spanish Code on structural concrete (EHE-08) [5].

Table 1: Characterization of the recycled aggregates

	RA-L	RA-H
Particle size distribution ratio [-]	2.54	5.00
Fines content [%]	0.06	0.08
Flakiness index [%]	14.75	32.13
Oven-dried density [Mg/m^3]	2.08	1.80
Water absorption [%]	8.53	10.77
Los Angeles coefficient [%]	40.99	40.00

A 50% replacement in weight of the natural coarse aggregate was selected for the design of the concretes with 25 MPa target strength at 28 days according to De la Peña method [32] and the Fuller parabola [33]. The experimental program was based on fixing both the cement and the total water/cement ratio (0.55) to be used as constant parameters among concrete mixtures. Table 2 shows the concrete proportions of the conventional (CC) and recycled mixtures studied (RC-L and RC-H).

Table 2: Concrete mixture proportions

	CC	RC-L	RC-H
Water (l/m^3)	215.00	215.00	215.00
Cement (kg/m^3)	390.91	390.91	390.91
Sand (kg/m^3)	480.48	703.46	821.06
Gravel 2-8 mm (kg/m^3)	1000.30	368.32	307.79
Gravel 8-16 mm (kg/m^3)	250.07	92.08	76.95
Recycled aggregate (kg/m^3)	0.00	460.40	384.74

Methods

Surface scaling. The degradation was evaluated based on the appendix D of UNE EN 1339 [34] on 28 days cured cylinders, drilled from a concrete slab (400x400x100 mm) and sawn in half to allow the differential characterization of both casting and trowelled surfaces. Six test specimens of 100x50 mm were glued into a polyvinyl chloride (PVC) tube to ensure continued exposure. After a leakage test to guarantee a correct sealing, a 5 mm thick layer of freezing medium (3 wt% NaCl) was placed on each specimen. Lastly, to avoid evaporation and concentration changes throughout the experiment a plastic film was used to cover each sample. Fig. 1 shows the specific configuration followed. Subsequently, the specimens were introduced in a freezing chamber at the beginning of a freeze-thaw cycle with temperatures ranging from -18 ºC to 20 ºC in 24 hours [34]. During the thawing phase of the 7th, 14th, 21th and 28th cycle, each specimen was rinsed with tap water into a filter paper to collect the scaled material that afterwards was dried a 105 ºC during at least 24 hours. Finally, the same quantity of freezing medium was poured again onto the test surface and the specimen was returned to the freezing chamber at the beginning of a new freeze-thaw cycle. Salt scaling resistance was assessed by subsequently weighing of surface mass loss per unit area.

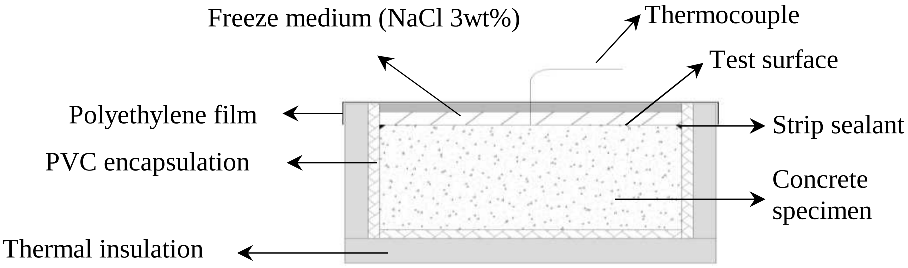

Figure 1: Test specimen for freeze-thaw attack with de-icing agents

Mercury intrusion porosimetry. Since there is no agreement in the method specimens should be prepared before undergoing MIP [35], it is worth mentioning that samples were dried to constant weight at 40 ºC and degassed with a vacuum pump for 30 minutes in order to ensure moisture removal. The test was conducted to ASTM D4404-10 [36] on a Micromeritics Autopore IV 9500 mercury intrusion porosimeter capable of operating at up to 33,000 psia (227.5 MPa). The operating parameters were mercury filling pressure of 0.45 psia (~3.10 Pa), maximum intrusion volume of 0.50 ml/g and equilibration time of 10 seconds.

Air void assessment. For each concrete mixture, four slices of approximately 2.5 mm in thickness were cut from the same 100x100 mm cube specimen. The test surfaces were mechanically flattened and polished with a sequence of wet diamond polishing pads (grit 50, 100, 200, 400, 800, 1500, 3000 and 8000 and further cut to remove the unavoidable unpolished parts due to the holding configuration of the test machine. Hence, specimens of 65x100 mm were finally obtained. To improve the image analysis, test surfaces were coloured black and white podwer ($BaSO_4$) was poured and tamped to fill the air voids taking care to scrape off any rests and re-colour the voids or cracks present in the aggregates, in which the white powder also penetrated.

The air void system was evaluated through the linear traverse method described in ASTM C457 [37] Procedure A by means of a RapidAir 457 apparatus. After adjusting the light and focus, the sample was automatically analysed using 5 traverse lines per frame and a total traverse length of 2413.1 mm. Two analyses were performed per sample, by turning the sample over 90° and an average of the two readings of the sample was reported

Results and discussion

Fig. 2 illustrates the deterioration of the surface layer of concrete exposed to 7, 14, 21 and 28 freeze-thaw cycles. While the casting surface layer of mixture RC-H was still pretty intact after the test, the rest of specimens exhibited a complete removal of the surface layer as consequence of a severe scaling. In addition, some aggregates pop-out to the concrete surface, especially in the trowelled faces. The pressure inside of the aggregate by the freezing of the water in its interior was the responsible for the generation of a pressure able to separate it from the surrounding cement paste [38]. Nonetheless, the gradual debonding and detachment of the aggregates occurred in similar manner in both the conventional and the recycled mixtures.

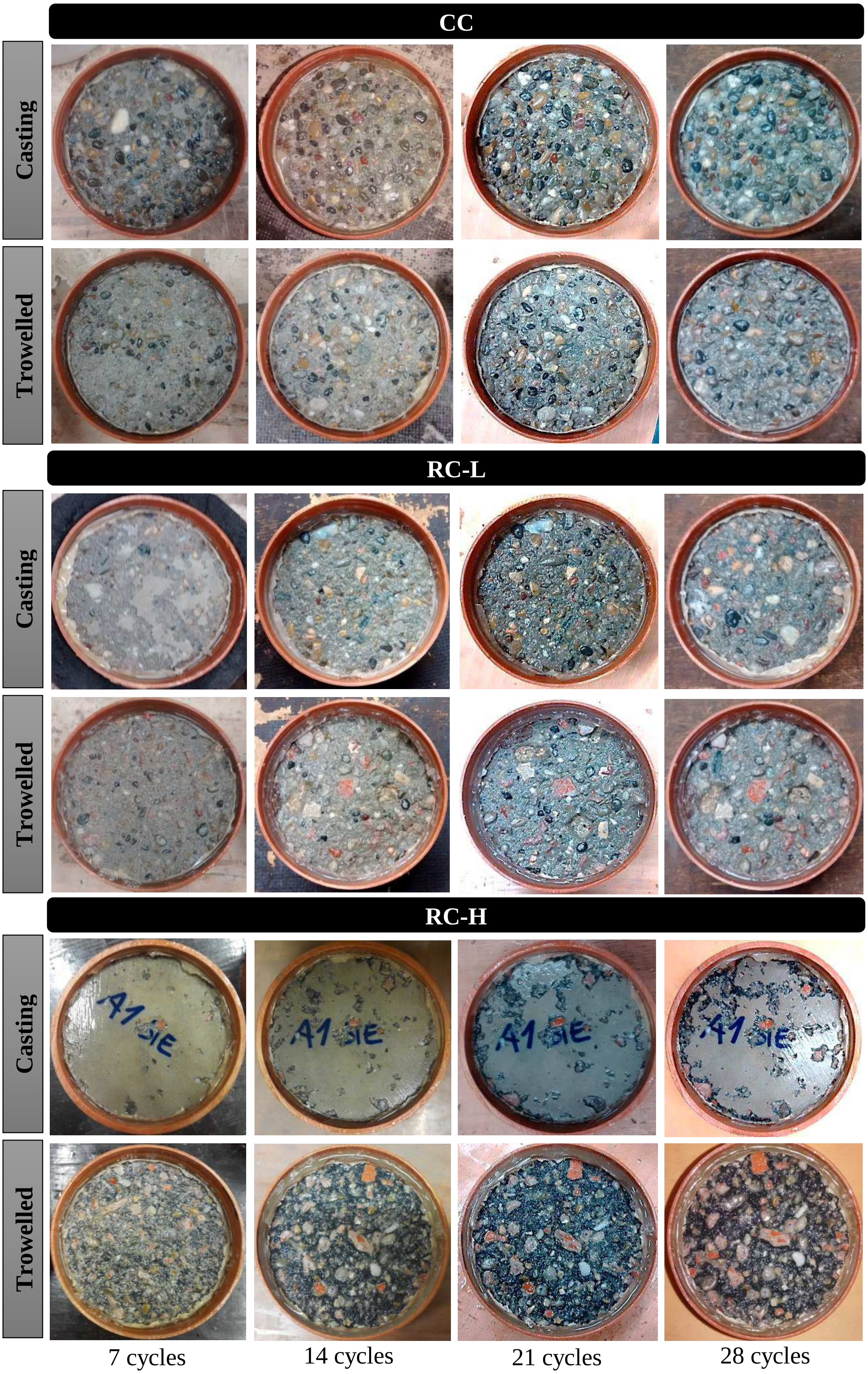

Figure 2: Surface of one sample of each concrete mixture subjected to freeze-thaw cycles under salt exposure.

Quantitatively, Fig. 3 displays the evolution of the frost salt scaling damage of concrete mixtures containing natural and recycled aggregates. Since, the strength of the surface is a factor influencing the scaling of concrete, mass loss per unit area was assessed on both casting and trowelled surfaces. For both superficial finishes, the mass loss was greater in the early cycles and decreased as the test progressed. This is due to the existence of a thin mortar layer with a different microstructure than the rest of the cement paste [39]. Nonetheless, at the end of the test, the deterioration was 44%, 66% and 95% lower in the casting face of CC, RC-L and RC-H, which suggests a higher thickness of the weak layer in the trowelled surfaces, especially in the conventional concrete. Medina et al. [26] and Pigeon et al. [39] also observed a faster scaling in the first stages of trowelled surfaces. Nevertheless, the worse performance of the trowelled surface extended during all freeze-thaw cycles. Especially significant were the differences observed for mixture RC-H (with mass losses between 58% and 95% lower in the casting surface). The high variability can be explained by the fact that some of the specimens lost both cement paste and aggregates, while others only loose cement paste flakes. Van den Heede [40] also observed this behaviour in concrete designed without air entraining agents and significant differences have been also reported between finished and sawn surfaces [39,41].

In the casting surface, mixture RC-H experimented the smaller mass loss (72% lower than CC). Moreover, meanwhile the performance of RC-L and CC was comparable at the end of the test, the mass loss of RC-L was slightly lower in the intermediate stages of the test, which was similar to the findings of Medina et al. [26], who attributed the results to the finer pore structure of the recycled concretes. In addition, the results suggest that a linear relationship exists between the scaling damage and the presence of ceramic materials in the total volume of coarse aggregates (Fig. 4), which indicates that the nature of the recycled aggregates plays an important role in the frost salt scaling resistance. Conversely, recycled concretes exhibited a worse performance than the conventional concrete in the testing of the trowelled surface. After 28 freeze-thaw cycles, CC presented a mass loss 26% lower than RC-L and 8% lower than RC-H. Additionally, no relationship was found between the scaling behaviour of the trowelled surfaces and the ceramic content incorporated in the concrete mixtures.

Finally, except the casting surface of specimens in mixture RC-H, both conventional and recycled concretes exhibited unacceptably high mass losses due to scaling and surpassed the limit of 1 kg/m^2 established in the UNE EN 1339 [34]. Nevertheless, it is worth mentioning that the standard establishes a highly severe compliance threshold that does not correlate with the real climatic conditions of the zones in which the recycled aggregates were produced, and thus more likely to be used. Table 3 shows the minimum temperature (Tmin) analysis performed for the collecting zones based on climatic data between 1980 and 2011 [42]. Firstly, the collected temperature data was converted to temperatures at ground level assuming a -5ºC difference. Then, the maximum and average number of days, consecutive and non-consecutive, in which key temperatures were reached were calculated. Since the damage ensues due to the alternation of temperatures able to produce the freeze and thaw of the material within 24 hours, the number of freeze and thaw cycles was assessed as days in which the minimum temperature was lower than 0ºC and the maximum temperature was greater than 0ºC. Hence, a maximum number of freeze-thaw cycles around 140 and an average number ranging from 111 to 121 were observed. However, on average, there were no 28 subsequent freeze-thaw cycles. In addition, the minimum temperature never reached –18 °C for neither of the locations considered, and therefore the conditions of those freeze-thaw cycles were not as severe as those proposed in the standard. Nonetheless, according to Valenza II and Scherer [43], significant salt scaling damage occurs at minimum temperatures below –10 °C. In this case, historic data show a maximum from 5 to 7 days and an average from 1 to 4 days at critical temperature, although subsequent days under that conditions occur on average once or twice a year with a maximum incidence between 4 and 7 days. Thus, under the climatic conditions occurring in the collecting zones, it would take, on average, no less than 14 or 28 years before concrete would be exposed to 28 critical freeze-thaw.

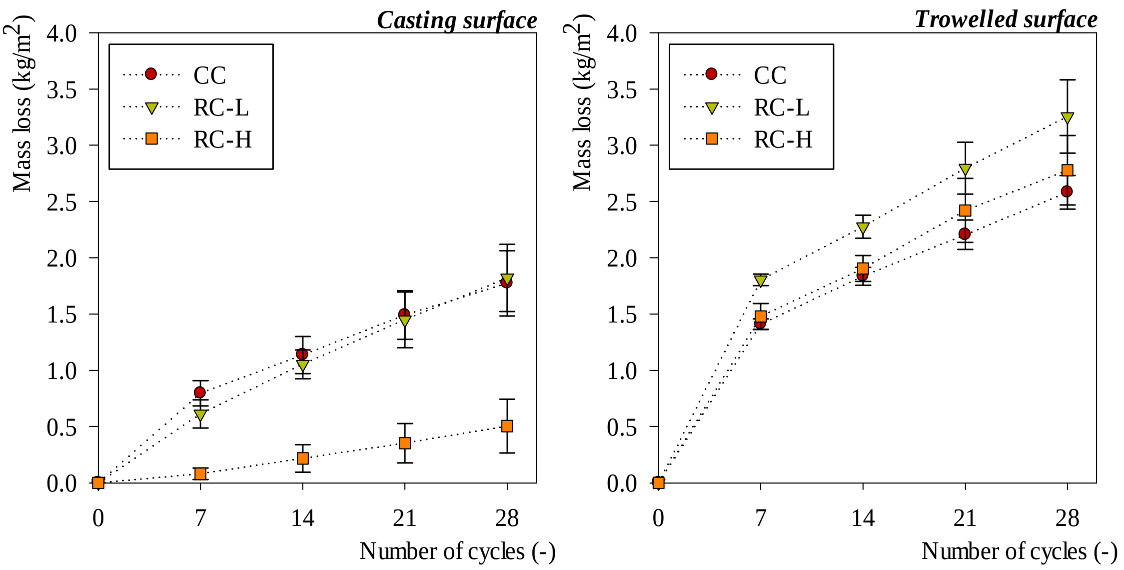

Figure 3: Cumulative mass loss due to superficial concrete scaling.

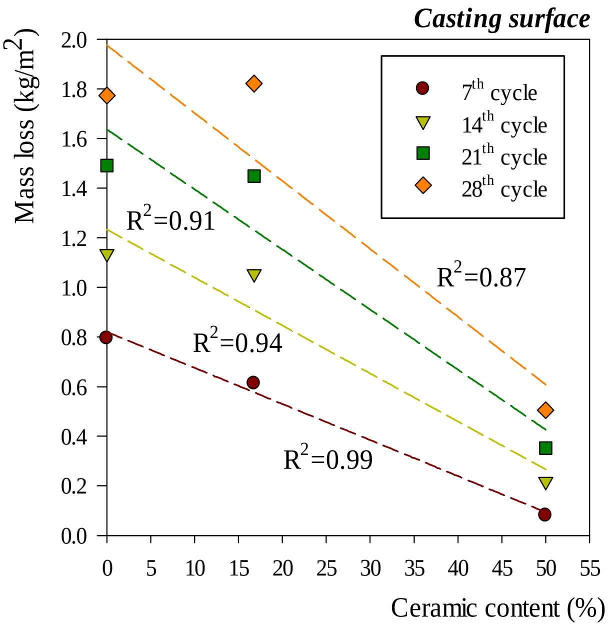

Figure 4: Relationship between the surface scaling and the ceramic content.

Table 3: Analysis of the minimum temperature values in the collecting zones at ground level.

	RA-L	**RA-H**
Average Tmin [ºC]	-9.9	-11.1
Maximum number of freeze-thaw cycles per year	140	139
Maximum number of consecutive freeze-thaw cycles per year	50	61
Average number of freeze-thaw cycles per year	111	121
Average number of consecutive freeze-thaw cycles per year	23	22
Maximum number of days with Tmin<-10ºC per year	7	15
Maximum number of consecutive days with Tmin<-10ºC per year	4	7
Average number of days with Tmin<-10ºC per year	1	4
Average number of consecutive days with Tmin<-10ºC per year	1	2

It is well known that the pore structure of concrete plays a major role in its freeze-thaw durability. As expected by the higher water absorption of the recycled aggregates, the recycled concretes exhibited a greater porosity than the conventional concrete. Total values of 11.10%, 14.20% and 11.50% were observed for CC, RC-L and RC-H, respectively. Fig. 5 illustrates de mercury intrusion curves of the concrete mixtures. For both the casting and trowelled surfaces, the results point to a strong relationship between the increase of the total porosity and the scaling damage (Fig. 5). Additionally, it can be observed that recycled concrete possess a finer pore structure (Fig. 5) that, as previously mentioned by Medina et al. [26], contributes to the good freeze-thaw performance of the recycled concretes due to the formation of a lower volume of ice [39,44] and the increase of the freezing point, which delays the damage [39,45]. Although the porosity of recycled aggregates originating from CDW has been recognised to provide a level of protection from freeze-thaw damage [30] due to the higher ease to dissipate the generated hydraulic pressures in the pore structure of concrete [46], this effect was only observed in the casting surface of mixture RC-H.

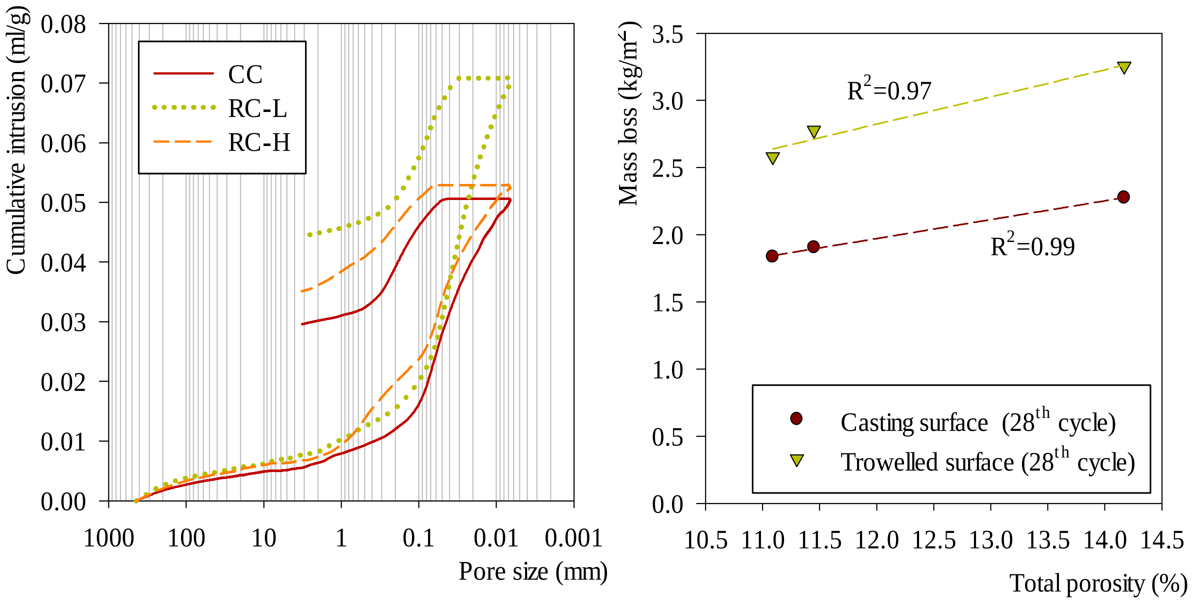

Figure 5: Cumulative pore intrusion of the concrete mixtures at 28 days.

In particular, the finer pore system of ceramic aggregates has been considered to have a similar effect as the use of air entraining agents by operating as additional spaces to dissipate the stresses created due to the water expansion [47–50]. As can be observed in Fig. 6, both recycled concrete mixtures presented higher air void content values than the conventional concrete, which has also been reported in other investigations [51,52]. However, all values fall below the recommended 5-8% air content necessary to ensure the frost resistance of concrete [53]. When only air voids lower than 0.5 mm are considered, i.e. entrained air [54], the beneficial effect that the incorporation of ceramic aggregates has on the air void system of concrete is more obvious, which is reflected in the improved durability in the casting surfaces of mixture RC-H. However, the concentration of the air voids within the brick aggregates instead of being well distributed throughout the paste may be responsible for hindering the beneficial behaviour in the rest of the samples.

Table 4 shows the parameters that characterize the air void system of the concrete mixtures, i.e. the air content, the specific surface and the spacing factor. The higher specific surface of the conventional with respect to the recycled concrete indicates a larger number of small air voids, which also can be observed in Fig. 6. According to Pigeon and Pleu [55], specific surface values in the range of 25 mm^{-1} to 45 mm^{-1} are considered acceptable for freeze/thaw durability. However, only the conventional concrete complies with the recommendation. Regarding to the adequate distribution of the air bubbles, the values of spacing factor for all concretes exceeded the recommended 0.2 mm [38], and recycled concrete mixtures displayed figures between 36% and 39% higher than the conventional concrete.

In brief, the fact that none of the recycled concrete mixtures complied with the recommendations in air content, specific surface or spacing factor is in agreement with previous results of lack of fulfilment of the UNE EN 1339 [34] standard requirement. Nevertheless, it is worth remarking that no air entrainment agent was employed in this research work. Hence, the use of such admixture will considerably increase the frost resistance of both conventional and recycled concrete mixtures, as Salem et al. [51] proved that the use of air entrainment agent in recycled concrete significantly improves the freeze-thaw resistance.

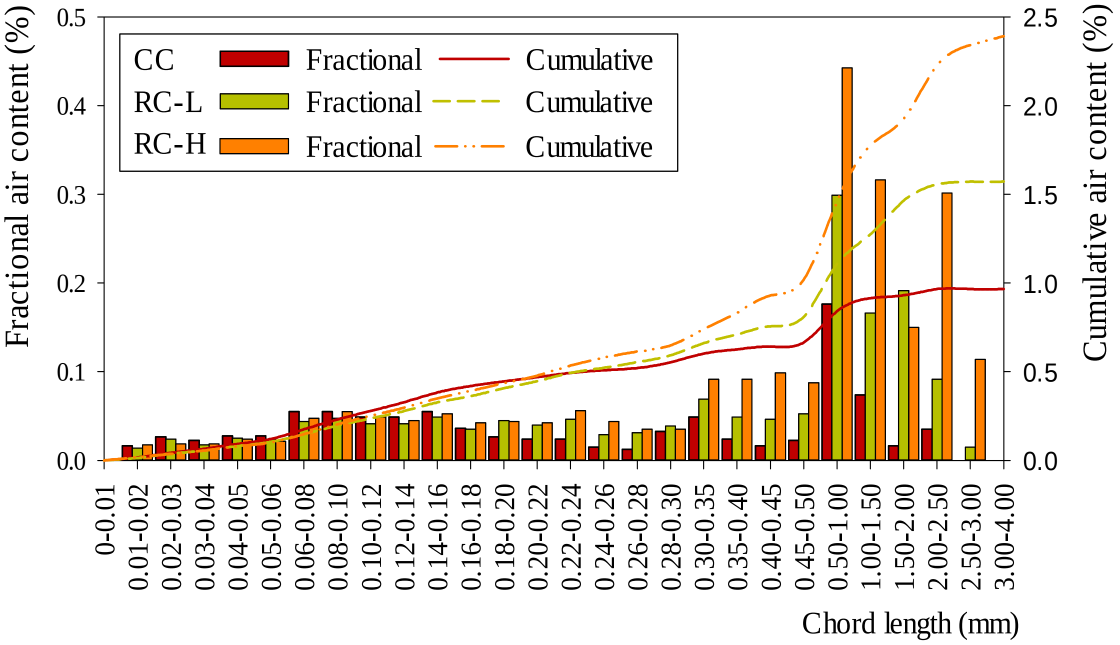

Figure 6: Air-void distribution from linear traverse measurement of the conventional and recycled mixtures

Table 4: Air void results by linear traverse method

	Air content [%]		**Specific surface [mm^{-1}]**	**Powers' spacing factor [mm]**
	Total	**<0.5 mm**		
CC	0.96	0.66	36.03	0.33
RC-L	1.57	0.81	22.43	0.45
RC-H	2.40	1.02	16.53	0.46

Conclusions

Despite general knowledge indicates that recycled aggregates present a low quality when compared to natural aggregates, their use in concrete proved to lead to similar and improved freeze-thaw durability in casting surfaces, for concrete containing low and high ceramic contents respectively. However, due to the finishing of the trowelled surface, both recycled concretes exhibited a worse behavior than the conventional mixture. Nonetheless, the presence of increasing ceramic contents had a beneficial effect in the final result. Thus, the mixture with high ceramic content suffered an 8% decline with respect the reference concrete, whereas the mixture with low ceramic content exhibited a 26% drop in freeze-thaw behavior.

Anyway, the results suggested that the composition of the recycled aggregates could be used as a factor to limit the differences in performance between recycled and conventional mixtures. Despite ceramic recycled aggregates have a greater porosity than natural gravel, and thus are able to hold more freezable water, the resulting finer porous network of the recycled concrete proved to be beneficial for the freeze-thaw resistance. Additionally, the ceramic content also led to improvements in the content of entrained air, which allow to dissipate some of the hydraulic stresses generated.

At compliance level, none of the concrete mixtures conformed to the mass loss threshold of the European standard. However, the climatic study of the collecting zones of the recycled aggregates, i.e. the more likely location for the use of the resulting recycled concrete, show that the natural exposure conditions are significantly less severe than those imposed in the laboratory test. And therefore, the ultimate freeze-thaw durability values reached by the recycled concretes should not be considered against the use of recycled aggregates in road applications subjected to frost salt damage. Nevertheless, it is worth mentioning that the use of an air entraining agent would significantly improve the final performance.

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