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Use of waste materials in the production of concrete

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Abstract: The world's demand for construction aggregates has been increasing over the last years, mainly due to the rapid economic growth of countries such as Brazil, China and India. Naturally, this growth stimulates the development of construction and demolition activities, thereby generating increasing amounts of waste. This paper presents a state-of-the-art review of the experimental research on the effect of incorporating aggregates of different types and shapes, sourced from construction and demolition waste. This review also covers studies on the incorporation of waste materials coming from industrial activities, emphasising those performed in the Instituto Superior Técnico, of the University of Lisbon, Portugal.

Introduction

The construction industry embodies one of the largest and most active sectors in the European Union (EU), consuming more raw matter and energy than any other economic activity. For this reason, wastes produced by its activities constitute the great majority of wastes produced throughout the EU.

The increasing consumption of natural resources, along with the excessive production of construction and demolition wastes (CDW), has been the cause of great concern in terms of the environment and economy. In order to reverse this trend, there have been several efforts to promote the ecological efficiency in the construction industry, one of them being the reuse of CDW in new construction works. The increasing production of industrial wastes is also an increasing concern to the environment, since its final destination is, in most cases, a landfill. Indeed, this option is without any economic potential as it precludes the reuse of the wastes. Bearing this in mind, the use of recycled aggregates (RA) as a replacement for natural aggregates (NA) in the production of concrete is considered as one of the most beneficial methods to an effective recycling of materials and thus increases sustainability in the construction industry.

Studies performed on the use of RA in the production of concrete have generally shown a decline of the mechanical and durability-related performances, when compared to those of natural aggregate concrete (NAC), with the same characteristics (mix design, curing conditions, strength class, etc.). There is also a consensus in that, as the replacement level increases, the greater the differences between the performances of recycled aggregate concrete (RAC) and that of NAC.

This paper displays the main results and conclusions of experimental research and reviews, concerning several themes related to the use of various types of RA in the production of concrete, performed in the Instituto Superior Técnico, of the University of Lisbon, Portugal.

Production of concrete with recycled aggregates from construction and demolition wastes

The study of RAC started in the 1970's. Initially, very basic observations and analysis were made relative to the behaviour of this material. Since then, several progressively more complex studies have been made, analysing several variables for different replacement levels.

Within the CDW, three main types of RA have been identified; they may come from crushed concrete, building masonry or mixed debris. Generally, recycled concrete aggregates (RCA) are composed of, at least, 90% of crushed concrete. The same amount is considered for recycled masonry aggregates (RMA), in which, instead of concrete, at least 90% must be composed of non-structural materials used for filling walls (ceramic bricks, lightweight concrete blocks, ground granulated blast furnace slag bricks, etc.) [1]. Mixed recycled aggregates (MRA) are composed of the two aforementioned aggregates, in which their contents vary according to existing specifications [2-15].

Recycled concrete aggregate

Evangelista and de Brito [16, 17] studied the mechanical and durability-related performance of structural concrete mixes produced with fine RCA. The results showed that it is possible to completely replace the fine aggregate fraction with compressive strength losses below 10% (Figure 1). However, for the same replacement level, the splitting tensile strength and the modulus of elasticity decreased 23% and 18%, respectively. The tensile strength is not as affected by the cement content as the compressive strength, so the tensile strength does not particularly benefit from the additional cement that is incorporated along with the fine RCA. Therefore, it is perfectly natural that a decrease occurs as the replacement ratio rises, due to the more porous structure of the RA. The concrete's modulus of elasticity is deeply related to the stiffness of the coarse aggregates, the stiffness of the mortar, their porosity and bond [18, 19]. Therefore, for small replacement ratios, it is possible that the overall stiffness is not significantly influenced, because the mortar stiffness is only one of several factors, while for total replacement the mortar withstands such a big stiffness loss that the concrete's modulus of elasticity is considerably affected.

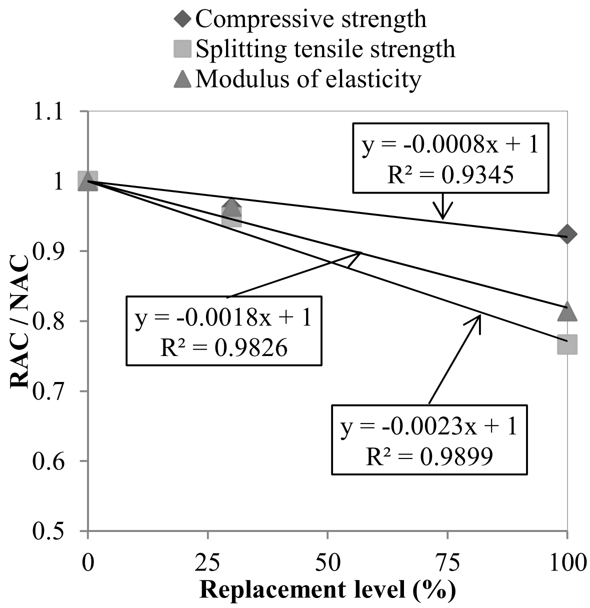


Figure 1 - Relationship between the 28-day mechanical properties of RAC and NAC of concrete mixes with increasing fine RCA content [16]

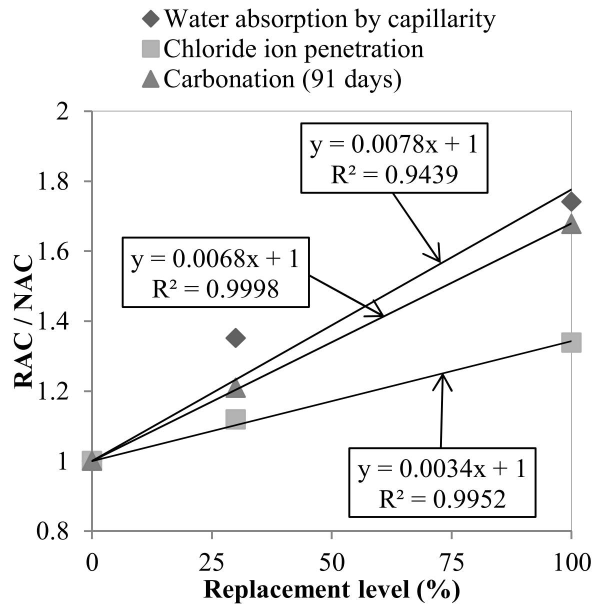


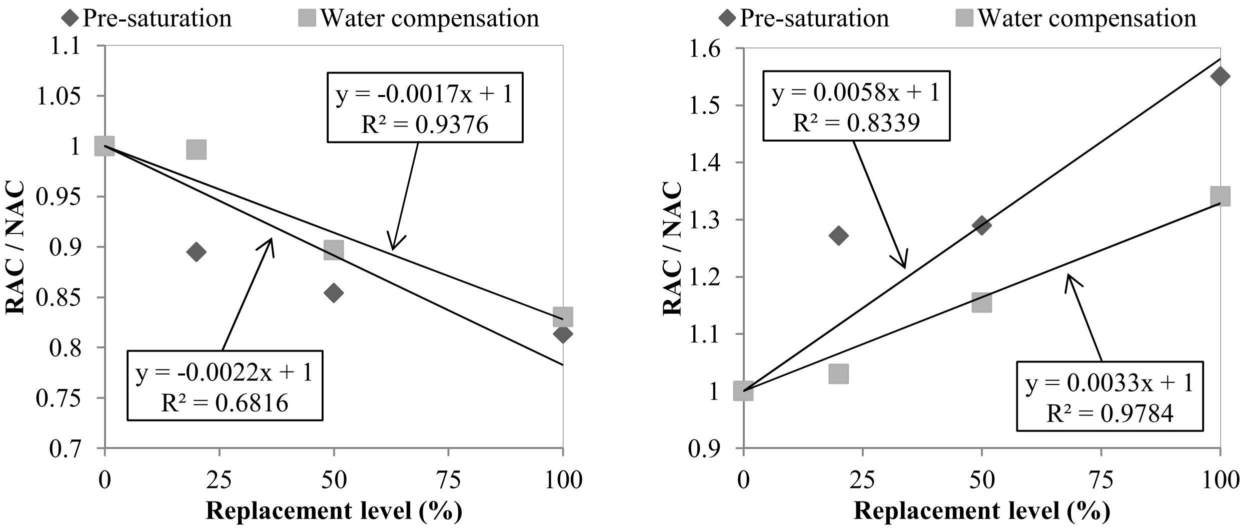
Figure 2 - Relationship between the durability-related properties of RAC and NAC of concrete mixes with increasing fine RCA content [17]

Concerning the durability-related performance, RAC mixes with 100% fine RCA content showed a considerable decline (Fig. 2). This was more noticeable in the water absorption by capillarity and carbonation depths (increases of 78 and 68%, respectively, when compared to the reference concrete). The authors concluded that, in order to produce structural concrete with acceptable losses in performance, the replacement level of fine RCA would have to be limited to 30% by volume.

The same authors [20] performed a life cycle assessment (LCA) on concrete mixes made with fine RCA in order to understand their real benefits. The results of this LCA consistently pointed to very positive impacts on the environment as a result of the direct replacement of sand with fine RCA, mainly due to the decreasing extraction of natural resources and all of its related activities.

Vieira et al. [21] studied the mechanical behaviour of concrete, made with coarse RCA, after having been exposed to fire. The authors came to the conclusion that, despite the greater porosity and different thermal properties in the interfacial transition zone (ITZ) between the RCA and the cement matrix of RAC, when compared to the reference concrete, mixes with increasing coarse RCA content did not exhibit significantly different thermal performance. Additionally, the variation of the residual mechanical properties (compressive and splitting tensile strength, and modulus of elasticity) of RAC specimens, after having been exposed to high temperatures, was quite similar to that shown by the reference concrete. In other words, the results suggested that there was no relationship between the degradation of the residual mechanical properties and the increasing coarse RCA content, regardless of the maximum exposure temperature.

A recent study was performed on the influence of curing conditions on the mechanical [22] and durability-related [23] performances of concrete with increasing coarse RCA. As expected, concrete specimens cured in drier environments behaved more poorly than those cured in a wet chamber or in water tanks, due to the less efficient hydration process of the cement particles. However, by comparing the properties of concrete mixes cured in different environments, it was concluded that the increasing replacement level had little or no effect on the relative performance of concrete.



a) b)

Figure 3 - Relative 28-day compressive strength (a) and water absorption by capillarity (b) of concrete mixes produced using different mixing methods and with increasing coarse RCA content [24]

Owing to the greater water absorption capacity of RCA, it was understood that, in order to avoid a significant loss in consistency, these materials must be used in saturated and surface-dried conditions [1]. Ferreira et al. [24] studied the influence of using pre-saturated coarse RCA against to another method for compensating the water absorbed by the RA [25]. Although the authors were able to produce concrete batches with equivalent workability for both mixing methods, the results of the consistency tests performed on mixes produced with pre-saturated RCA showed that these are somewhat more unstable than those with water compensated RCA. Furthermore, the compressive strength values of specimens made with pre-saturated RCA were slightly worse than those produced with water compensated RCA (Fig. 3a). This decline in performance was more noticeable in the water absorption by capillarity (Fig. 3b). Concrete mixes made with 100% coarse pre-saturated RCA exhibited values almost 60% higher than those of the reference concrete, whilst mixes made with the water compensation method presented values only 33% greater.

De Brito and Robles [26] registered patent no. PT103756 - "Methodology for estimating concrete with recycled aggregates", which, as the name suggests, allows a prediction of the performance of a RAC, based on an extensive state-of-the-art-review of international experimental research. The proposed methodology consisted on the prior determination of the main properties (density and water absorption) of all of the combined aggregates (NA + RA), as well as the 7-day compressive strength. This methodology was validated based on the graphical analysis of the main concrete properties produced with such aggregate combination (compressive and splitting tensile strength, modulus of elasticity, shrinkage, creep, water absorption, carbonation and chloride ion penetration). The authors concluded that this methodology may predict the long-term performance of RAC, when compared with the reference concrete. Given its low cost and the short time required to estimate the long-term performance of concrete, it was also realised that it may be adapted to the design stage of a concrete structure.

De Brito and Alves [27] applied the methodology of the previous work [26] to the experimental research performed in Portugal. Despite the smaller sample size (the majority of which came from studies performed in Instituto Superior Técnico) in comparison to the previous study [26], the results showed the validity of the proposed methodology to estimate the long-term performance of concrete.

Another subject matter of great interest, which oddly has not been studied enough, is the multiple recycling of concrete. In other words, determining how many times aggregates sourced from crushing concrete may be used in the production of new concrete mixes until a significant decline in performance occurs. De Brito et al. [28] studied the properties of such materials, sourced from three cycles of recycling. The results showed that all RAC mixes exhibited similar compressive strength class between them and to that of the reference NAC. These results suggest that concrete may be subjected to an endless number of recycling cycles without exhibiting a significant loss in performance. However, given the rather low number of studies on this subject matter, further research on this matter is needed, in which the durability-related performance is also analysed.

Recently, studies were performed on the influence of adding different types of water reducing admixtures (WRA), on the mechanical behaviour of concrete with coarse [29, 30] and fine [31, 32] RCA. The results led to the conclusion that it is indeed possible to produce RAC with high coarse or fine RCA contents with acceptable compressive strength loss. Apart from this, the authors found that, regardless of the replacement level, it is possible to produce high quality RAC using WRA. In one of the studies [29], the authors noticed that, for the same coarse RCA content, the compressive strength loss increased as the effective w/c ratio decreased, when compared with the reference concrete. As the w/c ratio of a concrete mix increases, the ultimate compressive strength becomes increasingly dependent on the strength of the aggregates, rather than that of the cement matrix. However, Pereira et al. [31] noticed that RAC mixes produced with a regular WRA (mixes with an effective w/c ratio around 0.45) exhibited a greater compressive strength loss as the fine RCA content increased (Fig. 4), in comparison to concrete mixes produced with a high range water reducing admixture (HRWRA) (mixes with an effective w/c ratio around 0.38). This behaviour was also noticed in another study [33], in which the durability-related performance of concrete produced with fine RCA was assessed. The results of Fig. 5 show that concrete mixes produced with regular WRA exhibited increasingly greater carbonation depths, as the fine RCA content increased, in comparison to the reference mixes and those produced with a HRWRA.

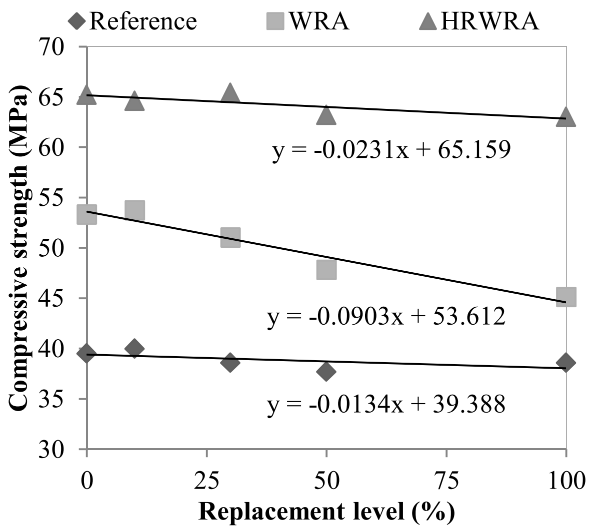


Figure 4 - 28-day compressive strength of concrete mixes with increasing fine RCA content [31]

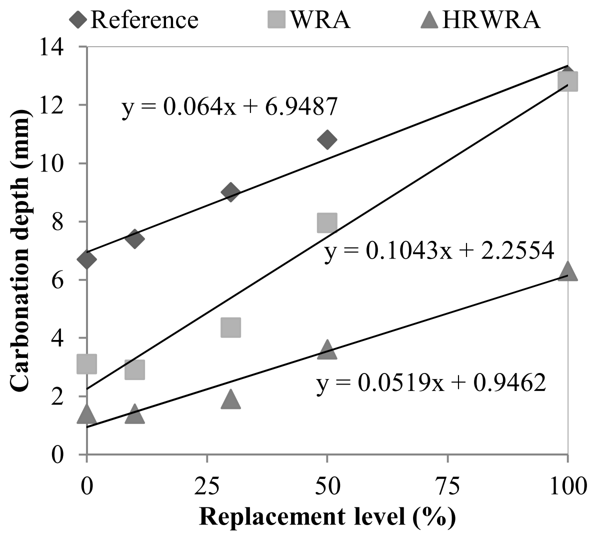


Figure 5 - 91-day carbonation depths of concrete mixes with increasing fine RCA content [33]

The alkali silica reactions (ASR) are degradation processes of conventional concrete mixes, which reduce their durability. Santos et al. [34] analysed several variables which could induce ASR in concrete with partial of full replacement of RA. By means of optic microscopy and scanning electron microscope (SEM), analysis performed on digital microscopic images executed in laboratory allowed improving the knowledge on these reactions. Some characteristics of RAC, such as greater porosity and lesser density, were also exhibited by the reference concrete mixes that showed less susceptibility to ASR development.

Bogas et al. [35, 36] studied the mechanical and durability-related performance of concrete mixes made with coarse RA, sourced from crushed lightweight concrete. The results allowed concluding that, although the introduction of RCA from lightweight concrete produced RAC mixes with enhanced mechanical performance and greater structural efficiency, these exhibited a decline in the durability-related performance.

Recycled masonry aggregates

De Brito et al. [37] and Correia et al. [38] studied the mechanical and durability-related performance, respectively, of concrete mixes made with coarse RA sourced from crushed ceramic bricks. As expected, the increasing RA content led to a decline in the mechanical performance of concrete (the use of 100% coarse RMA led to a 45% compressive strength loss, when compared with the control concrete). However, there was an improvement with the introduction of RMA in the resistance to abrasion (25% less material mass was removed when 100% coarse RMA was used).

In the experimental campaigns of Alves et al. [39] and Vieira [40] the mechanical and durability-related performance were evaluated, respectively, on concrete mixes using fine RMA. Two types of RMA were studied: from crushed ceramic bricks (which confirmed the same trends as those observed by Brito et al. [37] and Correia et al. [38]) and from sanitary ware rejects. The progressive inclusion of these materials led to interesting conclusions. Due to the similar water absorption between the fine RMA from sanitary ware and that of the natural sand, it was possible to produce RAC mixes with equal effective and global w/c ratio. However, as the replacement level increased a significant increase of the w/c ratio became necessary in order to maintain the slump. Besides their irregular shapes, this phenomenon was due to the bonding of the RA's vitreous surfaces owing to the Van der Waals forces of the water's hydrogen ions. Regarding the mechanical and durability-related performance, as expected, as the RMA content increased, these declined. This effect was more noticeable in concrete mixes made with fine RMA from sanitary ware due to the significant increase of the effective w/c ratio.

In the experimental campaign of Martins et al. [41], the behaviour of concrete, produced with coarse RA sourced from crushed ceramic bricks, after having been subjected to fire was studied. As expected, the compressive strength decreased with the increasing amount of these materials. However, as shown in Fig. 6, as the RAC mixes were subjected to progressively greater temperatures, those produced with increasing amount of coarse RMA showed a lower decline in mechanical performance. It was therefore concluded that the incorporation of these materials is capable of increasing the performance of concrete in terms of resistance to high temperatures.

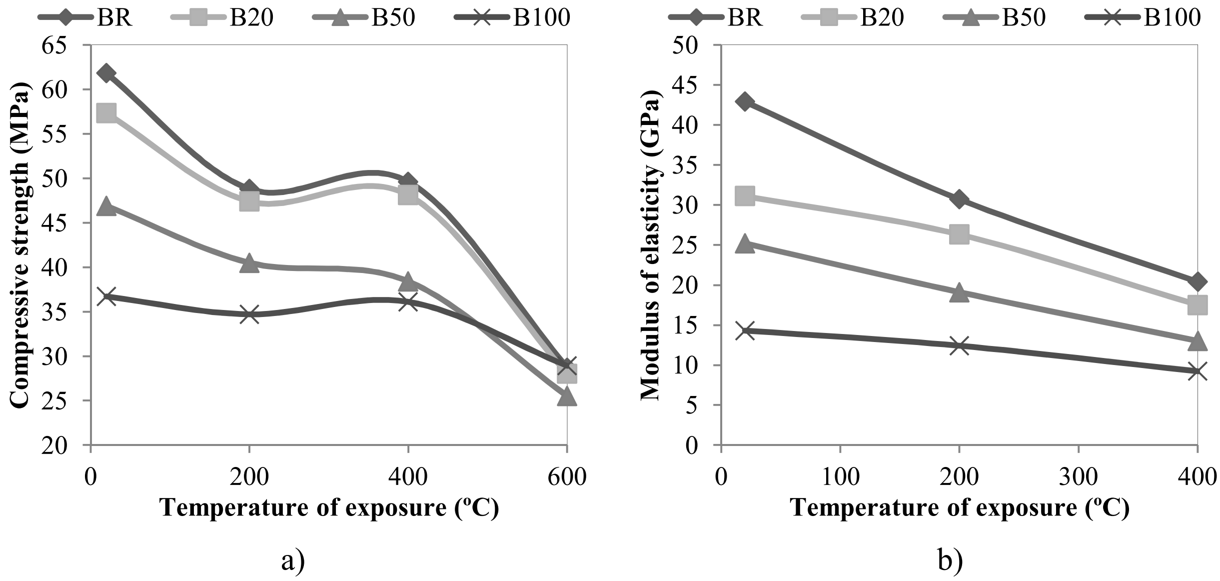


Figure 6 - Compressive strength (a) and modulus of elasticity (b) of concrete, produced with coarse RMA, after having been subjected to progressively greater temperatures [41]

Mixed recycled aggregates

Gomes et al. [42] and Gomes and de Brito [43] studied the mechanical and durability-related performance, respectively, of structural concrete mixes produced with various types of RA (i.e. RCA, RMA and MRA). Regardless of the RA type used, there was a decline of the mechanical and durability performances of concrete, which was more noticeable as the RA content increased. For the same replacement level, concrete mixes produced with coarse RCA exhibited a performance closer to that of the reference concrete, followed by concrete mixes made with MRA and finally, coarse RMA.

By studying the physical, chemical and mineralogical properties of fine MRA, sourced from Portuguese CDW recycling plants, Rodrigues et al. [44, 45] developed a test methodology, corresponding to patent no. PT105921, for the determination of the density and water absorption over time of fine RA. This methodology was essential because, after some time, the fine RA conglomerated, which therefore caused a problem in the process of determining the water absorption. The results of this study allowed the authors to conclude that, in order to improve the quality of fine RA, it is essential that CDW recycling plants add a washing stage to the recycling process prior to any application. This procedure would drastically reduce their silt content and would also practically eliminate all lightweight contaminants.

Production of concrete using recycled aggregates sourced from industrial wastes

The use of industrial wastes in the production of concrete is a practice which can be dated back to some decades. There is a wide range of cement blends produced with fly ash, ground granulated blast furnace slag and silica fume, all of which are wastes from industrial activities. At the present time, efforts are still being made to find new materials that can be used in the production of concrete, and thus contribute to a more sustainable construction industry.

Recycled aggregates from crushed marble

Martins et al. [46] and André et al. [47] studied the mechanical and durability-related performance, respectively, of concrete mixes made with coarse RA sourced from the marble industry. The authors compared the performance of these concrete mixes with those of conventional mixes made with basalt, quartzite and limestone aggregates. The full replacement of coarse NA caused a compressive strength loss of 10%, in comparison to the control concrete mixes. Except for modulus of elasticity and resistance to abrasion (losses up to 28% and 51%, respectively), generally, the introduction of RA from crushed marble only caused a slight decline in all properties.

Similarly to the previous studies [46, 47], Silva et al. [48] and Gameiro et al. [49] studied the mechanical and durability-related performance, respectively, but with the inclusion of the finer fraction of crushed marble. The results showed compressive strength loss values between 10 and 20%. The authors concluded that, in terms of durability, the introduction of fine RA from crushed marble could produce concrete mixes with similar performance to those of mixes made with fine granite, basalt or limestone.

Recycled aggregates from ground rubber tyres

Valadares et al. [50] and Bravo et al. [51] studied the mechanical and durability-related performance, respectively, of structural concrete mixes made with ground rubber from used tyres. The authors produced concrete mixes with replacement levels of 5, 10 and 15% with rubber tyres, with different sizes. Another property that was also taken into consideration was the production process of these materials, specifically the use of fine RA obtained through a cryogenic procedure. On average, the incorporation of 15% of these materials caused compressive strength loss values between 46 and 52% (Fig. 7). Generally, the use of RA from ground rubber tyres in the production of concrete caused a significant decline in the durability performance [51]. However, it was observed that the inclusion of these materials allowed producing concrete mixes with similar water absorption by capillarity values to those of the reference concrete (Fig. 8).

Similarly to the previous studies, Correia et al. [52] and Marques et al. [53] studied the behaviour of concrete mixes, made with RA from ground rubber tyres, after being subjected to fire. The results were very clear. The response to high temperatures of these materials was greatly influenced by the amount of RA from ground rubber, i.e. greater replacement levels caused a worse thermal response. This is due to the organic nature of rubber, which exhibited a greater flow and heat release, as well as a greater production of smoke.

Recycled aggregates from crushed glass

Serpa et al. [54] and Castro and de Brito [55] studied the mechanical and durability-related performance, respectively, of concrete mixes made with RA from crushed glass. The authors produced concrete mixes with replacement levels of 5, 10 and 20%, of NA with RA from crushed glass of different sizes. As expected, the 28-day compressive strength of concrete decreased with increasing amount of this material. This was due to the smooth and impervious surface of glass, which prevented an efficient bond with the cement paste. The degree of this decline increased when fine RA were introduced: compressive strength decreased around 20%, while the use of coarse RA only caused a 10% decrease, for the same replacement level of 20%. One interesting aspect of using these aggregates is that it allowed producing concrete mixes with a similar modulus of elasticity to that of the reference concrete. In terms of durability, the performance of these concrete mixes improved in terms of water absorption and carbonation resistance, but worsened for chloride ion penetration and shrinkage.

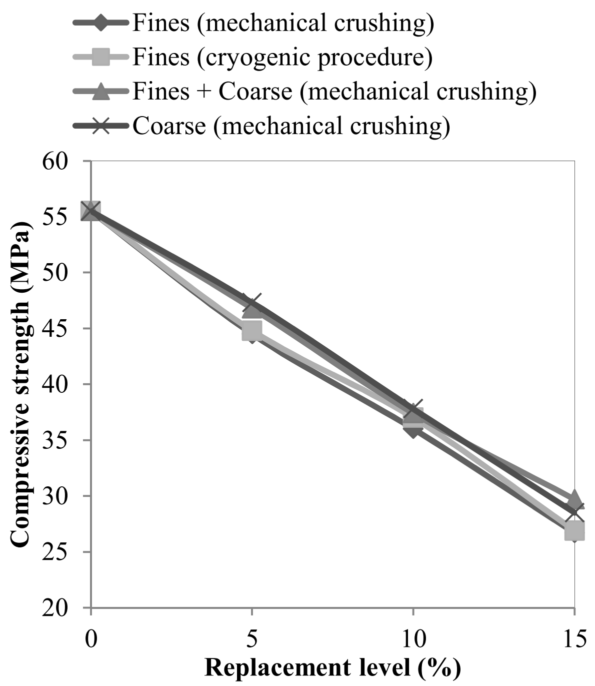


Figure 7 - Compressive strength of concrete with increasing RA from processed rubber tyres [50]

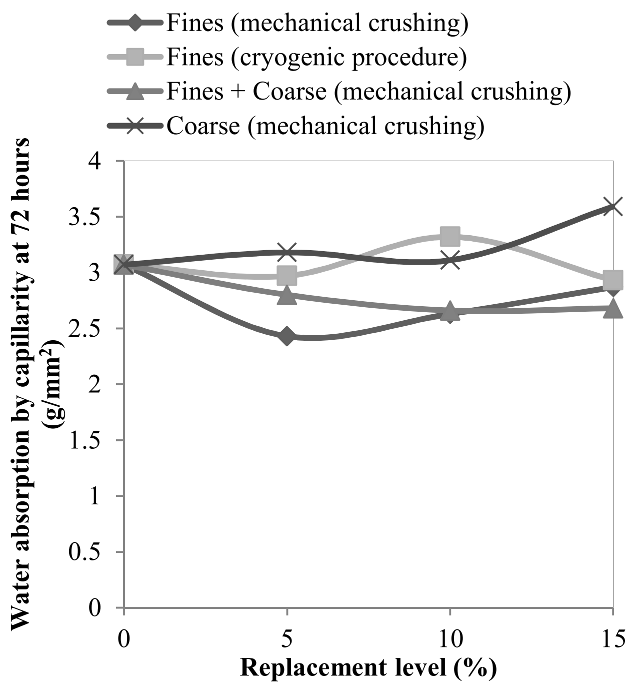


Figure 8 - Water absorption by capillarity of concrete with increasing RA from processed rubber tyres [51]

Recycled aggregates from plastic waste

Saikia and de Brito [56] produced a review on concrete mixes made with plastic RA, sourced from ground PET bottles. The incorporation of these materials caused a decline in the strength of concrete and mortars, due to the weak bond in the interfacial transition zone between plastic particles and cement paste. However, that reduction is less noticeable for splitting tensile and flexural strength. The use of these aggregates altered considerably the rupture mechanism of concrete; increased ductility, in comparison to the reference concrete, and strongly impaired cracking during concrete's failure. Another positive aspect of producing concrete mixes with these materials is that their resistance to abrasion, regardless of the size and shape of the plastic RA, is higher than that of the reference concrete [57, 58]. Concerning the durability-related performance, Silva et al. [59] noticed that the use of waste plastic RA caused a considerable decline in the performance of concrete. Such decline was aggravated by the use of plastic RA with greater sizes and with a flakier shape.

Correia et al. [60] studied the behaviour of concrete specimens, produced with RA from plastic waste with different shapes and sizes, after being subjected to very high temperatures. The mixes were produced with replacement levels of 7.5% and 15%. After being exposed to temperatures of 600 ºC and 800 ºC, a progressively greater decline was noticed in the mechanical performance as the replacement level increased. This was due to the rapid thermal decomposition of the waste plastic RA, in comparison to the other materials.

Other types of recycled aggregates

De Brito and Lopes [61] performed a qualitative analysis on the relative effects of incorporating several types of non-conventional RA, sourced from industrial wastes, on the mechanical and durability behaviour of concrete. Examples of such materials are leather, EVA (ethylene vinyl acetate), iron, coal, powder stone sludge, oyster shells, palm tree husk and even synthetic sewer sludge aggregates. Generally, the use of these materials as replacement for conventional aggregates caused a considerable decline in the mechanical and durability-related performance, unless they were used in very small amounts and/or as ultra-fine materials.

Conclusions

This paper, which describes the main results of various studies performed in Instituto Superior Técnico, studied the sustainability in construction of incorporating RA, sourced from processed CDW and industrial wastes, in the production of concrete. Indeed, the literature review on this subject allowed concluding that there is a wide range of materials acceptable in the production of concrete. However, for reasons of being more easily processed, compatibility with the construction materials and their availability in the market, only some of these materials may be used in a large scale.

Although some materials sourced from industrial activities (e.g. ground granulated blast furnace slag, and fly ash) have already proven their viability in producing good quality concrete, most of the industrial wastes are incompatible with the remaining constituents of concrete. As one of the studies revealed, generally, as the replacement level of these materials increases, there is a strong decline in the performance of concrete.

Concerning RA from processed CDW, three main types were identified, i.e. RCA, RMA and MRA. Of these, RCA were considered the most compatible with concrete production, mainly because these are sourced from crushed materials similar to those in which they are going to be reused. The use of these materials has led to considerably lower strength losses than when using other types of RA from CDW (RMA and MRA). Naturally, due to the variation of the quality and strength of the original concrete materials, from which the RCA are sourced, additional precautions are required, in order to ensure their best possible use in the production of structural concrete.

To ensure that good quality RA are produced, quality control must start during the construction and demolition activities. By performing a selective demolition, CDW will be sorted and stored correctly, which, apart from simplifying the job of recycling plant personnel, will also minimize contamination levels of future RA. The reduction of these contamination levels may be perfected with the use of processing techniques suitable for the type and size of a given material (e.g. a washing process applied to fine RA will practically remove all lightweight contaminants).

Generally, the introduction of RCA causes a decline in the fresh, mechanical and durability-related performance of concrete. However, this decline in performance is of little significance when analysed on the basis of the properties' absolute numerical values and can be easily counteracted by slightly adjusting the mix design of concrete. For each type of material it is possible to establish a maximum replacement level of NA with RA, which, by adjusting the cement and water reducing admixtures contents, will increase the feasibility of producing good quality structural concrete.

Regardless of the type of RA, the coarser fraction generally allows producing RAC mixes with a more similar performance to that of the reference concrete, rather than when using the finer fraction of the same materials. However, several studies have shown that it is indeed possible to produce concrete using fine RA, as long as these are applied with special precaution (e.g. compensation of the water absorbed by fine RA, strict limitation of the replacement levels, careful control of the quality of the original material).

Despite lack of information on multiple recycling of concrete, studies suggest that these can be subjected to a high number of recycling cycles without demonstrating a significant loss in performance. Nevertheless, this inference must be verified by additional research.

One of the most important conclusions drawn from the literature review is that RA from processed CDW may be considered as raw material for the production of concrete, as long as these are submitted to proper recycling procedures. This concept, in which RA are considered as valuable materials instead of useless wastes, is a step forward to a more sustainable construction industry.

References

[1] T.C. Hansen, Recycling of Demolished Concrete and Masonry, E & FN Spon, London, UK, 1992.

[2] JIS-5021, Recycled aggregate for concrete-class H, Japan Standards Association, 2011, 30 p.

[3] JIS-5022, Recycled aggregate for concrete-class M, Japan Standards Association, 2012, 74 p.

[4] JIS-5023, Recycled aggregate for concrete-class L, Japan Standards Association, Japan, 2012, 68 p.

[5] BCSJ, Proposed standard for the use of recycled aggregate and recycled aggregate concrete, Committee on Disposal and Reuse of Construction Waste, Building Contractors Society of Japan, 1977.

[6] BRE, Recycled aggregates, Building Research Establishment, 1998, 6 p.

[7] BS-8500, Concrete - complementary British Standard to BS EN 206-1 - Part 2: Specification for constituent materials and concrete, British Standards Institution, 2006, 52 p.

[8] DIN-4226, Aggregates for mortar and concrete, Part 100: Recycled aggregates, Deutsches Institut für Normungswesen (DIN), 2002, 29 p.

[9] EN-12620, Aggregates for concrete, Comité Européen de Normalisation (CEN), 2002, 56 p.

[10] LNEC-E471, Guide for the use of coarse recycled aggregates in concrete, National laboratory of Civil Engineering (Laboratório Nacional de Engenharia Civil - LNEC), 2006, 6 p.

[11] NBR-15.116, Recycled aggregate of solid residue of building constructions - Requirements and methodologies, Brazilian Association for Tecnical Norms (Associação Brasileira de Normas Técnicas - ABNT), 2005, 18 p.

[12] OT-70085, Use of secondary mineral construction materials in the construction of shelters, Objectif Technique, Instruction Technique, Schweizerische Eidgenossenschaft, 2006, 16 p.

[13] WBTC-No.12, Specifications facilitating the use of recycled aggregates, Works Bureau Technical Circular, 2002, 16 p.

[14] CCANZ, Best practice guide for the use of recycled aggregates in new concrete, CCANZ Publications, Cement and Concrete Association of New Zealand, 2011, 49 p.

[15] RILEM, Specifications for concrete with recycled aggregates, Mater. Struct. 27 (1994), 557-559.

[16] L. Evangelista, J. de Brito, Mechanical behaviour of concrete made with fine recycled concrete aggregates, Cem. Concr. Compos. 29 (2007), 397-401.

[17] L. Evangelista, J. de Brito, Durability performance of concrete made with fine recycled concrete aggregates, Cem. Concr. Compos. 32 (2010), 9-14.

[18] A.S. Coutinho, Production and properties of concrete: Volumes I and II [*in Portuguese*], LNEC, Lisboa, Portugal, 2006.

[19] A.M. Neville, Properties of concrete, Longman, London, UK, 1995.

[20] L. Evangelista, J. de Brito, Environmental life cycle assessment of concrete made with fine recycled concrete aggregates, in: Portugal Sb07 - Sustainable Construction, Materials and Practices: Challenge of the Industry for the New Millennium, Pts 1 and 2, 2007, pp. 789-794.

[21] J.P.B. Vieira, J.R. Correia, J. de Brito, Post-fire residual mechanical properties of concrete made with recycled concrete coarse aggregates, Cem. Concr. Res. 41 (2011), 533-541.

[22] N. Fonseca, J. de Brito, L. Evangelista, The influence of curing conditions on the mechanical performance of concrete made with recycled concrete waste, Cem. Concr. Compos. 33 (2011), 637-643.

[23] P. Amorim, J. de Brito, L. Evangelista, Concrete made with coarse concrete aggregate: Influence of curing on durability, ACI Mater. J. 109 (2012), 195-204.

[24] L. Ferreira, J. de Brito, M. Barra, Influence of the pre-saturation of recycled coarse concrete aggregates on concrete properties, Mag. Concr. Res. 63 (2011), 617-627.

[25] M.B. Leite, Evaluation of the mechanical properties of concrete produced with recycled aggregates from construction and demolition wastes [*in Portuguese*], Dissertation for the degree of Doctor in Civil Engineering, Federal University of Rio Grande do Sul, 290 p.

[26] J. de Brito, R. Robles, Recycled aggregate concrete (RAC) methodology for estimating its long-term properties, Indian Journal of Engineering and Materials Sciences. 17 (2010), 449-462.

[27] J. de Brito, F. Alves, Concrete with recycled aggregates: the Portuguese experimental research, Mater. Struct. 43 (2010), 35-51.

[28] J. de Brito, A.P. Gonçalves, R. Santos, Recycled aggregates in concrete production - Multiple recycling of concrete coarse aggregates, Revista Ingeniería de Construcción. 21 (2006), 33-40.

[29] A. Barbudo, J. de Brito, L. Evangelista, M. Bravo, F. Agrela, Influence of water-reducing admixtures on the mechanical performance of recycled concrete, J. Cleaner Prod. 59 (2013), 93-98.

[30] D. Matias, J. de Brito, A. Rosa, D. Pedro, Mechanical properties of concrete produced with recycled coarse aggregates - Influence of the use of superplasticizers, Constr. Build. Mater. 44 (2013), 101-109.

[31] P. Pereira, L. Evangelista, J. de Brito, The effect of superplasticisers on the workability and compressive strength of concrete made with fine recycled concrete aggregates, Constr. Build. Mater. 28 (2012), 722-729.

[32] P. Pereira, L. Evangelista, J. de Brito, The effect of superplasticizers on the mechanical performance of concrete made with fine recycled concrete aggregates, Cem. Concr. Compos. 34 (2012), 1044-1052.

[33] F. Cartuxo, Concrete with fine recycled aggregates from crushed concrete - Influence of water reducing admixtures on the durability-related performance [*in Portuguese*], Dissertation for the degree in Masters in Civil Engineering, Department of Civil Engineering and Architecture, Intituto Superior Técnico, University of Lisbon, 347 p.

[34] M.B. Santos, J. de Brito, A.S. Silva, Methods for the evaluation of the alkali-silica reactions of recycled aggregate concrete [*in Spanish*], Revista Ingeniería de Construcción. 24 (2009), 141-152.

[35] J. Bogas; J. de Brito; J. Figueiredo, Mechanical characterization of concrete produced with recycled lightweight expanded clay aggregate concrete, J. Cleaner Prod. [submitted for publication].

[36] J. Bogas; J. de Brito; J. Cabaço, Long-term behaviour of concrete produced with recycled lightweight expanded clay aggregate, Constr. Build. Mater [submitted for publication].

[37] J. de Brito, A.S. Pereira, J.R. Correia, Mechanical behaviour of non-structural concrete made with recycled ceramic aggregates, Cem. Concr. Compos. 27 (2005), 429-433.

[38] J.R. Correia, J. de Brito, A.S. Pereira, Effects on concrete durability of using recycled ceramic aggregates, Mater. Struct. 39 (2006), 169-177.

[39] A.V. Alves, T.F. Vieira, J. de Brito, J.R. Correia, Mechanical properties of structural concrete with fine recycled ceramic aggregates, Constr. Build. Mater. 64 (2014), 103-113.

[40] T. Vieira, Concrete incorporating fine recycled ceramic aggregates: Durability-related performance [*in Portuguese*], Dissertation for the degree in Masters in Civil Engineering, Department of Civil Engineering and Architecture, Instituto Superior Técnico, University of Lisbon, 278 p.

[41] D. Martins; J. Correia; J. de Brito, The effect of high temperature on the residual mechanical performance of concrete made with recycled ceramic coarse aggregates, Mate. Des. [submitted for publication].

[42] M. Gomes, J. de Brito, M. Bravo, Structural concrete with incorporation of coarse recycled concrete and ceramic aggregates: Mechanical performance, J. Mater. Civ. Eng. doi:10.1061/(ASCE)MT.1943-5533.0000973 (2013).

[43] M. Gomes, J. de Brito, Structural concrete with incorporation of coarse recycled concrete and ceramic aggregates: durability performance, Mater. Struct. 42 (2009), 663-675.

[44] F. Rodrigues, M. Carvalho, L. Evangelista, J. de Brito, Physical-chemical and mineralogical characterization of fine aggregates from construction and demolition waste recycling plants, J. Cleaner Prod. 52 (2013), 438-445.

[45] F. Rodrigues, L. Evangelista, J. de Brito, A new method to determine the density and water absorption of fine recycled aggregates, Mater. Res. 16 (2013), 1045-1051.

[46] P. Martins, J. de Brito, A. Rosa, D. Pedro, Mechanical performance of concrete with incorporation of coarse waste from the marble industry, Materials Research Journal [submitted for publication].

[47] A. André, J. de Brito, A. Rosa, D. Pedro, Durability performance of concrete incorporating coarse aggregates from marble industry waste, J. Cleaner Prod. 65 (2014), 389-396.

[48] D. Silva, F. Gameiro, J. de Brito, Mechanical properties of structural concrete containing fine aggregates from waste generated by the marble quarrying industry, J. Mater. Civ. Eng. dx.doi.org/10.1061/(ASCE)MT.1943-5533.0000948 (2014).

[49] F. Gameiro, J. de Brito, D. Correia da Silva, Durability performance of structural concrete containing fine aggregates from waste generated by marble quarrying industry, Eng. Struct. 59 (2014), 654-662.

[50] F. Valadares, M. Bravo, J. De Brito, Concrete with used tire rubber aggregates: Mechanical performance, ACI Mater. J. 109 (2012), 283-292.

[51] M. Bravo, J. De Brito, Concrete made with used tyre aggregate: Durability-related performance, J. Cleaner Prod. 25 (2012), 42-50.

[52] J.R. Correia, A.M. Marques, C.M.C. Pereira, J. de Brito, Fire reaction properties of concrete made with recycled rubber aggregate, Fire Mater. 36 (2012), 139-152.

[53] A.M. Marques, J.R. Correia, J. De Brito, Post-fire residual mechanical properties of concrete made with recycled rubber aggregate, Fire Saf. J. 58 (2013), 49-57.

[54] D. Serpa, J. de Brito, J. Pontes, Concrete made with recycled glass aggregates: Mechanical performance, ACI Mater. J. [accepted for publication].

[55] S. de Castro, J. de Brito, Evaluation of the durability of concrete made with crushed glass aggregates, J. Cleaner Prod. 41 (2013), 7-14.

[56] N. Saikia, J. de Brito, Use of plastic waste as aggregate in cement mortar and concrete preparation: A review, Constr. Build. Mater. 34 (2012), 385-401.

[57] L. Ferreira, J. De Brito, N. Saikia, Influence of curing conditions on the mechanical performance of concrete containing recycled plastic aggregate, Constr. Build. Mater. 36 (2012), 196-204.

[58] N. Saikia, J. de Brito, Mechanical properties and abrasion behaviour of concrete containing shredded PET bottle waste as a partial substitution of natural aggregate, Constr. Build. Mater. 52 (2014), 236-244.

[59] R.V. Silva, J. de Brito, N. Saikia, Influence of curing conditions on the durability-related performance of concrete made with selected plastic waste aggregates, Cem. Concr. Compos. 35 (2013), 23-31.

[60] J. Correia, J. Saraiva Lima, J. de Brito, Post-fire residual mechanical performance of concrete made with selected plastic waste aggregates, Cem. Concr. Compos. [submitted for publication]

[61] J. de Brito, R. Lopes, Concrete: An ecological end-of-life for industrial wastes [*in Portuguese*], in: 6º Congresso Luso-Moçambicano de Engenharia (CLME'2011), Maputo, Moçambique, 2011.