

New recycling technologies of demolished materials for sustainable finishes: the project of concrete reuse on site in Tres Cantos, Madrid

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Abstract: The work presented aims to analyse the feasibility of reusing concrete, once demolished from a building in Tres Cantos in Madrid, to manufacture finishing materials for buildings, as well as to design a procedure. The first phase consists of a bibliographic search on the reuse of materials, analysing the techniques adopted so far and the lines of work. The second phase related to the acquisition of data related to the production and recycling of Construction and Demolition Waste (CDW) at a European level. The third phase consists of the study of recycled aggregates resulting from demolitions or landslides, their treatment process. The fourth and final phase consists of the development of a laboratory test plan to evaluate varied materials for finishing exterior cement pavements with concrete from the demolition of the case study building. There were many conclusions and results of the project. The granulometry of the fine fraction of demolished concrete is suitable to produce non-structural products, such as building finishes and in particular non-driveway outdoor flooring. In terms of flexural and compressive strength, the mechanical behaviour of recycled mixes is lower than that of reference mixes. The recycled mixes show slightly higher capillary absorption capacities than the reference mixes, and the value is higher the greater the percentage of recycled aggregates used (a critical issue which can be resolved by pre-saturating the recycled material).

Keywords: reusing concrete, recycled aggregate, waste, sustainability, circular economy.

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1. Introduction

The paper presents the path and initial results of a research project aimed at the on-site reuse of demolished concrete to produce non-structural products such as building finishes. As a case study, the demolition of a building in Tres Cantos, a city in the autonomous community of Madrid in Spain, was chosen as a critical approach. The building, an office building that had been disused for years, was in a state of total disrepair with parts in disrepair and others in need of restoration. The objective of the contribution is to propose, firstly, a partial demolition and not a total demolition, reducing the amount of building waste, and secondly, to trigger an unprecedented process of reuse of the waste material, through a preliminary laboratory study on samples taken inside the structure. This solution would initiate a virtuous process by providing a plan to recycle materials on site already at the design stage.

On-site sifting of the demolished concrete revealed three different grain sizes, aggregates with a grain size greater than 4 mm, aggregates with a grain size of less than 4 mm, and finally, dust, i.e., aggregates smaller than 0.125 mm. Aggregates with a grain size greater than 4 mm are prepared for drainage paving in outdoor spaces, ensuring the absorption of meteoric water into the subsoil to replenish the water table. In addition, aggregates with a grain size of less than 4 mm, i.e., 0.125 mm and 0.063 mm, are excluded from the experiments as they are in the form of dust. Therefore, the study focused on aggregates with a grain size between 2 mm and 0.250 mm for the purpose of on-site production of non-driveway external paving products. In line with the objectives of the circular economy, the decision to use only screening to determine the particle size of the aggregates should be read, without resorting to machines to crush the aggregates, to avoid further processes with the inevitable related energy expenditure. In this research work, therefore, an alternative proposal to the total demolition of the building is put forward and, depending on the future use and state of conservation, the possibility of partial demolition is pursued. This makes it possible to recover rooms, with a consequent optimisation of the use of resources and, at the same time, to prepare on-site interventions aimed at recovering the demolished concrete.

2. State of the art

Recycling is not a prerogative of the modern age: it has been a human habit since prehistoric times. According to a study conducted by the Catalan Institute of Human Paleocology and Social Evolution and published in the *Journal of Archaeological Science*, humans relied

on recycling as early as thirteen thousand years ago, in the Upper Palaeolithic. An analysis of the tools found at the Upper Palaeolithic site of Molí del Salt in Tarragona, Spain, has revealed a double life for the tools. In fact, the stones, suitably sharpened to become rudimentary hunting tools, would have been modified when the blade was no longer sharp enough, converting them into tools for tanning skins or cooking. This propensity to salvage was dictated by the natural optimisation of processing times, it being more convenient to modify an already processed rock than a new one. In fact, prehistoric nomadic peoples often appropriated objects found in abandoned camps, so that they did not have to recreate them from scratch, a skill that could be considered as 'innate', i.e., the most logical choice for these very ancient populations (Vaquero, 2008).

In support of the thesis that the idea of reusing waste has always belonged to human beings, the texts of ancient civilisations give us evidence of this. Studies on Roman masonry reveal a mature knowledge of good practices for the recovery of materials, such as those that emerge from Vitruvius' *De Architectura*, where it is "fascinating to see how the ancients re-used oiled amphorae to lighten the weight of vaults or pieces of roof tiles as wall reinforcement; it is interesting to see how shards were pounded to be re-mixed and obtain new mortar, and it is also unusual to learn of fibrous-reinforcing hair for floors" (Trinchese, 2019). The city of Pompeii, buried by the eruption of Vesuvius in 79 A.D. during the post-earthquake reconstruction of 62 A.D., also offers an insight into the choices made in rebuilding the buildings that collapsed after the earthquake. The choice of construction techniques to be used was based on the re-use of collapsed materials both for reasons of cost and speed of retrieval. Certainly, the *opus latericium* (*opus latericium*), the *opus incertum* (*opus incertum*) and the *opus mixtum* (*opus mixtum*) responded best to the need to use waste material. Finally, Vitruvian work also lends the right to recall reuse in Greece; Vitruvius, in fact, extols the ability of the Greeks, even before the Romans, to reuse the plaster of old walls as bricks (Trinchese, 2019). Remaining in the Aegean territories, in many Hellenistic cities, during the long periods of Augustan peace, there was a reuse of massive defensive systems, both through the reuse of materials and through a redefinition of urban environments and boundaries, almost in contrast to what happened in the medieval period, when towers, walls and forts were built by reusing ancient material. In the medieval period, at times, the propensity to reuse spolia was fundamental in the initiation of new construction sites (Trinchese, 2020). In the 12th century, the *cosmatesque* style transformed the

re-use of materials into a new and prestigious art form that went beyond the borders of Rome and was used in numerous places of religious, political, and cultural power. A critical reading of studies on masonry, analyses of building materials over time, research on techniques for the construction of finishes, plasters, flooring and interior and exterior cladding, and investigations into the storage of construction site waste and its efficient use, all contribute to raising awareness about rehabilitation and lead to appropriately supported choices. In 2015, at the materials laboratories of the research group TEMA, Tecnología Edificatoria y Medioambiente of the Polytechnic University of Madrid, a doctoral thesis was conducted by Pablo Sáiz Martínez entitled: 'Utilización de arenas procedentes de Residuos de Construcción y Demolición, RCD, en la fabricación de morteros de albañilería' aimed at finding solutions that reduce the impact of Construction and Demolition Waste (hereafter abbreviated CDW) on the environment.

If the reuse of large residues is attested in ancient and modern history as backfill for ditches and roadbeds (Etxeberria, Gonzalez-Corominas, Galindo, 2016), the reuse of smaller particle sizes has interested more recent research. In fact, the use of the fine fraction of several types of recycled aggregates in the manufacture of masonry mortars represents a rediscovered avenue for the new use of CDW and is the focus of the doctoral thesis. The latter evaluated the incorporation of the fine fraction of recycled aggregates into masonry mortars and the feasibility of manufacturing recycled mortars by replacing the entire natural aggregate. The results indicated the feasibility of producing mortars for use in masonry using one hundred per cent recycled aggregate in compliance with current regulations (Sáiz Martínez, 2015).

The thesis considered previous studies that also aimed at the recovery of demolished materials for the construction of durable, economical, and environmentally friendly rigid pavements. The results showed that the best combination was compressed concrete and recycled steel fibres (Muscalu, Andrei, Taranu, Budescu, Lungu, 2013). The problem that was most frequently found in the other studies examined was the reduction in mechanical strength of the mix composed of recycled aggregates; For this, it was useful to take into account the three hundred freeze-thaw cycles carried out by the group of researchers from the School of Civil Engineering and Architecture, Chongqing University of Science & Technology in China, who indicated that the freeze-thaw cycle strength of fine recycled aggregate is not related to the type of aggregate, but is determined by the water-cement ratio, the reduction of which is an effective way to improve its strength (Bu et al., 2022).

Several studies are currently underway that cross-cuttingly address the reuse of CDW to reduce its quantity and impact.

3. Spain Construction waste management between Italy and Spain

Construction and demolition waste is generated in all the processes that make up the life cycle of a building. The data examined in this work conducted in collaboration between UPM's TEMA laboratory and the Department of Excellence DICEA, Department of Civil Architectural and Environmental Engineering of the University of Naples Federico II, refer to Italy and Spain. The seventeenth chapter of the new European Waste List (Decision 2001/118/CE) concerns the CDW, organised in three levels and marked with a six-digit code grouped in pairs:

- aa - Level I - corresponds to chapters;
- bb - Level II - corresponds to subcategories;
- cc - Level III - corresponds to the individual waste produced.

According to the Eurostat database, CDW constitutes in absolute terms the most significant stream of hazardous waste (definition in Art. 184 of Legislative Decree 152/06 - Environmental Regulations) produced in Europe. The average production figure for the European Union in 2016 is 924 Mt. This value represents 33% of the European Union's total production of special waste in the same year (2.538 billion t). The regulatory definition of 'waste' in Italy is given by Article 183 of Legislative Decree No. 152 of 3 April 2006, the so-called Consolidated Environmental Act: 'waste' is defined as 'any substance or object which the holder discards or intends or is obliged to discard' and in Article 184, waste is classified according to its origin and according to its hazardous characteristics. In 2018, according to ISPRA data, 103.3 Mt of special non-hazardous waste were sent for material recovery; of these, 61.2% were waste from construction and demolition operations. For CDW, a specific target of preparation for re-use, recycling and other material recovery is set by Decision 2011/753/CE in Annex III and is 70% to be achieved by 2020. Material recovery data confirm a growing trend also in 2018, with an increase in the total amount of waste from construction and demolition operations, compared to 2017, equal to 12% corresponding to about 3.7 Mt. The recovery rate of CDW, calculated based on production and management data of this type of waste, is 77.4% in 2018, above the 70% target set by Directive 2008/98/CE

for 2020. This percentage is more than two percentage points higher than in 2017.

In Spain, in the Community of Madrid, CDW are classified as follows:

- Level I: Excess CDW from excavations and earthworks (uncontaminated soil and stone materials). In Ordinance APM/1007/2017 they are called 'uncontaminated excavated soil and other excavated natural materials';
- Level II: CDW not included in level I, generated in the activities of the construction sector, demolition, house repairs and the implementation of services (supply and sanitation, telecommunications, electricity supply, gasification, and others).

Waste from construction and demolition activities generated in 2008 amounted to approximately 40 million tonnes [Mt]; in 2014 it amounted to 20 Mt and in 2018 it amounted to 14.5 Mt and represented 34% of the total non-hazardous special waste generated in Spain (43 Mt). Regarding the target set by the European Parliament in 2008 to take the necessary measures to recycle CDW up to 70% by 2020, Spain stands at around 72%. Furthermore, looking at the information provided by the Eurostat database, a decrease in the production of CDW in Spain can be seen. However, the phenomena of illegality, as such, cannot be measured except through estimates, which is why it cannot be claimed with certainty that the reported data is only due to the actual decrease in CDR production. Therefore, the possible mishandling of CDW or illegality, i.e., that CDW therefore have an unknown destination or are treated in unauthorised facilities, must be considered. In fact, since 2018, there have been multiple articles in *El País* about illegal activities in Madrid and in Spain in general. Spain's strategy for the circular economy, *España Circular 2030*, lays the foundations to promote a new production and consumption model in which the value of products, materials and resources is maintained in the economy for as long as possible, in which waste production is minimised and those that cannot be avoided are used to the maximum possible purpose. This is in line with the objectives of the two EU action plans for the circular economy, 'Closing the Loop - An EU Action Plan for the Circular Economy' of 2015' and 'A New Circular Economy Action Plan for a Cleaner and More Competitive Europe' of 2020.

4. An evolving sector: demolished concrete as aggregate in new buildings

The data show that both Italy and Spain have reached the 70% target set by Directive 2008/98/CE for 2020, unlike countries such as Greece, Belgium, Romania, Slovakia. Therefore, it is necessary to elaborate future perspectives and search for innovative solutions in the field of material recovery: introducing, therefore, the topic of recycled aggregates resulting from demolition or collapse, their treatment process, the sectors that use them, and the concept of CE marking, i.e., the certification required by the regulations in force to be able to define the end of the waste status and the simultaneous promotion to product. By establishing, for example, the 'material passport', it is possible to evaluate the material by its performance characteristics and not by its origin. The study conducted analysed the advantages and criticalities related to the use of recycled aggregates, by researching existing applications, which can be referred to, accompanied by actions to promote the development of the sector, such as regulatory and organisational adjustments, incentives, simplifications, and training of the operators involved. A particularly relevant aspect for the development of a circular economy is the existence of a market for recycled aggregates. According to ANPAR's elaborations (Italian national association of recycled aggregate producers) on 2018 association survey data, it is represented (81%) by the infrastructure construction sector (roads, railways, cycle paths), followed by fillings and other uses (12%), while an exceedingly small part is destined for the packaging of structural concretes. According to harmonised European standards, Recycled Aggregate (hereafter abbreviated to 'RA') is defined as 'mineral aggregate resulting from the recovery of waste inorganic material previously used in construction'. Aggregates can be used either as a finished product, e.g., in railway ballast or protective works, or as raw material for the manufacture of other important products for the construction sector, such as concrete, precast products, asphalt (composed of 90 per cent aggregates), lime and cement. To date, the possible uses of aggregates subject to regulation are:

- recycled aggregate for making the body of embankments of civil engineering earthworks and for making environmental recoveries, fills and backfills;
- recycled aggregate for making road, railway, and airport sub-bases, for making accessory layers (with anti-capillary, anti-freeze, draining functions, etc.);
- concrete: national technical regulations allow the mixing of concrete with RA.

For structural concretes, the maximum permitted percentage of recycled aggregates and the number and type of checks to be performed on the materials make their use exceedingly difficult. Legislative Decree No. 106 of 16 June 2017 specifies responsibilities, supervision, and sanctions in the event of violations of the rules for placing construction products on the market in the person of the designer, builder, construction manager, tester, manufacturer and notified body. The measures in the event of violation are administrative and criminal (structural uses). Even though studies attesting and demonstrating the high-performance characteristics of RAs are proceeding, their origin from waste induces an instinctive distrust in the potential user, also due to illegal practices that have sometimes occurred in countries.

In fact, waste that has not successfully completed its recovery treatment can, if used in place of traditional building materials, create serious problems for the construction company of both a legal nature (as this involves illicit trafficking of waste) and a technical nature (non-acceptance of the materials by the construction managers).

It is, therefore, essential to distinguish proper recycling activities, which lead to the production of quality aggregates, real construction materials.

In addition, designers and site managers tend to favour the use of natural products, for which the risks are moderate, rather than the use of recycled products, which presuppose the definition of characteristics at the design stage and acceptance checks during the execution of the work.

The rampant mistrust lies, therefore, in the lack of knowledge of the characteristics of materials and the control procedures to be applied. For several years now, the relevant harmonised European standards for RAs have introduced the concept that products placed on the construction market must be assessed for their performance characteristics and not according to their origin. Only the CE marking of aggregates can attest to the characteristics of the purchased material.

5. Demolition of office building in Tres Cantos, Comunidad de Madrid

The case study is the development of the project in Tres Cantos aimed at the reduction of the material to be demolished, through a partial demolition of the structure, and the reuse in situ of the resulting concrete. If for large residues it is customary to reuse them by providing an external draining pavement, for those of small granulometry a

laboratory study was prepared with the aim of analysing their characteristics and promoting new uses, one of which could be the realisation of non-structural products, such as building finishes and external non-driveway pavements. This experimental work was coordinated by the TEMA research group, which, among the many initiatives being developed, promoted the international research project - 'From waste to green decking: recycle demolition waste for new finishing products'. This made it possible to actively follow the demolition works of an office building in Tres Cantos, a city in the community of Madrid. The new project will consist of the construction of one of the supermarkets of the famous 'Ahorramas' chain, consisting of 250 supermarkets between Madrid, Guadalajara, Cuenca, and Toledo; the new use will involve changing the entire structure of the building, which is why its demolition is planned. As it is essential to conduct a selective demolition, the first step was to identify the waste material that cannot be transported to the recycling plants and whose destination is the disposal plant. Next, the company checked the stability of the structures, identifying load-bearing and non-load-bearing ones. On the site, the use of machines for the separation of post-demolition materials and recycling was authorised. Unlike in Madrid, where it is difficult to grant such permits due to both the noise that the machines would cause and the limited space available, in the case of the site in Tres Cantos it was possible to process the demolished concrete directly on site, saving time and resources and paying great attention to the environment, as transport costs for the landfill and material supply were eliminated. The study, as mentioned above, put forward an alternative proposal to the total demolition that was implemented: the suggested use is a multi-functional youth centre for the community of Tres Cantos. Changing the intended use and having the company 'AG Demoliciones Construcciones' also deal with partial demolition, the possibility of demolition of only the first floor of the office building is hypothesised, and interventions aimed at recovering the concrete are studied. For this purpose, part of the demolished crushed concrete from the construction site was kindly granted, the final grain size of which (0-100 mm) consisted of large and small residues, some of which were prepared for drainage paving and the others reused to produce green finishes, in particular non-driveway outdoor paving.

5.1 Preliminary studies and introduction to laboratory work

After a detailed historical and bibliographical research of scientific articles, theses, and specialised books, developed with the aim of gathering the main characteristics and properties of RAs, the study and characterisation of the RAs and materials used in the research proceeded. In this phase, the materials required to produce the

recycled and reference mix were characterised, i.e., standardised fine aggregate, demolished concrete, cement, and water. As part of the experimental programme, the study was conducted in the building materials laboratory of the Escuela Técnica Superior de Edificación de Madrid (ETSEM). First, the influence of the fine fraction of RA in mixes for external non-driveway pavements was analysed by replacing part of the conventional fine aggregate with RA in different percentages, to determine the effects produced as the percentage of use increased. The replacement percentages chosen were 0%, 45%, 50% and 55%. For the mixes, the use of a single cement (CEM II/B-L 32.5 R) and a dosage of 1:3:0.5 was sufficient. Then, we moved on to study the properties of the recycled mixes, analysing the following properties of the mixes by means of laboratory tests on specimens:

- mechanical strength (bending and compression);
- absorption by capillarity.

5.2 Preliminary studies and introduction to laboratory work

To determine the particle size of the aggregates, the prescriptions of the UNE-EN-933-1 standard 'Test for determining the geometric properties of aggregates', were followed. This method consists of placing a series of sieves in descending order according to the size of the mesh opening, mechanically shaking the sample for one minute and holding the material according to its size in the different sieves. The sieves used were mm: 4-21-0.50-0.250-0.125-0.063. Aggregate particles with a grain size greater than 4 mm were excluded to avoid the formation of preferential breaking lines within the specimen; furthermore, 4 mm is the limit that differentiates fine from coarse aggregate. Inerts of 0.125 mm and 0.063 mm were also excluded, as they were in the form of a dust. The component materials of the mix design are:

1. cement type CEM II/B-L 32.5 R;
2. standardised fine aggregate (river sand of siliceous nature);
3. drinking water from the Canal de Isabel II, responsible for water management in the Community of Madrid;
4. recycled concrete from the demolition of an office building in Tres Cantos.

The proportions of the different components were weighed separately with a 0.01-gram precision balance, respecting the ratio 1:3:0.5, 450 g of cement, 1350 g of fine aggregate dried 24 h in a kiln, 225 g of water. A graduated

cylinder was used to establish the proportions of fine aggregate and recycled aggregate. The 1350 grams of fine aggregate placed in the cylinder corresponded to 860 ml. From this, the proportions of fine aggregate and the relative replacements of the demolished concrete were established in the different percentages, i.e., 0%, 45%, 50% and 55%. To correct mix design, it was essential to evaluate some special properties of the recycled aggregate, including water absorption. As also highlighted by studies in the literature, the recycled aggregate, due to the cement mortar adhering to the original natural aggregate, has a higher water absorption value, as the cement mortar is more porous than the virgin aggregate. This negatively influences the maintenance of workability over time, which is why it was decided to pre-saturate the recycled aggregate with water before adding it to the other ingredients when mixing the mixture.

The demolished concrete was soaked in water for one hour. The production of each mix was conducted with a planetary mixer, model CIB-701 of the Ibertest brand, with a capacity of three litres. The water and cement are poured into the tank of the planetary mixer, while the aggregates are deposited in the hopper of this machine. The times used to produce the mixes were those established in standard UNE-EN 196-1 'Test methods for cements. Part 1: Determination of strengths'. To determine the flexural and compressive strengths, the fresh mix was poured into calibrated steel moulds consisting of three prismatic specimens measuring 160 mm x 40 mm x 40 mm. The moulds were filled in two batches by mechanically compacting each of them with twenty-five strokes in an automatic compactor model CIB 801 from Ibertest. Once the process is complete, the excess mixture is levelled off with a spatula and the mould is transferred to a climatic curing chamber for 24 hours, which is maintained at a temperature of $20^{\circ}\text{C}\pm 2^{\circ}\text{C}$ and a relative humidity of $95\%\pm 5\%$. After demoulding, the specimens (Figure 1) were repositioned in the moist chamber for up to 21 days with nomenclature 'A' and up to 28 days for those with nomenclature 'B'. The specimens of both types are numbered from 1 to 3, the first two to be broken in bending and then in compression, the third to be immersed in water to conduct the capillary absorption test. Finally, the type of RA (concrete) and the relative replacement percentage is indicated on each specimen.

5.3 Flexural and compressive strength

The flexural strength (Figure 2) is determined by placing each of the manufactured specimens in the machine, where a load is applied at uniform speed. The specimens rest on two steel rollers between 45 and 50 mm in length and $10\text{ mm}\pm 5\text{ mm}$ in diameter, $100\text{ mm}\pm 0.5\text{ mm}$

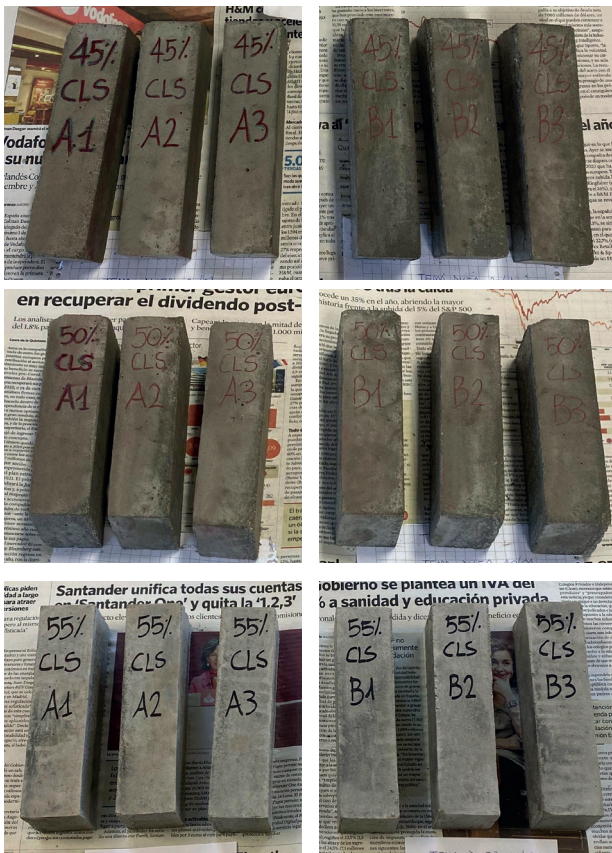


Figure 1 | Specimens performed with RA replacement in percentages of 45%, 50% and 55%.

apart and under a third roller located in the centre of the span, which is responsible for transmitting the load. The compressive strength (Figure 2) is calculated by applying a load without acceleration that progressively increases on two opposite faces of the prism until it breaks.

The samples, i.e., the two pieces resulting from the bending fracture, are placed between two plates 40 mm long x 40 mm \pm 1 mm wide and 10 mm thick.

5.4 Capillary absorption test

Concrete is a material characterised by a structure rich in pores, capable of absorbing water within it due to capillary forces that depend on several factors including surface tension, viscosity, density of the liquid. Absorption is one of the main water transport phenomena within the concrete about the deterioration mechanisms of the material itself. The specimens were placed inside a container with a flat bottom and positioned so that their lower base rested on stable supports.



Figure 2 | Flexural and compressive strength.

The receptacle was filled with enough water to reach a level of approximately 0.5 cm.

At the beginning of the test (Figure 3), specific time intervals were set (i.e., minutes: 0, 10, 20, 30, 45, 75) and the level reached by the water in the specimens RIF_A3, RIF_B3, A3 (45%, 50% and 55%), B3 (45%, 50% and 55%) was marked each time.



Figure 3 | Absorption test by capillarity.

5.5 Flexural strength results

The average and relative standard error of the two flexural strength values of the two specimens in each mould (A1 and A2 at 21 days and B1 and B2 at 28) were calculated using the following formulae:

$$average = (\sum_1^i R_i) / i$$

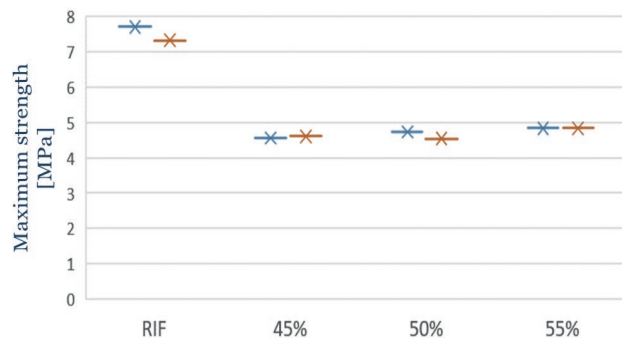
$$standard\ error = S / \sqrt{i}$$

Where: i = number of specimens (2 in the case of flexion and 4 in compression) and S = standard deviation.

The 21- and 28-day data obtained using the WinTest32 programme are shown in the following tables and graphs.

Table 1 | Results of flexural failure of specimens at 21 days as a function of replacement percentage.

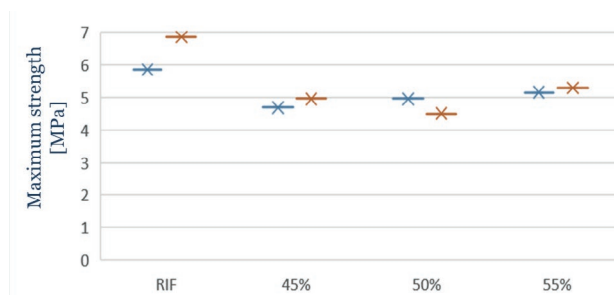
Identification	Medium strength	Standard deviation	Error
RIF_A1	7.51	0.27	0.19
RIF_A2			
CLS_45_A1	4.58	0.04	0.03
CLS_45_A2			
CLS_50_A1	4.64	0.13	0.09
CLS_50_A2			
CLS_55_A1	4.84	0.00	0.00
CLS_55_A2			



Graph 1 | Results of flexural failure of specimens at 21 days as a function of replacement percentage.

Table 2 | Results of flexural failure of specimens at 28 days as a function of replacement percentage.

Identification	Medium strength	Standard deviation	Error
RIF_B1	6.35	0.71	0.50
RIF_B2			
CLS_45_B1	4.82	0.18	0.13
CLS_45_B2			
CLS_50_B1	4.72	0.32	0.23
CLS_50_B2			
CLS_55_B1	5.22	0.10	0.07
CLS_55_B2			



Graph 2 | Results of flexural failure of specimens at 28 days as a function of replacement percentage.

The first consideration that can be made is that the average flexural strength of the reference specimen is the highest of all, both at 21 and 28 days, and this is a result that does not compromise the research, since it must be emphasised that the specimen with 0% RA replacement was made in order to have a benchmark with which to compare recycled mixes, but the purpose of the research is the realisation of green finishes (outdoor pavements) for which the desirable performance must not reach, or exceed, the requirements of the reference specimen, which are normally aimed at structural purposes.

In the 21-day case, the gradual increase in average flexural strength is evident as the percentage of replacement of the fine aggregate with demolished concrete increases.

In the 28-day case, there is a slight decrease in the 50% case and then an increase again in the 55% case.

Finally, when comparing the two tables, the flexural strength values at 21 days are lower than those at 28 days.

5.6 Compressive strength results

Similarly, the average and relative standard error of the four compressive strength values of the two specimens of each mould (A1 and A2 at 21 days and B1 and B2 at 28 days) previously broken in bending (compression is performed on the two halves obtained) was calculated.

A graph has been attached to the tables to observe the compressive strength as a function of the percentage of substitution of the fine aggregate with AR: the graph is called ‘box-and-whisker’ and relates a quantitative variable, i.e., the maximum compressive strength of the specimens, to a qualitative variable, i.e., the percentage of aggregate substitution in the mixes.

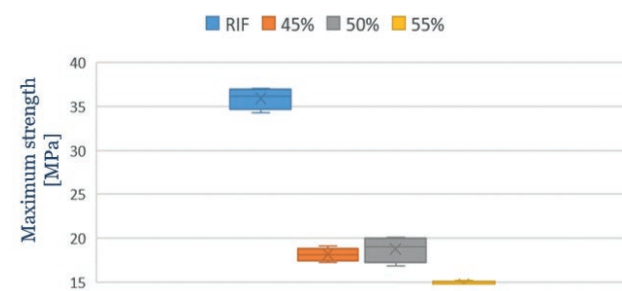
From a reading of Table 3 and the attached graph, it can be observed that the average compressive strength of the reference specimen is the highest of all and an increase, albeit slight, in the strength values is evident as the percentage of substitution of the fine aggregate with the demolished concrete increases.

Table 3 | Results of compressive failure of specimens at 21 days as a function of replacement percentage.

Identification	Medium strength	Standard deviation	Error
RIF_A1	33.08	3.22	1.61
RIF_A2			
CLS_45_A1	16.69	1.02	0.51
CLS_45_A2			
CLS_50_A1	17.52	0.38	0.19
CLS_50_A2			
CLS_55_A1	17.98	0.44	0.22
CLS_55_A2			



Graph 3 | Results of compressive failure of specimens at 21 days as a function of replacement percentage.



Graph 4 | Results of compressive failure of specimens at 28 days as a function of replacement percentage.

Table 4 shows the results of the compression fracture of the test specimens at 28 days. From reading the table and the attached graph, the optimum at 28 days is obtained in the case of 50% replacement of the fine aggregate with RA, presenting a higher average compressive strength than that associated with 55%.

Table 4 | Results of compressive failure of specimens at 28 days as a function of replacement percentage.

Identification	Medium strength	S	Error
RIF_B1	35.93	1.21	0.61
RIF_B2			
CLS_45_B1	18.16	0.75	0.38
CLS_45_B2			
CLS_50_B1	18.76	1.48	0.74
CLS_50_B2			
CLS_55_B1	14.76	0.30	0.15
CLS_55_B2			

6. Conclusions and future lines of research

The objective of the research work conducted is to study the feasibility of incorporating the fine fraction of demolished concrete in the production of non-driveway external pavements. The experimental study conducted is summarised in the following conclusions:

- the granulometry of the fine fraction of demolished concrete is suitable to produce non-structural products, such as building finishes and in particular non-driveway external paving;
- the workability of the recycled mix is inversely proportional to the percentage of AR used, so it was necessary to pre-saturate the recycled aggregate;

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- in terms of strength, both flexural and compressive, the mechanical behaviour of the recycled mixes is lower than that of the reference mixes. However, the results obtained meet the requirements for external paving (as it is a non-structural product);
- in terms of strength, both flexural and compressive, there is a slight increase as the percentage of replacement increases, except only for the mix consisting of 55% demolished concrete, broken in compression after 28 days: the latter shows a slight decrease;
- the recycled mixes show slightly higher capillary absorption capacities than the reference mixes, and the value is higher the greater the percentage of AR used.

Below are several aspects that have not been analysed in this research work or that have not been sufficiently developed and that could be studied in future research to expand the knowledge of recycled slurries. First, it is essential to extend the study of the relationship between the components by increasing the percentage of RA in relation to the amount of cement. Also, it is necessary to conduct tests to know the chloride content, total sulphur content and studies such as X-ray diffraction, thermo gravimetric analysis and X-ray fluorescence, then determine the adhesion resistance, shore D hardness, thermal conductivity coefficient and sound absorption coefficient. Then, continue the study on the influence of the fine fraction of RA in the mixes, from other materials such as brick, rubber.

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