30. Slovenski Kolokvij o Betonih
Ljubljana
7 November 2023

NEW DEVELOPMENTS IN THE RECYCLING OF CONSTRUCTION AND DEMOLITION WASTES FOR THE CONCRETE INDUSTRY

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Abstract

The management of construction and demolition wastes is now part of the circular economy. Increasing percentages of products that were previously considered as waste are recycled for manufacturing new mortars and concretes: the quality of crushing, sorting and preparation in approved recycling centres means that the quality of the products and the consistency of the properties of the recycled materials are constantly being improved.

The University of Liège (Belgium) is involved in numerous projects aimed at improving recycling conditions and increasing the rates incorporated into new concretes: rammed concretes, concretes based on brick fines and recycled sands for 3D printing are presented as examples. Measures to promote the use of Recycled Aggregate Concrete (RAC) are fully in line with strategic goals of the European Union (EU) and the scientific community has consistently argued that RAC is a technically suitable structural material.

Keywords: concrete, recycling, coarse aggregates, fine particles, durability, brick fine, 3D printing, rammed concrete

1 INTRODUCTION

The construction industry accounts for one third (37.5 %) of all the generated wastes and consists of one of the heaviest and most voluminous waste stream in the EU [1]. Construction and demolition wastes (C&DW) represent an amount of about 850 Mt generated every year by the EU-28 or 1.7 tonne produced per year and per EU inhabitant. In the other side the annual European demand in aggregates amounted to 2,99 Mt in 2021: the European demand represents about 10% of the global demand in aggregates [2].

Aggregate and sand materials are in high demand globally for construction purposes, with an annual growth rate of around 5% while the availability of sand is decreasing. A clear increase in sand demands over the previous and coming years is observed (https://iveybusinessreview.ca/6580/lafargeholcim-the-plastic-solution-to-the-global-sand-wars/graphic-2-world-sand-demand). The United States and China show overall the highest yearly demand of sand.

Figure 1 provides a synopsis of the 2021 national production tonnages categorized by country and aggregate type. Germany emerged as the leading producer, surpassing 500 million tons, followed by Russia, Turkey, France, the UK, and Poland. In contrast, smaller nations such as Malta, Montenegro, Iceland, Luxembourg, and Cyprus exhibited production levels below 5 million tons. National tonnages depend not only on economic strength, but also on geological availability of and access to deposits, national ambient climate, ruggedness of the terrain and local building traditions. Slovenia is consuming almost exclusively natural aggregates, probably due to local availability.

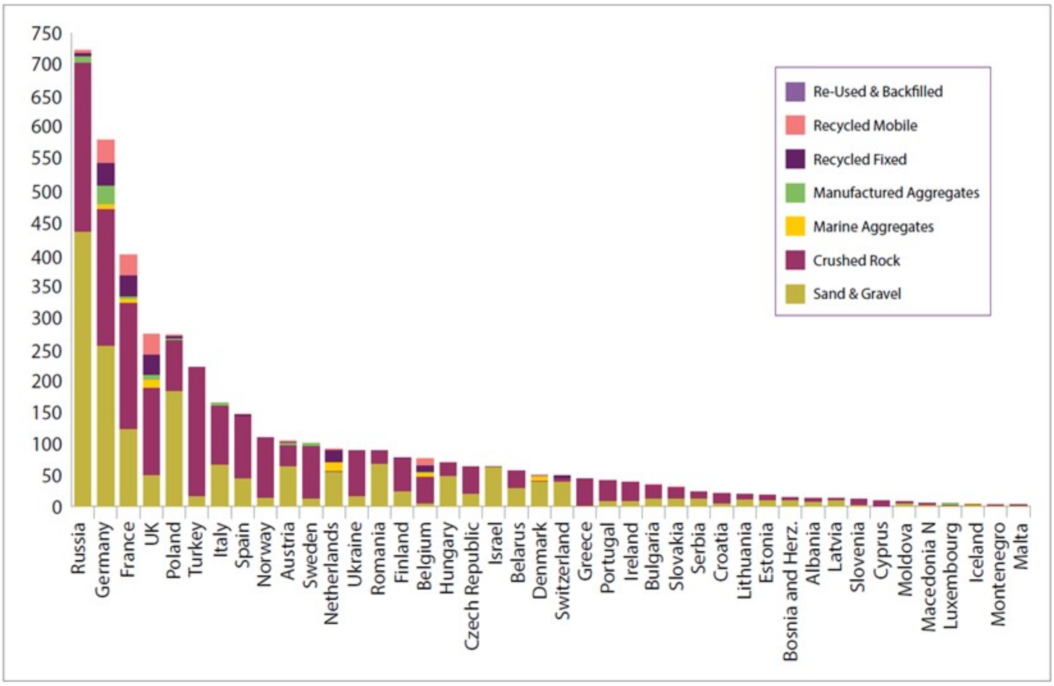


Figure 1: 2019 aggregates production in Europe [2]

The composition of aggregate types in the EU27+UK+EFTA countries in 2019 revealed that crushed stone accounted for 46.9% of all production, while sand and gravel constituted 39.7%. Aggregate production from recycled and reused materials contributed 9.3%, with marine and manufactured aggregates comprising the remaining 4% (Fig. 2).

Figure 2: Aggregate type percentages

The market of recycled sands and aggregates (RS&A) needs to be healthful at country scale to foster Member States to reach the target defined in the Waste Framework Directive (2008/98/EC). The most cited drivers that can boost C&DW recycling are: Green Public Procurement, taxation on C&DW landfilling, taxation on natural sands and aggregates, availability and cost of natural sands and aggregates, quality certification of RS&A, better public perception and increased consumer acceptance and low distance with C&DW recycling plants (e.g. [3]).

However, while recycling of coarse aggregates is now well developed [4, 5, 6], finer fractions do not still offer ways for valorization: they are actually stored or landfilled. Several research and master projects show there is an opportunity in substituting natural sands and fillers with recycled fine aggregates (RFA) or brick fines [7] for the development of existing or new applications in mortar and concrete technology.

2 MIXED RFA FOR THE PRODUCTION OF RAMMED CONCRETE ELEMENTS

Rammed earth has been a very common construction technique for centuries because it is using abundant cheap resources. This technique is requiring low maintenance, low-tech construction process and are economical to build [8].

Figure 3: Natural rammed earth color and texture variations [9]

Important volumed of RFA are produced all over the world and are lacking high end applications: their incorporation into the classical rammed earth method could improve the mechanical performance of the finished products. The main physical and mechanical properties of rammed concrete incorporating RFA have been investigated and the influence of the composition and curing conditions on those properties have been determined (Fig. 4).

Figure 4: mix for rammed concrete and rammed concrete specimen [10]

The results show that there is an optimum value of the water content around 7-8%wt maximizing the mechanical performances. While increasing the cement content yields better mechanical resistance, content as low as 5%wt produces good results with most masonry materials while limiting the environmental impact of the material (Fig. 5). Lastly, the use pretreated (washed) RFA leads to better mechanical performances which could allow for even lower cement content for masonry uses.

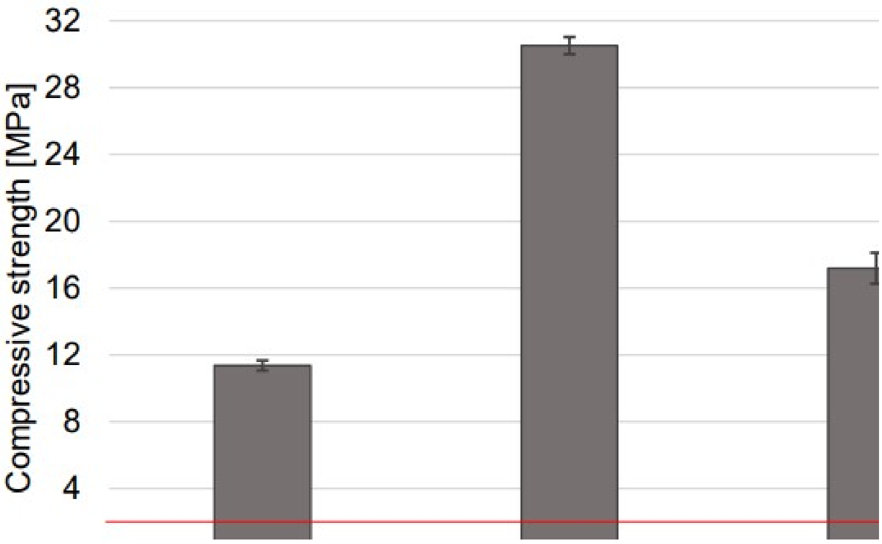


Figure 5: Compressive strength vs mixes used different aggregates (NS = natural sand – R2 = Original RFAs – WR = Washed RFAs [10]

A prototype has been manufactured by PhD students on the campus of ULiège and it shows the capability of producing on site or prefabricated elements (Fig. 6).

Figure 6: manufacturing rammed concrete walls with recycled fine aggregates

3 BRICK FINES FOR CEMENTITOUS MATERIALS

Bricks and ceramics represent around 2% of the Construction and Demolition Wastes produced in Belgium and North of France. An interesting alternative for Supplementary Cementitious Materials would be to substitute, as it is the case for cement, a part of a material known as fly ash or blast furnace slag with brick fines in order to develop materials with proper physical and mechanical performances [11, 12, 13]. Substituting cement by brick fines particles in concrete seems to give very good performances [13]. The addition of silicate materials such as in the form of brick fines results in a minor loss of strength but would increase durability performances; these results are due to the pozzolanic properties of the brick fines [15]. Low substitution rates with different particle sizes are possible; studies are pointing out a specific contribution of these fines in a hydraulic binder [14,16].

(a) (b)

Figure 7: Brick fine preparation (crushing and grinding) [17]

Three different particle sizes (B1 (D50=3.2 µm), B2 (D50=20.7 µm) and B3 (D50=180 µm)) into blended cement were prepared (Fig. 7): their pozzolanic activity, as well as their impact on fresh and hardened cement paste properties, have been investigated. Paste mixes with mass substitution of Portland cement by the three brick fines were studied (Table 1).

Table 1: Mix proportions of cement pastes with brick fines [11].

Type	Cement	10%	20%	30%	80%
Cement CEM I 52.5 N (g)	3000	2700	2400	2100	600
Brick fines (B1/B2/B3) (g)	0	300	600	900	2400
Water (g)	1350	1350	1350	1350	1350
W/B (with Binder= Cement + Brick fines)	0.45	0.45	0.45	0.45	0.45

The compressive strength of pastes for the different substitution rates is presented in Figure 8. A similar evolution for the three particle sizes was observed. The compressive strength of cement pastes decreased with the increasing proportion of brick fines for all the mixes with B1, B2 and B3 fines. Up to 28 days, samples with B1 fines had greater resistance than samples with B2 and B3 fines. At 90 days, for low substitution rates (10 and 20%), mixes with B2 seemed to be more efficient than B1 and B3 fines. The expected gain between 28 and 90 days with finer B1 fines was visible with higher substitution rates e.g. 30 and 80%.

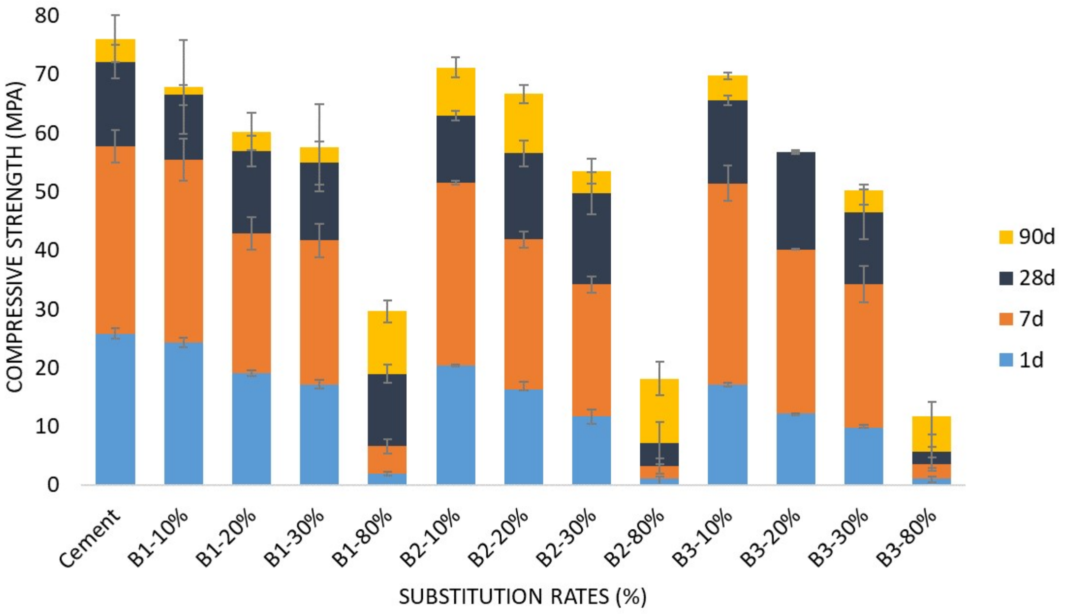


Figure 8: Compressive strength versus time.

At a young age, the fine bricks are favoring hydradation through the nucleation effect. This effect was visible very early for B1 with an increase in the portlandite generated and good activity index value [11]. In the longer term, the pozzolanic reaction occured with consumption of part of the portlandite generated by hydration. This was particularly observed for B2 and B3 at 80% with gains in mechanical strength (B1 at 80% presented an atypical value probably due to poor workability which would falsify influence the results). At 90 days, the mechanical performances in Figure 8, the obtained substitution rates up to 20% showed results close to the control sample, in particular for B2. Beyond 20% substitution, the coarser the fines, the lower the mechanical performance was. The total porosity of all samples decreased with the development of hydration products (Figure 9) but the larger the size of the fines, the greater the porosity. A refinement of the porosity was also observed over time in relation to the advancement of hydration. The best result was obtained with B2. B3 being coarser, the pore distribution was more extensive. for the B2 fines up to 20% substitution.

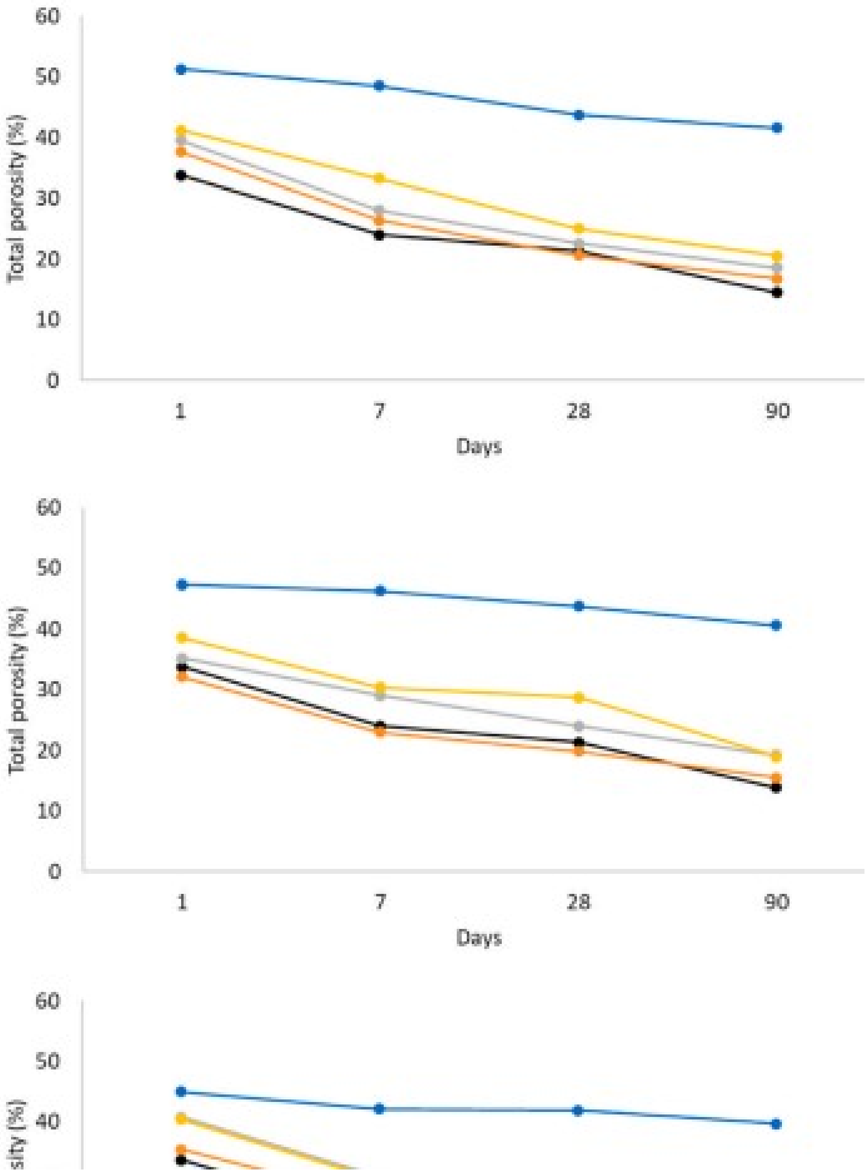


Figure 9: Evolution of porosity with time

A correlation between resistance and porosity results is noted: indeed, the total porosity of all samples decreased with the development of hydration products. However we also observed that porosity was increasing with the size of the brick fines.
From an environmental point of view, the manufacture of bricks emitted less CO_2 than Portland cement. For the manufacture of brick powder, the production of brick fines of a size equivalent to a cement powder was less energy intensive.

The reuse of brick fines was optimal for brick fines with a grain size close to the associated binder and with substitution rates up to 20% [11]. Beyond 20% substitution rate, the environmental gain increased but was not followed by technical performances of the material. Mixes with higher quantity of brick fines may be suitable for specific applications such as grouting, mortars or backfilling.

4 CONCRETE RECYCLED FINE AGGREGATES FOR 3D PRINTING MORTARS

In recent years, the construction industry has witnessed the development of a new building technology driven by innovations in additive manufacturing technologies, commonly referred to as 3D printing. Three-dimensional printing (3DP) is a groundbreaking technique that involves the sequential printing of layers, one on top of the other. This method was first introduced in 1986 for prototyping purposes [18]. This new technique is characterized by increased material efficiency and enhanced design freedom. Yet, it is still facing challenges linked to the important amount of cement and sand used in the process. One promising prospect towards improving the environmental impact of 3D printed concrete while promoting circular economy is the incorporation of recycled materials into 3D printing mortar formulations. This research investigates the influence of Recycled Fine Aggregates (RFA) on the mechanical and durability performances of 3D printed mortars. It involves the comparison of mortar samples produced with virgin sand or RFA. The aim is to determine how the incorporation of RFA affects the properties of the mortar. A battery of tests is conducted to assess various mechanical and durability properties, including compressive strength, tensile strength, flexural strength, porosity, water absorption, and resistance to environmental factors like freeze-thaw cycles.

Additionally, the study assesses the impact of the 3D printing process itself on mortar properties. To do this, the performance of mortar samples that were 3D printed are compared with those of samples that were cast using conventional methods. Direct tensile tests have also been used to assess if the cracking pattern followed the interface between two printed layers which would indicate the existence of a structural weak point in the material.

The natural sand used to produce the reference samples is a crushed limestone sand extracted from a quarry in the south of France. The RFA used are concrete RFA originating from an industrial recycling plant in Belgium. The plant is equipped with a log washer which is used to isolate floating unwanted elements such as wood, plastic or plaster. The end product obtain is a clean recycled concrete sand of 0/4 mm caliber. The only post-treatment the material required to be used for printing was to be sieved at 2 mm to keep the ratio between the nozzle diameter and aggregates maximum dimension at 10 [19].

The composition of the mortar is visible in Table 2. Two mortar formulations produced for the tests: a reference one using natural sand and the developed mix where 100% of the sand is substituted with RFA. The mixing water was adjusted to accommodate the higher water absorption of recycled sand, ensuring that the effective Weff/C remained constant.

Table 2: Mix proportions of mortar (kg/m³)

Cement	Sand	Water	Plasticizer	Viscosity agent	W_{eff}/C
905	995.60	313.52	22.63	1.81	0.29

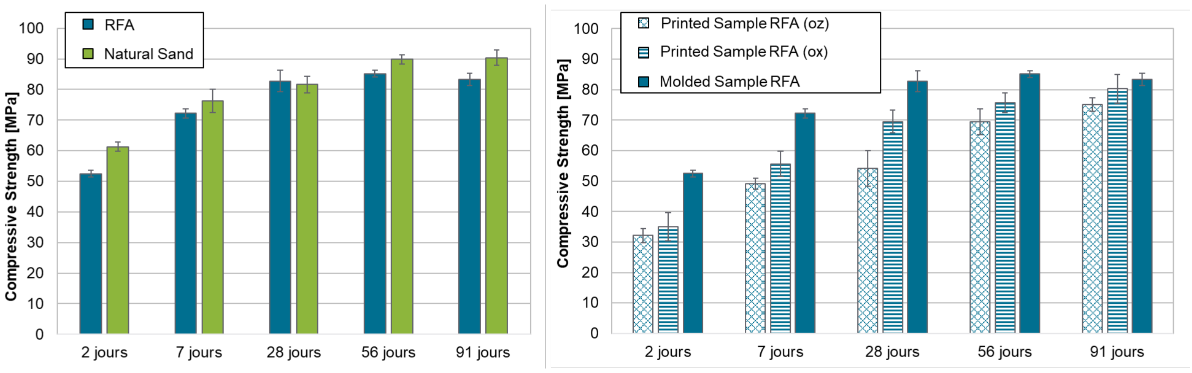
Cast samples were produced using the classical procedure. Printed samples were produced using the cartesian printer shown in Figure 10a. "S"-shaped elements have been printed as shown in Figure 10b. The printed layer is approximatively 6 cm wide and 1 cm thick and at least 6 layers have been printed. Adequate tests specimens are cut from the printed S-shaped elements for the different tests performed.

(a) (b)

Figure 10: Cartesian printer of IMT Nord Europe (a) and the printed element in « S » shape (b)

Flexural and compressive strength test

Flexural and compressive strength evaluations were executed following the protocols outlined in the established standard NBN EN 196-1. Test prisms with dimensions of 40 x 40 x 160 mm³ were tested at interval of 2, 7, 28, 56 and 91 days.



(a) (b)

Figure 11: Influence of the use of RFA (a) and of the printing process (b) on the compressive strength of mortars

The results regarding compressive strength of cast mortar samples containing recycled sand and natural sand are represented in Figure 11a. The compressive strength is slightly lower for mortar with RFA but remains very high with values around 80 MPa at 28days. As expected, the compressive strength shows an overall increase with time.

Figure 11b presents the influence of the printing process on the compressive strength. In general, the compressive strengths of the printed samples are lower than those of the cast samples. This could be due to differences in the curing condition as the printed samples are cured in ambient condition for the first 48h before being moved to a humid chamber. Moreover, the 3D-printed samples display anisotropic properties. Specifically, when a load is applied parallel to the printed layers (as shown by "oz" in Figure 11(b)), the resistance is lower compared to when the load is applied perpendicular to the layers (indicated by "ox" in Figure 11(b)). This finding is somewhat counterintuitive because it challenges the assumption that the interface between layers in 3D printing is typically weaker than other parts of the material.

Inter-layers adherence of 3D printing mortar

Cylindrical samples have been drilled in the printed “S” shaped elements and the layers outline has been marked as accurately as possible as shown in Figure 12a. The samples have then been submitted to direct tension test to evaluate the inter-layers adherence. The average tensile strength at 28 days is around 2.5 MPa but most notably, the observed failure mechanism never matched the interface between layers as visible in Figure 12b which suggest there may not be a pronounced weak point at the interface between layers in 3D-printed mortar elements.

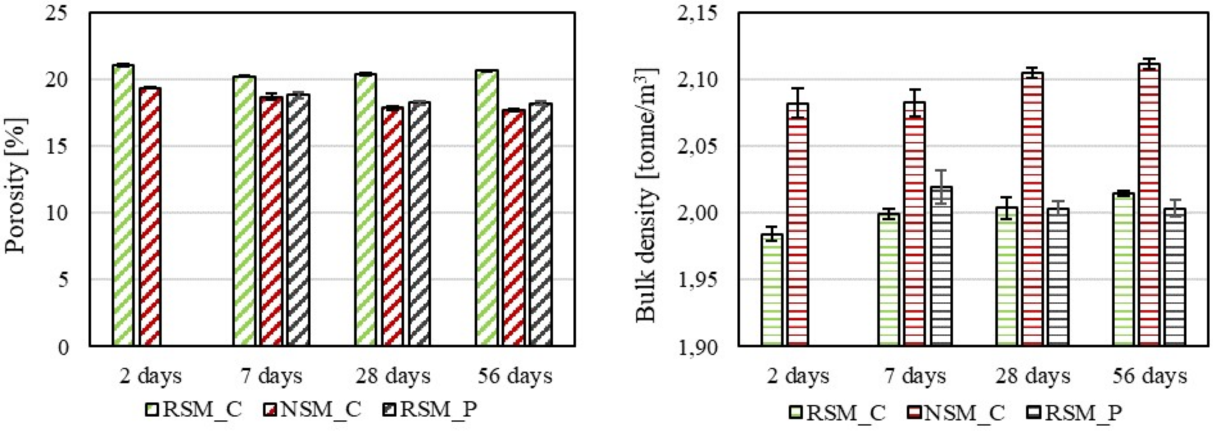
(a) (b)

Figure 12: Cylindrical samples drilled from the S-shaped elements (a) and failure mechanism after the direct tensile strength test (b)

These findings align with the results obtained from the compression tests. If the material had interfaces or weak planes between the layers, one would expect a lower compressive strength when the charge is applied perpendicularly to the direction of the layers (ox in Figure 11b) due to the influence of the Poisson’s ratio. However, this was not observed, further supporting the conclusion of material homogeneity.

Microstructure of 3D printing mortar

Porosity ε and bulk density ρd of the mortar were evaluated in accordance with standard NF P18-459. Overall, the porosity of mortar range between 17.4% to 21.1% and a decrease of porosity was observed as time passed (Figure 13a). As expected, the reference mortar exhibited a lower porosity than the mortar with RFA. Interestingly, though, the porosity of the printed mortar with RFA is also much lower than the porosity of the cast mortar with RFA and close to the porosity of the reference mortar. However, the bulk density of the reference mortar is significantly higher than that of both the printed and cast RFA mortars (Figure 13b). These finding seem to indicate that the printing process create a denser microstructure in the mortar compared to conventional casting.



(a) (b)

Figure 13: Porosity (a) and bulk density (b) of cast and printed specimens underwent water curing.

Freeze-thaw behavior of mix design

Figure 14 shows the outcomes of the freeze-thaw test following exposure to 91 freeze-thaw cycles under three distinct surface conditions. Overall, the results indicate that the specimens' surfaces experienced minimal damage after undergoing 91 freeze-thaw cycles, whether the mortar was cast or printed. The cumulative spalling particles after 91 freeze-thaw cycles were found to be less than 1 g/m^2. This resilience can be attributed to the favorable matrix of the mortar, which inherently contains micro-pores that are less susceptible to frost-related damage. A similar outcome was observed by Algourdin et al. [20], where no significant surface damage was detected in recycled sand-based mortar, even after subjecting it to 96 freeze-thaw cycles.

Figure 14**:** Visible spalling on the samples surface after 91 freeze-thaw cycles

The mechanical properties and durability of 3D-printed parts using a recycled sand-based mortar were determined and comparison with natural sand and sample moulding were performed.

- Shear and direct tensile tests showed that the adhesion between the layers was as good as the cohesion between the layers or within a layer, and that there are no planes of weakness at the interfaces.
- Compression tests revealed anisotropy but also good compressive strength, regardless of whether the layers were tested in the direction of installation or perpendicular to the direction of installation.
- Tests of water-accessible porosity and water absorption by capillary action showed that the 3D printing manufacturing process appears to create a different capillary network compared with conventional manufacturing. Indeed, manufacturing by 3D printing seems to improve porosity and transport properties, which is favourable from a durability point of view.
- The quantities of flaked particles were minimal during the freeze-thaw tests, even after 91 cycles. The printed samples therefore showed very good resistance to freeze-thaw cycles.

It means that the mortar tested is a compact material of very good quality that undergoes little ageing caused by its environment.

This mortar, developed as part of the CIRMAP project, contains a high proportion of cement and 100% recycled sand, can be used to print street furniture. Figure 15 shows a CaD rendering of the bench that is going to be printed as part of the CIRMAP project.

Figure 15: 3D printed bench project (CiRMAP project)

5 CONCLUSIONS

The use of Recycled Aggregates (RA) in concrete is a direct contribution towards the circular economy. Measures to promote the use of Recycled Aggregate Concrete (RAC) are fully in line with strategic goals of the European Union (EU) and the scientific community has consistently argued that RAC is a technically suitable structural material [21]. However, there are differences between RA and NA, so the behaviour of RAC is also different from that of Natural Aggregate Concrete (NAC). Using RA to produce concrete has several benefits for the construction sector and for Society that are priority targets of the European Commission:

- The amount of CDW that needs to be disposed of is reduced. The recovery of C&DW as RA keeps the valorisation of C&DW in the construction sector, which has operational advantages and, in most cases, is seen as a recycling operation that does not constitute downcycling.
- The consumption of NA decreases, reducing the extraction of mineral resources from riverbeds and quarries.

- In most circumstances, replacing NA with RA reduces the carbon footprint of the procurement of aggregates and, provided the RA are of good enough quality, the overall carbon footprint of recycled aggregate concrete (RAC) may also be smaller than that of Natural Aggregate Concrete (NAC).

Recycling waste has actually become a societal mandatory. And technical solutions exist.

ACKNOWLEDGMENT

The authors are grateful to INTERREG NWE, which provided financial support to this study as part of CirMAP research project entitled “Design and manufacture of customized 3D printed urban furniture using recycled sand” (2020-2023) and INTERREG NWE through SeRaMCo research project entitled “Secondary Raw Materials for Concrete Precast Products (introducing new products, applying the circular economy)” (2019-2022).

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