# Project RecycleSlab - Structural Behaviour of Recycled Aggregate Reinforced Concrete Flat Slabs with Drop Panels Under Seismic and Cyclic Actions

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**Abstract.** This paper presents the RecycleSlab research project, where a large-scale experimental test is being prepared. The specimen is a two-story building with flat slabs with drop panels, cast with concrete made with coarse recycled concrete aggregates (CRCAC), and will be tested under combined gravity and lateral loads. In this paper, the test setup is described in terms of structural design, test protocol, specimen dimensions and materials characterization. In addition, the research project will explore the effectiveness of innovative digital surveying techniques for the assessment of seismic damage in flat slab structures. For that purpose, the specimen will be measured in 3D before and after testing using laser scan technology with the aim of creating digital models. The testing of the full-scale two-story flat slab structure will be carried out at the ELSA laboratory of the European Commission's Joint Research Centre.

**Keywords:** Flat Slab · Punching · Concrete · Coarse Recycled Concrete Aggregates · Seismic Action; Circular Economy

## 1 Introduction

The structural application of flat slabs is widely prevalent in office, commercial, and residential buildings worldwide. However, their structural performance under seismic loads is not well understood, particularly in the slab-column connection area, where

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the combined effects of high gravity loads and earthquake-induced stresses make it a critical zone. One of the most critical aspects of flat slab design is their resistance to punching shear failure. Such failures are brittle and sudden, making their prevention through proper design essential. Although punching failure is a localized issue, it can trigger progressive collapse and, in some cases, even lead to the complete failure of the structure. The loss of a slab-column connection increases stress in adjacent connections, raising the likelihood of further failures.

From a mechanical perspective, incorporating CRCA (Coarse Recycled Concrete Aggregate) is expected to negatively impact punching shear capacity. This is because CRCA is weaker than Coarse Natural Aggregate (CNA), and CRCAC (Concrete with CRCA) tends to develop larger crack widths than Natural Aggregate Concrete (NAC) [1]. Both factors reduce aggregate interlock, which plays a crucial role in shear and punching resistance. Shear design proposals for CRCAC [1] have confirmed this effect and were considered in Annex N (*Recycled aggregate concrete structures*) of the second-generation EN 1992 standard [2]. However, no similar study has been conducted for punching shear due to the limited availability of experimental data.

A recent State-of-the-Art review [3] highlights that research on the punching behavior of flat slabs remains scarce and has primarily been conducted using unrepresentative test specimens. Most available test results stem from very thin slab specimens, limiting an accurate assessment of shear resistance. This could lead to unsafe design, due to material and structural size effects, as well as shear span ratios that are not typical in actual structural applications. The paper [3] strongly recommends further testing, particularly on slabs with realistic thicknesses and representative dimensions in relation to the maximum aggregate diameter, to enhance the understanding of CRCAC's punching shear behavior, given that this phenomenon is highly influenced by size effects. Besides that, no flat slabs subjected to earthquake induced displacements, or other types of horizontal cyclic actions, were studied.

Also, testing of multi-story reinforced natural aggregate concrete slab specimens remains limited [4]. In North America, some studies have been conducted on scaled reinforced concrete slabs [5] and post-tensioned slabs [6]. In Europe, tests have been performed on a three-story waffle slab supported by columns [7] and a two-floor flat slab structure [8, 9, 10] at the JRC ELSA facility. The latter study contributed to the development of a new formulation for assessing the drift capacity of flat slab structures [9].

To the authors' knowledge, no additional tests on floor assemblages with thick slabs designed for both gravity and lateral loads have been conducted in Europe. Large-scale multi-story structure testing is essential due to its representative scale, the ability to analyze load redistribution within floors, and the opportunity to evaluate the overall structural response in terms of ductility and energy dissipation.

## 2 Research Significance

This paper presents the experimental program proposed within the RecycleSlab research project-*Structural Behaviour of Recycled Aggregate Reinforced Concrete Flat Slabs with Drop Panels under Seismic and Cyclic Actions*—conducted under the ERIES project

(HORIZON-INFRA-2021-SERV-01–07) and funded by the Horizon Europe Framework Programme. The project aims to investigate the behaviour of large-scale flat slab floors with drop panels, constructed using CRCAC, under combined gravity and lateral loads. The ultimate goal is to contribute to the development of a European Seismic Code Regulation for such structures. This initiative will mark the world's first pseudo-dynamic and cyclic tests on CRCAC flat slabs, with proposed methodologies for structural assessment to be incorporated into future design codes.

Construction and demolition waste (CDW) accounts for more than one-third of the total waste generated in the European Union (EU27). Additionally, the construction aggregates industry is the world's largest non-energy extractive sector. As a result, recovering CDW as recycled aggregates for concrete aligns with the European Union's Circular Economy Action Plan, offering a sustainable solution for the construction industry. Given that concrete is the second most used material globally after water, the potential benefits of this approach are substantial. However, in many regions, recycled aggregates are predominantly landfilled or downcycled, such as in backfilling operations or in road construction.

The scientific community has extensively studied the material behaviour of concrete made with CRCA, identifying its key resistance mechanisms and confirming its viability as a structural material. Despite this, CRCAC is not widely produced on a large scale in most regions [11]. This is primarily due to scepticism among clients, contractors, and designers, driven by the lack of large-scale demonstrations of CRCAC's structural performance and the absence of comprehensive testing for specific structural elements. Consequently, clear design guidelines covering all relevant resistance mechanisms and structural components remain unavailable.

Flat slabs, a widely used and resource-efficient structural solution, exemplify this challenge. Slabs account for the largest portion of the total concrete volume in a building, making them an ideal candidate for CRCAC applications. However, research on the punching behaviour of CRCAC flat slabs under gravity loads is limited, restricting their practical implementation. Moreover, no studies have examined the seismic performance of CRCAC flat slabs, which is particularly critical in regions with moderate to high seismic activity. The lack of knowledge regarding their behaviour under both gravity and seismic loads, along with the absence of demonstrative examples, hinders the broader adoption of CRCAC. This highlights the pressing need for further research in this area.

Testing a drop-panel solution aligns with the UN's Sustainable Development Goals, particularly in reducing material consumption and associated $CO_2$-equivalent emissions. Over the past decades, flat slabs made of conventional concrete have been the predominant structural choice for buildings and parking garages. While they offer architectural benefits due to their flat soffit, they can be highly inefficient in material usage, leading to unnecessary environmental impact.

In a recent paper about sustainability in the construction industry [12] the authors conclude that for moderate to large spans, flat slabs exhibit significantly higher environmental impact, whereas drop-panel solutions lead to much lower emissions, while maintaining comparable economic and functional performance. This difference arises from the structural efficiency of drop panels, where material is placed only where needed, optimizing resource use. Additionally, when used efficiently, reinforced concrete structures have environmental impacts comparable to or even lower than other construction materials, such as timber or composite solutions. This underscores the importance of rational material use in achieving sustainable construction practices.

As the project aims to analyse and demonstrate a structurally and resource-efficient flat slab system, an environmental assessment will be conducted using a comparative life cycle assessment (LCA). This LCA will evaluate the environmental impacts of producing the tested prototype (constructed with CRCAC and drop panels) against a conventional flat slab system made with natural aggregate concrete, designed to exhibit similar structural behaviour but without drop panels. The comparison will be based on a truly equivalent functional unit, the flat slab system itself. This ensures a fair assessment of both systems as complete flat slab structures. This analysis will quantify the potential reduction in the carbon footprint achieved through the incorporation of drop panels and recycled aggregates, highlighting their environmental benefits.

Additionally, the research project will explore the effectiveness of advanced digital surveying techniques for assessing seismic damage in flat slab structures. The physical prototype will be captured in 3D both before and after testing using laser scanning technology, enabling the creation of detailed digital models for further analysis.

This research prioritizes public safety, economic efficiency, and the sustainability of the construction industry. Its goal is to enhance understanding of the seismic response of reinforced concrete flat slab structures made with CRCA. The group involved in this research comprises several European Universities and Research Centres, led by CERIS - Civil Engineering Research and Innovation for Sustainability, with team members from Nova School of Science and Technology and Instituto Superior Técnico from University of Lisbon, together with the Politecnico di Milano, the Imperial College London, the Slovak University of Technology in Bratislava and the Universidad Politécnica de Madrid, along two industry partners, Holcim (Itália) SpA and c5Lab - Sustainable Construction Materials Association, in collaboration with the Joint Research Centre of the European Commission. The experimental tests will be carried out at the ELSA laboratory of the European Commission's Joint Research Centre in Ispra, Italy.

## 3 Experimental Programme

### 3.1 Test Specimen

The two-story building specimen will feature two CRCAC flat slab floors with a three-by-two span configuration. The spans will measure 4.5 m and 5.0 m in the longitudinal direction and 4.5 m in the transverse direction, with a story height of 3.2 m (Fig. 1). The columns will have square cross-sections, with side dimensions of 0.4 m for internal columns, 0.35 m for edge columns, and 0.3 m for corner columns. Steel load cells will be installed at the mid-height of the columns during construction to measure internal forces. This experimental technique has been recently implemented at JRC ELSA and has undergone further developments [8, 9, 10].

The specimen's foundation will be a reinforced concrete beam grid (in order to move the specimen inside/outside the laboratory and to fasten the specimens to the laboratory's

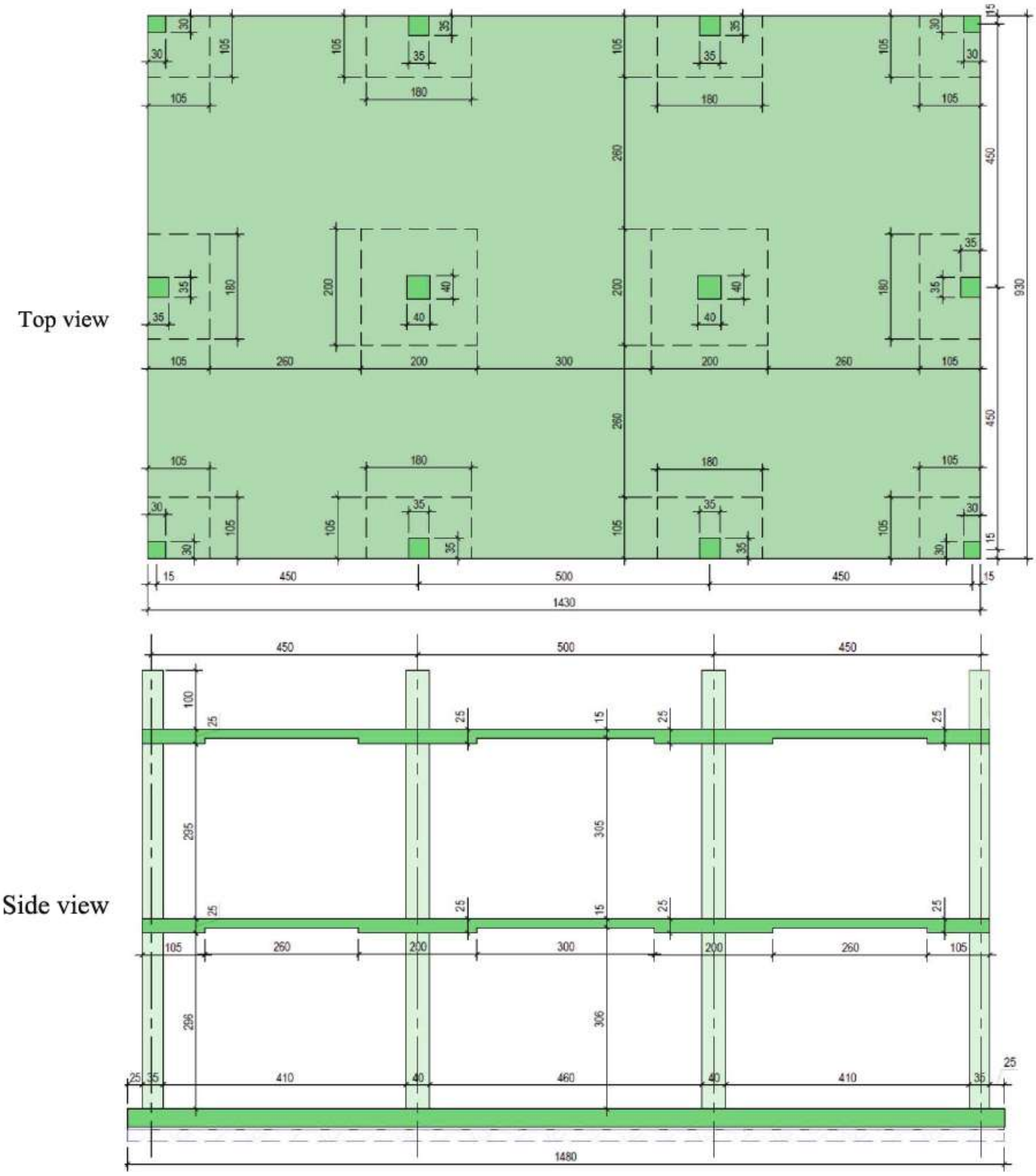

**Fig. 1.** Building geometry (dimensions in cm).

strong floor). The JRC ELSA Reaction wall has dimensions that allow testing the 6.4 m high, 14.3 m long and 9.3 m wide, two floors flat slab building proposed.

### 3.2 Materials

The reinforcement to be used will be B500 of ductility class C. At the columns, the splicing will be done using rebar couplers from Peikko.

The concrete was developed and produced by the industrial user partner Holcim (Itália) SpA. The aim was to have a C30/37 strength class, with a replacement ratio of 50% of the coarse aggregates (>4 mm), which translates to around a total 29% substitution ratio for all the aggregates. The cement used was 42.5R Type II/B-LL from Holcim, and the plasticizer was Mapei Dynamon. Table 1 presents the concrete composition. During the concrete development, the concrete compressive strength was assessed through tests on 15 cm concrete cubes (Table 2).

**Table 1.** Concrete composition.

| Cement (kg/m$^3$) | Water (l/m$^3$) | Sand 0/10* (kg/m$^3$) | Recycled Gravel 8/18 (kg/m$^3$) | Plasticizer (l/m$^3$) |
|---|---|---|---|---|
| 360 | 160 | 1289 | 520 | 2,88 |

* Sand 0/10 contains 40,4% of aggregates > 4mm

**Table 2.** Compressive concrete strength.

| Age (days) | 3 | 7 | 28 |
|---|---|---|---|
| $f_{cm,cube}$ (MPa) | 28,1 | 35,1 | 41,2 |

### 3.3 Structural Design

The building was designed for a dead load corresponding to the self-weight of the structural elements plus an allowance for the self-weight of non-structural elements of 3 kN/m$^2$. The live load was taken as 2 kN/m$^2$ assuming $\psi_2 = 0.30$ (for assessment of the quasi-permanent loading). The design earthquake action was taken as a 0.6% horizontal drift ratio.

The structural analysis was performed with ANSYS and SAP2000, to double check the design and to cover usual deviations in modelling of this type of structures, notably of the slab-column connection regions. All structural elements were modelled elastically to determine the internal force distribution. Lateral actions were applied as imposed displacements on the slabs corresponding to the specified drift level. To account for variations in stiffness between the slabs and columns throughout the loading process, two different stiffness scenarios were analysed: SS1 - all elements with constant (bulk) values of the stiffness and dimensions. This model shall cover the response before any cracking occurs or if the loss of stiffness between the slab and the columns are comparable; SS2 - the modulus of elasticity of the columns was reduced to 50%, and to 25% for the slabs, to determine the internal forces of the columns and slab-column connections, for a more realistic scenario concerning the earthquake action. This large reduction of the slabs' stiffness can be justified by the work of [13], where several flat slab-column connections under combined gravity and horizontal cyclic loading were analysed, and the experimental connection stiffness varied from 12% to 17% of the elastic stiffness.

Although not need from the design, it was decided to have a floor containing shear reinforcement (first floor), using shear studs. The shear reinforcement layout considered can be observed on Fig. 2. Initially the second floor, with similar longitudinal reinforcement, will not contain shear reinforcement, but provisions for a possible retrofitting using post-installed shear reinforcement were made, to be installed before the last experimental phase. The idea is to have information on the behaviour of flat slabs with or without shear reinforcement, a subsequently, and if possible, to study a strengthening/retrofitting technique applicable to this type of structures.

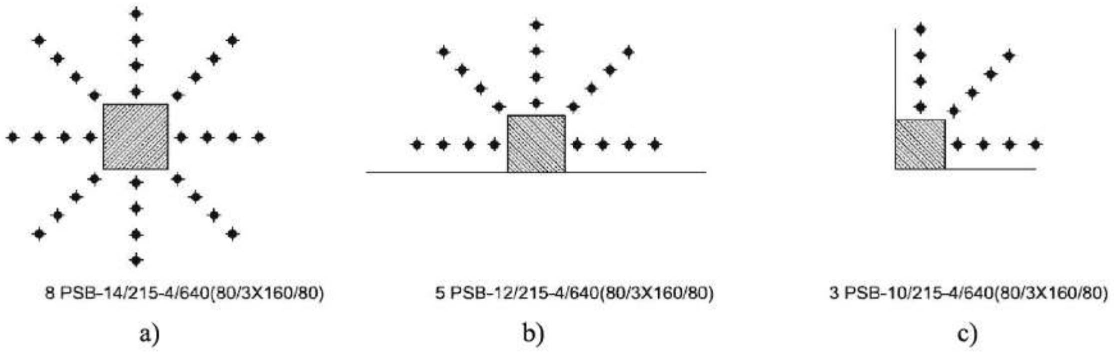

**Fig. 2.** Shear reinforcement on the first floor (Peikko PSB): a) central column; b) edge column; c) corner column.

### 3.4 Loading and Testing Program

To achieve all objectives of this research program the experimental campaign is divide in two sets of tests. First, and to appraise the seismic behaviour of flat slabs with ductile shear walls under a seismic action, two pseudo-dynamic tests will be carried out, for two levels of seismic motion: one for the serviceability limit state (SLS) and another for the ultimate limit state (ULS). Two numerical shear walls (the shear walls are only considered in the numerical model used to control the pseudo-dynamic tests) will be considered.

Subsequently quasi-static cyclic loading tests will be performed, without the numerical shear walls. The floors will be tested under combined gravity and lateral cyclic loading, with increasing horizontal displacements to near-failure conditions. The test sequence is planned to achieve progressive and controlled damage of slab-column connections.

The gravity loading will be the self-weight and supplementary weight provided by the use of water tanks placed on the slabs, to simulate the quasi-permanent load considered (3,6 kN/m$^2$) (see Fig. 3).

Horizontal loading will be applied by two hydraulic jacks per floor, with a capacity of 1000 kN each. These actions will be applied in "shear-keys", with prestressed unbonded connections to the side of the slabs at mid-span, in order to minimize the interference of this application in the behavior of the building.

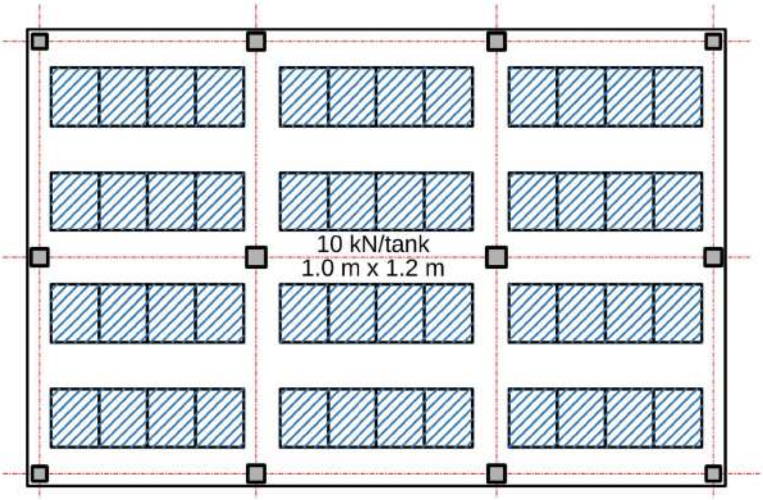

**Fig. 3.** Water tanks placement – supplementary weight.

### 3.5 Data Acquisition and Instrumentation Plan

Attending the uniqueness and scale of the planned experimental tests, a careful planning of the data acquisition system was carried out. During the planned test phases several measurements are going to be performed, in order to collect information about the behaviour of this type of structures under seismic and horizontal cyclic loading.

Two 1000 kN hydraulic actuators will be used at each floor to apply the horizontal forces. All actuators are equipped with a load cell mounted on the piston rod, to measure the force transferred to the structure. Horizontal displacements will be taken at the far end of the specimen, with respect to the reaction wall, using two displacement transducers per floor, in order to also monitor torsion.

In order to assess the evolution of crack widths along the slab´s thickness during testing, small holes in the slabs near the columns, obtained by placing a small plastic tube before casting, are going to be instrumented with LVDT fastened to the bottom face of the slab, with the target glued on the top face of the slab, at the other end of the hole. Also, inclinometers will be used to assess the slab's rotation near the slab-column connections.

For assessing the internal forces at the columns a special steel device (load cell), placed at the mid-height of the columns during the construction of the building. Three types of these devices will be produced and calibrated. Similar devices were already used in the SlabStress Project [8, 9, 10], but an improved version was developed for the current project.

The building specimen will undergo 3D surveying to evaluate the potential and effectiveness of advanced digital surveying techniques for assessing seismic damage in flat slab structures. Laser scanner measurements will be conducted both before and after testing, allowing for the creation of pre- and post-test digital models. These models can be examined, measured, compared, and analyzed at any time to accurately identify and assess damage.

### 3.6 Life Cycle Assessment

The project includes a life cycle assessment (LCA) conducted in accordance with relevant standards (EN 15804:2012 + A2:2019 [14], ISO 14044:2006 [15], and ISO 14040:2009 [16]) to evaluate the environmental impacts of the flat slab system from cradle to gate. This assessment covers the entire production process, including raw material procurement, transportation to the production site, and slab manufacturing.

The LCA will be comparative, incorporating different scenarios to analyze various assumptions and their environmental implications: Flat slab without drop panels and natural aggregates; Flat slab with drop panels and natural aggregates; Flat slab without drop panels and with recycled aggregates; Flat slab with drop panels and with recycled aggregates. Different transport distances of the raw materials used for concrete production will be considered.

The objective of this LCA is to: a) Assess the environmental benefits of using drop panels, particularly in reducing the volume of concrete required for the flat slab, thereby decreasing clinker consumption; b) Identify optimal conditions for the use of CRCA by conducting sensitivity analyses (e.g., evaluating different transport scenarios) to determine when CRCA result in a lower carbon footprint compared to natural aggregates; c) Demonstrate the impact of different functional unit choices (such as comparing a complete structural system versus one cubic meter of concrete) on life cycle impact assessments and overall findings.

The choice of the functional unit - the structural element itself - represents a significant contribution to the state of the art. Most environmental impact comparisons between NAC and CRCAC typically focus on: a) The procurement of coarse aggregates, without accounting for necessary adjustments in concrete mix design when using CRCA; b) The production of 1 $m^3$ of concrete, considering mix design changes but overlooking the impact of CRCA on concrete properties; c) The production of 1 $m^3$ of concrete normalized by compressive strength, which remains inadequate since CRCA influences various concrete properties in different ways. In designing the flat slab system, both elastic and long-term slab deflections must be considered, and the concrete mix will be tailored to achieve comparable durability properties. This approach ensures a truly equivalent functional unit, allowing for a more accurate comparison of the environmental impacts of CRCAC and NAC.

## 4 Final Remarks

This paper presents a large-scale test setup of a CRCAC flat slab building with drop panels, subjected to seismic and cyclic loading. This groundbreaking experimental study is expected to generate significant interest among the scientific and engineering communities, as well as the broader public, by demonstrating the potential of CRCAC in structural applications. The findings will be shared with academia and industry professionals, with a strong focus on disseminating design guidelines to practitioners.

Beyond its technical contributions, this research has a notable social impact by enabling the design of safer structures using sustainable materials. Additionally, the selection of efficient structural systems will encourage engineers to optimize resource use, thereby reducing the environmental footprint of construction. A key benefit of this project is its contribution to minimizing the extraction of natural resources and decreasing construction waste accumulation, which will have a meaningful impact, particularly in European countries.

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