REUSING CERAMIC TILE WASTE IN THE DEVELOPMENT OF CONCRETE PAVERS

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ABSTRACT:

The building industry is a large consumer of energy and natural resources, as well as a producer of CO_2 emissions. Therefore, it needs to evolve towards more sustainable, industrialised and circular construction that enables waste to be reduced and materials to be reused at the end of their service life. In this sense, one of the lines of research in the CERBUILD project, funded by the Generalitat Valenciana's Institute for Business Competitiveness (IVACE), was to reuse ceramic tile waste as a raw material with which to develop new products to adapt cities to climate change. Consequently, ceramic waste was used in the manufacture of various types of concrete pavers, both porous pavers (with and without thermal insulation) and compact pavers. After characterising the prototypes made (aesthetic finish, water absorption, bending strength, impact and slip resistance) and the permeability of the porous pavers, dosages and processes were optimised in order to improve paver properties. Subsequently, the most suitable formats among commercially available concrete pavers were selected, the necessary moulds were designed to produce them, and a pre-industrial development stage was carried out with the collaboration of a local firm specialising in precast concrete components.

The results obtained show that it is feasible to reuse ceramic tile waste as a raw material in the development of precast products with a cementing matrix. That would contribute to circular architecture by enabling both the reuse of ceramic waste in the manufacture of concrete pavers and the reuse of the developed products as a further source of raw material at the end of their service life.

1. INTRODUCTION

European regulations based on the Sustainable Development Goals (SDGs, 2023) are logically pushing towards a green and circular economy, with more efficient use of natural resources and the reduction, reuse and recycling of generated waste. In this regard, according to a report issued by The International Resource Panel (IRP UN, 2020), it is estimated that between 5% and 12% of total greenhouse gas emissions are associated with construction, and that around 80% of these emissions could be reduced by more efficient use of materials in buildings. According to the Spanish Association for the Recycling of Construction and Demolition Waste (RCDW, 2020), in the period 2012-2020, around 0.482 tonnes of CDW were generated in Spain per inhabitant per year, which implies a yearly average of 22,479,422 tonnes. Approximately 57% of this CDW was recovered, 19% was landfilled, and the rest was simply stockpiled or went uncontrolled. It is estimated that around 54% of CDW is ceramic in nature (CEDEX, 2014). In addition to such volumes of ceramic waste, there is also the waste generated by the ceramic sector itself when manufacturing its products. In the particular case of ceramic tiles, in 2019, Spain was the world's fifth-largest producer with an output of 510 million square metres (Baraldi, 2020), with approximately 94% of production located in the province of Castellon (ASCER, 2021). The sector already reuses all the clay waste it generates prior to tile firing and is making a major effort to integrate a large part of its fired ceramic tile waste into the manufacturing process (Rambaldi, 2021). In this sense, one of the objectives included in the CERBUILD project and in its follow-up, the ECOSISCER project, both funded by the Generalitat Valenciana's Institute for Business Competitiveness (IVACE), has been to investigate other possible ways of reusing ceramic tile waste and its reusability as a raw material in the development of both compact and porous concrete pavers.

2. METHOD

The development of more sustainable concrete pavers by reusing ceramic tile waste as recycled aggregate was carried out in 3 stages:

- STAGE 1: Preliminary design, manufacture and characterisation of compact and porous (with and without thermal insulation) concrete pavers.
- STAGE 2: Selection and optimisation of products based on the properties obtained.
- STAGE 3: Industrial development at a precast concrete company.

3. CERAMIC WASTE USED

The concrete pavers were produced using recycled aggregates from ceramic tile waste supplied by a waste treatment plant. Two different particle sizes (0/5 and 5/12) were used. The waste in this study consisted of mixtures of different types of red-body stoneware tiles, supplied directly by ceramic tile manufacturing companies, and therefore not mixed with other construction waste such as gypsum or adhesives.

The result was a fairly uniform chemical and mineralogical composition with a small fraction of impurities. As these recycled aggregates are obtained by crushing the original ceramic tiles, they have sharp edges and are generally acicular in shape. Although the possibility of rounding-off the aggregates was investigated, the results were not satisfactory, as it took a great deal of energy to produce a small amount of sample.

STAGE 1. PRELIMINARY DESIGN, MANUFACTURE AND CHARACTERISATION OF CONCRETE PAVERS WITH RECYCLED CERAMIC AGGREGATE

After analysing particle size and characterising the recycled aggregates (Roig-Flores et al., 2023), dosages and moulds were prepared to make the following concrete pavers: porous 400x400x30mm pavers with no thermal insulation (TI), porous 400x400x30mm pavers with TI (XPS extruded polystyrene), porous 400x400x50mm pavers, and compact 400x400x30mm pavers. Various surface treatments, such as washing or sandblasting, were also applied to improve surface finish of the developed pavers. Table 1 shows the tests carried out on each paver, together with their corresponding standards, to determine the most important properties for use as pavers.

Description		3 cm compact	3 cm porous/XPS	3 cm porous	5 cm porous
Dimensions, cm		40x40x3	40x40x3 + 40x40x6	40x40x3	40x40x5
Weight, kg		9.15	-	-	12.1
Breaking load (kN)	UNE-EN 1339. Concrete paving flags. Annex F	3.67	-	0.51	4.33
Bending strength (N/mm^2)		5.25	-	0.74	2.27
Impact break height 1000g	UNE 127748-2. Complement: Terrazzo tiles for external use. Annex C	> 1000	1000	700	> 1000
Breaking energy (Joules)		> 9.8	9.8	6.8	> 9.8
Water absorption (%) UNE-EN 1339. Concrete paving flags. Annex E		11.9	14.8	14.8	16.1
Permeability NLT-327/00		Imperm.	Intermediate	High	Intermediate
Smooth face slip resistance	UNE-EN 1339. Concrete paving flags. Section 5.3.5. Pendulum of friction Annex I. DB SUA 1. Tables 1.1 & 1.2	40-45 C2	83-87 C3	83-88 C3	83-87 C3
Rough face slip resistance		80-83 C3	84-88 C3	83-88 C3	84-88 C3

Table 1. *Properties of the concrete pavers developed with recycled ceramic aggregates.*

This initial stage of the study enabled the following conclusions to be drawn:

- It is feasible to produce outdoor terrazzo or concrete pavers using ceramic tile waste while still complying with the different standards and guidelines that govern use of such products. However, there is no improvement in the aesthetics of the resulting product over traditional ones, as the aggregate is covered by cement. The application of surface treatments, such as pressurised water sprayed onto the fresh paste or sandblasting, was not feasible as it produced an excessively aggressive texture with sharp edges at the surface of the paver. Despite the fact that it exhibits good performance in regard to slipperiness (Class 3, suitable for outdoor areas, swimming pools and showers, according to Tables 1.1 and 1.2 of Spain's Building Code (CTE DB SU, 2022), such a surface finish may be hazardous in practice.

- Making pavers with round aggregates was not feasible, as it would require a prior process of eroding the aggregates to produce rounded shapes, which would increase costs without adding significant value.

- The 3-cm-thick, porous pavers displayed lower strength, which was attributed to the presence of overly large pores with little cohesion between particles. Although the 5-cm-thick, porous products did exhibit properties suitable for use in paving, their surface appearance was not uniform.

- Incorporating thermal insulation (TI) on the back of the porous pavers is feasible (using XPS with grooves). Although TI-fitted pavers made with other types of aggregates, suitable for use in energy-refurbishing applications in building envelopes, are already commercially available, this option was discarded in future stages of the study, as TI is impermeable and water filtration is therefore bound to occur through the joints between pavers, which must be left open.

- It is considered feasible to produce terrazzo tiles with a polished finish, as the manufacturing process is similar to that of terrazzo. Although the result will be very similar to terrazzo manufactured with natural aggregates, the colour of the grain and surface glaze, typical of ceramic tile waste, could be highlighted by combining it with the colour of the cementing matrix or possibly using colourants.

STAGE 2. OPTIMISING THE PRODUCTS OBTAINED

Porous pavers were considered to be the most innovative system among those proposed in Stage 1 of the study and might provide improvement over existing products on the market. They could be used in low-traffic outdoor paving, where some water permeability is required for the construction of sustainable urban drainage systems. However, their homogeneity and dosage needed to be optimised in search of a balance between water permeability and mechanical strength. Furthermore, the option of adding thermal insulation to the back of the paver was rejected, as its presence restricts water permeability, which would have to be achieved through the joints between pavers.

Manufacturing terrazzo tiles (indoor and outdoor) with recycled aggregates from ceramic tiles was also feasible. However, it was necessary to optimise their aesthetic finish, as the surface finish produced by applying washing or sandblasting treatments was excessively aggressive and could even be hazardous for end users in the event of a fall, given the excess roughness caused by the sharp edges of the ceramic aggregates.

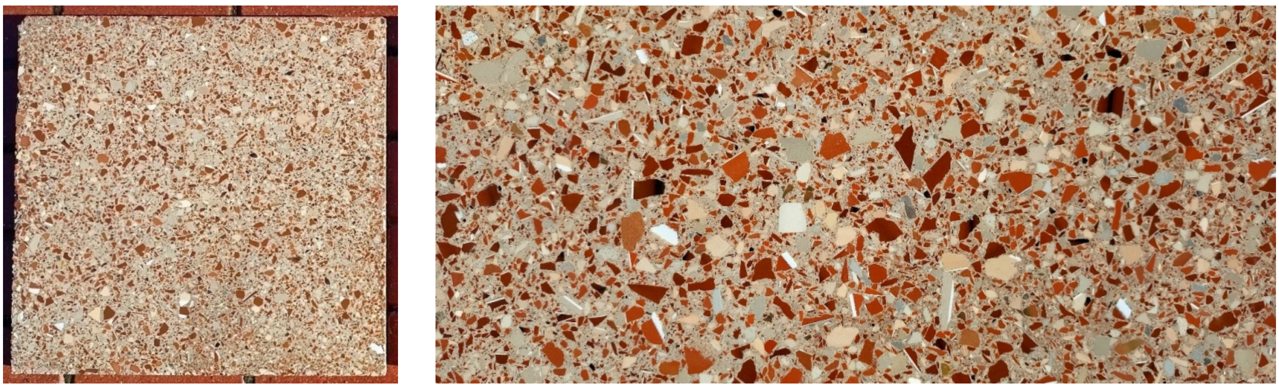
Despite the fact that the incorporation of these aggregates would definitely contribute to the circular economy and sustainability of the planet, the aesthetic finish of the pavers produced did not provide added value that could be used as a sales argument. Therefore, it was proposed to optimise homogeneity and dosage in the porous pavers (with no TI), and to improve the aesthetic finish and homogeneity of the terrazzo tiles by attempting to achieve a friendlier finish in which the recycled ceramic aggregate is visible.

In order to improve the homogeneity and surface finish of the terrazzo tiles, 40x40x3 cm pavers were made with BL I-type white Portland cement, optimising the manufacturing process. After 28 days' curing in a damp chamber (20ºC and 95% RH), an attempt was made to polish the specimens on an industrial polishing line, but the results were unsatisfactory. Subsequently, an attempt was made to improve the surface finish of the samples at a local marble company. Although the edges exhibited a certain brittleness, it was possible to successfully apply consecutive rough grinding, pumicing and polishing treatments, as well as sandblasting (Figure 1).

a b c

Figure 1. *Surface finish of compact pavers: a) Pumiced; b) Sandblasted; c) Polished.*

As shown in Figures 1c and 2, after optimising dosage, sample preparation process and polishing, satisfactory results were obtained.



a b

Figure 2. *Polished terrazzo tiles with ceramic tile waste: a) General view; b) Close-up.*

In order to improve the homogeneity and properties of the porous pavers, 40x40x3 cm pavers were made with CEM II/B 32.5-type grey Portland cement, combining 4/8 (30%) gravel and 2/4 mm (70%) sand and optimising the manufacturing process. As shown in Figure 3, these samples still displayed a certain heterogeneity, which was attributed to a differential distribution of the concrete mass in the mould, probably due to the small mixing volume. Although attempts were also made to improve surface finish on these pavers, complete surface rough grinding could not be applied, as the recycled ceramic aggregate particles are not sufficiently cohesive.

a b

Figure 3. *Porous concrete pavers with ceramic tile waste: a) General view; b) Close-up.*

The permeability of the pavers was determined (Figure 4), and much lower values were found on the rough-ground face than on the untreated face. Indeed, while a mean infiltration rate of 762 mm/h was measured on the rough-ground face with no drainage in the centre of the paver, mean infiltration on the untreated face was 11.882 mm/h, with a permeability coefficient in the centre of the paver of 36.1 cm/s · 10^{-2}. The infiltration rates obtained on the rough-ground face were not suitable for product use as drainage paving in an urban environment.

a b

Figure 4. *Determination of permeability in porous pavers; (a) Permeability test; (b) Rough-ground face of the porous paver.*

STAGE 3. INDUSTRIAL DEVELOPMENT AT A PRECAST CONCRETE FIRM

As the results obtained were satisfactory, it was decided to contact companies in the sector to investigate opportunities of production on an industrial scale. After assessing the most widely available formats on the market, the obtainable weights and resistances were estimated, based on the previously detected properties. On that basis, it was decided to produce two different types of pavers:

- Compact pavers measuring 40x40x6 cm (Figure 5), with a dosage made up of BL I 42.5 white cement and two particle sizes of recycled aggregate from red-body stoneware tile waste (0/5 and 5/12).

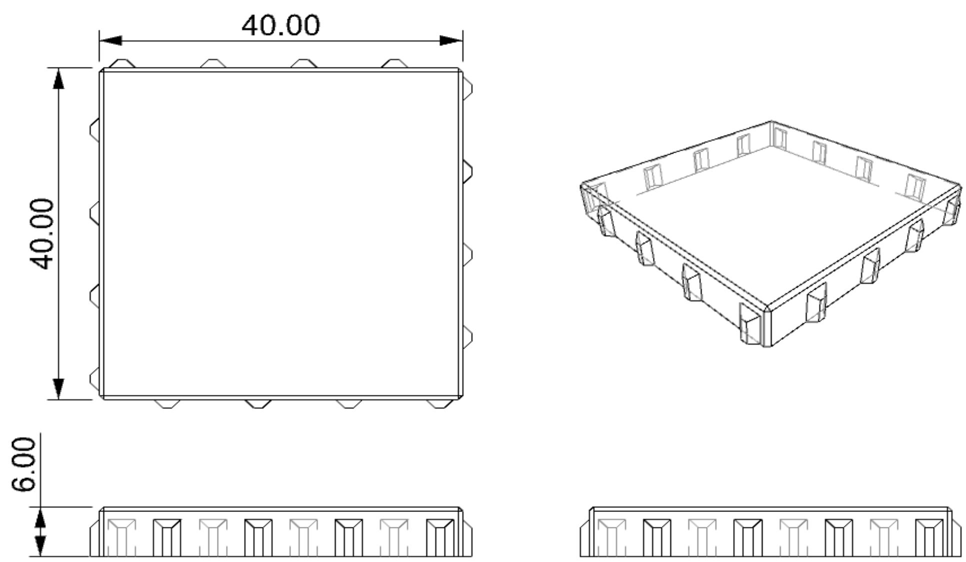


Figure 5. *Proposed mould for 40x40x6 cm compact pavers*

- Porous pavers measuring 40x40x8 cm (Figure 6). The 5/12 gravel was rejected and a dosage with 2/5 aggregate was proposed, to be made by removing fines with a 2-mm-mesh sieve from the 0/5 aggregate of the supplied red-body stoneware tile waste.

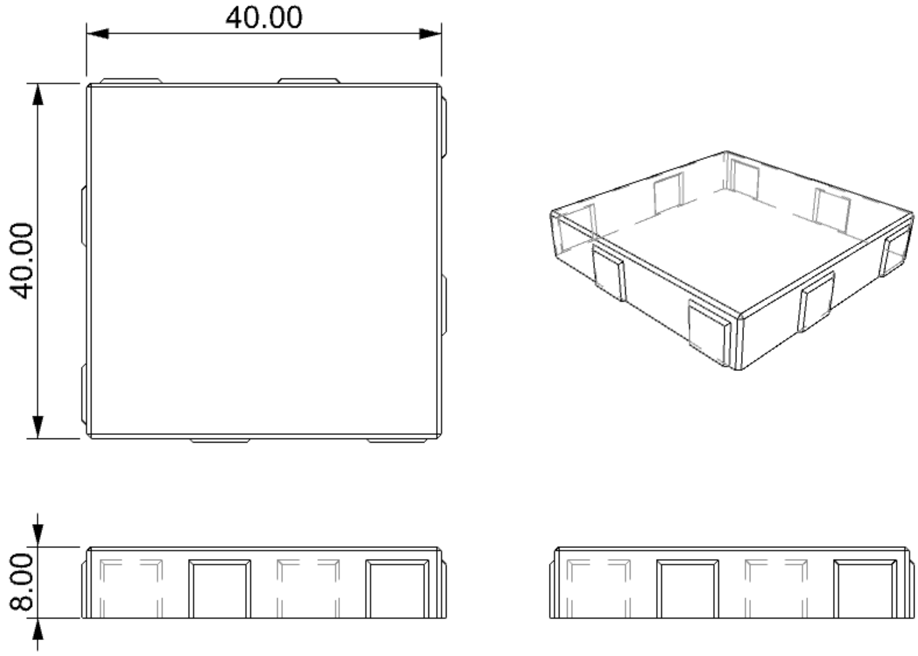


Figure 6. *Proposed mould for 40x40x8 cm porous pavers*

After evaluating this information, the precast firm proposed to make the pavers manually in order to avoid breakages. Figure 7 shows the pavers obtained.

a b

Figure 7*. Development of the pavers at the precast firm: a) compact, in mould; b) porous, demoulded.*

As shown in Figure 8, the developed pavers were tested for bending strength to determine their breaking load. The test was performed following the procedure described in Annex F of standard *UNE EN 1339 Concrete paving flags. Specifications and test methods* (UNE EN 1339, 2004). As shown in Table 2, they obtained Class 110 and 70, with a marking of 11 and 7 for the compact and porous pavers, respectively. This marking corresponds to a minimum characteristic breaking load under bending of 11 and 7 KN, respectively. This classification coincides with the one specified in the Terrazzo Guide (Palencia et al., 2010) as, according to the standard for outdoor terrazzo paving (UNE EN 13748-2, 2005), Class 7T corresponds to a mean breaking load under bending of 7,000 N. Therefore, the pavers developed are suitable for use in urban paving subject to intense pedestrian traffic and occasional passage of vehicles, such as pavements, walkways, parks, ramps, and promenades.

a b

Figure 8. Determination of bending strength of pavers produced by the precast firm: a) Compact; b) Porous.

Type	Dimensions (mm)	Bending strength (MPa)	Breaking load (kN)	UNE-EN 1339:2004 classification	
				Class	Marking
Compact	400x400x60	3.96	11.60	110	11
Porous	400x400x80	2.00[1]	9.80	70	7

Table 2. *Classification, according to Section 5.3.6 of standard UNE-EN 1339:2004, of concrete pavers produced by the precast firm with recycled ceramic aggregate.*

[1] $R_f = \frac{3 \cdot P \cdot L}{2 \cdot b \cdot e^2}$

4. CONCLUSIONS

Compact and porous concrete pavers were successfully developed using ceramic stoneware tile waste as recycled aggregate. The characteristics, homogeneity and aesthetic finish achieved at laboratory level could be replicated in the prototypes produced at an industrial precast concrete plant, and properties suitable for use in urban paving subject to intense pedestrian and occasional vehicle traffic were achieved.

Reusing ceramic tile waste generated in large quantities by industry in our area contributes to the circular economy by using and reusing existing resources. Furthermore, if such waste is reused by local companies, greater sustainability is achieved by reducing emissions related to transport. Moreover, the results obtained in this study are readily transferable to industry.

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