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An Innovative Ceramic Floor for Resilient Cities: LIFE CERSUDS

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Abstract

LIFE CERSUDS is a project carried out over the period 2016-2019 whom the main objective was to improve the ability of cities to adapt to climate change by promoting the use of green infrastructures in the renewal of urban environments. Under the project, an innovative permeable urban pavement (hereinafter, CERSUDS) was designed using ceramic tile stock of low commercial value. This pavement solution was tested in a demonstrator in the town of Benicàssim.

Once the demonstrator had been built, a monitoring period was run between August 2018 and July 2019, which enabled both the CERSUDS pavement system and the demonstrator's value as a rainwater management system to be validated.

This article presents the design process of the ceramic permeable pavement including the main results of the tests carried in the laboratory and the main results of the project relate to: environmental and economic assessment of the CERSUDS system, user's validation of the system, monitoring of the system's mechanical performance and permeability, and monitoring of the demonstrator's hydraulic response in terms of the quantity and quality of run-off water.

Keywords: Ceramic; Circular Economy; Sustainability; Permeability; SUDS

1. INTRODUCTION

Climate change resilience is one of the main priorities for Spain and other Southern Europe countries. According to PNACC (Ministerio de Medio Ambiente 2006) , in a scenario of an increase in temperature of 1ºC and a 5% reduction in rainfall, water provisions are expected to be reduced by 5–14%, and even by 20-22% by the end of the century.

On the other hand, hydrological variability will increase in the Atlantic basins, while in the Mediterranean and inland basins a greater irregularity of the rainfall regime will lead to an increase in the irregularity of the flood regime and of the flash or torrential flood regime. Thus, although climate change scenarios anticipate a decrease in the average value for annual rainfalls, high-volume rainfalls are expected. Therefore, drought and flood episodes are more likely to happen.

Southern Europe countries will face the continent's most adverse effects of climate change. The forecast is that heatwaves and droughts will increase mostly in these regions. According to the new report of the European Environment Agency (European Environment Agency, 2017). these extreme climate

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events will be most intense and frequent in these parts of Europe.

According to The SUDS Manual (Woods-Ballard et al. 2015), the Sustainable Urban Drainage Systems (SUDS), are among the most useful strategies for better management of the problem resulting from water scarcity or an excess of water in urban environments. During the rainy period, these systems allow for a lower superficial runoff, since they boost water infiltration to the soil while temporarily storing the water excess in their porous base structure. As the new Green Deal (European Commission, 2019) states, the natural functions of ground and surface water must be restored and this is crucial to preserve and restore biodiversity in lakes, rivers, wetlands and estuaries, and to prevent and limit damage from floods.

There are a lot of strategies to develop SUDS systems, but our project is focused on permeable pavements. Permeable pavements are those surfaces which, while being trafficable for both pedestrians and vehicles, allow for the filtration of water thus allowing for infiltration, groundwater recharge or water reuse (Woods-Ballard et al. 2015). Studies have shown these techniques to be especially effective for urban stormwater reduction and quality improvement (Jato-Espino et al. 2016). However, their widespread implementation is still at early stages and not yet accomplished. In such context, the LIFE CERSUDS project envisaged the execution of a SUDS demonstrator featuring an innovative solution based on the use of low commercial value ceramic material to develop a permeable pavement, which is described and analysed in this paper. These ceramic with low commercial value are products stocked in ceramic companies since customers tastes have changed, and it is difficult to introduce these products in the market again. Evidently, this situation clearly diminishes commercial value of this product.

According to data gathered from Spain, Italy and Portugal ceramic sectors (LIFECERSUDS, 2017), there are about 9.3 million square meters (183.210 ton) of ceramic product stocked with very low commercial value due to being out of the market which could be used for CERSUDS pavement. This includes different types of products such as red and white stoneware floor tile and porcelain stoneware focused on covering walls and interior floors in buildings.

The key concept of this new CERSUDS ceramic module is to manufacture them from low commercial value ceramic tiles cut into strips and bonded together with a specific adhesive. In this manner, emissions linked to tile production processes are reduced, and the new system will allow for urban adaptation to climate change in the Southern European regions.

To test this new permeable pavement and their functionality as urban pavement we made a demonstrator in the town of Benicàssim, Spain. The demonstrator project, with an intervention area of approximately 3000 m^2, has been developed by the architects of the Catedra Cerámica of the Polytechnic University of Valencia (UPV) and the hydraulic design system has been developed by Sara Perales Momparler of Green Blue Management. During the last year of the project (2019), the demonstrator was monitored in several aspects, showing a very good performance.

This project has been possible thank to the partners of the consortium: University Research Institute of Water and Environmental Engineering (IIAMA) of the Polytechnic University of Valencia (UPV), the Bologna Ceramic Centre (CCB), the Ceramic and Glass Technology Centre (CTCV), the Benicàssim Town Council, CHM, Trencadis de Sempre and the Institute of Ceramic Technology (ITC-AICE) acting as leader.

2. DEFINITION OF THE CERAMIC SYSTEM

Within the framework of this project, the complete design of this system was undertaken based in a preliminary concept (Figure 1) developed in a previous work (IMIDIC, 2010), as well as its evaluation using laboratory testing.

This initial concept had to evolve with two objectives: to present a permeability that meet the defined requirements for SUDS (Woods-Ballard et al. 2015) and to ensure its adaptation to the requirements of a pavement in urban space. The following section details the methods followed both in the design process and in the validation of the resulting product.

The selected ceramic tiles used in the demonstrator were glazed stoneware tiles measuring 33x33 cm and 9 mm thick. Those tiles came from a stock of low commercial value, manufactured between the years 1999 and 2017. About 15% of the total amount of this raw material are "leftovers" (tiles of which only 1 pallet or less of each model exist and which therefore

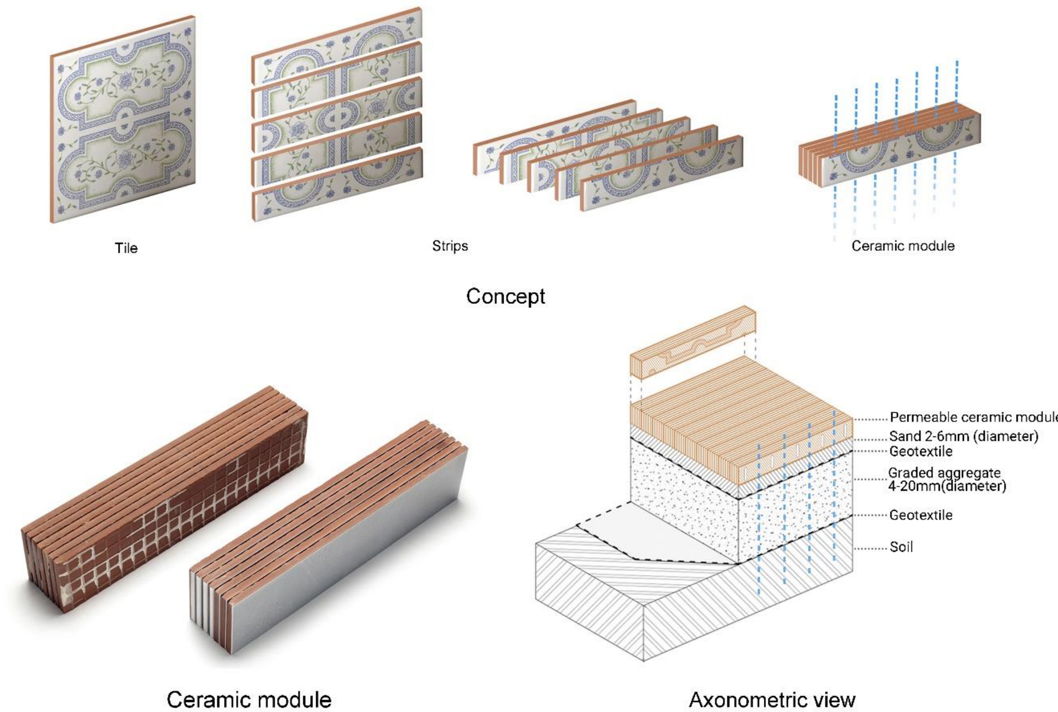

Figure 1. Ceramic module concept

cannot be sold profitably given the small amount available), while the sales value of the other 85% of the raw materials had diminished considerably.

3. METHODS

3.1 Design Process

To reach the requirements of permeability, resistance and to facilitate handling and efficiency in the installation, it was necessary to bond the strips with cementitious adhesive to obtain a module with the necessary separation between strips to achieve the required permeability.

The arrangement of the adhesive was considered essential to achieve both the desired permeability as well as the resistance to transverse breaking load. That is why the two corresponding tests, permeability and bending strength, were decisive for the choice of layout. The methods used and the results obtained from these two tests are presented below to later expose the rest of the tests that validate the module obtained in all its requirements.

Since it is an experimental product developed through a manual manufacturing process, this permeable ceramic module is outside the scope of existing standards. Consequently, both the regulations applicable to fired clay paving stones and those applicable to ceramic tiles have been used for the characterization of permeable ceramic modules. Furthermore, non-standardized test methods which were specially developed for the project have been adopted. Laboratory tests have been carried out in the Finished Product Laboratory of the Institute of Ceramic Technology.

3.2 Adhesive, Characteristics and Arrangements

The proposed adhesive was a C2 adhesive according to the standard UNE-EN 12004-1:2017[1] whose

[1] UNE-EN 12004-1:2017. Adhesivos para baldosas cerámicas. Parte 1: Requisitos, evaluación y verificación de la constancia de las prestaciones, clasificación y marcado.

Figure 2. The three families of arrangements

strength must be greater than 1 N/mm^2 once set and after ageing with heat and freeze/thaw cycles according to the standard UNE-EN 1348:2008[2]. Three different arrangements were proposed (Figure 2) in order to test which of them was the most suitable in terms of permeability and resistance. Family 3 was the option that provided an optimal balance in terms of permeability and bending strength.

3.3 **Permeability of the Ceramic Modules**

According to various authors (Woods-Ballard et al. 2015), the minimum permeability of this type of pavement should be 2,500 mm/h to hold the rainwater that falls on it. This high requirement takes into account the clogging of the pavement throughout its lifetime and therefore a safety factor of 10 was applied. This means that it would be capable of absorbing at least 250 litres/hour per square metre by reducing the permeability of the paving by ten. Besides, this permeability must be designed taking into account the impermeable areas of the SUDS. It was assumed that the impermeable area had a surface area A and the impermeable areas could reach up to 2A. Therefore, the permeable pavement must be capable of handling 3A. Given that the maximum intensity of precipitation in Benicàssim for the return period of 15 years was estimated at 154 mm/h, the recommended permeability for the permeable areas on the Benicàssim demonstrator would be 154*3*10 = 4620 mm/h. This was rounded up to 5,000 mm/h. To evaluate the permeability of the modules a laboratory test was carried out on the three proposed families using the standard NLT 327/00,2000 [3], obtaining the following results (Table 1)

Thus, family 1 was discarded in terms of permeability. In parallel with these permeability tests, bending tests were carried out, as further detailed below. Family 3 was ultimately selected as the optimal arrangement.

	F1	**F2**	**F3**
Draining time (s)	71,8	8,8	9,6
Permeability Coefficient K (cm/s x 10^{-2})	6,4	109,1	91,0
Permeability Coefficient K (cm/s)	0,064	1,091	0,97
Permeability (mm/hour)	2.304	39.276	34.920
	Not compliant	>recommended value	>recommended value

Table 1. Permeability tests results for the three arrangements

[2] UNE-EN 1348:2008. Adhesivos para baldosas cerámicas. Determinación de la resistencia a la tracción de los adhesivos cementosos.

[3] NLT 327/00, 2000. Permeabilidad in sítu de pavimentos drenantes con el permeámetro LCS.

Bonding agent distribution	Length (mm)	Thickness (mm)	No of strips	Width (mm)	Breaking load (kg)	Breaking load (N)	Breaking load (N/mm)
Family 1	330	65	10	88	1.639	16.077	182
Family 2					1.117	10.961	124
Family 3					1.597	15.671	178

Table 2. Bending strength tests carried out on the three families

3.4 Bending Strength

According to the standard UNE EN 1344:2015[4], the transverse breaking load of the pavement must achieve a T4 rating (greater than 80 N/mm). The test was conducted based on the same standard, consisting of exerting a progressive force at a constant velocity on the paving units, using a roller resting on their central area until they broke. Meanwhile, the paving unit was held on another two rollers, each located at a distance of 1.5 cm from the edges. The resulting breaking load enabled the transverse breaking load to be determined (N/mm^2). Therefore, the three families were subjected to bending tests with the following results (**Error! Reference source not found.**) and family 3 was eventually selected.

3.5 Thickness Tests

Once the optimum adhesive distribution on the strips had been selected, a series of tests on different ceramic module thicknesses were carried out according to the aforementioned in the standard UNE EN 1344:2015[5]. The values obtained are shown in Figure 3. Paving unit bending . It may be observed that from 40 mm thickness on, the values obtained were greater than the required 80 N/mm^2 in all tested lengths and materials (165 and 330 mm in length for red-body stoneware tile and porcelain stoneware tile).

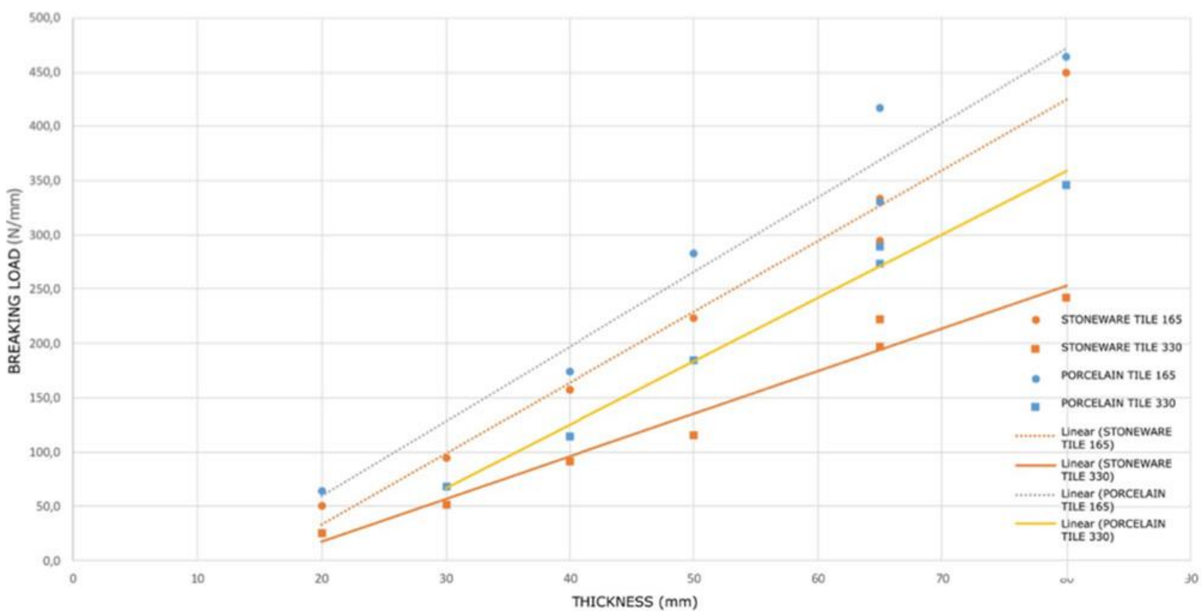

Figure 3. Paving unit bending

[4] UNE EN 1344:2015 “Adoquines de arcilla cocida. Especificaciones y métodos de ensayo”.

[5] UNE EN 1344:2015 “Adoquines de arcilla cocida. Especificaciones y métodos de ensayo”.

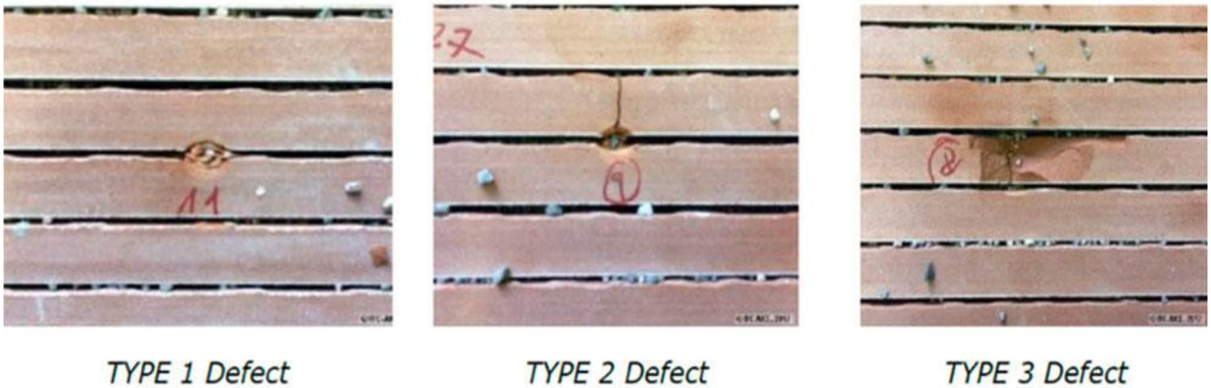

Figure 5. Types of defects after impact

Figure 4. Shear test

3.6 Shear

The test was carried out using the steel rod described in the standard ASTM C 648-04,20146. Owing to the new features of ceramic module, we had to adapt the procedure applying a progressive force, at a constant velocity, on the center point of the ceramic module, using a steel rod with a semi-sphere tip, until it separates from the rest of the tiles making up the paving unit. The paving unit was only supported by those tiles located at its ends on a smooth and continuous surface (Figure 4). The results are shown in **Error! Reference source not found.**A cyclical testing process was carried out to evaluate the ideal distribution and thickness of the adhesive layer to be applied. The results obtained indicated that the optimum distribution corresponded to family 4, with an adhesive thickness of 1.5 mm. Tests were conducted on modules made up of 7 strips, with a module length of 330 mm and with the following variations:

- Strips of porcelain stoneware tile and glazed stoneware tile
- Variable thickness of the strips: 65 mm and 80 mm

Error! Reference source not found. shows the average value of the tests carried out on 5 modules with several variations.

Therefore, both the porcelain stoneware tile and red stoneware tile were capable of withstanding concentrated loads greater than 400 kg in very unfavourable conditions.

3.7 Impact

The study was carried out based on the method described in annex 6 in the standard Cahier 3778:2017[7], which consists of dropping a steel ball with a mass of 510 g from a height of 80 cm. The paving units were then examined for defects. To simplify and group the defects, it was decided to classify them as follows (Figure 5):

- Type 1: Small chip
- Type 2: Breakage of the strip
- Type 3: Fragment detached from the strip

The test was carried out with paving units of various thickness and types of bodies to observe the effect of these variables. The paving units were installed over the granular sub-layers in a box with a surface area of 33 cm x 33 cm. 30 impacts were made on the paved surface of each type of paving unit with the aim of obtaining representative results. The results of the tests carried out on permeable modules of porcelain stoneware and glazed stoneware tiles, with a thickness of 80 mm, are detailed in 4.

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[6] ASTM C 648-04 (2014) “Standard test method for breaking strength of ceramic tile”

[7] Cahier 3778:2017 from the Centre Scientifique et Technique du Bâtiment, “Détermination de la tenue au choc lourd des carreaux céramiques non émaillés-choc à la bille de 510 g”

	No. of defects		
Body	Type 1	Type 2	Type 3
Red stoneware	24	4	2
Porcelain	19	5	6

Table 4. Impact defects. Number of defects

The tests revealed the following:

- The porcelain stoneware tile modules performed worse than the red stoneware ones, in the event of an impact, due to sharp fragments being produced when the strip was broken or detached.
- With ceramic module thicknesses greater than 70 mm, strip defects under impact were minimised. Nevertheless, given the characteristics of the paving unit, this was the weakest point of the system. For this reason, to be able to offer better guarantees, ceramic module thickness was set at 75 mm.

3.8 Frost

The test was carried out based on the method described in the standard UNE-EN ISO 10545-12:1997[8]. Firstly, the paving units were impregnated under vacuum, with a pressure depression of 400 mbar below the atmospheric pressure. The vacuum at this pressure was maintained for 30 min. After this time, the paving units were completely covered with water for 45 min. Then, they were subjected to 100 freeze-thaw cycles based on the following scheme. First, the temperature was lowered to -5°C at a rate no greater than 20°C/h. Second, the paving units were maintained at a temperature lower than -5°C for 15 min. Finally, they were immersed in water so that they reached a temperature above +5°C and kept there for 15 minutes. After 100 cycles the paving units were examined for defects. As expected, the ceramic material passed the test. However, separations resulted between some strips. This defect was more pronounced in the porcelain tiles because of their low porosity and therefore lower adhesive bonding. Nevertheless, these results were considered satisfactory given that the strips were not individually separated and that, due to the installation system, they remained in place and would not be expected to lift.

The Tile Guide (IVE,2019) does not recommend the use of glazed stoneware tile in areas with frost risk. However, as the position of the ceramic tile was different in this case, without exposing the glazed surface, this recommendation was not considered applicable.

3.9 Slipperiness

This test was carried out following the method described in standard UNE-EN 12633_2003[9]. The assembly consists of a pendulum with an arm length of 510 mm, which supports a 76 x 25 mm rubber slider whose IRHD hardness is 59±4. The height of the device was adjusted so that the slider, which supported a constant load of 22.2±0.5N, maintained contact with the surface over a travel distance of 126±1mm. The sample was immersed in water for at least 30 minutes before starting the test. Each of the tiles was tested in two opposing directions (0° and 180°), their surfaces being saturated with distilled water. All results were satisfactory, obtaining values greater than 60º so that the paving belongs to Class 3 according to DB-SAU-CTE[10].

3.10 Point Load

The test was carried out based on the method described in standard UNE-EN 12825_2002[11] . The test consists of uniformly applying an increasing load on an element until it breaks. The result is plotted on a graph showing element deflection versus the load. To carry out the test, the paving units were installed over the granular sub-layers in a box and a progressive force was applied at a constant rate at the centre point of a tile in the paving unit, using a steel rod with a semi-sphere tip. Next, in the same way, a progressive force was applied using a 50 mm side-

[8] UNE-EN ISO 10545-12: 1997 “Ceramic tiles - part 12: Determination of frost resistance”

[9] UNE-EN 12633:2003 “Method of determination of unpolished and polished slip/skid resistance value”

[10] CTE. Código Técnico de la Edificación. Documento Básico SUA, 2019. Seguridad de utilización y accesibilidad. SUA1 Seguridad frente al riesgo de caídas.

[11] UNE-EN 12825:2002 Section 5.2.1 “Raised access floors. Load test on element”

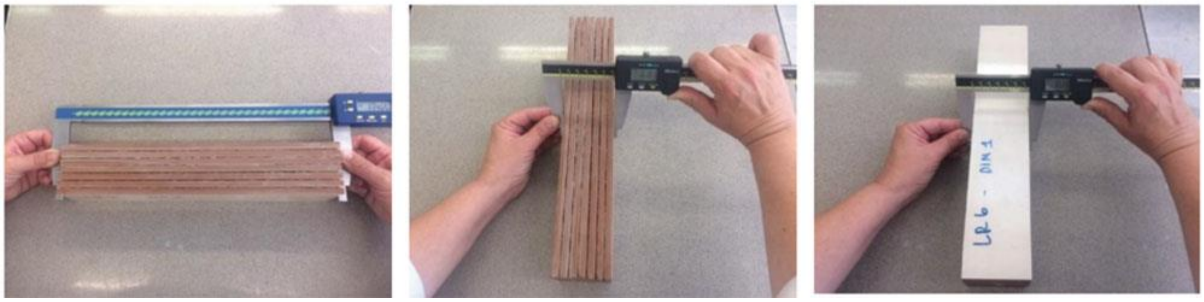

Figure 6. Dimensional stability tests on ceramic module

steel cube. The test with the semi-sphere-tipped steel rod was carried out at the centre of the tile and on the joint between two tiles of the same paving unit for the sake of comparison. The cube test was carried out at the centre of the paving unit. The length of the red-body stoneware tiles studied was 330 mm and the corresponding module thicknesses evaluated were 50 mm and 80 mm.

Concerning the 80-mm-thick modules, the test was performed at the centre of the strip and the obtained breakage values were greater than 4600 N. Additionally, the test was also carried out on the joint between strips, obtaining values greater than 9000 N. Additionally, the cube test was performed on the centre of the 80-mm-thick strips and the corresponding values were greater than 27000 N.

3.11 Abrasion

This test was carried out following the method described in standard UNE-ENV 1344:2015[12], which consists of scoring, on the visible surface of the pavers, a track using a steel disc rotating at 150 revolutions perpendicular to the surface test. A constant stream of corundum of FEPA grit size 80 is allowed to fall as abrasive between the steel disc and the tile surface. On ending the test, the resulting track is measured and the mass-loss volume is calculated. The value obtained (252 mm3) indicated excellent performance under abrasion: Class A3 (<450 mm3).

3.12 Dimensional Stability

The test was carried out based on the method described in standard UNE-EN 1344: 2015[13] which consists of measuring the length, width and thickness of pavers. The standard requires measurement of 10 pavers. In our case, 10 samples of the 6.5-cm-thick permeable paving units were measured. In addition, 5 samples of other lengths and thickness were measured to detect possible deviations in the production process (Figure 6).

The paving units measuring 330x60x65 mm passed the test, obtaining deviations below the maximum values set in the standard. Nevertheless, it was decided to be more restrictive regarding the deviations and therefore, in the quality control for the paving units the requirement would be as follows: The maximum deviation regarding the manufacturing dimensions must be length (±2 mm); width (±3 mm) and thickness (±2 mm). In addition, compliance with this test would guarantee the orthogonality of the paving units and the absence of “lipping” greater than 2 mm between strips.

3.13 Physical Characteristics of the Ceramic Module

[12] UNE-ENV 1344:2015 “Clay pavers - Annex E: Determination of abrasion resistance”

[13] UNE-ENV 1344:2015 “Clay pavers - Annex B: Determination of dimensions”

Based on the results obtained in the tests performed during the pavement design process, the characteristics of the Ceramic module have been defined. The nominal dimension of the Ceramic module is 335x65x75 mm with an approximate weight of 3.3 kg (see Figure 7).

4. ENVIRONMENTAL ASSESSMENT

Life Cycle Assessment (LCA) studies are based on an iterative method for assessing the environmental loads associated with the life cycle of any product, process or activity, in which its consumption of resources and emission of waste to the environment are identified and quantified in order to analyse impact on the environment and thus assess and implement possible improvement measures (ISO 14040:2006).

Within the framework of the LIFE CERSUDS project, LCA studies were carried out following the

Figure 7. Ceramic module

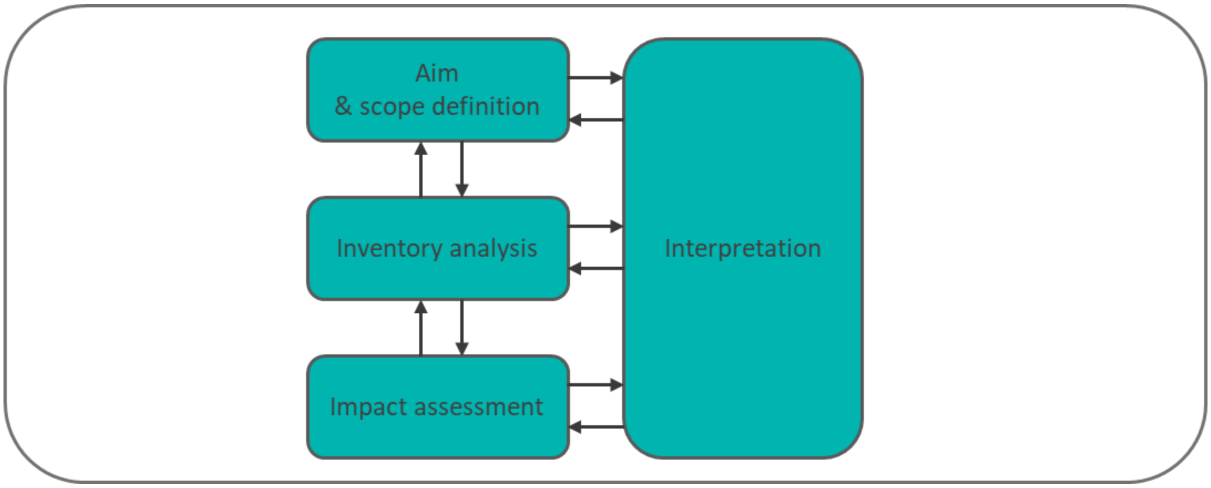

Figure 8. Stages in an LCA according to ISO 14040:2006

recommendations and requirements of standards ISO 14040:2006 and ISO 14044:2006 and EN 15804+A1, together with the recommendations of the ILCD/ELCD to support decision making. LCA studies comprise 4 phases, as shown in Figure 8.

Firstly, a LCA of the CERSUDS pavement system, which took the stock of low commercial value ceramic tiles and converted it into an aesthetically positive, high drainage capacity product, was carried out to determine its environmental strengths and weaknesses. Secondly, a comparative LCA with other permeable products on the market was carried out.

In any case, i) the scope covers exclusively to the CERSUDS pavement system, as the environmental advantages of the other parts of SUDS are already widely known; ii) the environmental results were related to the functional unit related as the amount of water drained (in l/minute) per m^2 of urban pavement; iii) the lifespan of the pavement was stated in 40 years; and iv) LCA modelling was performed with the support of GaBi software (Thinkstep AG, 2018a) and its associated databases (Thinkstep AG, 2018b).

It should be remembered that the results obtained are relative expressions and do not predict impacts on endpoint categories or the surpassing of any levels, safety margins or hazards. The results shown include both the inputs and outputs of direct material and energy during manufacture, as well as those from previous and subsequent processes that are implemented during the life cycle envisaged for the product.

4.1 Environmental Evaluation of the CERSUDS Pavement System

For the construction of 1 m^2 of CERSUDS pavement system, 9 m^2 of ceramic tiles were required. They were cut into strips, bonded as described in previous chapters and packaged; then, transported and installed dry, by hand, on a 2-6 mm sized gravel base and 1-2 mm grain sand used as grouting for the joints. 48 kg of gravel and 2 kg of sand were used per m^2.

After their installation, the use phase considered cleaning operations and a replacement of 5% over the entire time span considered. Finally, the end of life, consist of a deconstruction with a mechanical shovel, since the pavement was not glued and their waste management, which considers that 70% was recovered and the rest was landfilled (Eurostat 2017).

The inventory analysis used data provided by members of the project consortium and bibliography such as specific Environmental Product Declarations (EPDs) for glazed stoneware. Likewise, to obtain indirect data, for example, about the environmental loads associated with transportation, electricity production, etc., commercial LCA databases (Thinkstep AG, 2018b), were used.

As for the methods used to calculate and allocate the loads of the ceramic tiles used, the average environmental impacts of 3 EPDs of glazed stoneware tiles of similar characteristics were taken. Then, an economically based allocation procedure was applied to the low-cost tiles, considering the cost reduction in the market and even that some of them would inevitably go to landfill and therefore applying an avoided burden approach (Frischknecht, 2010; Häfliger et al., 2017; Silvestre et al., 2014). Specifically, 15% of the tiles used have no economic value and the rest have been considerably reduced (77% reduction in cost) due to changes in consumer preferences.

In this cradle-to-grave LCA, more than 95% of all the material and energy inputs and outputs to/from the system were included and only unavailable or unquantified data were excluded. Specifically, the industrial equipment and machinery used in the installation. Similarly, the treatment of water used for cutting (closed circuit), road transport infrastructure, plant lighting, management of assembly process waste, and possible tile and strip scrap during the cutting process was also excluded.

The impact assessment method was based on midpoint indicators proposed in UNE EN15804+A1. The characterisation factors applied are those included in the January 2016 revision of the CML-2001 method, while two additional indicators were chosen to define water and energy consumption.

Figure 9 presents the environmental impact of all life cycle of the CERSUDS system. As can be seen, the raw materials are the prime source of the environmental impact generated and that stage is therefore where possible improvement measures were focused.

4.2 Environmental Comparison of Draining Pavements

Finally, in order to quantify the environmental benefits of this solution, the results obtained from the modelling of the CERSUD pavement were compared with other conventional draining pavements. Table 5 shows the permeability of the draining pavements to be compared. It can be seen that the drainage capacity of these pavements is greater than the

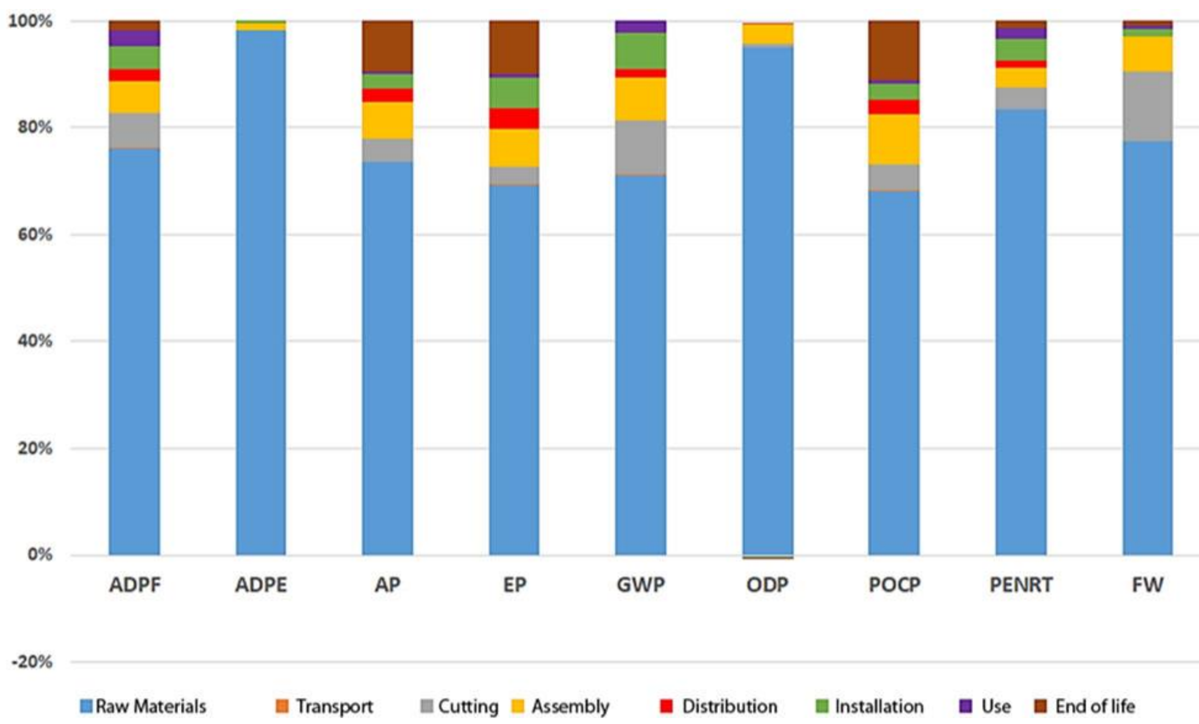

Figure 9. Impacts of the CERSUDS system
GWP: Global Warming Potential (kg CO_2 equivalent); **AP:** Acidification Potential (kg SO_2 equivalent); **EP:** Eutrophication Potential (kg PO_4^{-3} equivalent); **POFP:** Photochemical Ozone formation Potential (kg C_2H_4 equivalent); **ODP:** Ozone Depletion Potential (kg CFC-11 equivalent); **ADPE:** Depletion of Abiotic resources Potential – Elements (kg Sb equivalent); **ADPF:** Depletion of Abiotic resources Potential – Fossils (MJ); **PENRT:** Use of non-renewable primary energy, excluding non-renewable primary energy resources used as raw materials (MJ); **FW:** Net use of fresh water (m^3)

Permeable pavements	Considered permeability (cm/s)	Considered permeability (l/(min·m^2))	Area needed to achieve the permeability of the ground (m^2)
Ground	2.4E-06	1.4E-01	1.0
Permeable bricks	5.4E-03	1.6	8.6E-02 ≈ 1*
Continuous paving	2.7E-03	199.8	7.0e-04 ≈ 1*
CERSUDS	3.3E-01	583.3	2.0E-04 ≈ 1*

Table 5. Permeability characteristics

permeability of the soil (2.4E-06 cm/s, according to the data provided by the Universitat Politécnica de València (UPV), partners in the LIFE CERSUDS project) so that in case of heavy rainfall, the ground will saturate earlier, regardless of the permeability of the installed pavements, therefore, in this case, the comparative unit is 1 m^2 of pavement in any case.

Table 6 show the relative data for the product stages of the life cycle of the compared pavements (A1-A3), i.e. extraction and supply of raw materials, transport to the manufacturing plant and manufacture of the coatings.

As can be seen in Table 6, there is no preferred pavement for all impact categories. CERSUDS comes out as the most favourable solution for global warming potential (GWP). CERSUDS only comes out as the most unfavourable pavement in total primary renewable energy consumption (PENRT). In all other impact categories, CERSUDS ranks in the middle.

5. DEMOSTRATOR PROJECT

The demonstrator (Figure 10), recently executed in Benicàssim, is a practical case of the application of the CERSUDS system in urban regeneration interventions carried out in accordance with the criteria listed in the new Spanish Urban Schedule (FEMP, 2018) for sustainable development.

Impact category	Units	CERSUDS	Adoquines bricks	Continuous paving
GWP	kg CO_2 eq	17.9	23.9	21.9
ODP	kg CFC11 eq	1.0E-06	5.1E-11	1.3E-05
POCP	kg C_2H_4 eq	4.6E-03	1.3E-03	1.7E-02
AP	kg SO_2 eq	6.1E-02	4.2E-01	4.7E-02
EP	kg PO_4^{-3} eq	7.0E-03	5.9E-03	1.1E-02
ADPE	kg Sb eq	2.5E-04	3.4E-05	1.2E-01
ADPF	MJ	204.6	144.9	288.3
PENRT	MJ	322.8	162.6	288.3
FW	m^3	1.62E-01	2.4E-04	2.0E-01

GWP: Global Warming Potential (kg CO_2 equivalent); **AP:** Acidification Potential (kg SO_2 equivalent); **EP:** Eutrophication Potential (kg PO_4^{-3} equivalent); **POFP:** Photochemical Ozone formation Potential (kg C_2H_4 equivalent); **ODP:** Ozone Depletion Potential (kg CFC-11 equivalent); **ADPE:** Depletion of Abiotic resources Potential – Elements (kg Sb equivalent); **ADPF:** Depletion of Abiotic resources Potential – Fossils (MJ); **PENRT:** Use of non-renewable primary energy, excluding non-renewable primary energy resources used as raw materials (MJ); **FW:** Net use of fresh water (m^3)

Table 6. Life cycle environmental impacts (product stage) of drained urban pavements compared in this study.

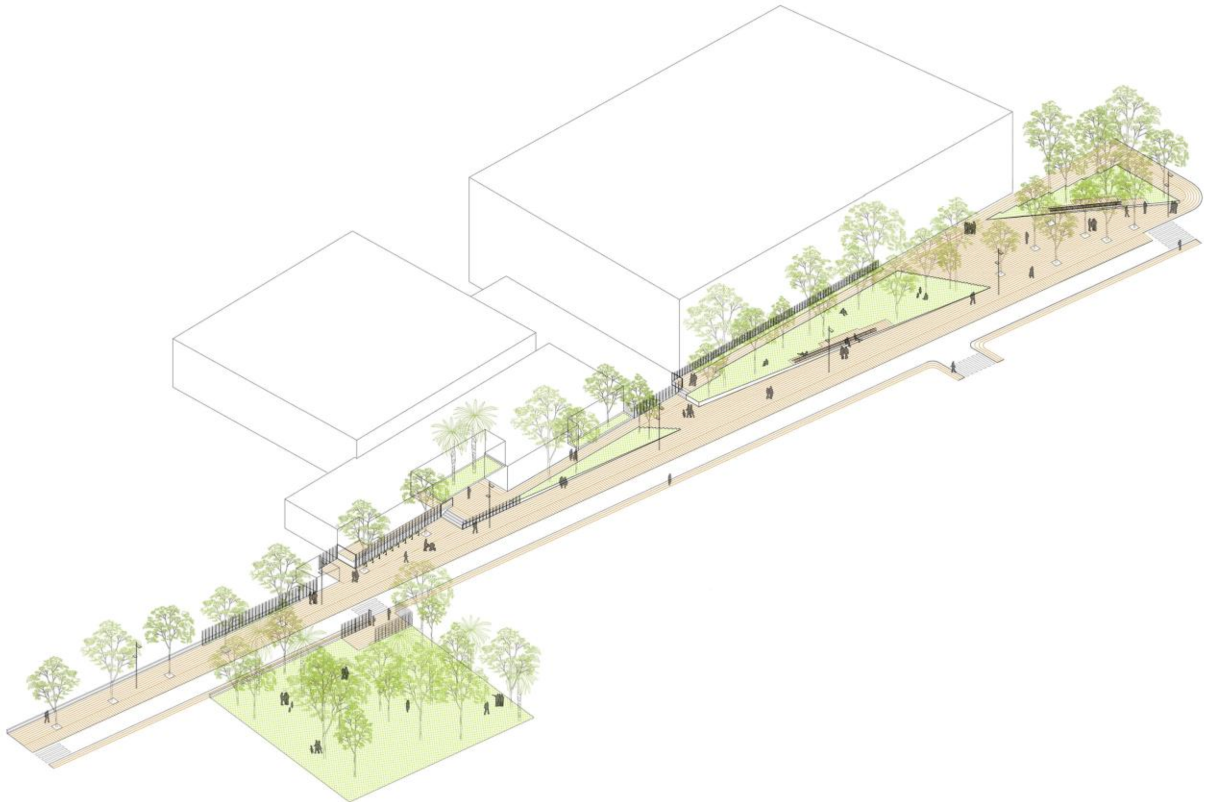

Figure 10. Axonometry of the demonstrator

5.1 Action Area

The action approaches the reurbanization and requalification of a stretch of Torre Sant Vicent Street. This is a historic route connecting the center of the city with the beach, defining a pedestrian North-West – South-East pedestrian route perpendicularly crossing the old railway on which the future Central Park will be developed. This makes Torre de Sant Vicent one of the main axes on which the future Urban Green Infrastructure will be articulated, connecting the areas with the highest environmental, landscape, social and cultural spaces while restoring their relationship with the land.

The demonstrator, executed between February and June 2018, was projected in the first stretch of the street, which defines a working framework of 3.209sqm, with a longitudinal development of 200m, a variable width ranging between 10 and 27 meters and a 1.5% descending longitudinal slope towards the sea.

This setting is located in a low-density residential area, characterized by the presence of several municipal sport facilities and a little children's park which makes the street not only a habitual transit point between the beach and the city center, but also an anteroom of the existing public facilities.

The traffic section prior to the works was made up of a central one-way driveway for motor traffic, featuring a cycle lane and elevated sidewalks with curbs. The spaces where the section widens, in front of the sports center and the municipal swimming pool, featured ramps and stairs necessary for proper access to public buildings as well as a little landscaped area, which was the only shaded area on the way to the beach. The urbanization solutions implemented, asphalt for the driveway and cycle lane and hydraulic tile for the sidewalks, sealed the ground practically in its whole extension, with punctual sinks for rainwater evacuation set along the street and connected to the rainwater drainage network.

5.2 Problems to be Tackled

The elaboration of the proposal for the demonstrator involved an analysis of the action area described above based on five parameters adopted as indicators for sustainability in public spaces:

- Sealed ground proportion: 93,16% sealed 6,84% permeable.
- Rainwater management style: 100% water discharge to network.
- Universal accessibility: No accessible environment.
- Sustainable mobility: Dangerous cycle lane. Insufficient section in pedestrian route.
- Environmental quality: Lack of shade areas in pedestrian itineraries and readability of seating areas.

5.3 Actions Proposed

The action proposal is structured around the transformation of the road section existing in a single-platform section, aiming at offering a unitary and integrated response to the problems arising from the relationship between sustainable mobility, universal accessibility, ground sealing, rainwater management and the quality of public spaces. The following actions are proposed in the project:

- Rearrangement of the existing road section, transforming it into a single platform. In so doing, pedestrian accessibility is improved, traffic speed is slowed down thus prioritizing soft mobility solutions and rainwater management is made easier.
- Substitution of the pavement impermeable solutions in cycle lanes and pedestrian areas for the CERSUDS recycled paver permeable pavement.
- Implementation of a Sustainable Urban Drainage System (SUDS) aiming at restoring the previous hydraulic behavior of the soil prior to sealing following urbanization process.
- Creation of a shaded pedestrian route, planting new trees and setting them along the walking areas.
- Extension of the existing green areas, using them as seating areas as an anteroom for public building accesses.
- Rearranging access to public buildings eliminating architectural barriers and ramps while creating pedestrian routes with slopes lower than 2%.

Figure 11. Finished demonstrator

The actions and solutions described above were concretized in a proposal that develops a permeable urbanization system is developed based on the pavement made from recycled ceramic pavers. In addition, this system defined four typical sections adapted to the different functions they will have to develop within the SUDS: drainage, filtering, catching, underground infiltration, channeling and storage.

Finally, the demostrator organises the system around the operation of rain gardens and are used as landscaped living areas. The pedestrian sidewalks working as infiltration areas and collecting runoff water, which is led to a channel-tank. This channel-tank, located under the bike path, stores the water needed for irrigation of the garden, covering 97% of the irrigation needs for the typical year and thus directly linking the sustainable management of rainwater and the improvement of environmental conditions in public spaces (Figure 11).

6. ECONOMIC ASSESSMENT

A comparative economic assessment was performed of the Sustainable Urban Drainage System (SUDS) installed on Torre Sant Vicent street in the town of Benicàssim within the framework of the LIFE CERSUDS project in comparison to an equivalent system with conventional drainage (separate stormwater system). For that purpose, the surface area of the demonstrator installed in Benicàssim was taken and a series of standard construction sections that represent each of the systems was identified. For each standard solution, the costs associated with constructing 1m2 over the model life cycle of 40 years were analysed. The costs of one square metre in either case multiplied by the surface area of each of the spaces under consideration gave us the total economic costs for each system.

6.1 Method

In order to carry out the economic assessment, the costs used in the reckoning were those associated with each of the life cycle stages contemplated in Sustainability in Construction standards (UNE-EN 15643-1:2012), following the calculation method developed in the project (Solconcer,2020). This assessment included module B7 Operational water use, which refers to the need to water the garden, plus a new module, called B8 Run-off Treatment, which refers to the costs of treating excess run-off water. The data relating to these two stages in the life cycle were drawn from the analysis using the computer tool developed in the framework of the E2STORMED project . In addition, multicriteria analysis was also carried out with the same tool.

The economic assessment did not consider all those elements common to both systems (public lighting circuit, telecommunications, street furniture...), and also omitted all elements forming part of the wastewater network (common to both systems). In the case of the conventional system, the concept used was of a separate sewer system and thus only the stormwater drainage network was assessed. Therefore, elements that form part of a traditional stormwater collection system (mains, drains, scuppers...) were considered. In the SUDS system, the role played by those parts is assumed by a series of other components, such as: the CERSUDS pavement system, the polypropylene cells and drain boxes.

6.2 Results

The Figure 12 shows the costs per square metre associated with each of the two systems and broken down according to the different stages in the life cycle considered in the calculation over a period of 40 years.

The square-metre cost of urbanisation in the demonstrator using the SUDS system was approximately 30% higher than for a conventional system. This difference is mainly due to the higher manufacturing cost of a permeable ceramic pavement compared to a conventional cement tile, since a handmade ceramic tile was considered for the SUDS (costing €44.80 per m^2), while a standard street tile is a standardised industrial product (€10.58 per m^2).

With respect to the costs associated with treating excess run-off, the SUDS solution proffers annual savings of 70%, which come from the significant reduction in run-off compared to the conventional system. As far as the costs associated with the need to use potable water for irrigation are concerned, in the irrigation scenario proposed for the project, the SUDS solution would enable 95% of that cost to be saved by making use of the water collected in the tank.

7. USER VALIDATION

In order to assess the degree of user satisfaction, a number of individual local inhabitants from the town

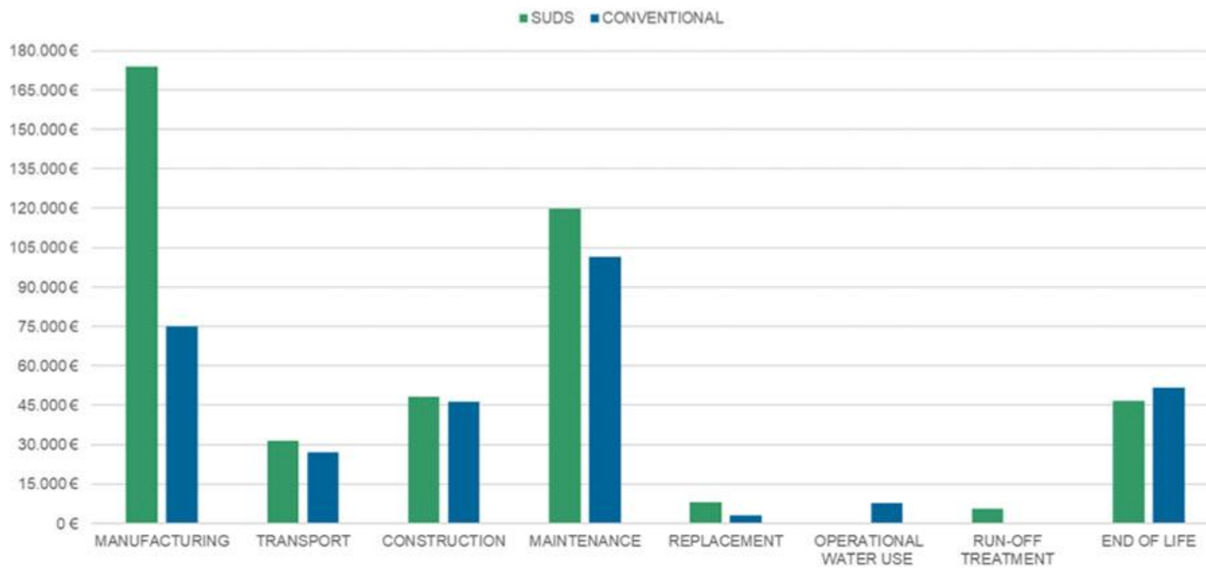

Figure 12.Costs associated with each stage in the life cycle per type of system

were surveyed in Torre Sant Vicent street, where the LIFECERSUDS prototype was installed, and asked to answer a series of multiple-choice questions on a tablet and with an interviewer to explain the questionnaire. Construction of the demonstrator was completed in August 2018 and six months later, in February 2019, 100 surveys were conducted on the 7th and 12th of that month. The results can be considered representative of the entire population (i.e. the population of Benicàssim), with an error margin of less than 10% for a confidence level of 95%.

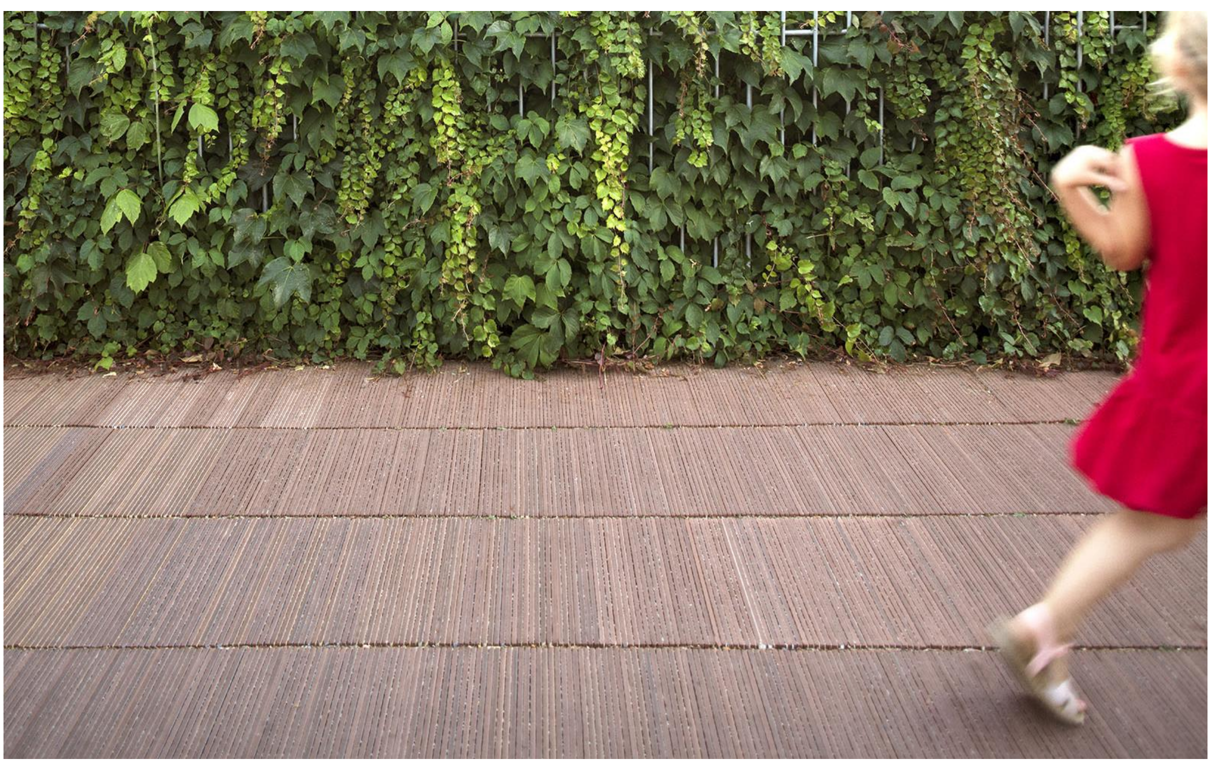

Figure 13. Detail of Finished demonstrator

The questions dealt with aspects such as comfort when walking, absence of run-off water during periods of heavy rain, general quality of the infrastructure, improvement of the urban space, etc. The survey included a total of ten questions in all and when any negative answers were given, the causes of dissatisfaction were investigated through an open question. The statistical mean of all the questions was 4 (on a scale from 1 to 5, where 1 was the worst score and 5 the best), indicating that a large majority of the interviewees considered the quality of the intervention to be good or very good.

8. DEMONSTRATOR MONITORING

To monitor the performance of this new pavement in a real environment, as urban and permeable pavement, we design and construct a demonstrator, in Torre Sant Vicent Street in Benicàssim, Spain. The demonstrator has been designed considering both the hydrology and pluviometry features of the area and the system consists of different layers. The first layer is made of CERSUDS ceramic module. Below, a layer of gravels with a specific distribution size was installed together with a layer of polypropylene cells to direct the water to the drainage network (de Miguel Arbones, E et al. 2020). Figure 13 shows the finished demonstrator.

Following we will explain the key results of this monitoring period.

8.1 Mechanical Behaviour

During the year this system has been in service, the CERSUDS system has performed satisfactorily and only the following defects have been detected in some places: a few slight bulges or soft spots and chipping on the end edges of the ceramic strips. In the case of the bulges, the main cause is the gravel in the underlay resettling when subjected to loads because, as it has no fines to allow water to circulate through it, proper compaction is prevented. Experiments in other countries on the use of this type of system show that it is a frequent pathology that could be minimised by installing geocells or geogrids. It is planned to include that type of mesh in future installations of the system.

As for the ends of the tiles breaking, that has only happened in areas where the ceramic modules were not separated from each other or the modules were not separated from the metal profiles that held them in place. In those cases, when the ceramic modules descend due to the aforementioned settling, the top edges of the modules were pressed together, causing those edges to break. Therefore, as in any installation using ceramics, it is important to respect joint spacing.

8.2 Permeability of the System

To monitor the permeability of the system, five-set points on the demonstrator street were chosen, as shown in

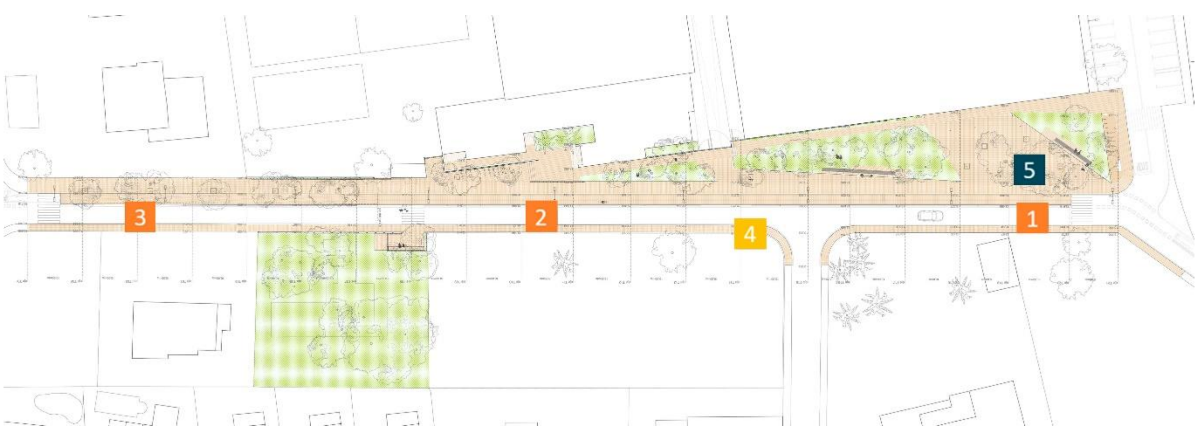

Figure 14. Monitoring points

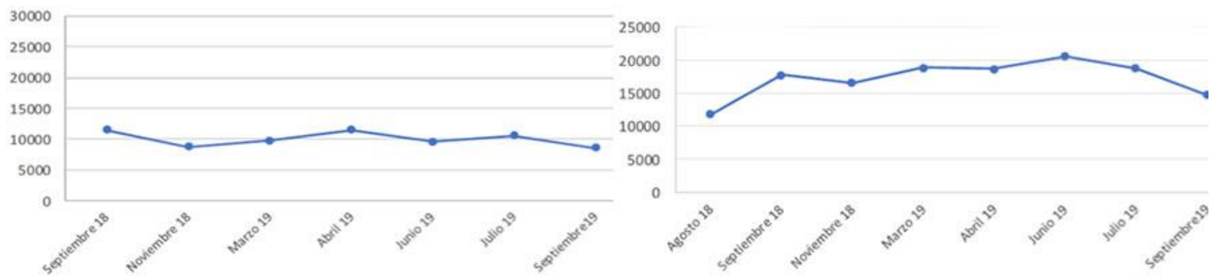

Figure 16. Left: NLT Method in mm/h. Average values. Right: ASTM Method in mm/h. Average values

Figure **14**.

The measurement of pavement permeability has been performed taking as a reference the test methods described in the Standard NLT 327/00,2000[3], and standard ASTM C1781 / C1781M [14] standards. The method described in standard NLT-327 was used during the design process of the pervious pavement, as we have seen. It is a method that has a water outlet hole of approximately 30mm in diameter. Although the permeable ceramic pavement that we are dealing with cannot be considered a homogeneous pavement since it is formed by the union of the ceramic strips through cementitious adhesive, during the pavement design process it was decided to use this method as it was considered a test recognized by the experts. However, during the on-site tests, the identification of these permeable areas was more complex and the permeability values could be significantly affected by the presence of adhesive in the test area. For this reason, in the on-site tests, it was decided to carry out the tests using the ASTM method together with the NLT test, since it is a test method that is carried out on a larger area, 300mm in diameter, which allows obtaining most representative permeability values of the installed pavement. The results of the measurements can be seen in Figure 16.

8.3 Hydraulic Behaviour

To monitor the demonstrator's hydraulic behaviour in terms of both quantity and quality of water, control equipment – comprising an automatic sampler, flow meters and level probes – was installed at three points along the street, as shown in Figure 15.

Point TM1 was located outside the demonstrator and served as a means of comparison to assess how the system was operating. Point TM2 was an

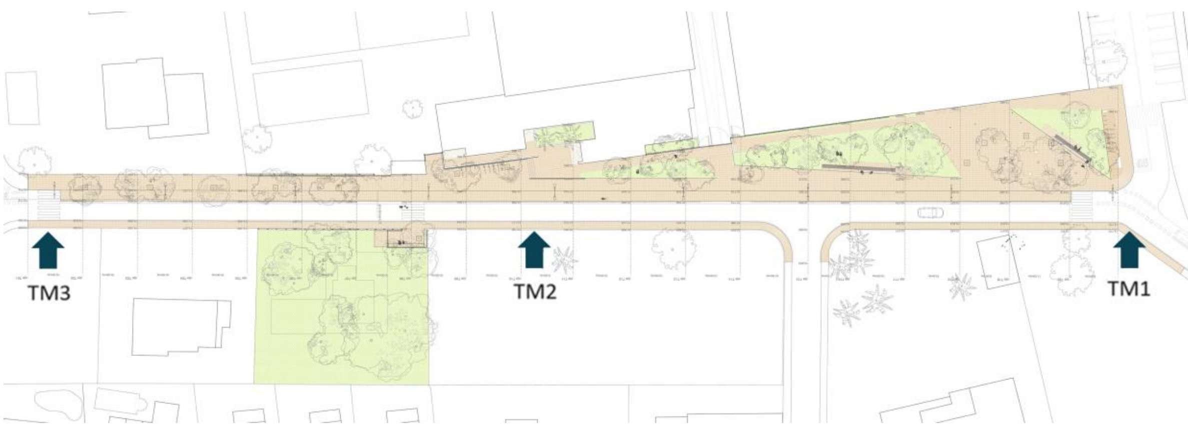

Figure 15. Location of control equipment

[14] ASTM C1781 / C1781M - 18e1. Standard Test Method for Surface Infiltration Rate of Permeable Unit Pavement Systems.

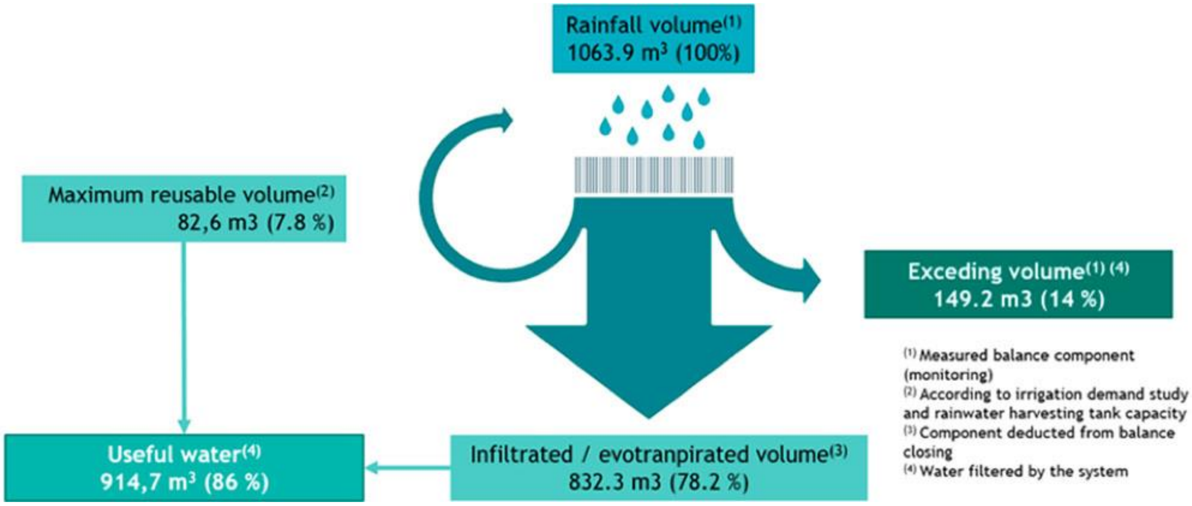

Figure 17. Hydraulic system balance

intermediate control, while Point TM3 was located just before the point where the waters collected and treated by the demonstrator exited towards the conventional drainage system. During the period under analysis (August 2018 to July 2019), 28 episodes of rainfall with a volume greater than 1 mm/day were recorded and the data collected shows that the system was able to handle 100% of the rainwater falling on its surface and that only 14% (149,255 litres) was discharged (once the water had been filtered) into the conventional drainage system. The remaining 914,695 litres (86%) was returned to the land once filtered. Figure 17 depicts the annual water balance in the system graphically:

Concerning the quality of the waters analysed, no conclusive data is available yet. However, from the data collected so far, everything seems to indicate that salt reduction is close to 80%, filtering has led to all organic matter being removed, and reduction in bacteria-forming units has had two different orders of magnitude (between $9.5x10^4$ at control point TM1 and $3.2x10^2$ at control point TM3). It is planned to continue this hydraulic monitoring to corroborate the above data over a larger series of rainfall events.

9. REPLICABILITY

During the development of the project, we analysed the possibilities of replication of this type of SUDS in other areas with climatic conditions similar to that of Benicàssim in Spain and Italy, the two European countries with the highest production of ceramic tiles, and Portugal for its great ceramic tradition. This analysis of potential replicas consisted in the study of climatological variables, prospective stocks of ceramic tiles of low commercial value available and regulations regarding SUDS. The scope was limited to areas close to the ceramic industries (radius of 200 km) in Italy, Spain and Portugal in order to avoid emissions due to transport.

As for Spain, the conclusions of this analysis are:

- The characteristic torrentiality in the south of the Valencian Community with respect to the rest of the studied area could be an aspect to be highlighted. However, this fact should not compromise the replicability of the demonstrator since the system has been designed for frequent precipitation events.
- The minimum temperatures indicate a large number of days of frost in the Lleida and Teruel stations that could have a certain impact on the response of the paving stone due to possible negative effects of the freeze / thaw cycles on the strips. However, in the freeze tests carried out, it has been observed that the defects caused by the freeze-thaw cycles consist of the detachment of some strips, which does not cause a malfunction of the ceramic system. Therefore, we can conclude that the entire analyzed area could host replicas of the proposed system.
- The ranges of precipitation variability are not very wide, in general the Benicàssim values are

found in average values of the range of results obtained for the area of influence, therefore, from the point of view of these variables, the infrastructure would potentially be replicable throughout the area, with reasonably similar hydrological results.

- Finally, regarding the culture of public powers and regulations, both Royal Decree 1/2016 for the revision of Hydrological Plans, and Royal Decree 638/2016, of December 9, indicate that new urbanizations, industrial estates and developments Urban developers should introduce sustainable drainage systems.

Regarding Italy, from the analysis carried out we can conclude:

- In the precipitation variables, something similar happens to the case of Benicássim, the Fiorano values generally being found in average values of the range of results obtained for the area of influence, with the exception of the Borgotaro station, located 112 km from Fiorano. Therefore, the infrastructure would be potentially replicable in other points of the area of influence of Fiorano.
- There are more days with temperatures below zero than in the Benicàssim area, which could have a certain impact on the response of the paving stone due to possible negative effects of freeze / thaw cycles on the strips. However, as indicated above, this circumstance would not cause a malfunction of the ceramic system.
- Regarding the culture of public powers and regulations, the Criteri Ambientali Minimi ministeriali (CAM Decree D. lgs. 01/11/2017) promote this type of climate change adaptation systems.

Regarding the aftershocks in the Aveiro area (Portugal), the following stand out:

the rainfall series of daily quantities obtained from the locations of Aveiro and Fiorano are short to be able to obtain results with the same statistical significance as those obtained for Benicàssim. However, the results of the analysis indicate that the daily precipitation volume percentiles of 80%, 85% and 90% are practically identical in the three geographic locations. This conclusion guarantees that, from a volumetric point of view, the performance of an infrastructure with characteristics identical to that of Benicàssim in Fiorano or Aveiro will end up having very similar performance.

On the other hand, it is also clear from the analysis carried out that the extreme percentiles (95% and 99%) begin to differ, with those of Benicàssim being clearly higher (in line with the torrential nature of extreme events) than those of Fiorano and Aveiro, more similar to each other and more moderate.

These values would be in relation to the calculation intensities that would determine the transport capacity needs of the hydraulic infrastructure. Therefore, it follows from this fact that the extreme calculation conditions are more unfavourable in Benicàssim than in the other locations, so that the replicability of the system as a whole is perfectly viable from the hydrological point of view.

Regarding the availability of ceramic material of low commercial value, the prospective carried out (include reference to the study) shows sufficient stock in the three countries to replicate the proposed system.

10. CONCLUSIONS

The Ceramic Sustainable Urban Drainage System project, carried out within the LIFE program promoted by the European Union for adaptation to climate change, has aimed to run a demonstrator to respond to soil sealing in cities, developing an sustainable urban drainage system using an innovative water-permeable ceramic floor made from low-commercial-value tiles.

Concern for the circular economy is at the origin of this initiative, given the 12.32 million square meters existing between Spain, Italy and Portugal, which is very difficult to market, with sale at a loss or discontinued.

This problem supports an investigation into its possible reuse in the form of a water-permeable urban pavement to reduce CO2 emissions associated with the manufacture and distribution of new materials, as well as the promotion of local employment generated by the transformation processes necessary for the realization of the CERSUDS cobble.

The CERSUDS paver is made up of 7 strips 7.5 cm wide and 33 cm long, obtained from ceramic tiles of low commercial value, assembled to work as a single module using a C2 cementitious adhesive arranged in transverse bands to achieve the required permeability.

The fact of using as raw material of low and no commercial value that, with high probability, would inevitably end up in landfill, means reductions in the environmental impact value of almost 80% with respect to a tile manufactured for this purpose.

The innovative product obtained is an element that can be handled by one person and within the weight range of other similar materials used in urban paving systems.

All the tests to which the ceramic modules were subjected: transverse breaking load, shear, impact, frost, slipperiness, abrasion, dimensional characteristics and flatness, achieved satisfactory results. Although the impact tests indicated that this was the weak point of the system, the behaviour in the real application has shown that the soil has a good performance.

The life cycle stage in the CERSUDS system that has the greatest influence on all categories of environmental impact is the supply of raw materials, that is, ceramic tiles used as raw material, their contribution exceeds 75% of the life cycle full on any impact.

The use of a higher proportion of "leftover" tiles would have a drastic influence on reducing environmental impacts. In this sense, to reduce environmental impacts, the production process would have to be industrialized to allow the use of ceramic tiles with a wider range of formats.

When CERSUDS is installed in low permeability soils (like the LIFECERSUDS project demonstrator) its impact on climate change is 20-25% less than permeable paving stones and continuous paving in the same area.

The cost per square meter of the system implemented in the LIFE CERSUDS demonstrator is higher than the cost of the conventional system, mainly due to the increase in the price of the CERSUDS flooring system compared to conventional flooring. However, the proposed system provides intangible benefits (ecosystem services, aquifer recharge and water quality, among others), which clearly counteract the purely economic criteria.

The proposed paving system has permeability coefficients higher than the recommended values. The average permeability after one year of monitoring is very high (more than 10,000 mm / h with the ASTM method) and well above the prescribed minimum values (2,500 mm / h). This result indicates that the system can function adequately as a sustainable urban drainage system.

The system has shown excellent hydraulic performance during the year follow-up, since around 86% of the water received by the demonstrator has been returned to the natural water cycle. Also, according to the data available to date, all filtered water is of good quality, both in terms of reduction of organic matter and reduction of colony forming units (CFUs) reduction in bacteria forming units (BFUs).

The validation by users of the LIFECERSUDS Demonstrator, through the completion of a survey, has been satisfactory. With an average score of 4 for all the questions on a scale of 1 to 5, the majority of the interviewees considered that the quality of the intervention was good or very good.

-Finally, and thanks to the mechanical, permeability and hydraulic results obtained, it is considered that the paving system developed from the reuse of depreciated products from the ceramic industry provides a replicable solution based on the circular economy that generates new value social, environmental and economic.

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