MONITORING OF CERAMIC CONSTRUCTION SOLUTIONS FOR FLAT ROOF RENOVATION

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1. ABSTRACT

One of the most significant ways of improving building performance in terms of energy demand and greenhouse gas emissions is by **renovating the thermal envelope**. Façades and roofs are the construction elements that protect the living spaces from the outside and their influence on a building's energy performance is considerable.

Such is the context in which the **ROOFTILES II project** is proposed, the main objective of which focuses on **monitoring and assessing ceramic systems used in renovating flat roofs** as contributors to improving building energy efficiency and sustainability. The following are some of the chief goals of the project:

- Analysis and selection of conventional and innovative ceramic systems to be assessed in flat roof renovation.
- Design, development and construction of purpose-built validation prototypes that allow several ceramic systems to be monitored simultaneously.
- Follow-up and updating of the monitoring system and display of the experimental data obtained from the prototypes.
- Analysis of results and assessment of the implementation of the various ceramic systems in flat roof renovation, in both warm and cold periods. The results obtained will be analysed in relation to a reference solution representative of roofs dating from the 1960s to 1980s.

This paper presents the main results obtained in the project entitled "Monitoring study of horizontal ceramic construction solutions for their energy assessment (ROOFTILES and ROOFTILES II)", references (IMDEEA/2021/34 and IMDEEA/2022/7). The project is funded by the Valencian Institute for Business Competitiveness (IVACE) through the European Regional Development Fund (ERDF).

2. INTRODUCTION

In Europe, the building industry accounts for 40% of total energy consumption, produces 36% of CO_2 emissions, is responsible for one third of water consumption, and generates one third of all waste.

The European Union (EU), through its energy performance of buildings directives (EPBDs), aims to **reduce energy consumption in the building sector** and, consequently, reduce greenhouse gas (GHG) emissions to mitigate climate change. The global challenge regarding climate change and sustainability calls for a transformation in the way we build and especially in our building stock: approximately 75% of the building stock in the EU is energy inefficient.

In Spain, the building stock comprises more than 10 million buildings and over 25 million homes. Approximately 90% of these buildings were constructed before Spain's Technical Building Code (CTE)[1] came into force and 60% of dwellings were built **without any energy efficiency regulations** (prior to NBE-CT 79)[2]. Energy renovation of the building stock has become a key priority in achieving the decarbonisation targets for the sector set by the EU for 2050 (European Green Deal)[3].

In this regard, the **building envelope** (façades and roofs) play a significant role in heat transfer between the outside and inside of the building. Specifically, **the roof** is the construction element of the building envelope that receives the greatest amount of solar radiation throughout the day and its influence on a building's thermal behaviour is significant.

All this is framed within a world context of climate change where, to cite just one example, 2022 broke all records in terms of the number of days of heat wave in the Iberian Peninsula (according to the Spanish Meteorological Agency AEMET)[4]. This new scenario we are facing calls for the development of renovation systems that improve building performance in the face of high temperatures and extreme weather episodes.

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[3] European Council, 2023. *European Green Deal*. Available at: https://www.consilium.europa.eu/es/policies/green-deal/

[4] AEMET, 2022. *Olas de calor en España desde 1975*. Climatology and Operating Applications Area. Available at: https://www.aemet.es/documentos/es/conocermas/recursos_en_linea/publicaciones_y_estudios/estudios/Olas_calor/Olas_Calor_ActualizacionOctubre2022.pdf

3. ENERGY RENOVATION SYSTEMS

3.1 STUDY OF RENOVATION SYSTEMS AND CONSTRAINTS

The first stage of the project analysed current types of building roofs and the various systems available for renovating flat roofs: raised access floors, adhered flooring, permeable flooring for trafficable roofs, and gravel and green or living finishes for non-trafficable roofs. All of them were assessed on the basis of environmental (A), economic (E) and performance (P) criteria using indicators, as shown in Table 1, with scores ranging from 1 for least favourable to 5 for most favourable.

Criteria assessed	Raised floor	Adhered flooring	Permeable flooring	Gravel	Green
A1. Thermal insulation – energy savings	5	4.93	4.98	4.93	4.91
A2. Recovery - Recycling	5	1	5	5	4
E1. Initial investment cost	3.21	3.43	5	4.87	3.14
E2. Maintenance (durability-cost-frequency)	5	3	5	5	3
P1. Ease of implementation	4	3	4	5	1
P2. Sound insulation	4	4	4	4	5
P3. Weight of system	1.3	0.9	1.13	5	0.33
P4. Waterproofing and watertightness	5	5	5	5	5
P5. Aesthetics	4	4	4	3	5
Mean values (before weighting)	**4.06**	**3.25**	**4.23**	**4.64**	**3.49**

Table 1. *Assessment of criteria in the defined solutions*

For prioritisation purposes, it was concluded that the highest number of favourable criteria corresponded to the gravel finish, followed by permeable flooring, raised floor, and adhered flooring. The green roof was the one with the highest number of unfavourable criteria, the system's weight being particularly significant in renovation, a factor that made its application practically unfeasible.

With these study results in hand and after surveying key users, a series of constraints were identified that need to be taken into account when projecting the renovation of flat roofs, the following being prominent constraints:

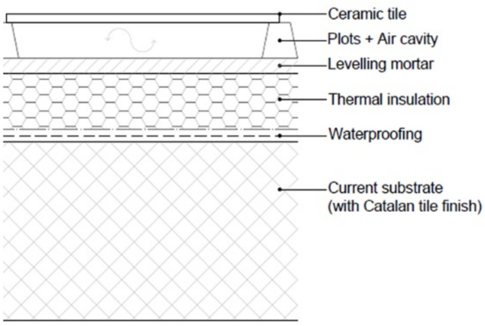
- **Excess weight** of roof renovation solutions is of great **importance** and conditions their implementation. However, its importance is not perceived as such by users and experts.
- Although **green** roofs are highly desirable from a **sustainability** viewpoint, they are hardly applicable as a renovation solution on existing buildings due to their **excess weight**.
- Users attach **greater importance to the investment cost**, which is a factor that sometimes determines renovation feasibility.

- Despite the importance of insulating the building envelope, **current regulations (DB HE1)** are only applicable to certain renovation scenarios.
- Today's **simulation tools** do not take into account some of the beneficial effects of innovative renovation solutions, such as ventilation in raised floors, reflectance of finish materials, or evapotranspiration of green roofs.

3.1.1. CERAMIC SYSTEMS SELECTED FOR EXPERIMENTAL ASSESSMENT

Once the different renovation systems had been analysed, **two ceramic systems** were selected for monitoring and experimental evaluation (Illustration 1):

- Inverted roof with **Ceramic Floor Panelling (PA)**. This is a solution in which thermal insulation is installed above the waterproofing membrane to protect it from external stresses.
- Inverted roof with **Raised Floor (STE)**. This is a construction solution similar to the one above, and it is characterised by the installation of tiles on plots that enable a ventilated cavity to be configured.



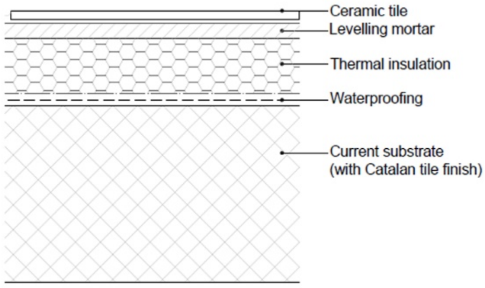


Illustration 1. *Diagram showing the different layers that make up the studied roof systems. Left (Roof with ceramic raised access floor). Right (Roof with ceramic panelling).*

Table 2 shows the main variables in the ceramic systems to be experimentally assessed during the monitoring period. The coding shown in brackets was used to identify the variables:

Roofing system	Tile colour	Tile thickness (mm)	Cavity opening	Cavity height (mm)	Thermal insulation thickness (mm)
Ceramic Floor Panelling (**PA**)	White (**b**) Reflective white (**bR**) Grey (**g**) Black (**n**)	12 8 6	-	-	No insulation (**A0**) 30 (**A3**) 50 (**A5**)
Raised Access Floor (**STE**)		12 8 6 6+core (**R**)	Closed (**cc**) Half-open (**csa**) Open (**ca**)	20 (**2**) 50 (**5**)	No insulation (**A0**) 50 (**A5**) 80 (**A8**)

Table 2. *Variables of the ceramic tiles and systems assessed*

For example, a system coded as "**STEn6cc2A5"** would correspond to a raised access floor system with 6 mm thick black tile, 20 mm high closed air cavity and 50 mm thick thermal insulation.

3.2 ESTIMATED POTENTIAL ENERGY SAVINGS

Parallel to the experimental analysis, a parametric thermodynamic simulation study was carried out on the renovation of **three types of residential buildings** (single-family, low-rise multifamily, high-rise multifamily) in **three different climate areas** in Spain (Seville-A4, Castellón-B3, Burgos-E1), in which the following variables were altered: façade orientation and colour of the envelope. In addition, two renovation scenarios were considered, one in which only the roof is renovated, and the other in which the entire envelope (roof, façade and external carpentry) is renovated.

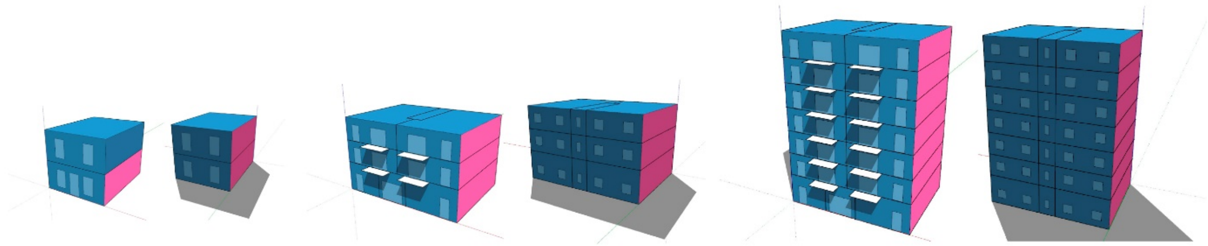


Illustration 2. *Thermal simulation models of building types. Left (single-family–RU), centre (low-rise multifamily–RPB), right (high-rise multifamily–RPA)*

Due to the extended scope of the study, this section focuses only on **roof renovation** in which the main façade faces **south** and the colour of the non-renovated building envelope has an **absorptance of 0.5** (mean colour). Table 3 shows the heat transmittance values considered for the simulation:

Thermal characteristics of the opaque enclosures	Original building 1980 (W/m^2K)			Building w/ renovated roof (W/m^2K)		
	A4	B3	E1	A4	B3	E1
Roof in contact with outside air	**1.79**			**0.44**	**0.33**	**0.19**
Walls in contact with outside air	**1.33**					

Table 3. *Transmittance values of the original building and of the renovated building (according to Annex E of the Basic Energy Saving Document (DB-HE) in Spain's Building Code (CTE)).*

Table 4 presents the results obtained in such a scenario. On the one hand, it shows the energy demand values of the non-renovated buildings (kWh/m^2) in the various climate areas and, on the other hand, it details the variation in energy demand in percentage terms (%) that can be achieved in each case by renovating the roof. It was considered that the roof in warm climate areas had been renovated with light-coloured tiles and in cold climate areas with dark-coloured tiles.

Climate area	Building Type	Energy demand Non-renovated building *(kWh/m²)*			Renovated roof colour *(Absorption)*	Variation in energy demand Renovated roof *(%)*		
		Heating	*Cooling*	*Total*		*Heating*	*Cooling*	*Total*
A4	RU	15.1	35.8	51	Light (0.3)	-15%	-32%	**-27%**
	RPB	9.6	29.4	39		-54%	-26%	**-33%**
	RPA	3.4	25.8	29.3		-37%	-16%	**-19%**
B3	RU	28.1	22.4	50.5	Light (0.3)	-16%	-37%	**-26%**
	RPB	19.6	18.2	37.8		-49%	-30%	**-40%**
	RPA	8	16.2	24.2		-30%	-19%	**-22%**
E1	RU	149.1	2.1	151.2	Dark (0.7)	-29%	+16%	**-28%**
	RPB	119.8	1.6	121.4		-42%	+21%	**-41%**
	RPA	73.1	1.7	74.8		-25%	+28%	**-24%**

Table 4*. Variation in energy demand with renovation, as a function of climate area, type of building and colour of the envelope.*

As might be expected, in non-renovated buildings with an envelope dating from the 1980s, blocks of flats or apartments (RPA, RPB) have lower heating and cooling demands per square metre, as they are more compact buildings with a lower ratio between envelope surface area and built surface area.

A comparison of the results obtained in the different climate areas for the various types of buildings shows the **potential energy savings** that renovation of the building envelope would provide, with **reductions in overall demand** between **19% and 41%**.

Looking only at **heating demands**, reductions ranging between **16% and 54%** are achieved in all cases, while in the case of **cooling demands**, improvements of up to **37%** can be observed in **warm climate areas (A4, B3)**.

It is worth noting that in **cold climate areas (E1)**, increases in cooling demand of around 30% are detected. These increases may be mainly due to the colour of the envelope and the effect of insulation that reduces heat losses from the inside to the outside during the night. As can be seen in the results for overall demand, the influence of this increase is minimal, as cooling values are very low compared to heating values.

On the other hand, after analysing the results obtained in the simulations, in which all scenarios and variables were considered, it was observed that:

- When **the entire envelope** (roof + façade + windows) is renovated, reductions in **overall demand** of nearly **70%** can be achieved in cold climate areas (E1) and of **50%** in warm climate areas (B3-A4).

- In addition, it was noted that, in certain cases, renovating the envelope with thermal insulation can lead to increases in cooling demand in both hot and cold climate areas. In order to achieve energy efficient performance in renovation, the **incorporation of thermal insulation** in the envelope **needs to be accompanied by other measures**, such as solar shading systems (principally in warm climate areas) and ventilation systems using heat recovery units, to ensure air renewal inside the building.

4. PROTOTYPE DEVELOPMENT AND VALIDATION

4.1 DESIGN, DEVELOPMENT AND CONSTRUCTION OF PROTOTYPES

To carry out our experimental analysis, **three validation prototypes** were designed and built as a fully **sensorised and temperature-conditioned energy laboratory**, enabling different ceramic construction solutions to be installed on flat roofs. Three prototypes recreate a trafficable roof from the 1980s that was finished with Catalan tile and had a thermal transmittance U=1.79 W/m^{2}K.

In one of the prototypes, the behaviour of a standard roof (**REFERENCE**) on an existing building (with no renovation or thermal insulation) with Catalan tile as the top finish was analysed. In the other two prototypes, different ceramic renovation systems were installed. They could thus be monitored and viewed simultaneously under the same environmental conditions (temperature, radiation, wind, etc.) to see how the different renovation solutions perform in both hot and cold periods.

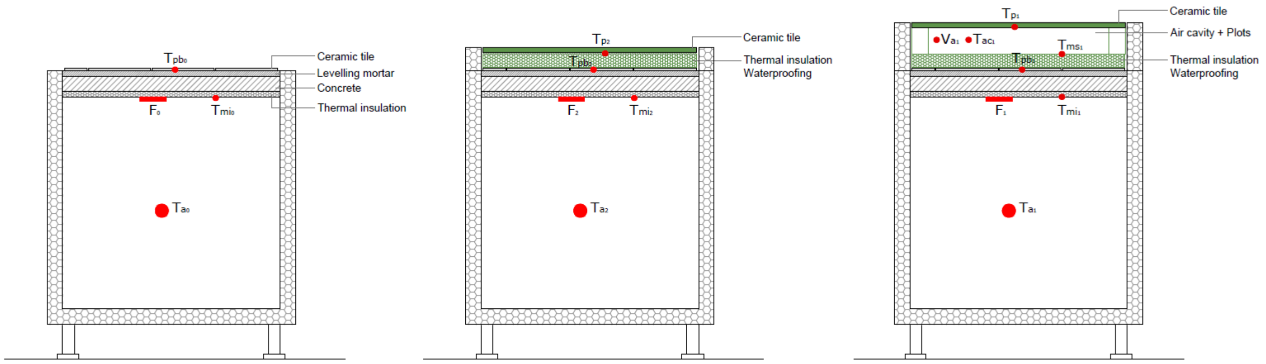


Illustration 3. *REFERENCE (REF) prototype (left). Renovated prototypes (A) (right) and (B) (centre).*

The photographs below show the prototypes installed on the rooftop of the Institute of Ceramic Technology (ITC) in Castellon.

Illustration 4. *Prototypes operating on the roof of the ITC building*

4.2 PROTOTYPE MONITORING

For continuous monitoring of the prototypes, a data acquisition system (based on ADAM modules) was set up to collect the readings generated by the sensors installed in each of the prototypes.

The main temperature variables collected for each prototype were as follows: Catalan tile (Tp), Top ceramic tile (Tps), Inner wall (Tmi), Top wall (Tms), Air inside the prototype (Tai), and air in the raised floor cavity (Tac). In addition, heat flow sensors were also installed inside the walls of each prototype. Moreover, variables relating to the environmental conditions (ambient temperature, radiation, wind speed and direction) were collected.

To view and analyse the data collected from the prototypes, a platform (Thingsboard) was implemented to monitor each system's behaviour in real time using custom dashboards, as shown in Illustration 5.

***Illustration 5**. Data display platform (dashboard) during monitoring stage*

5. EXPERIMENTAL RESULTS

After the monitoring study, the results were evaluated by comparative analysis of the variables that affect heat transfer through the roof in the different systems.

5.1 REFERENCE MODEL VS RAISED ACCESS FLOOR

Firstly, the thermal performance of a raised access floor (**STE**) renovation system, comprising a 6 mm thick black (n6) or white (b6) ceramic top tile, with a closed cavity (cc) and two insulation thicknesses - no insulation (A0) or 5 cm thick insulation (A5) - was evaluated in comparison with the reference non-renovated system (REF: Catalan tile).

Of all the variables in the experimental analysis, Tables 5 and 6 show daytime values for: ambient temperature and solar radiation, top tile temperature (mean and maximum), inner wall temperature and indoor air temperature. The tables also show the difference in wall temperature in the renovated prototypes compared to the non-renovated reference system (REF: Catalan tile).

INSULATION EFFECT

To analyse the effect of insulation, the mean results on sunny days for the systems in the group (**1.5** and **1.7**) in temperate (T) and warm (C) climates were compared on the basis of three variable insulation scenarios: with no insulation (A0), with 50 mm insulation (A5), and with 80 mm insulation (A8), as shown in Table 5.

One can see that in both temperate and warm climates, when the STE renovation system (with or without insulation) is used, even though surface temperature on the black ceramic top tiles is higher than the temperature of the Catalan tile, **temperatures in the inner wall remain lower** than those recorded in the reference prototype, thanks to the greater reduction in solar radiation produced by the ventilated cavity together with the insulation. In **temperate climates**, temperature differences of about 1 ºC were detected in the wall when comparing a system with no insulation to one with 50 mm insulation (1.5), but hardly any difference was seen on going from 50 mm to 80 mm insulation thickness (1.7).

Group	Prototype	System	DAY						
			Mean radiation (W/m²)	Mean ambient temp. (ºC)	Mean tile temp (ºC)	Max. tile temp. (ºC)	Mean cavity temp. (ºC)	Mean wall temp. (ºC)	Temp. diff. renov. wall vs Ref temp. (ºC)
1.5 Temperate	REF	Catalan tile	421	21.8	23.1	30.6	-	21.2	-
	A	STEn6cc2A0			33.3	49.2	24.9	20	-1.3
	B	STEn6cc2A5			35.4	54.0	32.5	19.1	-2.2
1.7 Temperate	REF	Catalan tile	442	18.6	21.8	29.9	-	19.7	-
	A	STEn6cc2A5			32.6	53.6	29.3	17.0	-2.7
	B	STEn6cc2A8			33.5	54.6	30.4	17.2	-2.5
1.5 Warm	REF	Catalan tile	501	25.3	31.2	41.4	-	28.4	-
	A	STEn6cc2A0			38.6	59.2	31.9	25.6	-2.7
	B	STEn6cc2A5			40.8	66.6	39.0	23.0	-5.4

***Table 5**. Comparison of daytime temperatures in STE with different insulation thicknesses*

In warm weather (**1.5C**), **temperature reductions in the inner wall** in the STE system with 50 mm thick insulation are significant in comparison with the Reference system, reaching differences of **over 5 ºC**. In this case, the negative difference values shown in the Table indicate that wall temperature in the renovated systems is lower than that in the non-renovated prototype (REF), thanks to lower heat gain provided by the STE system with insulation. Such reductions in daytime heat gains lead to lower cooling demand in hot weather.

COLOUR EFFECT

As can be seen in Table 6, in a **temperate climate (1.6T)**, the black top tile absorbs more radiation and reaches a higher temperature than the Catalan tile in the Reference system (12 ºC on average, with a maximum peak of 24 ºC), but the effect of the STE cavity and the insulation reduces heat transmission considerably, such that wall temperature is ultimately lower than temperature in the non-renovated wall (REF). The difference in wall temperature between the two renovation systems with different tile colours is 1 ºC, the highest wall temperature being reached when renovated with a dark-coloured tile.

Group	Prototype	System	DAY						
			Mean radiation (W/m²)	Mean ambient temp. (ºC)	Mean tile temp (ºC)	Max. tile temp. (ºC)	Mean cavity temp. (ºC)	Mean wall temp. (ºC)	Temp. diff. renov. wall vs Ref temp. (ºC)
1.6 Temperate	REF	(Catalan tile)	446	19.3	21.8	30.1	-	19.6	-
	A	STEn6cc2A5			33.9	53.9	30.7	16.7	-2.8
	B	STEb6cc2A5			16.4	23.7	16.6	15.7	-3.9
1.6 Warm	REF	(Catalan tile)	473	28.2	35.9	45.7		33.7	-
	A	STEn6cc2A5			45.1	66.6	42.9	28.9	-4.8
	B	STEb6cc2A5			28.6	37.0	29.3	28.0	-5.7

Table 6. *Comparison of mean daytime temperatures in STE with black and white top tiles*

In a **warm climate (1.6C)**, the same trend can be seen: the STE renovation prototype with a white top tile produces the greatest heat dampening and lower temperatures in the top tile, cavity and inner wall. As the graph in Figure 2 shows, although temperature differences between the black and white tiles are very significant, the differences in wall temperature in the STE system hardly vary thanks to the effect of the insulation. If the temperature differences between the reference wall and the renovated wall are compared at the end of the day, the non-renovated prototype is found to have a wall temperature (1TmiREF) almost 12 ºC higher than that of the renovated wall (1TmiA and 1TMiB).

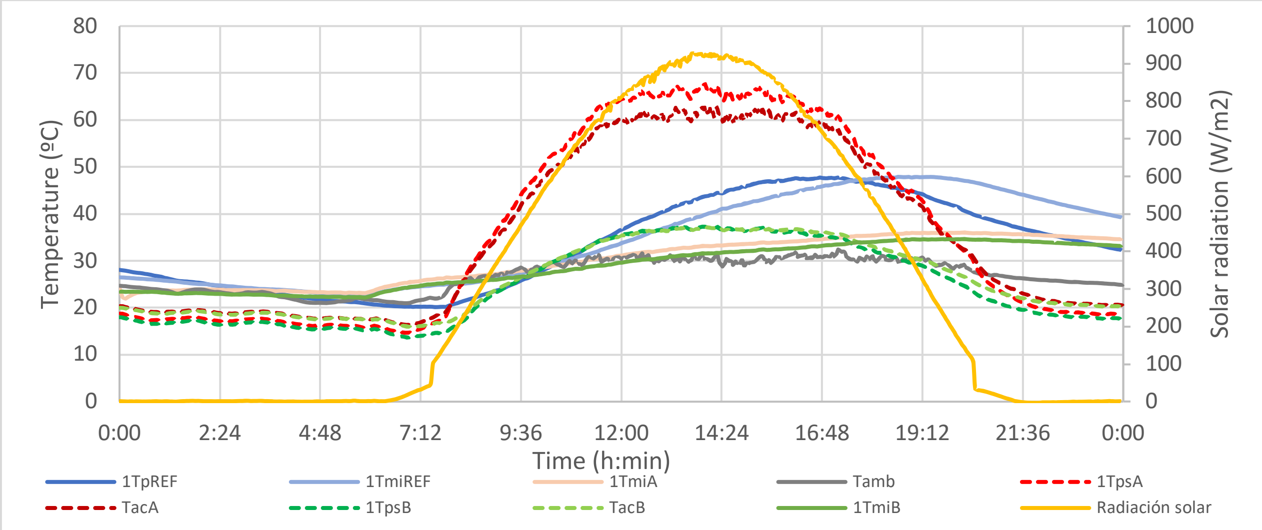


Figure 1. *1.6C SYSTEM: REF prototype / Prototype A (STEn6cc2A5) / Prototype B (STEb6cc2A5) 24-06-2023*

5.2 REFERENCE PROTOTYPE VS FLOOR PANELLING SYSTEM VS RAISED FLOOR

On the other hand, the performance of the raised access floor renovation system (**STE**) was assessed against the ceramic floor panelling system (**PA**), where both systems involved a 6 mm thick ceramic tile coloured black (n6) or white (b6) and 5 cm insulation (A5).

When the PA system is compared to the STE system in a **temperate climate with a black tile** (2.1T), the STE system is seen to produce a mean temperature in the wall almost 1 ºC higher than when renovated with ceramic panelling (Table 7), due to the fact that the air temperature in the cavity (Tac) is much higher than the ambient temperature (Tamb) (see Figure 3).

In the **warm period** (2.2C), the systems with a **white tile** were compared and it was found that, in all three prototypes, temperatures in the inner wall exceeded 30 ºC, due to the heat that accumulates in hot weather with high night-time temperatures. When the renovated systems are compared with each other, temperature differences in the inner wall are seen to be similar, although slightly lower in the STE system, as detailed in Table 7.

Group	Prototype	System	DAY						
			Mean radiation (W/m²)	Mean ambient temp. (ºC)	Mean tile temp (ºC)	Max. tile temp. (ºC)	Mean cavity temp. (ºC)	Mean wall temp. (ºC)	Temp. diff. renov. wall vs Ref temp. (ºC)
2.1T	REF	Catalan tile	497	17.3	21.1	30.3	-	18.2	-
	A	PAs1n6A5			34.3	53.1	-	15.7	-2.6
	B	STEn6cc2A5			35.3	53.9	32.3	16.5	-1.7
2.2C	REF	Catalan tile	424	27.4	34.0	42.4	-	35.8	-
	B	PAs1b6A5			26.9	34.5	-	35.3	-0.5
	A	STEb6cc2A5			27.2	35.3	26.8	34.8	-1.0

Table 7. *Comparison of mean daytime temperatures between STE and AP systems with black and white tiles.*

In the cases studied, it was observed that the STE system with a black tile in a temperate climate and with a white tile in a warm climate has better thermal behaviour than the PA floor panelling system.

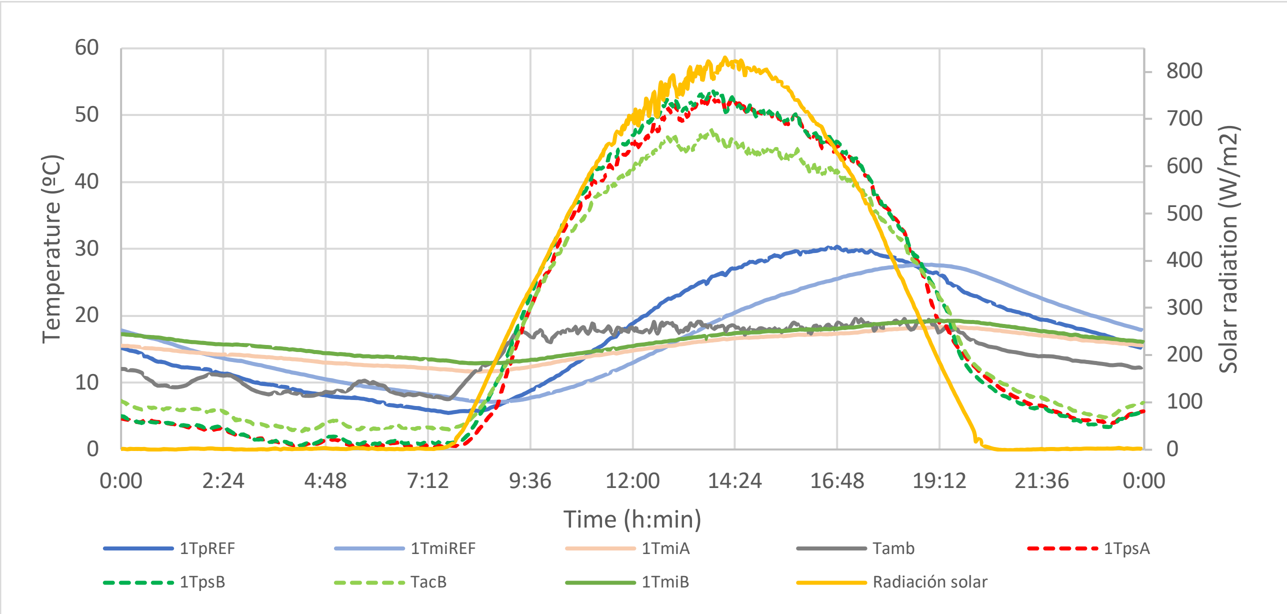


Figure 2. *SYSTEM 2.1T: REF prototype / Prototype A (PAs1n6A5) / Prototype B (STEn6cc2A5) 04-04-202*

6. CONCLUSIONS

This paper presents the partial results obtained in the ROOFTILES II project, the main focus of which is energy assessment of ceramic building solutions for the renovation of flat roofs:

- An analysis was performed of current types of roofing on buildings and of the commercial systems available for their renovation, **identifying the constraints** to be reckoned with in the energy renovation of flat roofs.

- Energy simulations were conducted to assess the potential improvement afforded by energy renovation, where it was seen that **reductions in overall energy demand of up to 40%** can be achieved by renovating the roof of a building.

- **Three validation prototypes were designed and built** as a fully sensorised and temperature-conditioned energy laboratory that enables flat roof systems to be assessed under the same environmental conditions. A **monitoring and control platform** based on private cloud services was implemented for data acquisition and display.

- Different ceramic systems were **monitored at an experimental level** (inverted roofing with floor panelling and raised access floor) in which different variables (tile colour, insulation thickness, cavity ventilation, etc.) were altered, along with more innovative ceramic systems (reduced thickness tiles with reinforcements, mixed insulation and mortar systems, reversible tiles, etc.).

- The results obtained during monitoring made it possible to **assess the influence** of insulation, as well as of ceramic tile colour and of the raised floor cavity, on thermal gains through the roof. A comparison of the assessed systems against a non-renovated Reference enabled the temperature differences achieved in each case to be quantified. In **warm climates**, renovation using floor panelling or raised access floor systems with insulation **enables heat gains to be reduced**. It was observed that tile colour has a significant effect on the temperature reached on the roof surface tiles and that light colours do not reach such high temperatures. However, this effect decreases at inner wall temperature level because the insulation attenuates heat transmission.

- From the cases assessed in this study, better performance was observed in renovations with a **Raised Access Floor** system with black tiles in temperate climates and with white tiles in warm climates. In order to optimise the performance of these systems in roof renovation, two innovative solutions have been proposed within the framework of the project, one based on using the hot air generated in the raised access floor cavity during cold periods, and the other on using reversible tiles with two colour finishes.

7. ACKNOWLEDGEMENTS

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