Developing Affordable Cool Roof Tiles from Construction Waste for Thermal Insulation in Hot Climates: An Experimental Study

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Developing Affordable Cool Roof Tiles from Construction Waste for Thermal Insulation in Hot Climates: An Experimental Study

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Abstract: *Cool roofs are advanced/high-tech. approaches to improving the energy efficiency of buildings. The study develops a novel cost-effective cool roof tiles using Construction Waste (CW) materials to address both thermal insulation and sustainability challenges in hot climate regions. Six tile mixtures were fabricated using varying proportions of silica fume, glass waste, terrazzo powder, and marble chips, combined with white cement through a hand-molding process. Among these, a tile—comprising 40% cement, 40% terrazzo powder, and 20% glass waste—exhibited the best thermal performance, achieving a low thermal conductivity of 0.215 W/m·K. This marks a 10–50% improvement over previously reported waste-based tiles while maintaining mechanical integrity with a compressive strength of 23.3 MPa, and a water absorption rate of 13.58%. The study demonstrates that integrating CW into tile production offers a sustainable, affordable alternative to conventional roofing materials, contributing to energy efficiency and circular economy practices in the built environment.*

Keywords: Construction waste; Terrazzo powder; Glass waste powder; Thermal properties; Hot regions

Abbreviations

Abbreviation	Description
CW	Construction Waste
SF	Silica Fume
GW	Glass Waste
TP	Terrazzo Powder
MCW	Marble Chips Waste
W-C	White Cement
M-CWT	Marble Construction Waste Tile
G-CWT	Glass Construction Waste Tile
GS-CWT	Glass & Silica-Fume Construction Waste Tile

1. INTRODUCTION

The production of Ordinary Portland Cement (OPC) significantly impacts the environment due to its high CO2 emissions [1]. The environmental impact of Ordinary Portland Cement (OPC) is significant because its production emits large amounts of CO2. Therefore, it's essential to develop energy-efficient and environmentally friendly strategies to reduce carbon emissions [2]. Additionally, urban areas suffer from heat island effects, highlighting the need for roofing materials that can mitigate this issue. Implementing energy-saving building practices, such as using reflective roofing and green roofs, can further reduce temperatures and enhance energy efficiency in urban environments [3]. Therefore, implementing sustainable roofing systems, such as cool roofs [4]and cooling materials, offers an effective passive solution to decrease buildings' cooling demand, potentially reducing energy consumption by 10-30% [5]. Using OPC and dense aggregates also increases the drawbacks of typical roofing tiles. Tony, Fernando, and Rafael (2023) developed tiles using iron ore tailings (IOT) [6], a form of mining waste, as a partial substitute for OPC in extruded concrete tiles, these tiles have desirable physical, mechanical, and thermal properties.

In related research, Satya and Sreekanth (2024) [7], created an innovative type of recycled plastic roof tile that includes Phase Change Material (PCM) and is coated with hollow-glass-microsphere-based white paint. However, despite its innovation, this PCM-enhanced solution is not fully cost-effective. Previous research has mainly focused on using construction waste in concrete and masonry instead of roof tiles. In the limited cases, where waste has been incorporated into roof tiles, it usually involves mixing with expensive additives. This study seeks to produce an affordable cool roof tile by substituting the OPC cement layer in the tile with construction waste. The resulting tiles demonstrate suitability in terms of physical, mechanical, and thermal properties compared to those in previous research, complied with international standards.

2. EXPERIMENTAL PROCEDURE

2.1 Raw materials

Selected types of construction waste (CW) materials are identified for inclusion in the new tiles. Selecting Silica Fume, Glass Waste, Marble Waste, and Terrazzo Powder for research on construction waste materials draws from past studies that highlight their potential benefits and limitations in construction applications. Silica Fume is often noted for its ability to improve the mechanical properties and durability of concrete, although it may negatively impact certain performance aspects, such as electrical conductivity [8]. Testing highlights these effects, offering a foundation for its study. Glass Waste [9]is recognized for its effectiveness in reducing thermal conductivity and enhancing insulation, making it ideal for energy-efficient applications like cool roofing systems. In contrast, Marble Waste, while enhancing mechanical properties , has minimal impact on thermal conductivity, explaining its secondary role in this research [9]. Terrazzo Powder has been studied as a sustainable filler or aggregate, contributing positively to the aesthetic and environmental sustainability of building materials without significantly affecting their mechanical integrity. By focusing on these materials, the study builds on existing literature while exploring innovative ways to improve the performance and environmental impact of construction materials.

2.2 Tile specimen mix design

The tile samples are composed according to adjusted production ratios, guided by research and standards (ASTM and ECP 204), to be suitable for hot arid climates [10]. The new, innovative mix design includes white cement mixed with construction waste materials like SF, MCW, GW, and TP, as detailed in Table 1. Marble chips waste (MCW) is generated from the mining, and cutting processes of marble, in a construction site. Silica fume (SF), also known as micro silica, is a byproduct of the production of silicon metal or ferrosilicon alloys. Glass waste (GW) comes from recycling was sourced from leftover construction waste from a construction site at the Egypt-Japan University of Science and Technology in New Borg El Arab, Egypt. Terrazzo powder (TP) typically consists of finely ground waste material from terrazzo products. This waste can include various aggregates bound in a cement-based matrix. This innovative tile is fabricated using a smart design mixture that incorporates varying percentages of these specific alternative construction waste materials to replace cement content, thereby reducing its production, encouraging recycling, and promoting sustainability. Fabrication of a one-layer construction primarily relying on the strength of the white cement and waste mixture. Six tiles were fabricated using a hand-molding technique, each with dimensions of 0.2m x 0.2m and 0.015m thick. The density (ρ) of the optimized G-CWT-4 tile was measured to be 1055 kg/m^3, with a volumetric heat capacity (c_v) estimated at 897 kJ/m^3.K assuming an average specific heat (c_p) of 850 J/kg (ASTM E1269-17). K based on its composite materials. The corresponding thermal diffusivity (α) was calculated as 2.40 x 10 $^{-7}$m^2/s, confirming the tile's capability to store significant amounts of thermal energy, contributing to its superior insulation performance.

Although, its solar reflectance [11] of this new mixture made from white cement, terrazzo powder, and glass waste was estimated using a weighted average equation, R_total = Σ (R_i x W_i), where R_total is the total reflectance, R_i is the reflectance value of each material, and W_i is the weight fraction of each material. Based on the proportions of each material (40% white cement, 40% terrazzo powder, and 20% glass waste) and their individual reflectance values (0.8, 0.7, and 0.75 respectively), the calculated solar reflectance of the tile was approximately 0.75. This indicates a relatively high reflectance, making it suitable for cool roofing applications according to ASHRAE and ASTM E903 standards.

Table 1. Tile Mix Design Sample Composition

Mix ID	WATER (G)	Tile materials					
		W-C (g)	W-C (%)	TP(%)	MCW (%)	GW(%)	SF (%)
M-CWT-1	360	720	60%	30%	10%		-
G-CWT-2	360	720	60%	30%	-		-
M-CWT-3	240	480	40%	40%	20%	-	-
G-CWT-4	240	480	40%	40%	-	20%	-
GS-CWT-5	180	360	30%	40%	-	20%	10%
GS-CWT-6	240	400	40%	30%	-	20%	10%

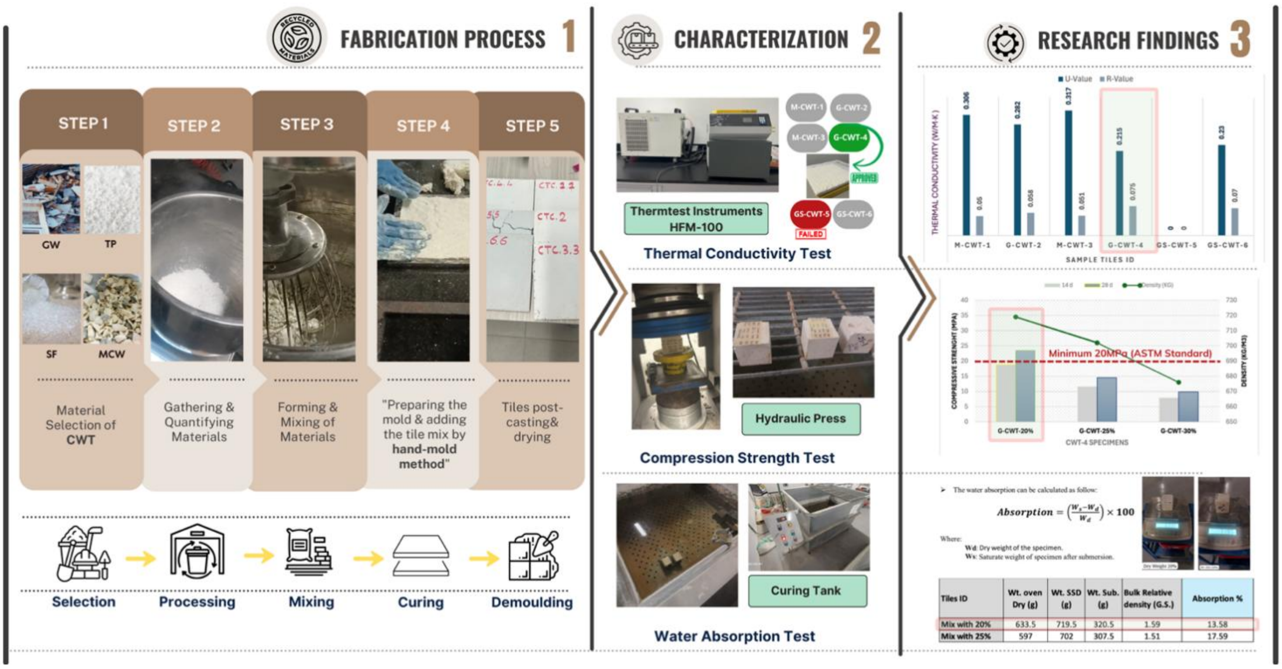

Fig. 1. Methodology framework of the study.

3. RESULTS AND DISCUSSION

3.1 Procedure phases

The study implemented a systematic three-phase approach to develop new cooling tiles using waste composites. This approach, illustrated in Figure 1, involves three key stages: (1) the Fabrication Process, (2) Characterization, and (3) Research Findings. In [Phase 1], undergoes five main steps, which illustrates the collection & selection of the waste materials utilized and fabrication and manufacturing process of tiles "CWT "according to the different material types and percentages at laboratory scale using "hand-mold technique" [Phase 2], The experimental procedure for analyzing tiles involves several key steps. It begins with measuring the thermal conductivity of the tiles, as this is essential for selecting the optimal design. The study evaluates six innovative tile designs using four different construction waste materials—SF, TP, MCW, and GW—in various proportions to optimize thermal performance. Once the ideal tile is identified, it undergoes a compression strength test, with the resulting percentage values used as benchmarks. Following compression strength guidelines, three cubes are produced with varying water content levels. The procedure concludes with an investigation into the water absorption properties of the two selected cubic tiles. In [Phase 3], the outcomes of the three tests on the specimens will be detailed: thermal conductivity, mechanical, and water absorption. Additionally, the findings will be compared with those from previous studies.

3.2 Thermal Characterization

The thermal conductivity of the newly developed tiles was measured using the Thermtest HFM-100, revealing superior insulating properties compared to traditional roofing materials, thereby indicating their potential for enhancing energy efficiency in buildings. The analysis aligns with ASTM C518, which is a standard method for assessing the thermal transmission properties of materials using a heat flow meter. Cement-based and mosaic tiles, commonly used on Egyptian roofs, usually exhibit thermal conductivity values ranging from about 0.7 to 1.2 W/m·K [12]. Initial testing on the six fabricated sample tiles showed that lowering the Ordinary Portland Cement (OPC) content resulted in decreased thermal conductivity. As detailed in (Fig. 2), thermal conductivity values ranged from a low of 0.215 W/m·K to a high of 0.317 W/m·K. Tiles containing (MCW)—specifically M-CWT-1 and M-CWT-3—had the highest conductivities, measuring 0.306 W/m·K and 0.317 W/m·K, respectively. In contrast, tiles made merely with Glass Waste (GW) exhibited lower conductivity than their marble waste counterparts. Notably, G-CWT-2 and G-CWT-4 showed conductivities of 0.282 W/m·K and 0.215 W/m·K, with G-CWT-4 achieving the lowest level. This tile served as the benchmark for subsequent evaluations, with tests for specific heat capacity and solar reflectance conducted using analytical methods, along with assessments of compression strength and water absorption. However, incorporating SF adversely affected the outcomes. In samples GS-CWT-5 and GS-CWT-6, combining SF with GW and reducing the W-C ratio to below 40% led to tile failure. In contrast, GS-CWT-6, which maintained a 40% W-C ratio, recorded the second-lowest thermal conductivity of 0.23 W/m·K.

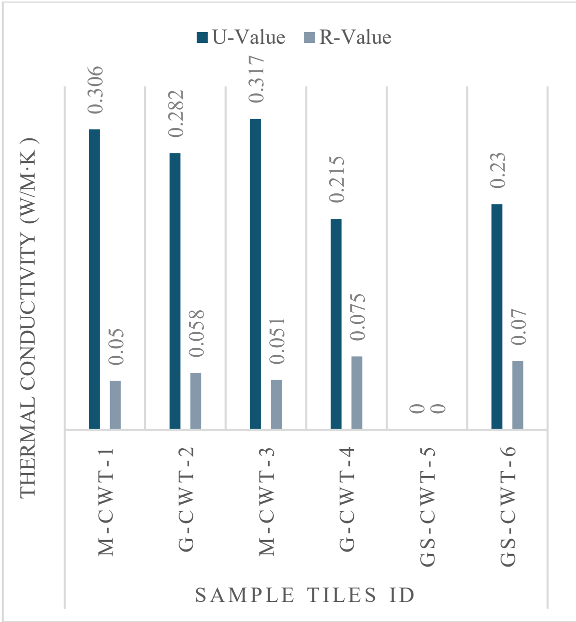

Fig. 2. Results of thermal conductivity for six tiles.

In the referenced study of the PWT+PCM roof tile with a thermal conductivity of 0.387 W/m·K, when applied to a prototype room measuring 1.5 m × 1.5 m in India [5], it achieved an indoor temperature reduction of approximately 8 °C under peak summer conditions, which can be correlated with significant energy savings. According to thermal comfort and energy performance research, each 1 °C decrease in indoor temperature demand may lead to a 3–5% reduction in cooling energy consumption. Extrapolating this to an 8 °C reduction suggests potential cooling energy savings ranging from 24% to 40%, depending on building configuration and HVAC efficiency. Given the superior thermal insulation of the developed G-CWT-4 tile, with a conductivity of 0.215 W/m·K, even greater energy-saving potential may be achievable, especially in hot arid regions where cooling dominates energy use. Traditional roof tiles made from recycled materials such as (IOT) and (WGWT) with 0.52 W/m·K and 0.61 W/m·K have higher thermal conductivities than these new tiles, while conventional options range from 0.65 to 1.2 W/m·K (Fig.4)[13],.

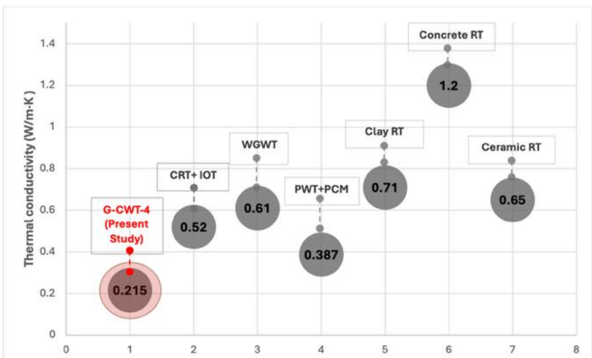

Fig. 4. Thermal properties Comparison of G-CWT-4 with conventional and different waste roof composite: White Sintered Glass-Ceramic Tiles (WGWT); PWT+PCM (Hollow-Glass-Microsphere-Coated Phase Change Material–Cow Pie Embedded Recycled Plastic Tiles); Clay roof tiles (CRT) [12][7][1][10][13].

3.3 Compression Strength test

Tile "G-CWT-4" was selected for mechanical and absorption tests based on thermal characterization. Compressive strength was evaluated using a Hydraulic Compression Testing Machine, following ASTM C109/C109M, aiming for 15-30 MPa, with a minimum of 15 MPa [14]. The tests used 7x7x7 cm cubic specimens per ASTM C39 standards. According to the standards and as illustrated in (Fig. 3), the breaking load was measured at two intervals: 14 days and 28 days of curing. The experiment involved three sets of specimens with differing water content levels: 20%, 25%, and 30%. These specimens were submerged in treated water for 14 days, followed by moist curing, and tested on the 15th day. Notably, the 'G-CWT-20%' sample exhibited the highest performance, achieving a compressive strength of 18.3 MPa, equivalent to 80% of its theoretical maximum capacity. After 28 days, this specimen reached a compressive strength of 23.3 MPa. In comparison, the 'G-CWT-30%' specimen only reached a compressive strength of 9.875 MPa and failed early in the test, while the 'G-CWT-25%' specimen achieved a compressive strength of 14.5 MPa, which did not meet the minimum standard requirements.

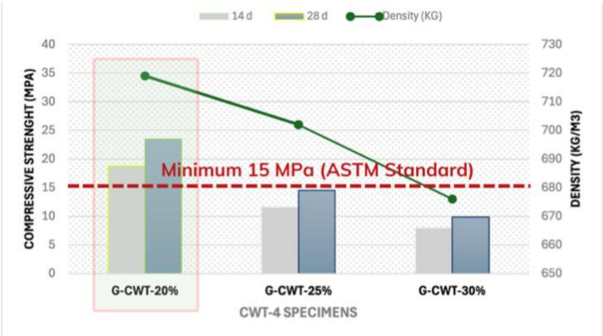

Fig. 3. Compression strength results.

3.4 Water Absorption test

The water absorption test is an essential quality control method for assessing roof tiles' resistance to water. It involves comparing the tile's weight before and after immersion to calculate the absorbed water as a percentage of the tile's initial dry weight. This test helps evaluate the tiles' moisture resistance and suitability for roofing applications. The exact percentage will depend on various factors, including the desired properties of the tiles, the specific type of cement used, and the environmental conditions under which the tiles will cure. Lower water content leads to stronger and more durable tiles, but adequate water is necessary for proper hydration of the cement and workability of the mix. As per ASTM C373, typical water absorption on non-porous tiles is 0.1-0.5% while the porous products can exhibit water absorption in the range 9-15%.

The study test results were obtained from various percentages of the two cubic tiles, each with differing levels of water content in the mixture. It was observed that water absorption increases as the water content in the mixture rises. The cubic samples, measuring 7cmx7cmx7cm, weight, noted as W_D , and immersed in water for. (24 hours), Following the immersion period, the samples were wiped with dry cloth, reweighted, and recorded as W_S . The difference in water absorption was calculated using Equation (1).

$$Water\ absorption = \frac{W_S - W_D}{W_D} \times 10$$

where W_S = saturate weight of specimen after submersion and W_D = dry weight of the specimen.

The cubic tiles G-CWT-4 with water content levels of 20% and 25% have reached water absorption rates of 13.58% and 17.59%, respectively (see. Table 2). However, when water absorption is too high, more moisture is retained in the tiles, leading to the growth of small plants and moss on the roof. This growth negatively affects both the durability and appearance of the tiles. The study indicates that the water content for the new G-CWT-4 tile mixture should remain under 20%, which is within the acceptable water absorption limit for mosaic or cement roof tiles, set at a maximum of 15%.

Table 2. Water Absorption results

Tiles ID	Wt. oven Dry (g)	Wt. SSD (g)	Wt. Sub. (g)	Bulk Relative density (G.S.)	Absorption %
Mix with 20%	633.5	719.5	320.5	1.59	13.58
Mix with 25%	597	702	307.5	1.51	17.59

4. CONCLUSIONS AND FUTURE WORK

Researchers are working to advance technology for developing, analyzing, and evaluating cool roof materials. Nonetheless, it is critical to address the potential barrier of high implementation costs, which might hinder widespread adoption in developing countries, as it highlights the difficulties associated with widespread adoption of advanced cool roof techniques and the transition to more economically viable materials. The challenge is to create a roofing material that not only utilizes waste materials but also offers thermally efficient properties to tackle both waste disposal and urban heat issues effectively.

In this study, a proposed novel method for producing cool roof tiles by employing a blend of construction waste materials, which enhances both the aesthetic and functional qualities of roofing solutions. The study involved extensive experimental procedures, including material selection, processing, and characterization, indicating a high workload but justified by the comprehensive results obtained. A key modification involves the replacement of traditional gray cement with white cement, which imparts a reflective white surface that effectively reduces heat absorption by reflecting solar radiation. Overall, these innovative tiles are competitive in performance and demonstrate enhanced cost-effectiveness compared to traditional roofing materials.

Additionally, as shown in (Fig.5) which compares the final research outcomes between commercial roof cementitious tiles, marble chip mosaic tiles, and plain cement tiles, known as Sanjabi tiles. This comparison is based on usage aspects, material mix ratios, and their sectional designs, categorized as either single-layer or two-layer tiles. As a result, the G-CWT-4 tile introduces a new green mixture that represents a sustainable approach involving four key elements: affordability through reduced-density materials, replacing conventional materials in commercial tiles with recycled waste materials, substituting ordinary Portland cement (OPC) with white cement, and incorporating reflective materials to enhance energy efficiency through the cool roof concept. The tile significantly reduced thermal conductivity with 0.215 W/m·K and enhanced reflectance, was approximately 0.75, meeting the intended goals for thermal insulation. This specimen although reached a compressive strength of 23.3 MPa, and a water absorption rates of 13.58%. This further reinforces the tile's suitability for hot arid regions where mitigation of indoor heat gain is critical for energy conservation and occupant comfort.

This innovative tile design aligns with Sustainable Development Goals (SDGs) 7, 8, 11, 13, and 12, thereby promoting sustainability. The optimized composition, consisting of 40% cement and its recyclable counterparts, not only ensures the production of a robust roofing solution but also reflects a commitment to environmentally sustainable design. By integrating high-efficiency performance with eco-friendly practices, this tile design sets a new standard for cool roofing, fostering energy conservation and sustainability in modern architectural frameworks. However, a direct experimental evaluation using a scaled prototype model is recommended to validate these theoretical estimations and confirm the tile's real-world performance. In the future, this tile has the potential to serve as cladding material for building insulation, improving thermal efficiency.

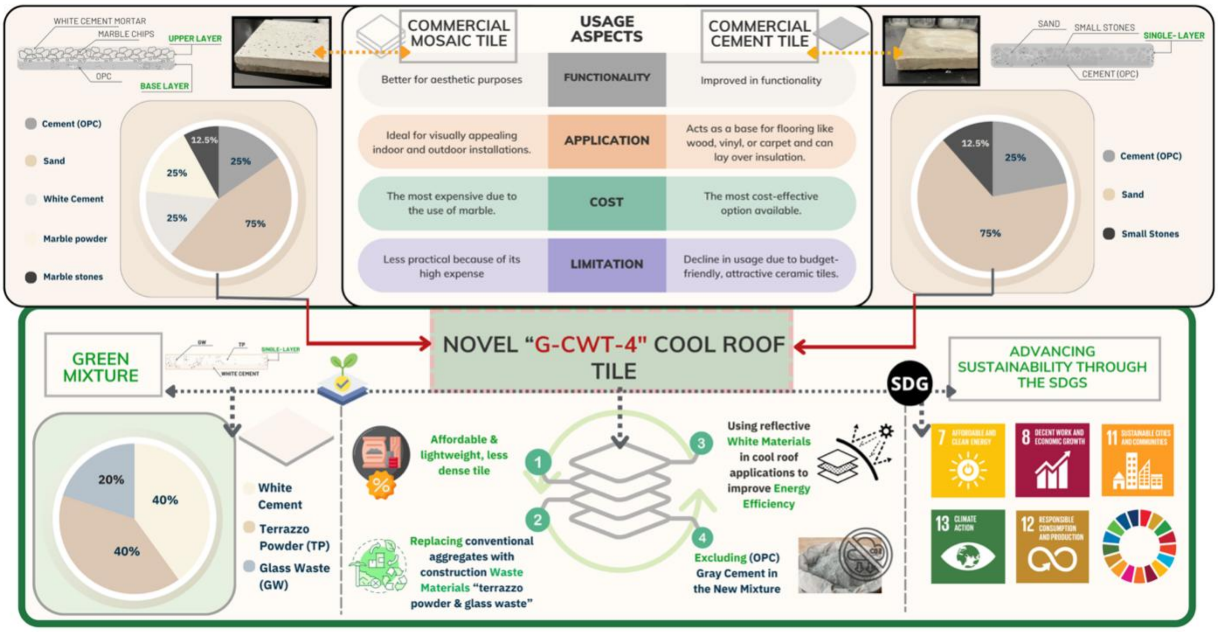

Fig. 5 Novel G-CWT-4 tile compared with commercial tiles.

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