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Article

Ultraviolet exposure and thermal mass variation on surface temperature responses in building materials

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SUMMARY

With the European Union's Copernicus Climate Change Service documenting the hottest temperatures ever recorded in Europe during the summer of 2023, the demand for heat-resistant construction materials becomes critical. This study, undertaken in Madrid, addresses this escalating issue by investigating the response of conventional construction materials (brick, wood, granite, and concrete) to ultraviolet (UV) solar radiation and ambient temperature. Moreover, the study examines innovative laminated plasterboard systems like Pladur®, emphasizing their potential in mitigating the urban heat island effect. We hypothesized that the materials' surface temperature would increase proportionally with higher UV indices. Additionally, we hypothesized that materials with greater thermal mass values would display a less significant temperature increase upon exposure to a constant high ambient temperature condition. We also proposed a third hypothesis: high UV radiation exerts greater influence in surface temperature responses of materials than ambient temperature alone. The results obtained affirm the hypotheses, revealing a positive proportional relationship between the UV index and surface temperature. Notably, Pladur® emerged as a heat-resistant alternative during the study. The thermal mass experiment highlights the importance of opting for high thermal mass construction materials, like concrete or granite, in hot climates. Despite inherent limitations, including uncertainties in temperature readings, this study yields valuable insights into the interplay between UV exposure and thermal mass on construction materials. The findings suggest the potential of laminated plasterboard systems in sustainable urban construction, signaling a shift toward energetically efficient, insulating building solutions.

INTRODUCTION

With quickly rising global temperatures and intensifying heatwaves of the future, a radical rethinking of our construction approaches, particularly in focusing on heat-resistant, insulating construction materials in cities, has become increasingly relevant in the field of civil engineering. Spain, in particular, grapples with this growing issue, witnessing a 3.54% increase in the average temperature of its major cities between 1971 and 2022 (1). Madrid is heavily affected by the heat island effect, a phenomenon in which the local temperature in large cities or urbanized areas increases due to the replacement of vegetation with buildings, resulting in more absorbed solar radiation. The heat island effect alters the urban microclimate, ultimately affecting the energy performance and comfort of the buildings (2).

Granite and wood are naturally occurring materials that were commonly used in construction during ancient times and have remained central to the development of modern urban cities. In contrast, brick and concrete are artificially created materials derived from mineral and stone aggregates mixed in clay or cement that have become equally as important in current building projects (3).

UV exposure refers to the solar radiation directly incident on the surface of each sample. The UV index is a daily forecast of the intensity of UV radiation levels based on a 1 to 11+ scale in an ascending order of UV exposure, with 1 being the lowest exposure category (4). Sun-derived UV radiation causes an increase in temperature, consequently inducing more radiation emission. Therefore, the first hypothesis is that the surface temperature of the materials will be higher as the UV index increases. In addition, ambient temperature also links to the thermal mass of the building materials. Thermal mass, or volumetric heat capacity (VHC), is defined as an object's ability to absorb, store, and release heat (5). This study examines the effect of thermal mass on each material's ability to heat up under controlled temperature conditions. The higher the thermal mass, the more energy it takes to increase the temperature of the material, leading to the second hypothesis: the materials with a greater thermal mass will display a lower increase in surface temperature upon heat exposure than those with lower thermal mass values. Combining the results for both aforementioned experiments, the study explored a third hypothesis: under similar air temperature conditions, variations in UV radiation levels contribute more substantially to material surface temperature increases than ambient temperature alone.

This investigation aimed to address the heat island effect by analyzing the response of commonly used construction materials, including brick, wood, granite, and concrete, to both ultraviolet (UV) solar radiation and ambient temperature, as well as comparing them with newer laminated plasterboard systems like Pladur®.

All hypotheses were supported by the investigation. In the UV experiment, we observed a generally positive correlation between UV index and average surface temperature for all materials examined, indicating that UV radiation contributes to surface heating. In addition, materials with lower thermal mass values exhibited greater temperature increases compared to those with higher thermal masses after heat exposure under controlled ambient temperature conditions.

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These findings suggest that while ambient temperature played a role in surface temperature increases, UV radiation was the more influential factor, particularly in driving the observed responses of low thermal mass materials.

RESULTS

The investigation aimed to uncover the relationship between the UV index, thermal mass, and the surface temperature of materials. The effect of exposure to high levels of UV radiation (9 ≤ UV Index ≤ 11) on the surface temperature of samples of construction materials (brick, wood, concrete, granite, and Pladur®*)* was tested in July during a 14-day period, with temperatures ranging from 30 ºC to 36*ºC*. Each sample was labeled and placed from 9:00 to 15:00 on a soil ground 5 cm apart from each other (**Figure 1**). The temperature of each sample was recorded three times consecutively at exactly 9:00 and 15:00 using an infrared (IR) thermometer (**Figure 2**).

The UV experiment aimed to investigate whether UV index and surface temperature have a positive proportional relationship. Over the 14-day period, we observed how the different materials responded to changes in UV exposure (**Figure 2A**). On Day 5, with a UV index of only 5, the average surface temperatures for Pladur®, granite, and wood were lower than for any other day, while for brick, Day 5 displayed the second lowest temperature, behind Day 8 at 45.9ºC (**Figure 2A**). Furthermore, comparing Day 2 (UV index = 9) with Day 3 (UV index = 11) for each material demonstrated that the higher the UV index, the higher the average surface temperature reached (**Figure 2**). All materials experienced an average temperature increase from Day 2 to Day 3 of 3.62ºC (**Figure 2A**).

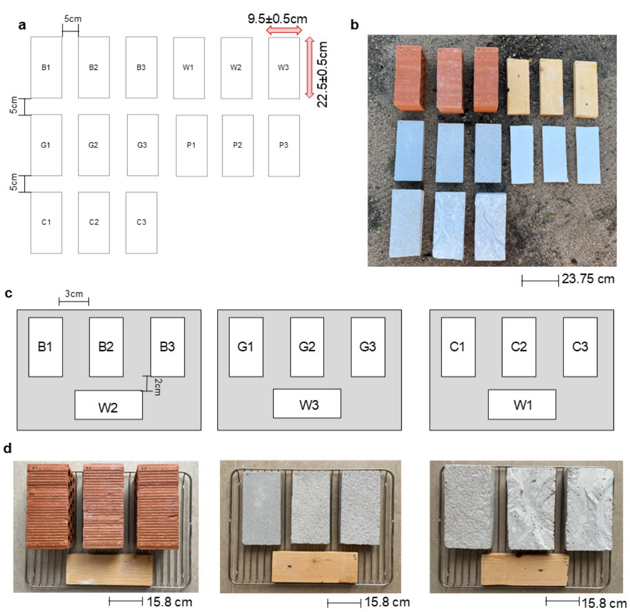

Figure 1: Setup for UV and thermal mass experiments. A) Labeled diagram of the setup for UV experiment. B) Photograph of the setup for UV experiment. C) Labeled diagram of the setup for thermal mass (oven) experiment, D) Photographs of the setup for thermal mass (oven) experiment. The letter on the sample corresponds to the first letter of the material (W = Wood; B = Brick; G = Granite, C = Concrete; P = Pladur®).

Granite heated up the most when exposed to high levels of UV radiation, averaging a temperature of 50.97ºC, while Pladur® exhibited the lowest average temperature over the 14-day period, at 45.71ºC (**Figure 3A**). We observed a significant temperature difference between the average overall temperature of all four conventional construction materials and Pladur® (two-tailed *t*-test, Brick p = 8.090E-05 < 0.05, *t*-statistic = 4.667; Wood p = 3.561E-03< 0.05, *t*-statistic = 3.205; Concrete p = 8.090E-05 < 0.05, *t*-statistic = 4.667; Granite p = 9.721E-06 < 0.05, *t*-statistic = 5.472) (**Figure 3A**).

Our findings support the initial hypothesis that the sample temperature is proportional to the UV index and exposure, as we demonstrated a generally positive correlation between the two variables (**Figure 4A**). When average surface temperatures were plotted against UV index, strong linear relationships were evident for several materials, particularly concrete (R^2 = 0.999), granite (R^2 = 0.789) and Pladur® (R^2 = 0.9643), demonstrating a clear association between increased UV exposure and material heating (**Figure 4A**). Brick (R^2 = 0.3431) and wood (R^2 = 0.3522), while showing weaker correlations, still followed the overall trend despite an unexpected drop in mean surface temperature between UV indices 9 and 10 (**Figure 4A**). In contrast, when individual surface temperature readings were considered, all materials displayed considerably lower R^2 values (R^2 < 0.41) and non-significant regression slopes (one-way ANOVA, all p > 0.05), suggesting that UV index alone explains only a small proportion of the variability in single measurements (**Figure 4B**). Brick and Pladur® also showed near-significant differences in surface temperature across UV levels (one-way ANOVA, Brick p = 0.05956; Pladur® p = 0.06484). Nonetheless, the trend observed in the averaged data underscores a consistent positive relationship between UV index and surface temperature (**Figure 4A**).

We then aimed to investigate whether materials with lower VHC values had a greater increase in surface temperature when exposed to constant ambient temperature conditions. After the samples cooled to their initial indoor room temperature of 26.7ºC, they were placed in an oven set at 35ºC, the closest value to the mean high temperature of July in Madrid, Spain (33ºC) (**Figure 1**) (6). By investigating material temperature increases under constant environmental conditions, this procedure aimed to determine whether the changes in the surface temperature of the materials observed in the UV experiment were due to UV exposure rather than fluctuations in outdoor ambient temperature, thus tackling our third hypothesis. Pladur® samples were excluded from this experiment to prevent the bulging effect caused by high-temperature conditions, as stated by our supplier from LevelUp® construction.

Wood exhibited the highest surface temperature readings, averaging 43.48ºC, while concrete recorded the lowest average temperature at 34.07ºC (**Figure 5**). Granite, despite having a slightly greater VHC value than concrete, obtained the second lowest average surface temperature (40.56 ºC) (**Figure 5A**). A significant temperature difference between wood and concrete was observed (two-tailed *t*-test, p = 1.093E-07 < 0.05), allowing rejection of the null hypothesis that there is no difference in the observed surface temperatures. The results obtained for wood remained the highest out of all the materials until Day 11, when brick exhibited higher

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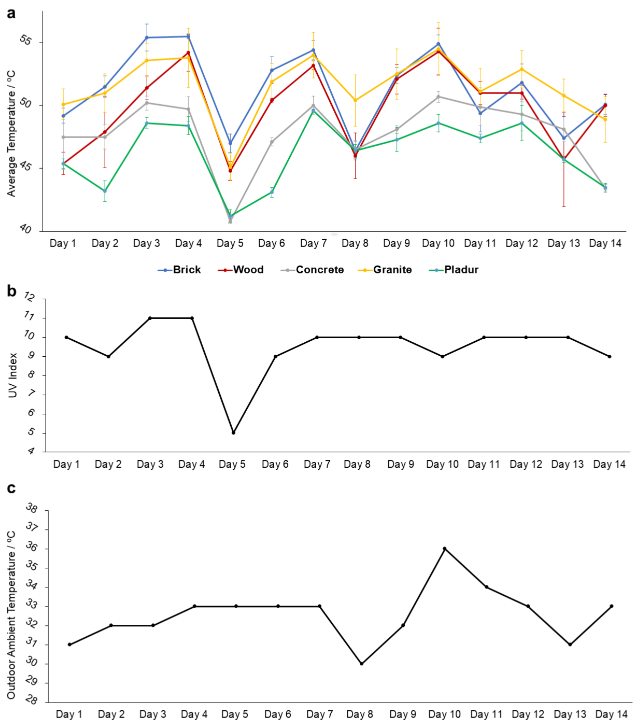

Figure 2: Average surface temperature of construction material during high-UV (9 ≤ UV Index ≤ 11) hours per day. A) Average temperatures of construction materials, measured across 14 days. The temperature of the three samples of each material were measured using an IR thermometer and then averaged. B) UV Index per day. C) Outdoor daily ambient temperature. UV exposure lasted six hours. Error bars represent the standard deviation on the averages.

temperatures over the remaining three days (**Figure 5A**). An inverse relationship between VHC and average surface temperature was identified. Materials with lower VHC values, such as wood with VHC = 0.231 $MJm^{-3}K^{-1}$, were shown to reach higher surface temperatures under identical heating conditions (**Figure 5B**). In contrast, materials with higher VHC values (Granite VHC = 2.125 $MJm^{-3}K^{-1}$; Concrete VHC = 2.086 $MJm^{-3}K^{-1}$; Brick VHC = 2.018 $MJm^{-3}K^{-1}$) exhibited lower average surface temperatures (**Figure 5B**). However, the correlation is relatively weak (R^2 = 0.2628) likely due to the small sample size of different materials (**Figure 5B**).

A statistically significant difference was found between the surface temperatures recorded for the UV and thermal mass experiments for all materials tested (two-tailed *t*-test, Brick p = 4.300E-09 < 0.05, *t*-statistic = 8.614; Wood p = 7.513E-06 < 0.05, *t*-statistic = 5.570; Concrete p = 3.736E-15 < 0.05, *t*-statistic = 16.28; Granite p = 6.824E-13 < 0.05, *t*-statistic = 13.01) (**Figure 6**). These results confirm that UV radiation is a more influential factor in surface temperature increases than ambient temperature alone. While the outdoor ambient temperature was relatively high during the UV experiment, controlled oven conditions (~35ºC) ensured that ambient temperature was held constant, virtually isolating the impact of UV radiation. This was also evidenced by the visible difference between the graphs obtained for both experiments (**Figure 2A, 5A**). Since the outdoor and the oven temperatures were very similar (~35ºC), the fluctuations in the graph for the UV experiment during the 14-day period can be mostly attributed to UV exposure. Among the materials, wood displayed the smallest temperature difference and concrete the largest (**Figure 6**), highlighting material-dependent variability in thermal response to UV exposure.

DISCUSSION

In this investigation, we aimed to determine whether UV index and the surface temperature of materials had a positive proportional relationship, and whether materials with lower thermal mass values displayed a greater increase in surface temperature in controlled ambient temperature conditions. Firstly, for the UV investigation, the higher the UV index, the greater the increase in average temperature (**Figure 4A**). When comparing Day 5 (UV Index = 5) with every other day of the 14-day period (9 ≤ UV Index ≤ 11), all materials achieved much higher temperatures under high UV indices (**Figure 2A**). To this extent, our data supported our first hypothesis. While raw temperature data showed considerable scatter and weak statistical significance, the averaged results demonstrate a clear and consistent positive correlation between UV index and surface temperature for all materials tested. This indicates that UV radiation plays a significant role in material surface heating, although individual readings are subject to high variability (**Figure 4**).

Furthermore, the data for the thermal mass experiment is consistent with the hypothesis that the materials with a lower thermal mass (VHC) would display a more significant increase in surface temperature (**Figure 5B**). Concrete has a standard VHC of 2.086$MJm^{-3}K^{-1}$ and was therefore expected to heat up less than wood, with VHC = 0.231$MJm^{-3}K^{-1}$ (7). Granite, with the highest VHC value, displayed the second lowest surface temperature increase, likely due to limitations in the experimental protocol, including potential uneven temperature distributions inside the oven or heat loss during the interval between oven removal and temperature measurement. While the observed trend supports the expected inverse relationship between thermal mass and surface temperature, the low coefficient of determination (R^2 = 0.2628) could suggest that VHC alone does not entirely account for the variation in thermal response among materials (**Figure 5B**). This weaker correlation may also be attributed to the small sample size used in the experiment, as only four materials were tested.

In addition to these hypotheses, the results also support

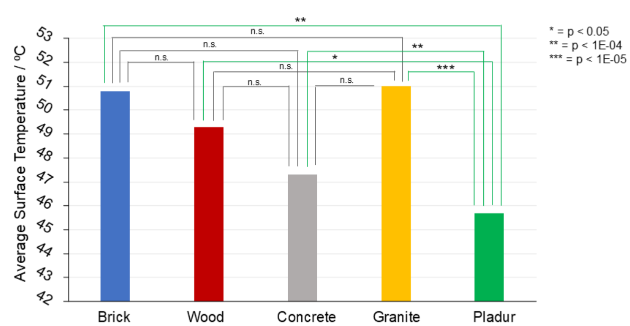

Figure 3: Average surface temperature of all five construction materials. A statistical difference (p < 0.05) was noted between Pladur® and all other materials, but not between any of the other four materials.

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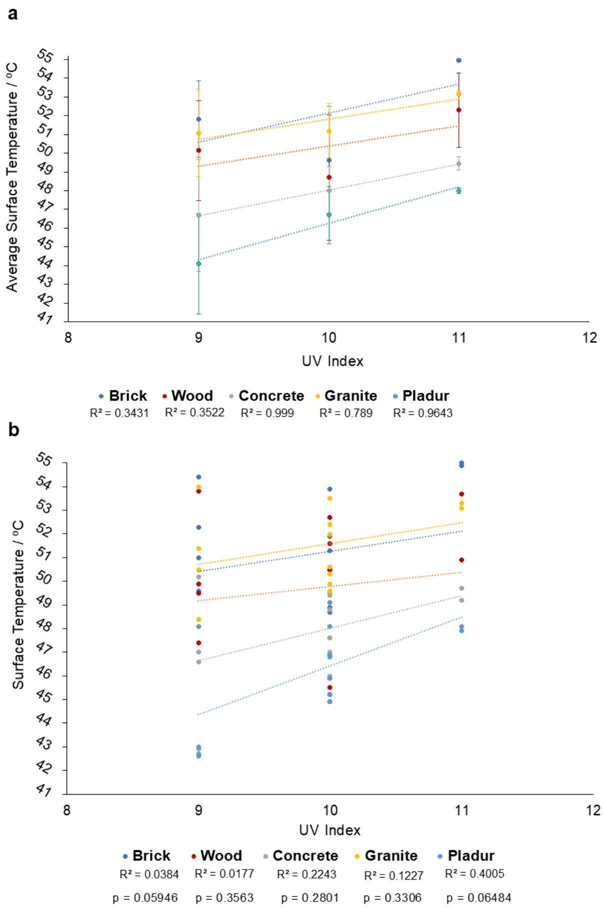

Figure 4: Linear regression of UV index versus surface temperature of brick, wood, concrete, granite, and Pladur®. UV exposure lasted six hours. The R^2 and *p*-value calculated using a one-way ANOVA test of each material is shown below each material in the legend. No significant difference ($p < 0.05$) was noted. A) Average surface temperature of brick, wood, concrete, granite, and Pladur® at UV indices 9, 10 and 11. Error bars represent the standard deviation on the averages taken across multiple days with the same UV index. B) UV index versus individual surface temperature measurements.

the third hypothesis, showing that UV radiation is a more influential factor in surface temperature increases than ambient temperature alone. This was evidenced by the significantly higher average surface temperatures in the UV experiment compared to those in the ambient-controlled oven setup, even though both experiments operated at similar temperatures, as well as the statistically significant differences recorded for all materials ($p < 0.05$) between both experiments (**Figure 6**). The graphed surface temperature results for each material per day are also much visually similar to the graphed UV index per day than the ambient temperature equivalent (**Figure 2**).

We carefully controlled for variations in environmental conditions by conducting the experiment over a 14-day period. We also recorded three replicates per sample per day in order to improve accuracy. In addition, the same three samples of each material were used to obtain the results over the course of the 14 days instead of changing them each time, meaning that the investigation considered the effect of high UV exposure over a relatively prolonged period of time. The results are, therefore, reproducible in real-life construction applications where materials are rarely substituted or changed. Also, both experiments benefited from using samples of almost identical cross-sectional area dimensions, which contributed to methodological robustness. In addition, variations in the surface characteristics (in terms of color, surface roughness, and uniformity) among the three samples of each material further ensure the representativeness and reproducibility of the results across diverse contexts.

Ultimately, the results obtained in this study suggest that both UV radiation and thermal mass contribute to the change in surface temperature of materials. The UV experiment reveals that new laminated plasterboard systems like Pladur® are a heat-resistant and sustainable alternative to older common construction materials. Pladur®'s superior insulating ability when exposed to high UV radiation in contrast to brick, granite, concrete, and wood indicates its future importance in the construction of buildings located in urban areas that suffer from a heat island effect, like Madrid. This can be explained on a chemical level knowing plasterboard is made of a calcium sulfate dihydrate mineral called gypsum (8). Gypsum permits a high percentage of light transmission when exposed to UV light, limiting its absorption of UV radiation and explaining its thermal insulating capacity in contrast to other conventional building materials (9). Pladur®*'s* chemical composition enhances its reflecting properties, resulting in lower average surface temperatures than materials like brick, with higher volumetric heat capacities and heat-retaining aggregates like sand (10).

Furthermore, materials with high thermal masses like concrete and granite also displayed heat-resistant and energetically efficient properties, as the increases in surface temperatures were not as significant as those of materials with a lower thermal mass like wood. This highlights the

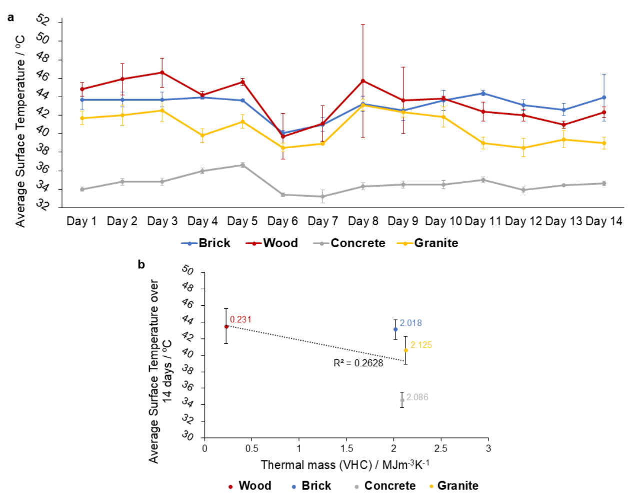

Figure 5: Average surface temperature of brick, wood, concrete, and granite when placed in an oven set at 35ºC conventional heating. Oven exposure lasted 15 minutes. Error bars represent the standard deviation on the averages. The temperatures of the three samples of each material were measured using an IR thermometer and then averaged. A) Surface temperature of brick, wood, concrete, and granite per day. B) Linear regression of average surface temperatures over the 14-day period versus thermal mass (VHC).

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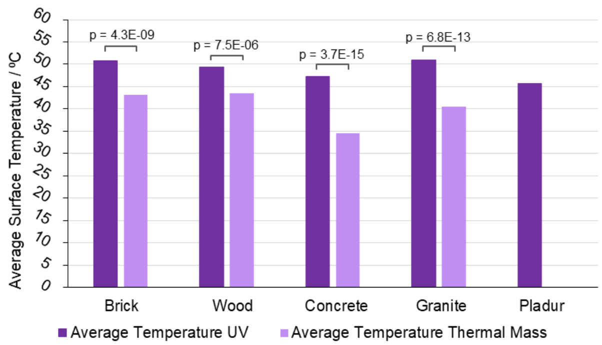

Figure 6: Average surface temperature of different construction materials for UV and thermal mass experiments. A statistical difference ($p < 0.05$) was noted between both surface temperatures for all materials.

significance of high thermal mass materials in the construction of buildings and infrastructure in hot climates.

However, there are some experimental limitations that should be considered. Firstly, the lack of calibration of the infrared (IR) thermometer introduces systematic error, as the average temperature of the study site in the UV experiment (32.6ºC) and in the thermal mass experiment (35ºC) was greater than the temperature of the storage location of the thermometer (26.7ºC) by more than 5ºC, impacting the precision of the overall average temperatures measured. Reducing this error would involve wrapping the IR thermometer in a thermal glove or placing it outdoors for 60 minutes before the UV experiment readings to ensure calibration (11). Additionally, the color of the cross-sectional area exposed to the sun in the UV experiment may also have a considerable effect on the temperature readings of each material, as darker colors emit more IR radiation. Furthermore, while the values for wind speed, ambient temperature, and humidity were recorded for the 14 days, these variables could not be controlled for in the UV experiment, thus becoming a source of random error (**Table 1**). Humidity, despite ranging between 21% to 26% for 9 days, displayed notable variations, reaching a maximum of 35% on Day 7 and a minimum of 13% on Day 11. These fluctuations introduce an uncertainty about the validity of some results of the UV experiment, as relative humidity increases convection heat transfer between the object surface and the surrounding atmosphere, meaning a higher humidity would result in higher material temperatures (12). However, given the relatively stable outdoor temperature range of 30-36ºC, the impact of this variable remains less significant compared to the systematic error in the temperature readings. For the thermal mass experiment, the humidity was controlled by selecting the medium humidity setting and ensuring all samples were fully dry throughout the procedure.

There are other pertinent limitations with the experimental protocol and setup. Firstly, the surface temperature of each sample recorded for the UV experiment was likely slightly lower than the true value due to the heat transfer via conduction to the cold ground from the hotter contact surface area of the material, which could have been reduced by suspending the samples above the soil on oven racks to ensure airflow. Moreover, for the thermal mass experiment, the irregular temperature distribution in the oven may have contributed towards the overall systematic error. Even though the samples were placed in the same positions each time to improve consistency and comparison validity, the lack of temperature uniformity in the oven may have introduced a constant error, as some samples may have been exposed to higher ambient temperatures, thus displaying a greater increase in their measured temperature. This could have been mitigated by making batches of only the same material, so their VHC is the same, as well as rotating the position of the samples on the oven rack to avoid errors associated with uneven temperature distribution. Furthermore, since the temperature readings were made outside of the oven, taking around two minutes, some samples may have experienced more heat loss than others. Nevertheless, most materials reached temperatures higher than the 35ºC setting in the oven as they absorbed more heat than they released, concordant with their respective VHC values.

While the investigation was carried out for an extended period of time, the effect of material photodegradation due to sun exposure was not entirely considered. Susceptible materials, such as concrete or wood, known to degrade and experience cracking under intense, prolonged UV radiation, may exhibit distinct material behavior compared to more resilient materials like brick (13). Specifically, naturally occurring polymer materials like wood are adversely affected by high-energy UVB content of UV solar radiation, damaging certain mechanical properties that limit their long-term use (14). Therefore, further investigations may aim to uncover the presence of such polymers, namely rubbers such as polyvinyl chloride (PVC) and expanded polystyrene (EPS), in new construction materials like Pladur® and other laminated plasterboard systems to assess their suitability over extended periods of time (15). This divergence may potentially explain the shift observed after Day 11, where wood was no longer yielding the highest average surface temperature at a constant ambient temperature of 35ºC in the oven. Further studies may investigate the effect of UV exposure on material deterioration or even compare the rate at which materials absorb heat. Additionally, the effect of other aforementioned ambient factors like humidity and wind speed on the surface temperature responses of construction materials could also be considered in future investigations.

Ultimately, the investigation concludes that higher UV indices and lower thermal mass values of materials will

Day	Ambient Temperature / ºC	Average Wind Speed / kmh^{-1}	Humidity / %
1	31	9	25
2	32	6	26
3	32	7	22
4	33	14	24
5	33	12	24
6	33	5	32
7	33	12	35
8	30	17	31
9	32	12	22
10	36	8	23
11	34	14	13
12	33	9	15
13	31	12	24
14	33	12	21

Table 1: Ambient temperature, average wind speed, and humidity values throughout the 14-day period. Values were obtained from Apple's Weather Services.

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yield greater surface temperature increases. In particular, the results obtained reveal the increasing importance of heat-resistant laminated plasterboard systems like Pladur® in mitigating the heat island effect in the face of growing urbanization. Further research may compare newer building materials to determine the most efficient, economical, and sustainable solution to quickly rising global temperatures.

MATERIALS AND METHODS

Materials and Experimental Setup

This experiment used three rectangular samples of brick, wood, concrete, granite, and Pladur® (Pladur® Solidtex 13), each with a cross-sectional area of 9.55 x 22.5 (±1.0) cm^2 (16). Throughout the investigation, we used a Wintact IR thermometer with a temperature range of -50ºC-550ºC and a ±0.5ºC reading uncertainty to measure the temperature of the materials.

For the UV investigation, the samples were placed on a flat soil ground. Each sample was equally spaced with 5 cm between samples, to reduce thermal energy transfer by both conduction from the underpart of the materials and radiation from the surrounding heated materials. For the ambient temperature/thermal mass experiment, the samples were placed in an oven set at 35ºC.

Experimental Protocol

For the UV experiment, all 15 samples were positioned at 9:00 on the exterior soil surface, until 15:00. The temperature measurements were taken from the center cross-sectional area of the surface to ensure consistency, as the edges of the material are more prone to errors and discontinuities. Given that IR thermometers measure radially over a circular area, measuring from the center allowed the temperature of a greater area of the surface to be determined, thus improving the accuracy. The temperature was recorded a total of three times for each sample and the results were later averaged. Furthermore, the numerical UV index values were determined using Apple's Weather Service, which obtains its data for Madrid via the European Centre for Medium-Range Weather Forecasts (ECMWF) (17). ECMWF forecasts daily UV index predictions in Europe using data provided by Copernicus Atmosphere Monitoring Service. Small variations in Madrid's UV index presented a potential limitation in the investigation.

The thermal mass experiment used the same samples from the UV experiment after 7 hours of storage away from UV exposure and left to cool to reach an equilibrium temperature of approximately 26.7ºC, which was confirmed using an IR thermometer before proceeding. Pladur® samples were not used in this experiment under the recommendation of the supplier of the local construction firm LevelUp®, due to the warping and bulging effect of hot conditions on this particular Pladur® model, which displays marginally lower heat-resistant properties than other alternatives. Therefore, to avoid sample deterioration and ensure safety given the lack of professional laboratory apparatus, Pladur® was not tested.

Samples were placed in three batches on an oven rack placed at medium height in an oven set at 35ºC conventional heating (top and bottom), the closest value to the mean high temperature of July in Madrid, Spain (33ºC). After 15 minutes had elapsed, the temperature of each sample was measured three times using an IR thermometer and then averaged.

Statistical Analysis

To determine if the surface temperature of the materials was significantly different from one another, we performed a two-tailed *t*-test in Python. With the significance level set at $p<0.05$, both *p*-values and *t*-statistics were obtained. To compare each material against each other, the UV experiment and the thermal mass experiment each required a distinct python code (**Appendix S1** and **Appendix S2**). Another python code was used to compare the temperatures of the same material in the two experiments (**Appendix S3**). A *t*-test was deemed the most appropriate parametric statistical test, as the samples compared were fully independent from each other (18). In addition, one-way ANOVA was used in the investigation of individual surface temperatures versus UV Index in the UV experiment.

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APPENDIX

```
import scipy
import itertools

material_data = {
    'Brick': [48.7, 51.0, 54.9, 55.0, 46.5, 52.3, 53.9, 45.9, 51.9, 54.4, 48.9, 51.3, 46.9, 49.6],
    'Wood': [44.9, 47.4, 50.9, 53.7, 44.3, 49.9, 52.7, 45.5, 51.6, 53.8, 50.5, 50.5, 45.2, 49.5],
    'Concrete': [48.7, 51.0, 54.9, 55.0, 46.5, 52.3, 53.9, 45.9, 51.9, 54.4, 48.9, 51.3, 46.9, 49.6],
    'Granite': [49.6, 50.5, 53.1, 53.3, 44.6, 51.4, 53.5, 49.9, 52.0, 54.0, 50.6, 52.4, 50.3, 48.4],
    'Pladur': [44.9, 42.7, 48.1, 47.9, 40.7, 42.6, 49.1, 45.9, 46.8, 48.1, 46.9, 48.1, 45.2, 43.0],
}

# Set your significance level
alpha = 0.05

# Get all combinations of two materials
material_combinations = list(itertools.combinations(material_data.keys(), 2))

# Perform t-test for each combination
for material_pair in material_combinations:
    material1 = material_pair[0]
    material2 = material_pair[1]

    temperature_material1 = material_data[material1]
    temperature_material2 = material_data[material2]

    # Perform independent t-test
    t_statistic, p_value = scipy.stats.ttest_ind(temperature_material1, temperature_material2)

    # Print results
    print(f'Test for {material1} and {material2}:')
    print(f'T-statistic: {t_statistic}')
    print(f'P-value: {p_value}')
```

```
    # Check for statistical significance
    if p_value < alpha:
        print('Reject the null hypothesis. There is a significant difference in temperatures.')
    else:
        print('Fail to reject the null hypothesis. There is no significant difference in temperatures.')

    print('\n' + '='*40 + '\n')  # Just for better separation in the output. ================
```

Appendix Section 1: Code for two-tailed T-test comparing the daily average temperature of the materials written in Python for UV experiment.

```
import scipy
import itertools

material_data = {
    'Brick': [43.7, 43.7, 43.7, 43.9, 43.6, 40.1, 41.0, 43.2, 42.5, 43.6, 44.4, 43.1, 42.6, 43.9],
    'Wood': [44.8, 45.9, 46.6, 44.2, 45.6, 39.7, 41.1, 45.7, 43.6, 43.8, 42.4, 42.0, 41.0, 42.3],
    'Concrete': [48.7, 51.0, 54.9, 55.0, 46.5, 52.3, 53.9, 45.9, 51.9, 54.4, 48.9, 51.3, 46.9, 49.6],
    'Granite': [34.0, 34.8, 34.8, 36.0, 36.6, 33.4, 33.2, 34.3, 34.5, 34.5, 35.0, 33.9, 34.4, 34.6],
}

# Set your significance level
alpha = 0.05

# Get all combinations of two materials
material_combinations = list(itertools.combinations(material_data.keys(), 2))

# Perform t-test for each combination
for material_pair in material_combinations:
    material1 = material_pair[0]
    material2 = material_pair[1]
    temperature_material1 = material_data[material1]
    temperature_material2 = material_data[material2]

    # Perform independent t-test
```

```
    t_statistic, p_value = scipy.stats.ttest_ind(temperature_material1, temperature_material2)
    # Print results
    print(f'Test for {material1} and {material2}:')
    print(f'T-statistic: {t_statistic}')
    print(f'P-value: {p_value}')

    # Check for statistical significance
    if p_value < alpha:
        print('Reject the null hypothesis. There is a significant difference in temperatures.')
    else:
        print('Fail to reject the null hypothesis. There is no significant difference in temperatures.')

    print('\n' + '='*40 + '\n')  # Just for better separation in the output. ================
```

Appendix Section 2: Code for two-tailed T-test comparing the daily average surface temperature of the materials written in Python for the thermal mass experiment.

```
temperature_brickUV = [48.7, 51.0, 54.9, 55.0, 46.5, 52.3, 53.9, 45.9, 51.9, 54.4, 48.9, 51.3,
46.9, 49.6]
temperature_brickOVEN = [43.7, 43.7, 43.7, 43.9, 43.6, 40.1, 41.0, 43.2, 42.5, 43.6, 44.4, 43.1,
42.6, 43.9]

# Perform independent t-test
t_statistic, p_value = scipy.stats.ttest_ind(temperature_brickUV, temperature_brickOVEN)

# Set your significance level
alpha = 0.05

# Print results
print(f'T-statistic: {t_statistic}')
print(f'P-value: {p_value}')

# Check for statistical significance
if p_value < alpha:
    print('Reject the null hypothesis. There is a significant difference in temperatures.')
```

```
else:
    print('Fail to reject the null hypothesis. There is no significant difference in temperatures.')
```

Appendix Section 3: two-tailed T-test in Python code for two-tailed T-test comparing the daily surface temperature of the same material (in this sample, brick) in the UV and thermal mass experiments.