Journal of Sustainable Cities and Built Environment (JSCBE)

Original Article

The impact of temperature and humidity on the thermal resistance of waste materials for the efficiency of the building envelope

Ashraf M. Soliman *[1&2] **and Samy Elbialy** [1&3]

[1] College of Architectural Engineering & Design, Kingdom University, Bahrain; a.soliman@ku.edu.bh, s.bialy@ku.edu.bh
[2] Faculty of Engineering, Minia University, Egypt; arcgroupfec@gmail.com
[3] Faculty of Engineering in Elmataria, Helwan University, Egypt
*****Correspondence: a.soliman@ku.edu.bh; Tel.: 00973-13302932 *ORCID ID*: https://orcid.org/0000-0003-1957-7937

Abstract

A thermal insulation material's effectiveness is influenced by its thermal conductivity and ability to maintain its thermal characteristics, particularly in hot and humid environments. In this study, different waste materials used in building envelopes are investigated for their thermal conductivity under temperature and humidity variations. Four materials are being studied experimentally; rubber, paper, plastic, and foam are mixed separately and proportionally with plain mortar. Thermal conductivity in testing samples is determined using heat-flow meters. Testing waste materials in a room environment for 14 days revealed varying degrees of thermal resistance. Compared to plain mortar, the inclusion of rubber, plastic, paper, and foam increase thermal resistance by 1.6, 43.4, 50.5, and 101.4%, respectively. In a climatic testing chamber, samples were exposed to extreme temperatures and humidity levels consistent with Bahrain's monthly average temperatures. To determine the effect of changes in temperature and humidity on each waste material's thermal properties, the thermal resistance of the samples was measured after 24, 48, and 72 hours. The change in environmental factors seems to have a mild impact on rubber's thermal resistance. Most materials are foam and plastic, while paper and paperboard are moderately affected. Such a change is not substantial for the four tested waste materials during the July environment. Foam, which has demonstrated more significant changes throughout the January environment, shows fewer changes than rubber, paper, and plastic. In an extreme environment, all the tested waste materials, except for plastic, are highly influenced by exposure to extremities of temperature and relative humidity.

Keywords: Sustainability; building envelope; waste materials; thermal resistance.

Citation: Soliman, A.M., Elbialy, S. (2023). The impact of temperature and humidity on the thermal resistance of waste materials for the efficiency of the building envelope. *Journal of Sustainable Cities and Built Environment*, 01(02), 01-19. Retrieved from http://jscbe.ku.edu.bh
DOI: https://doi.org/10.58757/jscbe.ithtrwmebe.01

Publisher: [KU] Kingdom University.

Editor-in-Chief: Dr. Ashraf M. Soliman

Managing Editor: Dr. Adeb Qaid

Received: 20 April 2023

Accepted: 18 June 2023

Published: 15 July 2023

1. Introduction and Literature review

1.1. Introduction

Human health and the environment are adversely affected by many waste materials such as rubber, plastic, paper, and foam. Waste materials pollution has instigated a serious environmental problem for decades, therefore new initiatives have been taken around the world to recycle wastes into construction materials in recent years [1]. The management of waste is crucial to reducing this impact. The health of society needs to reduce the exposure of humans to toxicants generated by plastic garbage. Moreover, biodegradability with no harmful residues will protect ecosystems [2]. There has been a rapid increase in recycling rates for various materials across the globe. Between 1973 and 1991, the U.S. Department of Agriculture (USDA) and the Food and Paper Industry (FPI) reported a 40% increase in wastepaper recovery worldwide [3]. Despite the negative impacts of recycling waste materials, scientists predict that the positive impacts will outweigh the negative effects.

Consequently, exporters and importers may benefit economically from international trade in recycling-derived secondary materials. Besides reducing health and environmental problems, it may also reduce pollution [4]. A well-planned and carefully executed waste management benefits all three "pillars" of sustainable development: environmental, economic, and social sustainability. The issue of environmental protection has been receiving considerable attention in recent years. Industry and households generate substantial amounts of waste, contributing to the degradation of our environment. Several efforts are being undertaken to reduce waste, like increasing reuse and recycling. [5]. Waste management benefits future generations by creating a more robust economy, a fairer and more inclusive society, and a cleaner environment [6]. There was an increase of nearly 20% in paper recycling in Europe during the last decade, reaching 72% in 2012. The total amount of recyclable material produced every year may include lower-quality paper particles as well [7].

Plastics are chemically synthesized polymers used in various materials such as clothing, medical supplies, water bottles, food packaging, electrical items, and construction materials [8]. HDPE is a high-density polyethylene primarily used as a material to make freezer and shopping bags, buckets, shampoo and ice cream containers, and milk containers. The consumption of this material (HDPE) can cause stomach ulcers and harm human health. It is hard to semi-flexible, has a waxy surface, and is resistant to chemicals and moisture [9]. Many products are made from low-density polyethylene (LDPE), including garbage bags, irrigation tubing, mulch film, and cling wrap. Despite its waxy translucent surface, it is soft, flexible, and softens at 70 degrees Celsius. This product cannot be recycled [10]. Approximately 40% of total plastic usage in Europe was accounted for by single-use packaging in 2008, with global plastic production estimated at 245 million tons. [11]. The global production of plastics was estimated at 311 million tons in 2017, which is expected to quadruple by 2050. [12]. Because of the huge waste materials that have been mentioned above, the authors thought for reusing such materials to produce cladding panels with effective thermal properties for building insulations, that lead to sustainable architectural solutions.

1.2. Literature review

According to the literature, one of the most efficient waste materials in terms of thermal resistance is straw, which has a thermal conductivity between 0.03 to 0.15 W/m K depending on temperature and density [13]. According to Sabapathy and Gedupudi, straw saves from 67% to 96% of cooling energy when used as thermal insulation in the building envelope in the Indian climate; for a 40 cm thick straw, the savings are from 88% to 100% [14]. However, straw is not used in this research due to its scarcity in the study region. In light of the statements outlined above, this research significantly impacts sustainable building in both economic and environmental ways by promoting the development of affordable and efficient materials for building envelopes, reducing energy consumption in buildings, and improving local environmental sustainability. The only way to achieve sustainable development could be through sustainable construction [15]. Heat transfer in a building is significantly impacted by moisture transfer in a humid climate. To ensure a sustainable future, buildings need thermal insulation to improve their energy efficiency [16] & [17]. It is, however, costly to use polyurethane foam, polystyrene, and mineral wool for regular thermal isolation. The use of waste materials could therefore provide an economical and effective way to insulate high-temperature spaces. There is no doubt that waste-based materials have suitable thermal storage properties, but tests on long-term evaluation, reproducibility, and stability can pose challenges. [18]. A passive building's excellent design provides excellent protection from hot and humid conditions [19].

To assess thermal insulation properties, it is important to study the impact of temperature and humidity, particularly when using waste-based materials. Several Studies have revealed that temperature and humidity are essential parameters influencing the thermal conductivity of insulation materials [20]. Literature shows that insulation materials conduct heat more readily as the temperature rises and humidity rise. However, the degree of change depends on the material. Sugarcane bagasse waste fibers were tested as an insulation material, and results indicated that they performed reliably at low- and mid-frequency [21].

According to a study by Sair and other researchers, the fiber composite material can be used in various applications due to its thermal and hygrometric properties; the material can be made from fibers, cork, and cardboard with gypsum reinforcement [22]. Gounni and other researchers have developed a thermal insulation material based on acrylic and wool. Their study conducted on an external wall subjected to actual climatic conditions indicated that the insulations were competitive for annual loads compared to conventional insulations [23]. A study of thermal insulation using wastepaper and lime has discovered significant thermal insulation capacity associated with low thermal conductivity values [24]. Replacing 20% of aggregate and 10% of sand with crumb rubber could improve the thermal conductivity of the produced concrete [25]. Other researchers have tested the concrete includes coconut shells. Thermal conductivity of the tested samples has been reduced in comparison with the plain concrete [26]. As the research area has no coconuts farms, therefore, the authors have included the rubber in the comparison investigation with the other four materials. Overall, insulation materials show a linear relationship between thermal conductivity and temperature [27], [28], [29] & [30].

1.3. The issue and objective

Although there is a huge amount of waste materials which have high thermal resistance, few researchers have thought of utilizing such waste materials in building insulations, most researchers focus on the materials that are made especially for insulation. In this research, the authors aim to fill this gap by improving the thermal performance of building envelopes using local waste materials in humid and hot regions at an affordable cost. Waste materials are various in terms of thermal properties, range of availability, and operational safety. The challenge was selecting the most suitable materials for investigation. Thus, the research focused on most safe and available materials in Bahrain for laboratory investigation.

2. Methodology

2.1. Scope of the Study

Approximately 17% of the total solid waste generated worldwide is paper & cardboard, 12% is plastic, and 2% is leather & rubber [31]. Bahrain has more waste generators per capita than any other country. Solid waste is produced yearly at a rate of 1.2 million tons [32]. Eventually, the costs associated with arranging waste within the landfill will need to be increased, opening up opportunities for other recycling. The recycling industry is currently experiencing prequalification for tire reusing. In recent years, such companies have had waste management consultations that foster and strengthen the reusing office [32]. Therefore, the researchers included paper, cardboard, the foam used in electronic device packaging, shopping bags, and rubber from damaged tires in this study. These materials were exposed to selected environments based on the absolute and extreme values of Bahrain's average temperature and humidity to study the effect of temperature and relative humidity on thermal conductivity and resistance. Mathematically, it is impossible to expose the test samples to these many different environments if the air temperature ranges between 1°C and 50°C and the relative humidity ranges between 1% and 100%. Furthermore, due to the non-linear relationship between air temperature and relative humidity, these 5000 environment trials were not possible, since this depends on dew point temperature, as stated by Lawrance in the formula (1) [33]:

$$T_d = T - \frac{(100 - R_h)}{5} \quad (1)$$

Where,

T_d = Dew point temperature in degrees Celsius

T = Observed air temperature in degrees Celsius

R_h = Relative humidity percent

Below figure 1 portrays Bahrain's monthly average maximum and minimum air temperatures and relative humidity. It illustrates that January and July represent winter and summer sessions. July 22nd, 2021, marked Bahrain's highest air temperature of 112.5 ˚F [45 ˚C]. In the summer, August 20th has the highest chance of being muggy 98% of the time, while January 29th has the lowest humidity, 1% of the time. Consequently, eight environments were created using combinations of January and July average values, two environments were created using combinations of absolute extreme values, a normal room environment, and a different environment was created by considering the absence of relative humidity by exposing the samples to 100 °C.

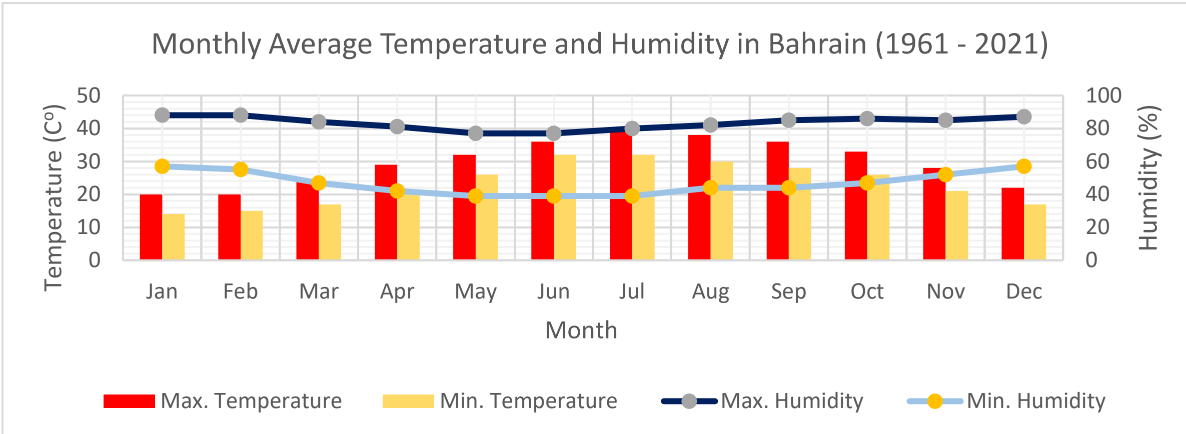

Figure 1. Monthly average maximum and minimum temperature and humidity in Bahrain.
*Data Sources: Average temperature measurements **[34]** , Relative humidity measurements **[35]** & & day and night temperature measurements **[36]**.

2.2. Methods

In this manuscript, the main focus is to individually investigate the impact of incorporating various waste materials on the thermal conductivity of mortar. The applied materials in this study are ordinary Portland cement (ASTM C-150 Type-I) [37], fine aggregate (sand) passing through 2.36 mm sieve and four waste materials; crumbed rubber obtained from scrap car tires sized into 3-5 mm, expanded polystyrene (foam) collected from electronic store wastes and crushed into 3– 8 mm particles, shredded wastepaper spreader into 3 by10 mm peace, and shredded plastic bags sliced into 3 by 10 mm. The applied waste materials are illustrated in Figure 2.

(a) Rubber **(b)** Paper **(c)** plastic **(d)** foam

Figure 2. The experimented-on waste materials

Experimental density measurements were performed by dividing the mass of each waste material by the volume of the 0.3x0.3x0.07m standard box filled with 0.3mx0.3mx0.07m waste. The cement, sand, and waste materials were combined individually in a 1:2:1 ratio (cement: sand: waste material) and constant water to cement ratio w/c of 0.40 [38]. Using a concrete mixer machine. According to Figures 3 & 6, the mixtures were cast in wooden forms to produce testing tiles measuring 30x30x2cm to fit the testing field of the thermal conductivity instrument.

Figure 3. Wooden form.

Figure 4. Climatic chamber Model: LT-C0120 & LT C0121 & LTC0122

Figure 5. Dray Oven
[Model: LT-G0205 - 700 Liter]

Figure 6. Instrument of thermal conductivity
[Model: H112N_E_4_042]

Tests were conducted in different environments based on Bahrain's average and extreme temperatures and humidity. Figure 4 shows the climatic testing chamber, and Figure 5 shows the dry oven where the samples were exposed to different environments. To enhance the precision of the measurements, each sample's thermal conductivity was measured three times. The thermal conductivity of the samples is determined using the heat-flow meter method. Among other materials, it allows for measuring thermal conductivity in metals, rocks, and solids. The heat-flow meter method is relatively accurate and fast compared with the transient method. When insulation materials are measured at room temperature, the uncertainty ranges between 3% and 20%, and at high temperatures, the uncertainty ranges between 10% and 20% [39].

Also, a smaller thermal conductivity level entails higher uncertainty, while a larger thermal conductivity value entails lower uncertainty [40]. Table 1 shows the calculated densities of the waste materials and the testing specimens.

Table 1. Densities of the experimented waste materials and testing specimens.

Mix	Applied waste material	The density of the waste material (kg/m^3)	Testing Specimens				
			Weight (kg)	Surface Area (m^2)	Thickness (m)	Volume (m^3)	Density (kg/m^3)
Mix-1	None	-	4.086	0.09	0.0235	0.002115	1.931
Mix-2	Crushed Rubber	450.0	4.206	0.09	0.0245	0.002205	1.869
Mix-3	Shredded Paper	120.32	3.878	0.09	0.0250	0.00225	1.696
Mix-4	Shredded Plastic	49.5	3.762	0.09	0.0254	0.002286	1.645
Mix-5	Foam	10.0	3.644	0.09	0.0267	0.002403	1.516

The specimen is placed between two plates (heated and cooled) at different temperatures, as shown in Figure 6. A heat flux transducer measures the amount of heat flowing through a specimen. Measuring the voltage drop across an electrical resistor makes it possible to determine the heat flux in a current. Changes in thermos voltage and measured signal are proportional to temperature drop throughout the plate [41]. A thermal conductivity measuring instrument like the one shown in Figure 6 is used to determine the value of the heat flow meter and the thickness of the test specimens required in conjunction with the calibration constants of the instrument, and then calculate the thermal conductivity using a formula (2) and the thermal resistance using formula (3) [42].

$$\lambda = \frac{T_s\,[(k_1+(k_2*\dot{T}))+((k_3+(k_4*\dot{T}))*HFM)+((k_5+(k_6*\dot{T}))*HFM^2)]}{dT} \quad (2)$$

Where,

λ = Thermal Conductivity (W/m˚C)
T_s = Test Specimen Thickness (m)
T2= *The* warm surface temperature of the sample during the measurement (˚C)
T1= The cold surface temperature of the sample during the measurement (˚C)
$\dot{T}$ = The average temperature of T1 & T2
HFM = Heat Flowmeter Reading (mv)
$dT = T_2 - T_1$
k_1, k_2, k_3, k_4, k_5 and k_6 are calibration constants.

$$R = \frac{T_s}{\lambda} \tag{3}$$

***Where*,**

R = Thermal Resistance ($m^{2\circ}c/w$)
λ = Thermal Conductivity ($W/m^\circ C$)
T_s = Test Specimen Thickness (m)

Testing was performed 32 times on each testing tile, with the first test done after 14 days in a room environment without any treatment (environment 1). In the next step, the tiles were exposed to different environmental combinations for 24, 48, 72, and 96 hours (environment 02-09). Lastly, they were exposed to extreme monthly temperatures and humidity levels in January and July (environments 10-11). At the end of the experiment, specimens were exposed to the hottest temperature with a humidity of 0% (environment 12). Thermal conductivity was measured by inserting the samples into the instrument immediately after getting out of the climatic chamber to avoid heat and humidity changes. Heat flowmeter readings and the sample's thickness and warm and cold surface temperatures were recorded in a spreadsheet. Thermal conductivity and thermal resistance are calculated by substituting the measured values in formulas 1 and 2. Based on the measurements of thermal resistances of the samples, the average differences between the 1st and 2nd days were 1.2% and 0.14%, respectively, and 0.03% between the 2nd and 3rd days. Temperature and humidity reached equilibrium after the samples reached equilibrium. Therefore, the 4th day's readings were overlooked, while the 3rd day's readings were considered saturation values.

Table 2. Companions of testing environments and exposure durations.

Reference	Environment Number	Timeline	Temperature		Humidity	
			Min.	Max.	Min.	Max.
Room environment	01	NA	24		20	
Average	02	January	14		57	
	03		14			88
	04			20	57	
	05			20		88
	06	July	32		39	
	07		32			80
	08			39	39	
	09			39		80
Absolute	10	extreme		45	90	
	11			45		97
Dry hot	12			100	0	

3. Results

3.1. Validation of the measuring method

The authors tested three reference materials to validate the experimental method that was used to calculate thermal conductivity: acrylic (PMMA), ceramic (XPS), and medium-density fiberboard (MDF). The average values for each material were recorded after three tests, as shown in Table 3. Based on these measurements, it was determined that they are within the range of their standard values [13], [43], [44], [45] [46], [47], [48] , [49], [50] & [51]. The validation results confirmed that the experimental method has been verified and can be applied to measure the thermal conductivity and the extracted thermal resistance.

Table 3. Validation of the measuring method.

Reference material	**The standard range of thermal conductivity W/m ºC**	**Temperature ºC**	**The range of thermal conductivity of all referenced materials W/m ºC**	**Measured thermal conductivity W/m ºC**
PMMA (Acrylic)	0.187 - 0.216 [43] 0.18 - 0.195 [13] 0.2 - 0.205 [44] 0.19 [44] 0.182 [44] 0.195 [45]	NA 33:56 22:60 32 62 25	0.18 – 0.216	0.18
XPS (Ceramic)	0.07 [43] 0.031 - 0.033 [13] 0.032 [46] 0.0345 [47]	NA 25:38 25 15:20	0.031– 0.07	0.04
MDF (Medium Density Fiberboard)	0.1012 - 0.1168 [48] 0.05 - 0.14 [49] 0.0889 - 0.0973 [50] 0.09 [51]	NA NA NA NA	0.05 – 0.14	0.10

3.2.Outputs of the experiment

For each sample, the thermal conductivity was measured three times to ensure the readings were not shifted. Rubber and plastic have an uncertainty of 2.5% under room temperature, whereas foam and paper have an uncertainty of 3%. Increasing humidity and temperature resulted in uncertainty ranging between 10 and 15%. The thermal resistance of each waste material was determined according to the average values of thermal conductivities measured for each waste material in each environmental condition. Figure 7 compares thermal resistance levels among the four mixes materials used in environment 01 (room conditions). The inclusion of rubber in mortar mix shows the lowest thermal resistance in comparison with plain mortar, one-tenth of a degree Celsius per square meter. The inclusion of Paper and plastic mixes provides medium differences in thermal resistance of 0.0192 and 0.0166 m^2 C/W, respectively, while the inclusion of foam mix shows the greatest difference of 0.0387 m^2 C/W. As a result, rubber, plastic, paper, and foam improved the efficiency of thermal resistance by 1.6, 43.4, 50.5 & 101.4%, respectively.

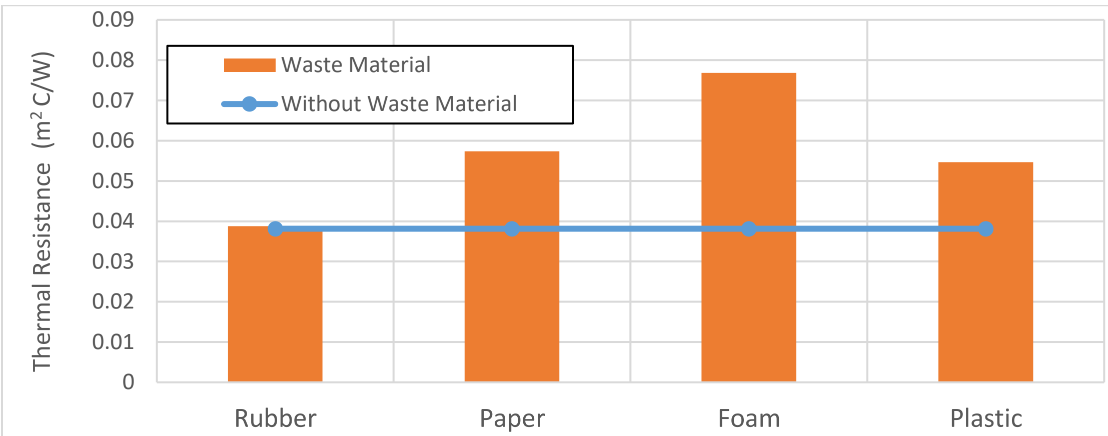

Figure 7. The thermal resistance of different waste materials after 14 days in environment 01.

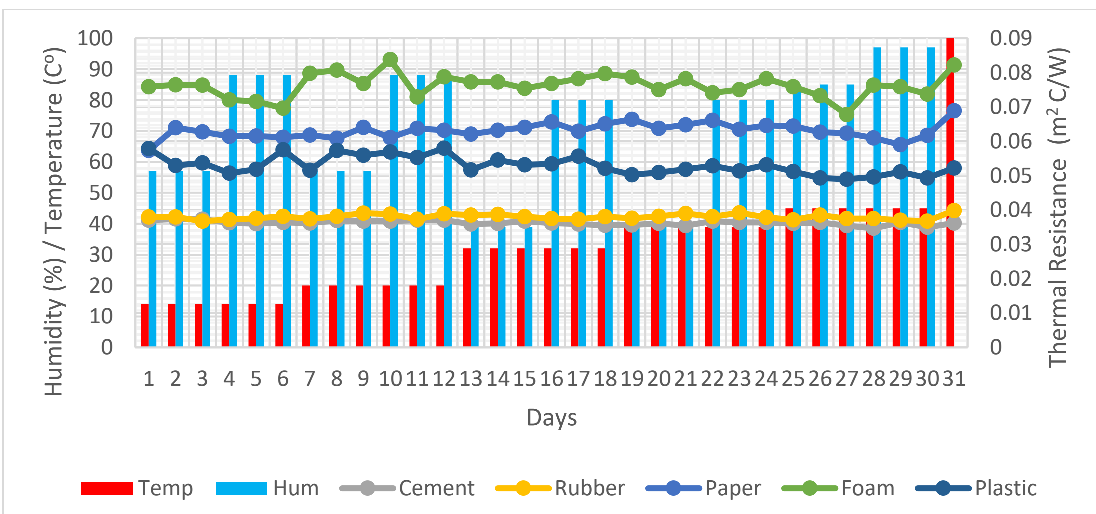

Figure 8. The thermal resistance of different waste materials in different environments.

Figure 8. illustrates the obtained values of the thermal resistance of the testing 0 samples measured after exposure to different environments inside the climatic test chamber for three days. As shown in Figure 7, the results collected from the samples exposed to different environments correspond

to those collected from the samples exposed to a room environment. Thermal resistance values recorded for foam were the highest, and those for rubber were the lowest throughout the entire testing procedure. The authors studied the effect of temperature and humidity on the insulation properties of the applied waste materials. Unlike the plain cement sample, which was exposed to the same conditions as the samples exposed to different environments, it was essential to compare the measured thermal resistance of the samples exposed to different environments. Figure 9. illustrates the percentages of changes in thermal resistance. Table 4 summarizes the percentage of changes in thermal resistance for the waste materials exposed to all proposed environments.

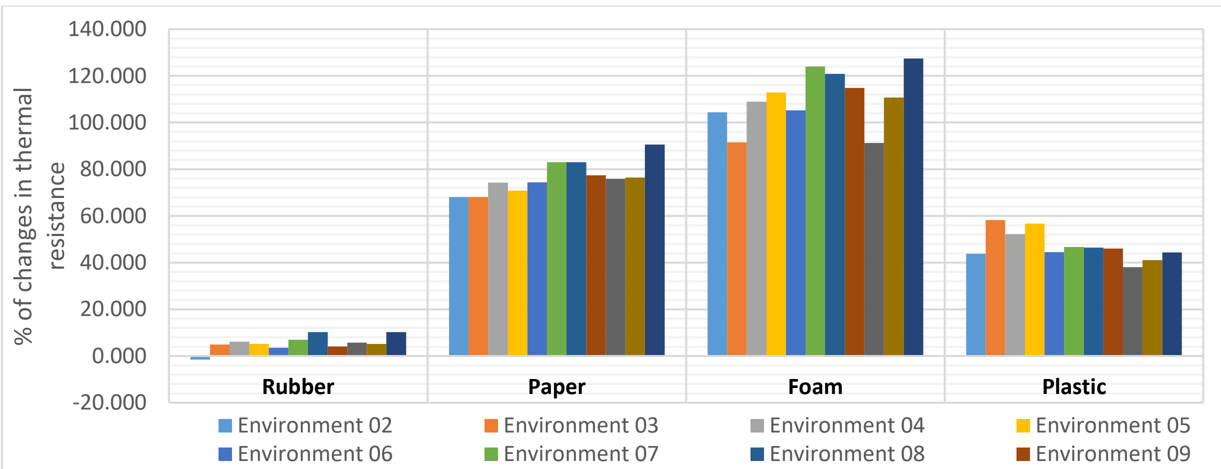

Figure 9. Changes in thermal resistance of samples containing waste materials compared to plain ones.

Table 4: Peak change in thermal resistance

Environment Number	Temperature ºC	Humidity %	Change in thermal resistance (%)			
			Higher		Lower	
01	24	20	No waste material	-	No waste material	-
02	14	57	foam	104.4	Rubber	-1.6
03	14	88	foam	91.4	rubber	4.8
04	20	57	foam	109.0	rubber	6.1
05	20	88	foam	113.0	rubber	5.1
06	32	39	foam	105.3	rubber	3.5
07	32	80	foam	124.0	rubber	7.0
08	39	39	foam	120.8	rubber	10.2
09	39	80	foam	114.8	rubber	4.1
10	45	90	foam	91.3	rubber	5.7
11	45	97	foam	110.7	rubber	5.1
12	100	0	foam	127.5	rubber	10.2

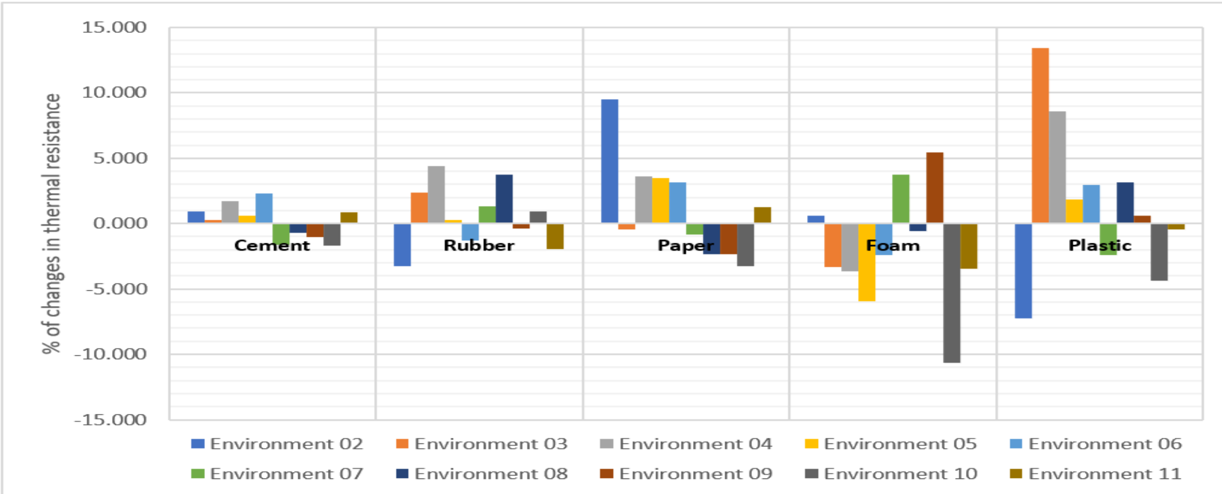

Figure 10. Changes in thermal resistance within the testing period for each environment.

There is no doubt that foam is better insulated than rubber, whereas rubber performs worse. While plain mortar is relatively inefficient, plastic and paper are moderate to relatively effective. The authors analyzed thermal resistance changes in each sample during three days of exposure to air temperature and relative humidity to further investigate their impact. A three-day exposure to different environments changes thermal resistance, as shown in figure 10. A comparison was made between the first and third days of the same exposition in the same environment. The thermal resistance of the sample without waste material, paper, and foam have improved in environment 02 (14 Co and 57% R. Hum.), while it has regressed for other samples. An increase of 9.5% in thermal resistance was observed in the sample containing paper in this environment 02. However, the plastic material sample showed the greatest decrease in thermal resistance of 7.2%. Table 5 summarizes the results of the remaining environments.

Table 5. Peak changes in thermal resistance within the testing period for each environment.

Environment Number	Temperature °C	Humidity %	Change in Thermal Resistance (%)			
			Max +ve		Max –ve	
02	14	57	Paper	9.5	plastic	7.2
03	14	88	plastic	13.5	foam	3.3
04	20	57	plastic	8.6	foam	3.7
05	20	88	Paper	3.5	foam	6.0
06	32	39	plastic	2.9	foam	2.4
07	32	80	foam	3.8	plastic	2.4
08	39	39	rubber	3.8	Paper	2.3
09	39	80	foam	5.4	Paper	2.3
10	45	90	rubber	0.9	foam	10.7
11	45	97	paper	1.3	foam	3.5

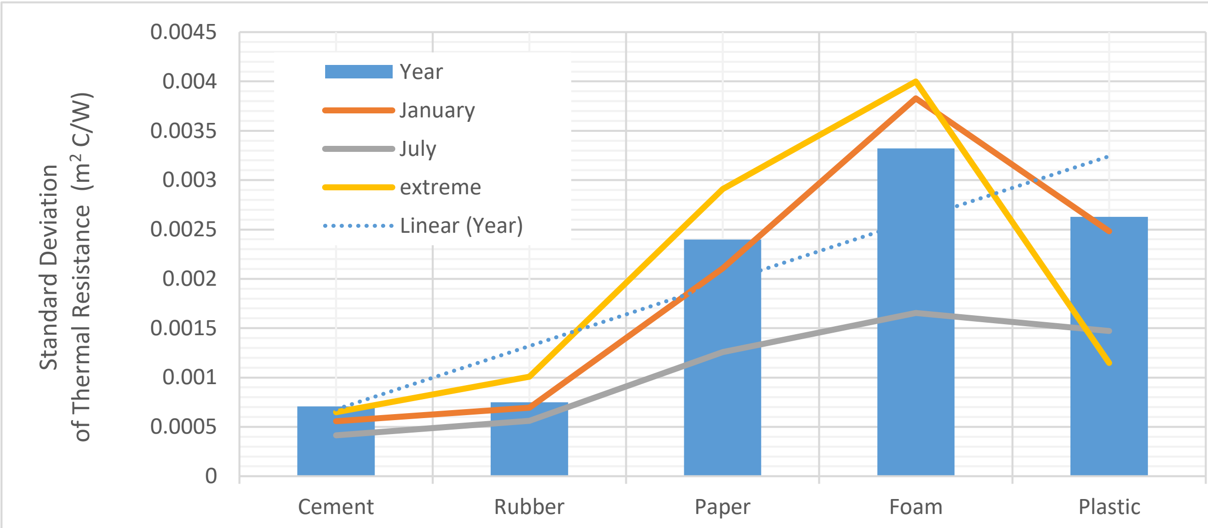

Figure 11. The Standard deviation of the thermal resistance of different waste materials.

Figures 10 and 11 show that rubber withstands different environments with the greatest amount of thermal constancy. The lowest standard deviation characterizes changes in thermal resistance values. In contrast, foam is the least consistent in thermal resistance constancy when exposed to a different environment due to its highest standard deviation. Paper and plastic exhibit similar thermal resistance characteristics when exposed to different environments. The standard deviation of the change in thermal resistance values is the lowest. Moreover, when exposed to different environments, foam and plastic show the highest standard deviation values and the lowest thermal resistance constancy values. There is a medium consistency in thermal resistance between paper and plastic when exposed to different environments.

4. Discussion

Thermal insulation can be achieved economically and effectively using waste materials. A composite of waste material can be used in several structures if mixed with reinforcement materials such as cement. On a global scale, waste materials, particularly plastic, are increasing in all countries, and waste management is essential for reducing the harmful impacts of waste on the environment. This has led to a rapid increase in recycling rates for different materials. A sustainable design solution requires innovative recycling processes to solve the problem of waste materials. A substantial amount of waste materials can be changed from being a problem-maker to a problem-solver by integrating the materials to improve the thermal performance of the building envelope and reducing the U value of the building envelope with cladding tiles made of a mixture of cement, sand and any of the tested waste materials (rubber, paper, foam, and plastic). Some waste materials, such as textiles, acrylics, paper, and wool, have significant thermal insulation capacity. According to studies, temperature and humidity are important parameters that affect insulation materials' thermal conductivity; as temperature and humidity increase, insulation materials' thermal conductivity increases, but depending on the material, the degree of change varies. The majority of studies, however, considered either temperature or humidity when examining the thermal properties of the stand-alone material. This study examined the effect of temperature and relative humidity on mixed waste materials mixed with cement mortar. As a result of this production process, building envelopes can become more efficient, especially in climate zones with arid conditions. Stand-alone building materials are tested for their thermal conductivity through many experiments. However, the thermal resistance is more significant for determining the overall U value of the building envelope that consists of multiple layers. The overall U value is the reciprocal of the overall thermal resistance as mentioned in the formula: $U_{value} = (1/R_T)$ [52], where U_{value} is the overall thermal conductivity, and R_T. is the sum of thermal resistances of all layers composed the building envelope.

5. Conclusion

This paper concludes that mixing the tested waste materials (rubber, plastic, paper, and foam) with plain mortar improves the efficiency of thermal resistance by 1.6, 43.4, 50.5 and 101.4%, respectively, compared to the thermal resistance of plain mortar. A change in environmental factors slightly influences rubber's thermal resistance during a year, while foam's thermal resistance is heavily influenced. In contrast, paper and plastic's thermal resistance is moderately impacted. The July environment did not significantly affect the four waste materials in Bahrain. Foam is the most influential factor during the January environment, followed by rubber, paper, and plastic. Temperature and humidity extremes have a greater influence on all tested waste materials except plastic. Mixing foam with cement and sand makes the foam more thermally resistant; its resistance increases by 91.3% to 127.5% under different conditions. In an environment where temperatures exceed 100°C, rubber increases thermal resistance by 10.2%.

The four tested mixes maintain thermal resistance to a certain extent with constant climatic conditions (temperature and relative humidity). After 48 hours in a climatic chamber, the rubber's thermal resistance changed by no more than 3.8% under 39°C and 39% humidity. A change of +13.5% in thermal resistance was recorded in the plastic after 48 hours at 14°C and 88% humidity, as opposed to the plastic showing the least stable thermal resistance.

The authors recommend that developers: use the waste materials of foam, paper, plastic, and rubber in the cladding of building envelopes to raise the thermal resistance and reduce the energy consumption for air conditioning, particularly in the summer season. Studying the effects of changing cement mortar and waste material ratios is also recommended, as well as examining the thermal resistance in different thicknesses. In addition, such proposed cladding materials need to be investigated for their geometrical, aesthetic, and mechanical properties such as durability, water absorption, and dimensional stability to improve their efficiency.

Acknowledgment

The authors confirm that the data applied in this study is primary data and were generated at the building materials laboratory of Kingdom University in Bahrain. They declare that this research was funded by Kingdom University, Kingdom of Bahrain, grant number 2017-42. The authors acknowledge the support given by Eng. Moath Majdi Zaki, the laboratory technician at Kingdom University. He was very cooperative while conducting the experiments.

References

[1] S. Elbialy, “Compressive Strength Evaluation of Cured Cement Mortar including Rubber, Foam, Plastic and Paper Wastes as Partial Replacement with Sand.,” *Journal of Sustainable Cities and Built Environment (JSCBE),* vol. 01, no. 01, pp. 50-70, 05 01 2023.

[2] A. A. Adeniran and W. Shakantu, "The Health and Environmental Impact of Plastic Waste Disposal in South African Townships: A Review.," *Int. J. Environ. Res. Public Health,* vol. 19, no. 2, pp. 779-789, 2022.

[3] P. H. v. Beukering and A. Duraiappah, "The Economic and Environmental Impact of Waste Paper Trade and Recycling in India: a Material Balance Approach.," *CREED Working Paper No. 10,* pp. 1-26, 1996.

[4] P. V. A. Beukering and R. Curlee, "Recycling of materials Local or global?," in *Managing a Material World Perspectives in Industrial Ecology*, vol. 13, The Netherlands, Springer Science+Busine, 1998, pp. 229-238.

[5] UNEP, "Guidelines for National Waste Management Strategies," United Nations Environment Programme, United States, 2013.

[6] B. Abu-Jdayil, H. Al Abdallah, A. Mlhem, S. Alkhatib, A. El Sayah, H. Hussein and A. Althabahi, Utilization of Polyurethane Foam Dust in Development of Thermal Insulation Composite., vol. 12, Buildings, 2022.

[7] P. Kostyantyn, E. Eriksson and F. Astr, "Waste paper for recycling: Overview and identification of potentially critical substances," *Waste Management,* vol. 45, pp. 134-142, November 2015.

[8] R. Proshad, T. Kormoker, S. M. Islam and M. A. Haque, "Toxic effects of plastic on human health and environment: A consequences of health risk assessment in Bangladesh," *International Journal of Health 2018,* vol. 6, no. 1, pp. 1-5, 2018.

[9] M. K. Eriksen, J. D. Christiansen and A. E. Daugaard, "Closing the loop for PET, PE and PP waste from households: Influence of material properties and product design for plastic recycling," *Waste Managment,* vol. 96, no. 1, pp. 75-85, 2019.

[10] J.-J. Guo, X. Pei Huang, L. Xiang and Y.-Z. Wan, "Source, migration and toxicology of microplastics in soil," *Environment International,* vol. 137, no. 1, 2020.

[11] L. W. Filho, U. Saari, M. Fedoruk, A. Iital, H. Moora, M. Klöga and V. Voronova, "An overview of the problems posed by plastic products and the role of extended producer responsibility in Europe," *Journal of Cleaner Production,* vol. 214, no. 1, pp. 550-558, 2019.

[12] D. E. MacArthur, D. Waughray and M. R. Stuchtey, "The new plastics economy, rethinking the future of plastics. 2016, 2016, 36.," in *World Economic Forum,* Switzerland, 2016.

[13] A. S. Karthik and S. Gedupudi, "Straw bale based constructions: Measurement of effective thermal transport properties," *Construction and Building Materials,* vol. 198, no. 1, pp. 182-194, 2019.

[14] A. S. Karthik and S. Gedupudi, "On the influence of concrete-straw-plaster envelope thermal mass on the cooling and heating loads for different climatic zones of India," *Journal of Cleaner Production,* vol. 276, 2020.

[15] J. Adamczyk and R. Dylewski, "The impact of thermal insulation investments on sustainability in the construction sector," *Renewable and Sustainable Energy Reviews,* vol. 80, no. C, pp. 421-429, 2017.

[16] C. Diakaki, E. Grigoroudis and D. Kolokotsa, "Towards a multi-objective optimization approach for improving energy efficiency in buildings,," *Energy and Buildings,* vol. 90, no. 9, pp. 1747-1754, 2008.

[17] R. Galvin, "Thermal upgrades of existing homes in Germany: The building code, subsidies, and economic efficiency," *Energy and Buildings,* vol. 42, no. 6, p. 834–844, 2010.

[18] R. Jacob, D. Sergeev and M. Müller, "Valorisation of waste materials for high temperature thermal storage: a review," *Journal of Energy Storage,* vol. 47, p. 103645, 2022.

[19] V. Pukhkal, M. Tanić, N. Vatin and V. Murgul, "Studying Humidity Conditions in the Design of Building Envelopes of “Passive House” (in the case of Serbia)," *Procedia Engineering,* vol. 117, pp. 859-864, 2015.

[20] Y. Wang, K. Liu, Y. Liu, D. Wang and J. Liu, "The impact of temperature and relative humidity dependent thermal conductivity of insulation materials on heat transfer through the building envelope," *Journal of Building Engineering,* vol. 46, p. 103700, 2022.

[21] S. Mehrzad, E. Taban, P. Soltani, S. E. Samaei and A. Khavanin, "Sugarcane bagasse waste fibers as novel thermal insulation and sound-absorbing materials for application in sustainable buildings," *Building and Environment*, vol. 211, p. 108753, 2022.

[22] S. Sair, B. Mandili, M. Taqi and A. E. Bouari, "Development of a new eco-friendly composite material based on gypsum reinforced with a mixture of cork fibre and cardboard waste for building thermal insulation," *Composites Communications*, vol. 16, pp. 20-24, 2019.

[23] A. Gounni, M. T. Mabrouk, M. E. Wazna, A. Kheiri, M. E. Alami, A. E. Bouari and O. Cherkaoui, "Thermal and economic evaluation of new insulation materials for building envelope based on textile waste," *Applied Thermal Engineering*, vol. 149, pp. 475-483, 2019.

[24] B. Mandili, M. Taqi, A. E. Bouari and M. Errouaiti, "Experimental study of a new ecological building material for a thermal insulation based on waste paper and lime," *Construction and Building Materials*, vol. 228, p. 117097, 2019.

[25] I. Marie, "Thermal conductivity of hybrid recycled aggregate – Rubberized concrete," *Construction and Building Materials*, vol. 133, pp. 516-524, 2017.

[26] A. M. Mhaya, S. Shahidan, H. A. Algaifi and S. Zuki, "Thermal Conductivity of Coconut Shell-Incorporated Concrete: A Systematic Assessment via Theory and Experiment," *Sustainability*, vol. 14, no. 23, pp. 1-19, 2022.

[27] U. Berardi and R. Nosrati, "Long-term thermal conductivity of aerogel-enhanced insulating materials under different laboratory aging conditions," *Energy*, vol. 147, p. 1188–1202, 2018.

[28] U. Berardi, L. Tronchin and M. Manfren, "On the effects of variation of thermal conductivity in buildings in the Italian construction sector," vol. 11, no. 4, 2018.

[29] M. Khoukhi, "The combined effect of heat and moisture transfer dependent thermal conductivity of polystyrene insulation material: impact on building energy performance," *Energy Build*, vol. 169, p. 228–235, 2018.

[30] P. Tsilingiris, "Thermophysical and transport properties of humid air at temperature range between 0 and 100◦C," *Energy Conversion and Management*, vol. 49, no. 5, pp. 1098-1110, 2008.

[31] TheWorldBank, "Trends in Solid Waste Management," 07 March 2022. [Online]. Available: https://datatopics.worldbank.org/what-a-waste/trends_in_solid_waste_management.html.

[32] S. Shanavas, "Bahrain : An overview of solid waste management in bahrain," 07 March 2022. [Online]. Available: https://www.wasterecyclingmea.com/news/waste-management/bahrain-an-overview-of-solid-waste-management-in-bahrain.

[33] M. G. Lawrence, "The relationship between relative humidity and the dewpoint temperature in moist air: A simple conversion and applications.," *Bull. Amer. Meteor. Soc.*, vol. 86, no. 1, pp. 225-233, 2005.

[34] "Weather History in Manama Bahrain," 07 March 2022. [Online]. Available: https://weatherspark.com/h/d/104944/2021/7/22/Historical-Weather-on-Thursday-July-22-2021-in-Manama-Bahrain#Figures-Temperature.

[35] "Climate in Manama," 07 March 2022. [Online]. Available: https://weather-and-climate.com/average-monthly-Rainfall-Temperature-Sunshine,manama,Bahrain.

[36] Meteorogical_Directorate, "Climate," 07 Feb 2022. [Online]. Available: http://www.bahrainweather.gov.bh/web/guest/temperature.

[37] ASTM, "ASTM C. 150 standard specification for Portland cement. West Conshohocken," 2005.

[38] J. Sridhar and R. Malathy, "Study on compressive strength of," *International Journal of*, vol. 4, no. 6, p. 1139–1144, 2011.

[39] H. Czichos, T. Saito and L. E. Smith, Handbook of Materials Measurement Method, S. S. &. B. Media, Ed., New York: Springer, 2006, p. 1208.

[40] M. Koniorczyk and W. Grymin, "Influence of the Thermal Conductivity and Ambient Temperature Uncertainty on the Heat Losses through the ExternalWall.," *Buildings*, vol. 11, no. 84, 2021.

[41] A. Almusaed and A. Almssad, Insulation Materials in Context of Sustainability, London: IntechOpen, 2016.

[42] "H112N Manual - Instrction Manual," P. A. Hilton Ltd, Engineering Teaching Equipment, London, 2019.
[43] "MatWeb material property data," Elmet Technologies, 2022. [Online]. Available: https://www.matweb.com/search/DataSheet.aspx?MatGUID=3cb08da2a0054447a3790015b7214d07&ckck=1. [Accessed 4 May 2022].
[44] M. Rides, J. Morikawa, L. Halldahl, B. Hay, H. Lobo, A. Dawson and C. Allen, "Intercomparison of thermal conductivity and thermal diffusivity methods for plastics," *Polymer Testing,* vol. 28, no. 8, pp. 480-489, 2009.
[45] W. N. d. Santos, "Thermal properties of polymers by non-steady-state techniques," *Polymer Testing,* vol. 26, no. 4, pp. 556-566, 2007.
[46] Al-Ajlan and S. A., "Measurements of thermal properties of insulation materials by using transient plane source technique," *Applied Thermal Engineering,* vol. 26, no. 17-18, pp. 2184-2191, 2006.
[47] S. Dubois and F. Lebeau, "Design, construction and validation of a guarded hot plate apparatus for thermal conductivity measurement of high thickness crop-based specimens," *Mater Struct,* vol. 48, no. 1, p. 407–421, 2015.
[48] D. Ustaomer and U. E. Baser, "Thermal and Fire Properties of Medium-density Fiberboard Prepared with Huntite/hydromagnesite and Zinc Borate," *BioResources,* vol. 15, no. 3, pp. 5940 - 5950, 2020.
[49] "Wood Panel Industries Federation," BM TRADA, London, 2014.
[50] M. U. Derya USTAÖMER, "Bazı kimyasal maddeler kullanılarak üretilmiş orta yoğunlukta liflevhaların (MDF) ısıl iletkenliği," *Kastamonu Univ., Orman Fakültesi Dergisi,* vol. 17, no. 4, pp. 603-607, 2017.
[51] K. Li, C. Fleischmann and M. Spearpoint, "Determining thermal physical properties of pyrolyzing New Zealand medium density fibreboard (MDF)," *Chemical Engineering Science,* vol. 95, no. 1, pp. 211-220, 2013.
[52] Unified Guidebook of Building Permit Regulations, Kingdom of Bahrain: [Online], 2018.