DOI: 10.61782/fa.2023.1094

FROM WASTE TO DESIGN: THE POTENTIALS OF RECYCLED COFFEE, TEA RESIDUE AND CARDBOARD CUPS AS ACOUSTICAL PANELS

Ece Sel[1*] **İpek Düzova**[2] **Zühre Sü Gül**[3]
[1] Faculty of Architecture and the Built Environment, Delft University of Technology, Netherlands
[2] The Architectural Association School of Architecture in London, England, UK
[3] Department of Architecture, Bilkent University, Turkey

ABSTRACT*

This study aims to enhance acoustical comfort levels in indoor environments by addressing the excessive residue disposal and usage of single-use cardboard cups resulting from the increasing consumption of coffee and tea. This research is a follow-up phase of a study initiated to increase acoustical comfort levels in architectural design studios by research and production of sound absorptive panels. In the first phase, coffee and tea residues are used as a system and their sound absorption performance is tested by impedance tube measurements that showed promising potentials. This second phase has incorporated recycled cardboard cups and recycled coffee bags as a front layer to the previously tested coffee panels. As it is not possible to test the panels by impedance tube due to their sizes, the panels are produced in an overall 10 m2 to be tested in a naked design studio having dimensions closer to a reverberation chamber. Variations of the product are tested and compared. Results highlight the additional contribution of cupboards to the sound absorption performance of the backing materials. Thus, the system has the potential to be a cost-minimized, sustainable and biodegradable acoustic solution with an aesthetic value to be applied in indoor spaces.

Keywords: *room acoustic, sound absorption materials, waste materials, sustainability*

**Corresponding author*: e.sel@student.tudelft.nl.

1. INTRODUCTION

The significance of utilizing circular and eco-friendly materials has been gaining increasing importance as the world faces an unpredictable future caused by the utilization of non-environmentally friendly materials. In the current era, a material's life is often limited to one use, and its value decreases after the use as the value hill implies [1]. Whenever something is considered functional, the choice often goes for a new material made from raw conditions. But what qualifies as "new"? Is it a material that is not yet in the industry, or can a material turn into circular and be called new? Circular thinking allows for the recovery of value, bringing it closer to its original stage. In the field of acoustics, traditional sound-absorptive materials used in architectural applications are typically based on mineral stone, or glass wool, which have a significant carbon footprint and involve an energy-intensive production process, resulting in a high environmental impact [2,3]. Therefore, the need to look for circular materials is becoming increasingly important. Coffee and tea are among the most consumed beverages globally, with over 9.2 million tons of coffee and 6 million tons of tea consumed in 2017 [3]. Also, the consumption and resulting waste from these beverages are increasing. This leads to a huge environmental problem as the waste often ends up in landfills, where it takes a long time to decompose naturally and can cause additional health problems [4,5,6]. The waste produced from coffee and tea can be found as a possible option to address this issue. Therefore, the objective of this study is to explore the acoustic properties of recycled and waste materials as a viable solution to address these issues. By repurposing the materials, the aim is to develop effective and sustainable sound-absorbing materials for real-life applications and reduce the environmental impact of the production of new materials.

2. BACKGROUND STUDY

2.1 Literature review

Materials made out of waste have been investigated by other researchers. Buratti et al. (2016) investigated the potential of recycled paper and scrap materials, such as wool and nonwoven polyester fabric, in the production of sustainable acoustical panels. The research found that the panels exhibited great acoustical performance at higher frequencies, resulting in reduced reverberation times, as well as showing a lower environmental impact compared to traditional extruded polystyrene [2]. Yun et al. explored the potential of coffee waste as a raw material for sound-absorbing materials, highlighting its porosity. They recycled coffee waste and combined them with urea resin to create sound-absorbing samples. These samples were found to have promising sound absorption coefficient values for application in reducing noise levels in café environments [7]. Another study conducted by Choi et al. [8] investigated the utilization of coffee waste as a building material by developing a composite material incorporated bio-based microencapsulated phase change material with coffee waste. This composite exhibited promising thermal and acoustic performance, presenting it as an eco-friendly solution in construction applications. Furthermore, Sena da Fonseca et al. conducted a study on the utilization of spent coffee grounds as an additive in clay-based ceramics for construction. The research examined the physical and mechanical properties of clay/coffee waste, highlighting their potential to reduce waste, improve thermal insulation, and lower costs in ceramic fabrication [9].

2.2 Origin of the study

The original research of this study is conducted as part of a term project for the ARCH 341, a course in Architectural Lighting and Acoustics offered by the Department of Architecture at Bilkent University in Turkiye. The main objective is to address the noise complaints of students and instructors due to the high reverberance within studios. The project aims to improve the acoustic comfort levels in the architectural studio FBZ01 whose before and after images can be seen in Figure 1 and Figure 2. The findings reveal that the reverberation time in mid and low frequencies in the FBZ01 studio are as high as 1.75 s and 2.09 s, respectively. To address this issue and enhance speech intelligibility, a two-layered panel system is developed, utilizing used cardboard cups collected for the first layer (see Fig. 3), and thick mineral wool for the second layer [10]. These materials could not be acoustically tested during the course semester, and the research continued afterward.

Figure 1. The studio before panel application

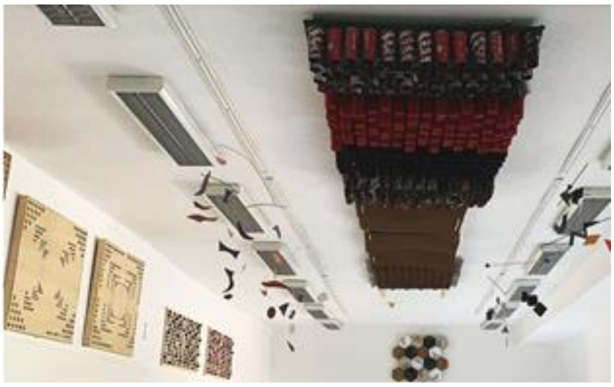


Figure 2. After the term project submission; students' panels applied to the design studio

a. b. c. d.

Figure 3. Arrangements of the panels, a) cut-in-half cardboard cups (CC) placed horizontally, b) cut-in half CC placed vertically, c) CC having different sizes placed randomly, d) CC having different sizes arranged linearly in a pattern based on size.

2.3 Initial stage

The first phase of this research [10] focuses on investigating the properties of coffee panels (CP) and coffee-tea panels (CTP), using three different composite samples evaluated through experiments to assess their sound absorption performances. The samples, that can be seen in Figure 4, are tested for their ingredients, baking time, and exposure to heat, by impedance tube measurements (see Fig. 5) and room acoustic simulation ODEON. The results indicate that using coffee and tea waste in the production of acoustical panels has promising potential as a sound-absorbing material, and further research in this area is necessary [10]. Therefore, this paper is a follow up research with field tests of this first phase study.

a. b. c.

Figure 4. Test specimens, a) Sample A (CTP), b) Sample B (CTP), c) Sample C (CP).

a. b.

Figure 5. a) Impedance tube with Sample A, b) molded test specimen.

2.4 Current stage

In the second phase, recycled cardboard cups, as the layer put in the front, and recycled coffee bags, as the covers, are integrated into the CTP panels. Due to the large dimensions of the panels, it is not feasible to evaluate their acoustic performance using an impedance tube. Instead, 10 m^2 of samples are produced to be tested in a naked studio, with dimensions closer to a reverberation chamber. Two different variations of the product are produced, and explained in the methodology.

3. METHODOLOGY

This section presents the methodology used for production of samples and the measurements. As mentioned, two different panels, coffee-tea panels (CTP) and coffee-tea panels with cardboard cups at the front layer (CTP-CC) are produced. Subsequently, field tests are conducted to measure the reverberation times in the studio under three different conditions: the current condition of the studio, the CTP application, and the CTP-CC application. The sound absorption coefficient values are calculated to evaluate the sound absorption coefficients of the panels across 1/1 octave bands.

3.1 Sample preparation

Collecting waste materials is the key point of this research. Thus, the coffee and tea waste and the cardboard cups are collected by various coffee chains and household consumption. After the waste is collected, the coffee and tea wastes are left to air-dry at room temperature as seen in Figure 6 [10]. Based upon the impedance tube measurements held previously [10] the best performing sample, which is CTP baked for 2 hours at 200ºC, is selected for the following field test measurements. To meet the requirements of BS EN ISO 354:2003, minimum test specimen area of 10 m^2 [11], corresponding to 512 panels with dimensions of 14 cm, and a thickness of 2 cm, has been produced for field tests. To enhance the structural integrity and bind the waste materials together, a starch-based organic material is used. This material is chosen for its natural and biodegradable properties, as well as its ease of production. The coffee and tea residues are mixed with an adhesive composed of flour, vinegar, and water. The adhesive is heated on a stove for 5 minutes until it reaches a dense consistency capable of binding the materials together. Afterward, the adhesive is mixed with a 1/3 ratio with the waste to bind the materials (see Fig. 7). Generally, an equal amount of coffee and tea waste has been mixed for the waste mixture. However, due to the large amount of samples and the varying quantities of waste material collected over time, the ratio of waste materials has been occasionally adjusted. These changes in the waste material ratio also affected certain properties of the materials. Subsequently, the mixture is molded into square panels measuring 14cm by 14cm.The panels are baked for 2 hours in a home oven, producing the material referred to as CTP (see Fig. 8)

a. b.

Figure 6. a) TW collected from household
b) SW collected from coffee chains and household.

Figure 7. Mixing the waste and the binder

The CTP is wrapped with porous jute fabric to keep the panels in place and allow for easier transportation and assembly, as shown in Figure 9. The permeable quality of the fabric enables the material to function as an absorber while preventing the panels from getting damaged. To evaluate the recycled cardboard cups' sound-absorbing performance as backing for the CTP, an additional layer of cardboard cups is used. To achieve this, different sizes of cardboard cups are collected and pierced from their top to create a hole as shown in Figure 10, in order to provide a neck for sound penetration.

Figure 8. CTP panels

Figure 9. The jute fabric wrap and the CTP.

Figure 10. Cardboard cups at the front layer of the panels, showing their different sizes and the cuts.

3.2 Field test

The field test was conducted on September 7th, 2022, between 9:30 am and 11:00 am, following the BS EN ISO 354:2003 standard [11]. The room FBZ1, which is a design studio at Bilkent University, is chosen as the field test location since it is not proposing a suitable studio environment in terms of acoustical comfort, and mostly functioning as a storage space. The room measurements are 10.6 meters by 10.6 meters, resulting in a total area of 112 m^2. Although the height varies throughout the room, its average height is 4.5 meters, giving the room a total volume of 506 m^3. Throughout the experiment, the temperature was 24.5^{o}C, and the humidity level was 19%. For acoustic excitation, a dodecahedron omnidirectional sound source of type B&K 4292-L is utilized, along with a B&K 2734-A power amplifier. To capture the room impulse responses, a B&K type 4190ZC-0032 microphone is used. The dodecahedron omnidirectional sound source located 150 cm above the floor and the microphone positioned 120 cm above the floor. To carry out the field tests, two different source positions and six different receiver positions are used (see Fig. 11 for their plan and the locations).

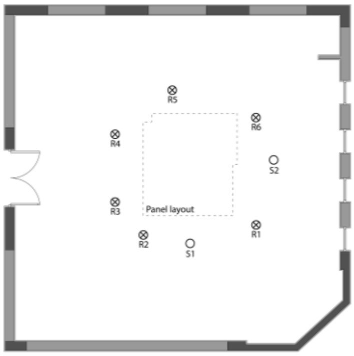


Figure 11. Positions of omnidirectional sound source (S1-S2) and the microphone (R1-R6).

For each source position, six measurements are taken, totalling 12 measurements per set. In order to receive the e-sweep noise signals, the DIRAC Room Acoustic software with type 7841 v.4.1 is used, from which the room impulse responses are collected (RIR). T20 values are then post-processed for 1/3 octave bands. The first set of measurements is performed in the empty room conditions without any intervention. Later, two other sets of measurements are performed, by using the previously established source and receiver positions. For the second set, the layer of CTP having a 10 m^2 surface area is placed on the ground (see Fig. 12). The panels are placed on 5 cm wedges to elevate them from the ground. The third set measures the combined effect of CTP and coffee cups, (CTP-CC) to evaluate the effect of the recycled cardboard cups on sound absorbers performance of backing coffee and tea-waste residue. To produce the CTP-CC panels, cardboard cups are added on top of the CTP layer, and the measurements are performed accordingly (see Fig. 13).

Figure 12. Second set of measurements of CTP.

Figure 13. Third set of measurements with the double-layered system, CTP-CC.

3.3 Determination of sound absorption coefficients

The BS EN ISO 354:2003 require the consideration of T20 for estimating sound absorption coefficient values. T20 values for 1/3 octave bands are extracted between 100 Hz and 5000 Hz, as a reliable range to estimate sound absorption coefficients in given volume of the room. For measured source-receiver configurations average T20 of each scenario as N/A, CTP and CTP-CC are calculated. To evaluate the material properties of both CTP and CTP-CC, the alpha values are calculated using equation (1), (2) and (3) from the EN ISO 354:2003 standard [11].

$$A_T = 55{,}3V\,[1/(c_2T_2) - 1/(c_1T_1)] - 4V\,(m_2 - m_1) \quad (1)$$

$$c = (331 + 0{,}6\; t\,/\,^{O}C) \quad (2)$$

$$\alpha_s = A_T / S \quad (3)$$

where;
c: velocity of the sound at which it propagates through the air when the temperature is at a certain t value.
T: duration, taking for sound to decay by 60dB in a reverberation room after introducing the test specimen.
m: power attenuation coefficient,
A_T: the test specimen's equivalent sound absorption area
S: Area covered by the test specimen.

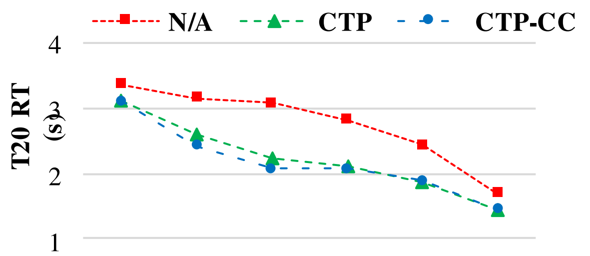
4. RESULTS

This section presents the results of the measured T20 values for all scenarios, along with the estimated sound absorption coefficient values of the CTP and CTP-CC test specimens. Furthermore, these results are compared with the findings obtained during Phase I of this study, where impedance tube measurements are utilized [10].

4.1 T20 results

This section presents the T20 values of different studio conditions (see Fig. 14). The initial studio environment has a very high reverberation time of 3,09 s at 500 Hz, which is far above the recommended limit for a suitable classroom environment, which is around 1 s.

After the application of the test specimens, this value decreased to 2,25 s for CTP and 2,07 s for CTP-CC at 500 Hz. The decrease in reverberation time between the 1/1 octave bands of 125 Hz and 4000 Hz varies between 0,25 s and 0,84 s with an average of 0,54 s for CTP; and 0,24 s and 1,02 s with an average of 0,60 s for CTP-CC. When comparing the results of both scenarios, CTP-CC shows a higher decrease in the T20 for the given area, implying that the cardboard cup at the front layer provides an additional improvement in the overall sound absorptive qualities of the material. Although this intervention could not aid the reverberation times in reaching the desired level for a studio environment, it still results in a significant decrease. Thus, further interventions to the classroom, such as increasing the application area of developed panels can be suggested.

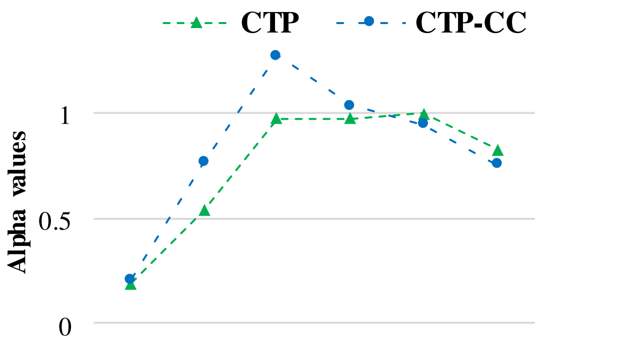


	125 Hz	250 Hz	500 Hz	1 kHz	2 kHz	4 kHz
N/A	3,38	3,17	3,09	2,83	2,45	1,69
CTP	3,13	2,61	2,25	2,10	1,87	1,44
CTP CC	3,11	2,43	2,07	2,07	1,89	1,45

Figure 14. Average T20 results of different scenarios as empty condition (N/A), after CTP intervention, and after CTP-CC intervention, for 1/1 octave bands between 125 Hz - 4000 Hz.

4.2 Alpha results

The sound absorption coefficient is expected to be between 0 and 1 with an average value of 0,75 to be considered as an effective sound absorber. The alpha values of the test specimens are found to be between 0,19 and 1,00 for CTP; and 0,21 and 1,28 for CTP-CC between 1/1 octave bands of 125 Hz and 4000 Hz, as shown in Figure 15. When comparing the results of both test specimens, CTP-CC demonstrates better values for the 1/1 octave bands of 125 Hz and 2000 Hz, although CTP has a higher value at 4000 Hz, which is not the most critical frequency in the chosen studio environment. Therefore, CTP-CC exhibits higher alpha values, indicating that the cardboard cups placed in front of the panel effectively enhance the product's sound absorption performance. This potential outcome could not be tested in the previous set-up of the impedance tube, which is utilized in the first phase of the study.



	125 Hz	250 Hz	500 Hz	1 kHz	2 kHz	4 kHz	NRC
CTP	0,19	0,54	0,98	0,98	1,00	0,83	0.88
CTP CC	0,21	0,77	1,28	1,04	0,95	0,76	1.00

Figure 15. Sound absorption coefficient values of the test specimen CTP and CTP-CC for 1/1 octave bands in between 125 Hz and 4000 Hz; and their corresponding NRC values.

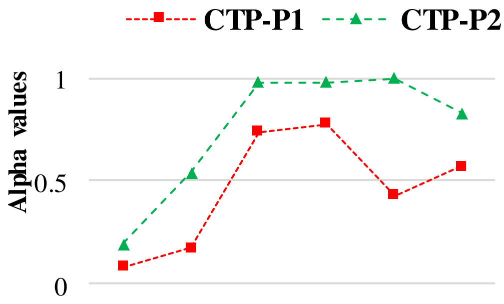
The noise reduction coefficient (NRC) is a measure of the sound absorption performance of materials, based on the average absorption coefficient values at 250 Hz, 500Hz, 1000 Hz, and 2000 Hz. To compare the sound absorption performance of different test specimens, the NRC parameter is utilized, and the results are presented in Figure 15. The results show that the NRC value is 0,88 for CTP and 1,00 for CTP-CC. Both test specimens exhibit high sound absorption performance as the NRC values are greater than 0,80.

Figure 15 shows that certain alpha values exceed the maximum value of 1. This type of error is commonly seen in the reverberation chamber due to the diffraction effects and edge absorption caused by the sample's sides. Thus, the Sabine absorption coefficients may often exceed the value of 1 [12].

4.3 Field test and impedance tube results comparison

In this section, the comparison of the alpha results of two different measurement methods for test specimens CTP is presented (see Fig. 16). The first set of measurements, referred to as CTP-P1, is obtained through impedance tube measurements in phase I [10], while the second set of measurements, referred to as CTP-P2 (also referred as CTP in earlier sections), is obtained through field testing in phase II. As the impedance tube measurements do not allow for the measuring of the coffee cupboard, the comparison have been done with CTP-P1 and the CTP-P2. The CTP-P1 shows an average of 0,29 lower alpha result than the CTP-P2 across the 1/1 octave bands between 125 Hz and 4000 Hz. For 500 Hz, the CTP-P1 shows an alpha value of 0,78 while the CTP-P2 shows almost full absorption.

The observed differences in the alpha values could be attributed to several factors. One possible factor, in terms of material quality, is the additional covering layer present in CTP-P2, while CTP-P1 does not have any covering. Moreover, although the panels share the same thickness and production method, the difference in their width can result in lower density and a more porous texture. This may facilitate higher sound absorption. Another potential factor is the test environment as the empty studio environment is close but not exactly a reverberation chamber. Furthermore, the angle of sound incidence (random incidence in comparison to plane waves) could contribute to higher values of sound absorption of the tested specimen in studio conditions, replicating a reverberation chamber as much as possible, in comparison to the impedance tube method. Additionally, the values over 1 in absorption coefficients are most probably caused by the diffraction effects and edge absorption at the sides of the samples in the reverberation chamber setup as mentioned earlier [12].



	125 Hz	250 Hz	500 Hz	1 kHz	2 kHz	4 kHz	NRC
CTP P1	0,08	0,17	0,74	0,78	0,43	0,57	0,87
CTP P2	0.19	0,54	0,98	0,98	1,00	0,83	0,53

Figure 16. alpha values of test specimen CTP measured by impedance tube (P1) [10], and field test P2); and their corresponding NRC values.

4.4 Further discussion

An important aspect to consider is the density of the materials, which has been observed during the production stage. Samples with a higher proportion of tea-based waste exhibit lower density and result in more porous panels. On the other hand, panels with a higher proportion of coffee-based waste are denser and tend to develop molds due to insufficient drying within the allocated time. Therefore, there is room for improvement in the drying process. Additionally, currently, the life cycle analysis of the material is of the current phase but will be considered in the following stages.

5. CONCLUSION

In conclusion, the importance of utilizing circular and eco-friendly materials is increasing due to the risk associated with non-environmental friendly material usage. Therefore, a circular replacement of the current materials in the field of acoustics needs to be considered, particularly considering the high environmental impact and expensive production process of traditional inorganic sound-absorptive materials [2]. This study aims to address this issue by exploring the potential of using waste materials from coffee chains, as global beverage consumption leads to a significant amount of materials ending up in landfills. Through experimentation, it has been found that the produced panels have the potential to be used as sound absorptive materials. This potential can be further enhanced by utilizing CTP-CC (which is cupboard faced coffee-tea waste panels), resulting in a decrease of 1.02 s at T20 values in the tested studio. The resulting design not only addresses concerns about unsustainable materials but also adds value to the product's post-use stage. The use of these low-cost and aesthetical acoustical panels can improve indoor spaces, particularly in design studios as well as cafes where the waste is sourced from.

6. ACKNOWLEDGEMENTS

The authors would like to express their gratitude to Mezzo Stüdyo Ltd., Ankara for providing equipment for room acoustic measurements, software, and impedance tube measurements; and also to Bilkent University, where this study was conducted. The authors also greatly appreciate the support of the coffee companies in providing the waste for this study. The authors extend their appreciation to their colleague, Anıl Ege Şireli, for his significant contributions, with whom they have been working on this project in the first phase; Efekan Ağar and Ertuğ Erpek for their valuable help in maintaining the products, and to the authors' families for their valuable help in collecting and producing the products.

7. REFERENCES

[1] E. Achterberg, J. Hinfelaar, and N. Bocken, "Master Circular Business with Value Hill." Available: https://www.circonnect.org/wp-content/uploads/2022/09/value-hill-white-paper.pdf

[2] C. Buratti, E. Belloni, E. Lascaro, G. A. Lopez, and P. Ricciardi, "Sustainable Panels with Recycled Materials for Building Applications: Environmental and Acoustic Characterization," Energy Procedia, vol. 101, pp. 972–979, Nov. 2016, doi: https://doi.org/10.1016/j.egypro.2016.11.123.

[3] S. A. Saldaña-Mendoza et al., "Use of wastes from the tea and coffee industries for the production of cellulases using fungi isolated from the Western Ghats of India," Systems Microbiology and Biomanufacturing, vol. 1, no. 1, pp. 33–41, May 2020, doi: https://doi.org/10.1007/s43393-020-00001-z.

[4] H.J. Van Hilten, et al., "The Coffee exporter's guide: The Markets for Coffee," 3rd ed. International Trade Center, 2011.

[5] A. Deloraine, D. Zmirou, C. Tillier, A. Boucharlat, and H. Bouti, "Case-Control Assessment of the Short-Term Health Effects of an Industrial Toxic Waste Landfill," Environmental Research, vol. 68, no. 2, pp. 124–132, Feb. 1995, doi: https://doi.org/10.1006/enrs.1995.1016.

[6] K. Joseph, S. Rajendiran, R. Senthilnathan, and M. Rakesh, "Integrated approach to solid waste management in Chennai: An Indian metro city," Journal of Material Cycles and Waste Management, vol. 14, no. 2, pp. 75–84, Apr. 2012, doi: https://doi.org/10.1007/s10163-012-0046-0.

[7] B. Y. Yun, H. M. Cho, Y. U. Kim, S. C. Lee, U. Berardi, and S. Kim, "Circular reutilization of coffee waste for sound absorbing panels: A perspective on material recycling," Environmental Research, p. 109281, Feb. 2020, doi: https://doi.org/10.1016/j.envres.2020.109281.

[8] J. Y. Choi *et al.*, "Evaluation of thermal/acoustic performance to confirm the possibility of coffee waste in building materials in using bio-based microencapsulated PCM," *Environmental Pollution*, vol. 294, p. 118616, 2022. doi:10.1016/j.envpol.2021.118616B.

[9] B. Sena da Fonseca, A. Vilão, C. Galhano, and J. A. Simão, "Reusing coffee waste in manufacture of ceramics for construction," *Advances in Applied Ceramics*, vol. 113, no. 3, pp. 159–166, 2013. doi:10.1179/1743676113y.0000000131

[10] E. Sel, İ. Düzova, A. E. Şireli, B. Yazıcı, and Z. Sü Gül, "Reuse of coffee waste and paper cups for acoustical panel applications in architectural studios," in INTER-NOISE and NOISE-CON Congress and Conference Proc., Aug. 2021, vol. 263, no. 3, pp. 3779–3789. doi: https://doi.org/10.3397/in-2021-2515.

[11] BS 354:2003. Acoustics-Measurement of sound absorption in a reverberation room.

[12] A. Jaramillo and C. Steel, Architectural Acoustics: Sound in Enclosed Spaces. Routledge, 2014. doi: https://doi.org/10.4324/9781315752846.