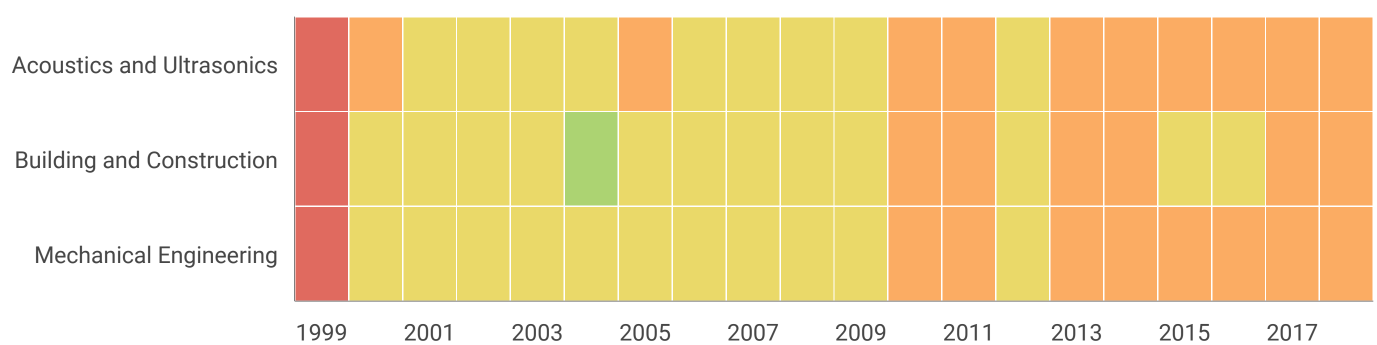
Building Acoustics

Country	United Kingdom - SIR Ranking of United Kingdom
Subject Area and Category	Engineering Building and Construction Mechanical Engineering Physics and Astronomy Acoustics and Ultrasonics
Publisher	SAGE Publications
Publication type	Journals
ISSN	1351010X
Coverage	1999-ongoing
	Join the conversation about this journal

21

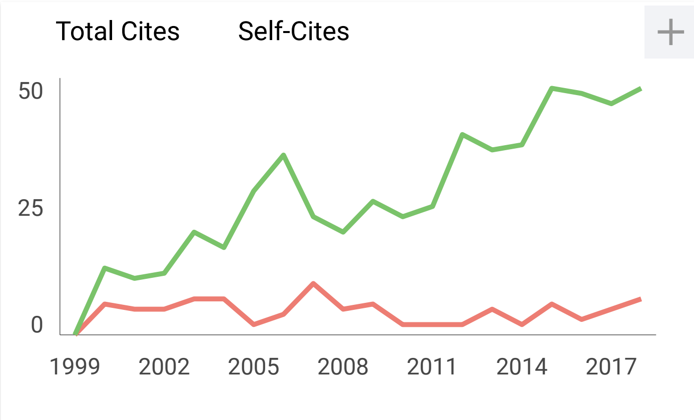
H Index

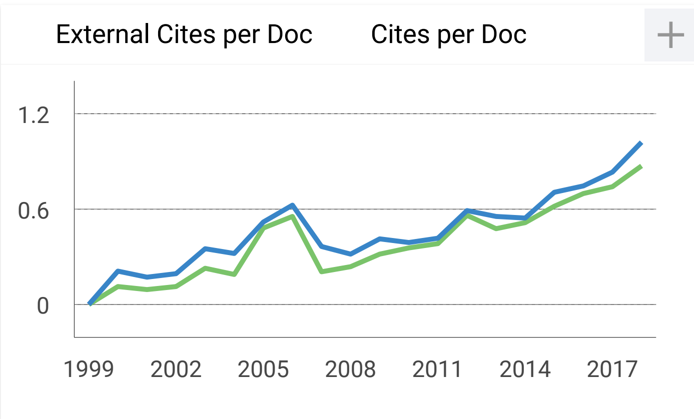
Quartiles

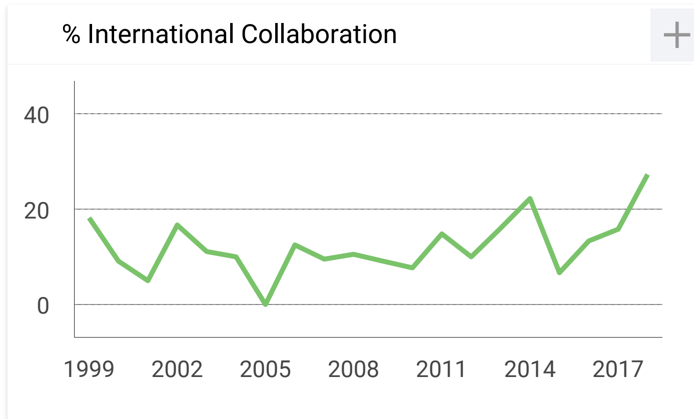


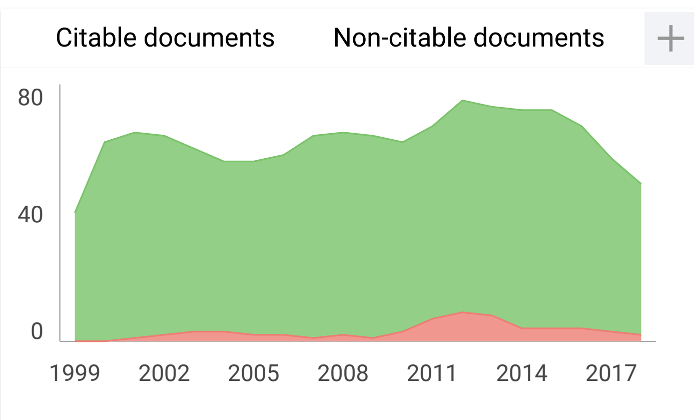
SJR

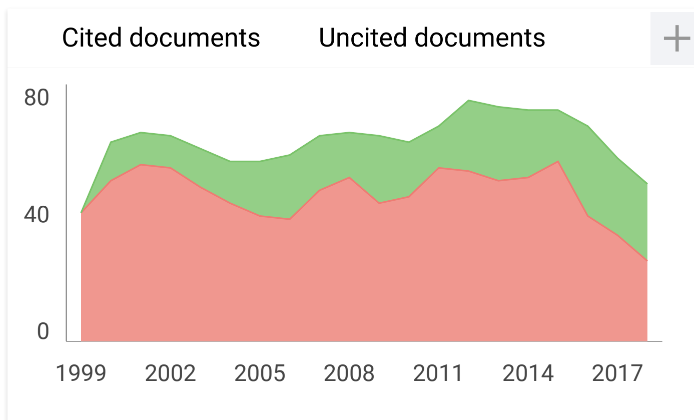
Citations per document

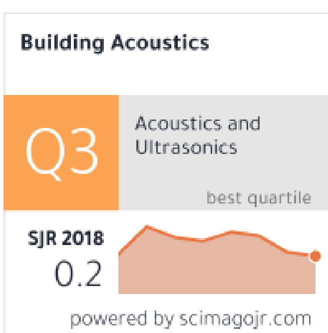








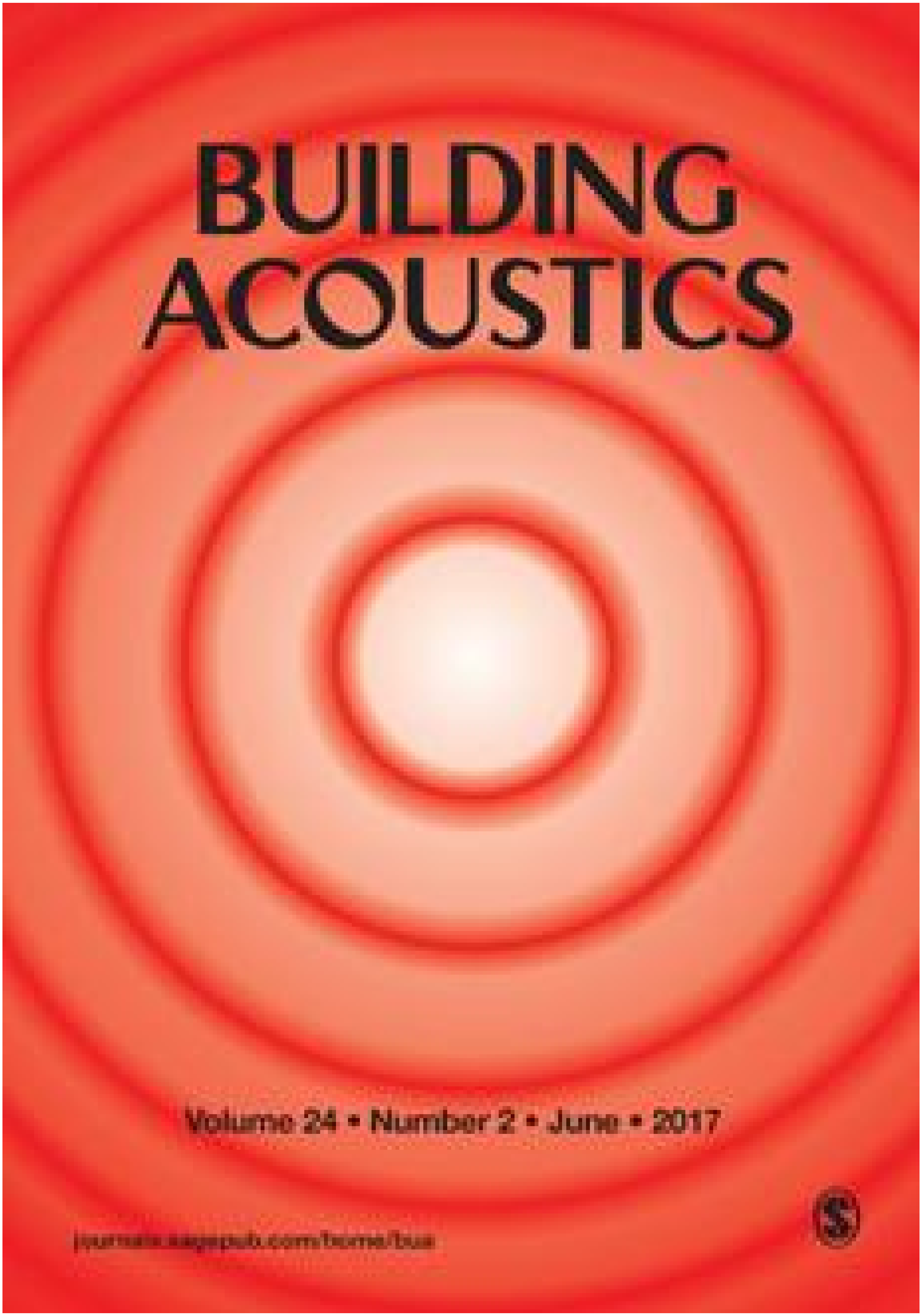




← Show this widget in your own website

Just copy the code below and paste within your html code:

<a href="https://www.scimag


BUILDING
ACOUSTICS
Volume 24 • Number 2 • June • 2017
journals.sagepub.com/home/bua

Building Acoustics

Editorial Board

Hide All

More about this journal

Description

Aims and Scope

Abstracting/Indexing

Submit Paper

Building Acoustics

Journal Description

Building Acoustics is a quarterly peer-reviewed journal concerned with acoustics in the built environment. The goal of the journal is to be the main publishing option for authors writing on building acoustics and related topics, as well as a forum to integrate the relevant research community of the field. Potential readers are scientists, consultants, engineers, architects, builders and representatives of public bodies carrying out research and development in the field of acoustical aspects of buildings. There is an emphasis on the application of new knowledge and the provision of information useful to the practitioner.

More about this journal

Aims and Scope

Editorial Board

Abstracting/Indexing

Submit Paper

Building Acoustics

Table of Contents

Volume 24 Issue 2, June 2017

Original Research

Enhancing egg cartons' sound absorption coefficient with recycled materials

Prasasto Satwiko, **Verza Dillano Gharata**, **Herybert Setyabudi**, **Fefen Suhedi**

First Published May 30, 2017; pp. 115–131

Abstract
> Preview

Original Research

BUILDING ACOUSTICS

Building Acoustics
1–17

DOI: 10.1177/1351010X17709986
journals.sagepub.com/home/bua
SAGE

Enhancing egg cartons' sound absorption coefficient with recycled materials

Prasasto Satwiko[1], Verza Dillano Gharata[1], Herybert Setyabudi[1] and Fefen Suhedi[2]

Abstract

Egg cartons have popularly been used as sound absorbers because they are inexpensive, easy to install and easily available. However, acoustic experts have demonstrated that egg cartons are bad sound absorbers. This study developed Enhanced Egg Carton – Dry and Enhanced Egg Carton – Wet using additional recycled materials (shredded rice straw paper, textile waste, 2-cm cut rice straws) to improve the cartons' sound absorption coefficient while retaining their original advantages. Enhanced Egg Carton – Dry and Enhanced Egg Carton – Wet were tested based on the ASTM C423-02 method of sound absorption measurement. Enhanced Egg Carton – Dry has a noise reduction coefficient of 0.6 and a sound absorption average of 0.59, while Enhanced Egg Carton – Wet has a noise reduction coefficient of 0.54 and sound absorption average of 0.54. The maximum sound absorption coefficients of Enhanced Egg Carton – Dry and Enhanced Egg Carton – Wet are, respectively, 0.77 at 500 Hz and 0.67 at 630 Hz. Enhanced Egg Carton – Dry has a sound absorption coefficient $\geqslant$0.5, between 315 and 2500 Hz, which makes it able to absorb sound energy of the lower to upper mid-range frequencies. With their high sound absorptivity at mid-range frequencies, Enhanced Egg Carton – Dry and Enhanced Egg Carton – Wet are suitable for mosques and auditoriums, where the human voice is the dominant noise source and where an inexpensive sound absorber is needed. The production of Enhanced Egg Carton – Dry and Enhanced Egg Carton – Wet is so simple that users can do it themselves using basic home tools.

Keywords

Egg carton, low cost, recycled material, rice straw, sound absorption

Introduction

Egg cartons have long been considered by the general public to provide good sound insulation and absorption. They have three main positive points, which make them popular as acoustic material; they are inexpensive, easy to install and easily available. Even in wealthy countries, where good acoustic materials are affordable, people still like using egg cartons for their sound insulation and

[1]Universitas Atma Jaya Yogyakarta, Yogyakarta, Indonesia
[2]Center for Research and Development of Housing and Settlements, Bandung, Indonesia

Corresponding author:
Prasasto Satwiko, Universitas Atma Jaya Yogyakarta, Babarsari 43, Yogyakarta 55281, Indonesia.
Email: satwiko@mail.uajy.ac.id

absorption needs, for example, in music studios and other non-acoustic critical rooms. In Indonesia, a developing country, egg cartons are widely used in low-cost music studios. Contrary to general public opinion, however, acoustics experts have shown that egg cartons are poor sound insulators and absorbers, backed up by laboratory tests, such as those done by Quintero Antonio.[1] Thus, egg cartons should not be used if good acoustic quality rooms are expected.

Correcting the public's view of egg cartons as good acoustic material is not easy. In Indonesia, for example, where acoustic material choice and availability are limited, egg cartons offer a simple, more realistic solution for sound absorption. To some degree, people do find empirically that egg cartons work as sound absorbers. The public also sees manufactured (commercial) acoustic materials as luxurious and only feasible for acoustically critical buildings such as concert halls and auditoriums. An ordinary manufactured acoustic panel (an acoustic panel on a hollow light metal frame attached to a wall with rock wool in the cavity) will add around US$ 10/m^2 to the wall cost, which is considered economically unnecessary for most building owners.

The fact that egg cartons are popular and can partially absorb sound makes them material with the potential of being improved further to a high-quality sound absorber which can compete with manufactured acoustic materials. This article reports research on enhancing the sound absorption coefficient of common Indonesian egg cartons, so they can become good sound absorbers. It was expected in this study that the enhanced egg cartons (EECs) would still keep the original advantages (inexpensive, easy to install and easily available) while having the same sound absorption quality as their manufactured counterparts. The EECs were not to change their original form and material properties. Moreover, in improving the egg cartons' sound absorption coefficient, recycled materials were used, which is in line with the present trend towards a greener earth. In the future, green noise absorbers which are environmentally friendly, degradable and recyclable might be preferable. A recent review by Asdrubali et al.,[2] for example, found that currently used acoustic materials are not sustainable (in terms of energy consumption and greenhouse gases emissions) and are harmful to human health. New materials are lighter and safer, and they enjoy more efficient technology.[3] It is hoped that this research will conclude the debate surrounding the sound absorption performance of egg cartons.

Literature review

Sound absorption of egg cartons

Indonesian egg cartons are made from recycled paper and are used to hold eggs during transportation to avoid cracking. Various used papers are mixed with water, blended to a pulp, moulded and dried. They are lightweight (70 g per piece, 60 kg/m^3) and crumble easily if they are exposed to water. Since they are intended for temporary egg holding only, they are left rough, which makes them not very aesthetically pleasing.

The acoustic performance of egg cartons has long been studied, with most studies finding that the cartons are neither good sound insulators nor good sound absorbers. The sound insulation capability of egg cartons is very low, so it should not be considered a sound insulator at all. However, Kassim and Goh, using a non-standardized test method, found that rock wool–filled egg cartons can block 14.42% of low frequencies, 13.01% of medium frequencies and 17.71% of high frequencies.[4] This study may be seen as an initial indication that if combined with rock wool, egg crates may have sound insulator value. A standardized measuring method, such as ASTM E90-09, can be adopted to obtain precise data.[5]

The egg cartons' sound absorption coefficient profile shows an unsmooth curvilinear line, which results in poor sound absorption distribution. This poor distribution can result in poor

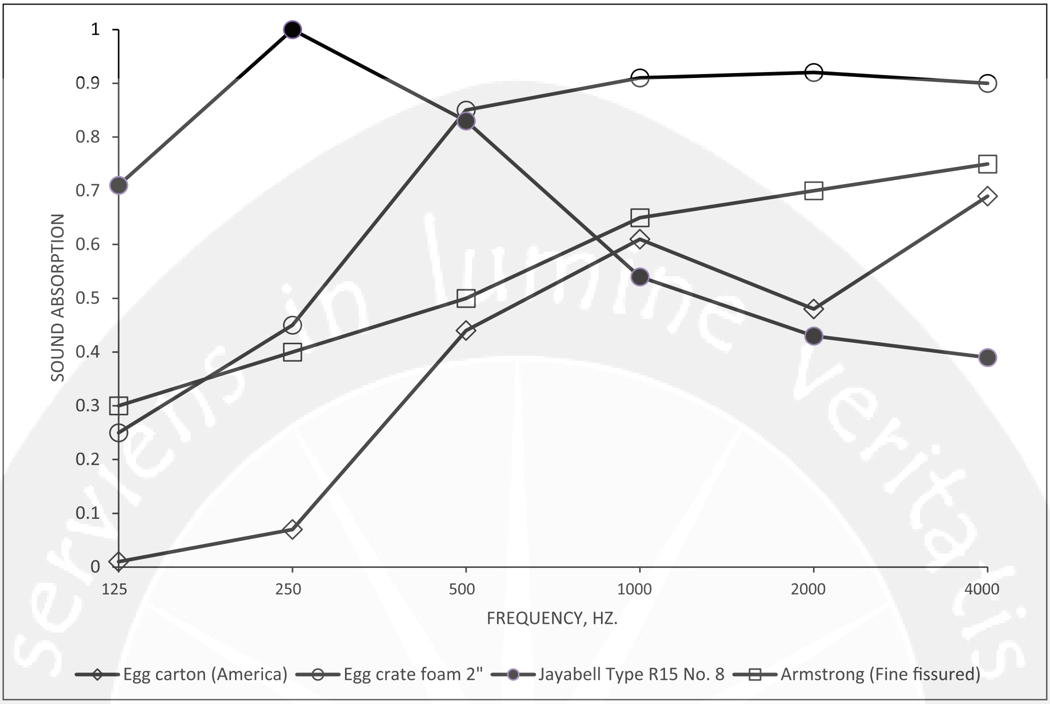


Figure 1. Comparison between a common American egg carton's sound absorption coefficient profile and other materials' profiles. Jayabell Type R15 No. 8 (see Figure 2) and Armstrong Type Fine Fissured (see Figure 3) are two popular acoustic materials in Indonesia.

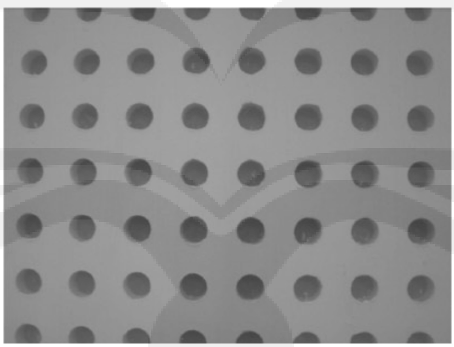


Figure 2. A common perforated gypsum board available in Indonesia, Jayabell Type R15 No. 8, with porosity 0.11 (15 mm diameter of holes), weight: 9.5 kg/m^2, thickness: 12 mm, density: 792 kg/m^3, 100-mm plenum filled with 80-mm mineral wool (density: 10.5 kg/m^3) and NRC: 0.77.[8] This board is usually applied on walls and is intended to absorb low- to mid-range frequencies.

music sound consistency. A study by Riverbank Acoustical Laboratories in 1988, published by *Acoustics First*, found that American egg cartons started absorbing sound above 250 Hz but dropped at around 2 kHz before rising up its absorption coefficient again to 0.8 at 5 kHz (Figure 1). The sound absorption capability of egg cartons (noise reduction coefficient (NRC)

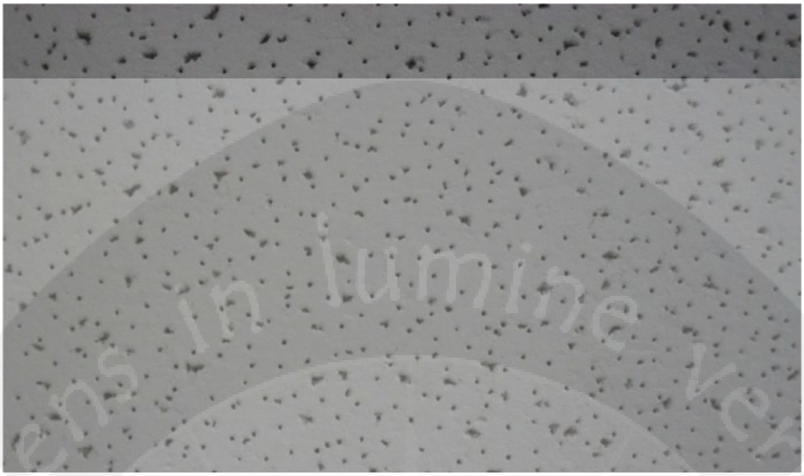


Figure 3. A common acoustic panel available in Indonesia, Armstrong Type Fine Fissured, weight: 3.5 kg/m^2, thickness: 15 mm, density: 233 kg/m^3, NRC: 0.60.[9] This panel is commonly used in ceilings and is intended to absorb mid- to high-range sound frequencies.

= 0.4) is not high enough to allow them to be called good sound absorbers.[6] Another study by Carvalho[7] found that an egg carton's NRC of 0.87 can be obtained by facing the surface normal to the sound direction, applying small apertures and placing absorptive polyurethane foam boards behind the cartons. However, the sound absorption coefficient profile of an egg carton in this case shows that it has an absorption peak of 0.98 at 630 Hz, down to 0.45 at 2000 Hz and up again to 0.62 at 5000 Hz. Thus, experts do not recommend egg cartons as sound absorbers.

A different result was obtained by Sim et al.[10] To make a low-cost, environmentally friendly sound absorber, they made a 20-mm panel from egg carton pulp. Using the tone burst method, they found an optimum NRC of 0.5, which minimally qualified the panel for sound absorption. The maximum sound absorption coefficient of 0.98 was achieved in the range of 1575–1675 Hz. This panel performed better than coir fibre and polyester absorbers. The recycled egg carton panel had a density of 226 kg/m^3 and a porosity of 0.64.

Sound absorption of recycled materials

The sound absorption capability of waste and industrial byproducts has been studied. Tea residue, cassava residue, coir and rice straw were studied, respectively, by Ersoy and Kucuk,[11] Sari,[12] Zulfian[13] and Mahzan et al.[14] The studied materials did not give a detailed or broad range of sound frequency. However, Table 1 shows that most of the materials absorb middle to upper mid-range sound, between 1000 and 4000 Hz, while the rice straw composite absorbs the upper bass (see Table 2.). The authors used compression tools and binding agents to create recycled sound absorbers.

Tea residue, cassava residue, coir and rice straw are some common wastes easily found in tropical countries such as Indonesia. These agricultural industry byproducts are abundantly available and are often left unused. Many efforts have been made to recycle them into usable products such as paper and sound absorption materials.

Table 1. Sound absorption of common waste.

Researcher	Material	Specification	Frequency (Hz)	Sound absorption coefficient (α)
Ersoy and Kucuk[11]	Tea residue	3.0-cm thick, with backing plate	500	0.12
			2500	0.44
			3500	0.55
			4500	0.60
			5500	0.65
Sari[12]	Cassava residue	1.4-cm thick, without backing plate	500	0.11
			800	0.21
			1000	0.36
			1200	0.62
			1300	0.88
			1400	0.62
			1600	0.55
Zulfian[13]	Coconut fibre (coir)	2.0-cm thick, 150 kg/m^3	500	0.23
			1000	0.86
			2000	0.97
			4000	0.81
Mahzan et al.[14]	Rice straw composite	2.5 cm, 25% rice straw in polyurethane	250	0.82
			500	0.60
			1000	0.50
			2000	0.20

Table 2. Sound frequency spectrum.

Bass (Hz)		Mid range		High (kHz)	
20–300		300 Hz–5 kHz		5–20	
20–40	Deep bass	300 Hz–600 Hz	Lower mid range	5–10	High end
40–80	Low bass	600 Hz–1.2 kHz	Middle mid range	10–20	Extreme high end
80–160	Mid bass	1.2 kHz–2.4 kHz	Upper mid range		
160–300	Upper bass	2.4 kHz–5 kHz	Presence range		

Enhancing sound absorption of egg cartons

The literature contains no previous record of the common Indonesian egg carton being tested for its sound absorption coefficient. These egg cartons have the following features which determine their responses to sound:

1. They are made of recycled paper pulp, which forms light, micro-porous cartons approximately 2-mm thick. The micro-pores give the egg cartons the potential to absorb sound energy from the upper mid-range to high frequencies, as porous materials tend to absorb these frequency ranges.[15,16]
2. The grooved form of the egg cartons means that a square metre section of the carton contains more material than just 1 m^2. This increases the amount of absorbed sound energy.[17]
3. The grooved form of the egg cartons creates cavities between the cartons and the walls and between the egg cartons themselves (in cases of two-layered egg cartons). Cavities can

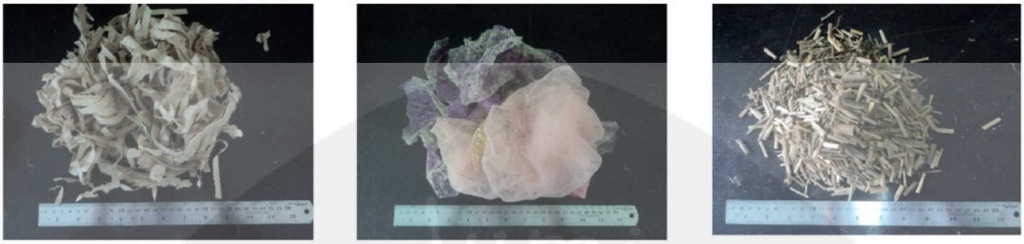


Figure 4. Recycled materials for egg carton fillers.

attenuate sound energy by converting it into heat and damping it. Inside a cavity, sound bounces and gradually reduces its energy; each time it hits the cavity's interior wall, its energy is partially absorbed.[18,19]

This research focused on the use of rice straw, textile waste and rice straw paper to fill the egg cartons (Figure 4). Rice straw is the vegetative part of rice (*Oryza sativa* L.) which is usually cut at or after the grain harvest. This rice industry byproduct is usually burned or wasted, although there are some efforts to recycle it, for example, for mushroom growth media, livestock feed, compost, handicrafts, and light concrete blocks. Annually, Indonesia produces 9% of the world's rice and 20 million tons of rice straw as waste. Rice straw consists of cellulose (39%), hemicellulose (27%), lignin (12%) and ash (11%). Its density is 75 (loose) to 100 kg/m^3 (compacted), and its porosity is 71.21%–85.28%.[20] It is resistant to bacterial decomposition, which makes it suitable as a building material. Textile waste is the waste of the garment industries, and it is usually recycled into patchworks (e.g. bed covers and carpets) when it can still be stitched. Otherwise, it is disposed of or burnt. Textile waste is also used as room partition filler for sound insulation and absorption. Rice straw paper originated from China, Korea, Japan and Vietnam was initially used for writing, painting and room partition. In daily life, the term 'rice straw paper' is used for paper made from rice straw and bamboo. This research used rice straw paper made from rice straw. Rice straw paper has a rough surface and pores and absorbs water as well as oil. This paper is commonly used for wrapping bread and absorbing the excess oil from fried food.

Two EECs were prepared, namely, Enhanced Egg Carton – Dry (EEC-D) (dry processed) and Enhanced Egg Carton – Wet (EEC-W) (wet processed) (Figure 5). The dry process used small net bags (50% shredded rice straw paper and 50% textile waste) to hold recycled materials (Figures 6 and 7). These small net bags were inserted into the cavities between two egg cartons, which were attached to each other on their undersides. The wet process involved the use of a binding agent, a mixture of calcium oxide (CaO) and tapioca, in the proportion of 1:4, to bind the 2-cm cut rice straws (Figures 8 and 9).

The mixture of calcium oxide and tapioca was chosen as the binding agent, as it is light and hard and not easily broken when dry. This binding agent was lightly mixed with cut rice straw, creating random pores and air cavities when dry, which acted as sound energy absorbers. The EEC-W cartons were sun-dried.

Most of the aforementioned recycled materials absorb well the mid-range to high frequencies. Enhancing the low sound absorption capability of egg cartons is more difficult, as they need membrane-like features, such as those found in a bass trap. Alternatively, a low sound frequency can be absorbed by creating a space, at least one-fourth the wavelength of the frequency, between the

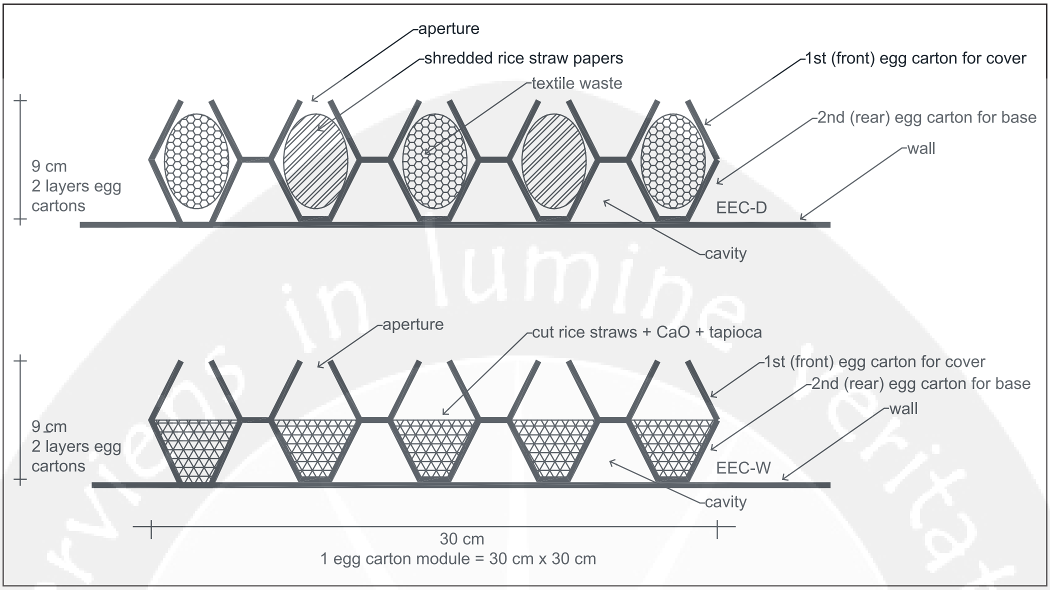


Figure 5. Sections of EEC-D and EEC-W 'sandwiches'.

Figure 6. EEC-D was made by filling the egg carton with shredded rice straw paper (light brown colour) and textile waste (various colours) in small net bags. The proportion of shredded rice straw paper and textile waste was 1:1.

absorber and the wall.[21] However, considering that the EECs should be kept simple, providing a space behind them is not recommended. Doubling the egg cartons will create 9-cm thickness and create 9-cm cavities between the peaks of the egg cartons and the walls. Filling the cavities with recycled fibrous materials, thus, 9-cm-thick, will enhance the low sound frequency absorption.[18] The peaks of the niches are cut to form small holes (apertures), which trap the sound energy and

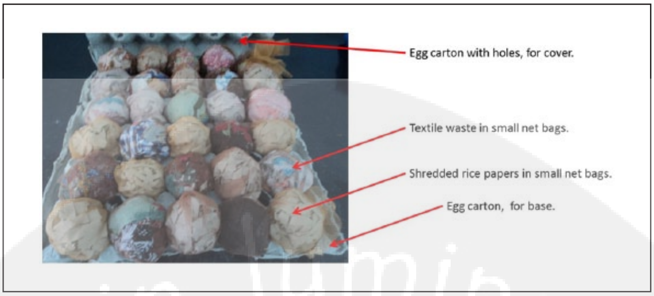


Figure 7. EEC-D before closure.

Figure 8. EEC-W was made by filling the egg carton's niches with 2-cm cut rice straw bound by a mixture of CaO and tapioca. The proportion of CaO and tapioca was 1:4.

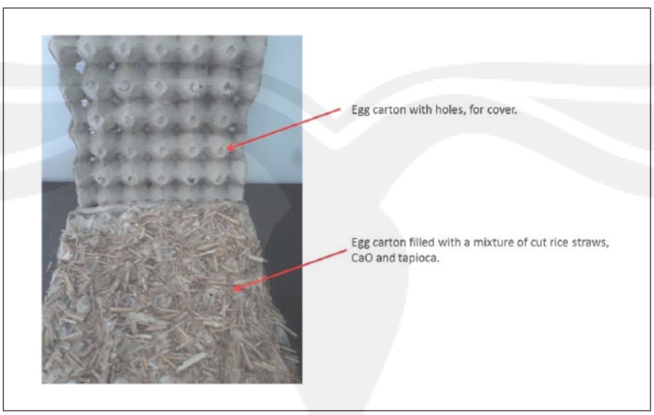


Figure 9. EEC-W before closure.

allow it to be absorbed by the recycled materials (Figure 10). These small apertures trap sound waves in the egg cartons' cavities and convert the sound waves' energy to heat.

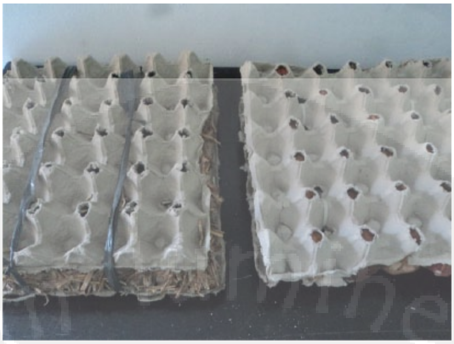


Figure 10. Small apertures were created on the covers of the EEC-D (right) and EEC-W (left). These apertures were intended to trap the sound energy. The ugly appearance of the 'sandwich-like' EEC-D and EEC-W can easily be improved by covering them with textiles to match the interior design of the room.

The EEC-D cartons contained shredded rice straw paper and textile waste at a ratio of 1:1. Since an egg carton has 30 niches, 15 niches were filled with shredded rice straw paper, and 15 were filled with textile waste, all in small net bags. The niches of the EEC-W cartons were filled with a mixture of CaO, tapioca and 2-cm cut rice straw when the binding agent was still liquid.

Applications

As was its original intention, EEC is applied in buildings or rooms where the budget for acoustic treatment is very limited. In Indonesia's context, examples of such buildings include modest churches, mosques, public school auditoriums and rental music studios (Table 3). Among these examples, mosques are unique, since the only source of sound inside these buildings is the human voice, the use of musical instruments in mosques being forbidden.

Indonesia is not an Islamic country, but 85% of its 250 million population are Muslims. Thus, there are more than 850,000 mosques in Indonesia, spread out all over the country. Surprisingly, acoustics have not been a dominant consideration in mosque design, even though people do feel that there is a serious acoustic problem. Bad speech clarity is a major issue together with outdoor noise penetration. There has not yet been any in-depth study of Indonesian mosque acoustics. Indonesian mosque acoustics might be unique, as Indonesia is not an Arabic-speaking country, and only 0.5% of its Muslims can read Arabic. Thus, in terms of Arabic speech, the need for mosque acoustic that can provide clarity might not be too crucial.

Most of Indonesia's roughly 56,000 churches also suffer from bad acoustics. Even in new churches with relatively sufficient budgets, the acoustic aspects are not really considered when the churches are still in the design stage. Church management usually seeks acoustic help when their churches have started services and they realize that the acoustics are disastrous; their congregations can hardly hear the sermon and only hear chaotic music. For most churches, however, a limited budget is the biggest problem as they are built with their small congregations' donations.

School auditoriums also usually have bad acoustics. (What is commonly called an auditorium in Indonesia is usually just a hall or a large room with a roof and walls and no acoustic treatment at all.) Having unavailable budget is also a common major reason for this. However, a lack of understanding of acoustics also contributes to bad acoustics. Public school auditoriums are usually for multipurpose use. They host various activities such as sports, music performances, bazaars and seminars. People are not usually concerned about an auditorium's acoustics until they find that they

Table 3. Rooms targeted for EEC applications.

	Churches	Mosques	School auditoriums	Rented music studios
Sound sources	Human voices (sermon, songs, choir); music instruments	Human voices (sermon, recitation)	Human voice (speech, cheering, singing, shouting); music instruments; sports gear and their impact on walls and floor	Human voice (singing, speech); music instruments
Sound receiver	Human ears; microphones for indoor loudspeakers and recording	Human ears; microphones for indoor and outdoor loudspeakers	Human ears; microphones for indoor loudspeakers	Human ears; recording microphones
Sound character	Soft gospel music to gospel full orchestra and electric bands	Soft 'nasal' voice	Soft to hard (heavy metal music)	Soft to hard (rock bands)
Expected frequent sound frequency range	125 Hz–8 kHz	500 Hz–4 kHz	125 Hz–8 kHz	20 Hz–20 kHz for acoustic instruments (electronic music instruments can be directly connected to the recording system)
Standard reverberation time	1.4–2.0 s for conservative churches (dominated by acoustic instruments); 0.8–1.2 s for contemporary churches with electric band	No standard yet	1.5–1.8 s	0.3–0.7 s
Mechanical impact on walls	Low	Low	High	Low

Since it is intentionally dedicated to higher sound quality, a concert hall is considered acoustically critical, is subject to a high acoustic design standard and needs precision materials. Thus, a concert hall is not targeted for the enhanced egg carton application.

cannot hear what a speaker says during a seminar. There are roughly 12,500 senior high schools in Indonesia which are supposed to have auditoriums with reasonable acoustic quality, but as yet, there is no available data on their acoustic quality. The reverberation time (RT_{60}) of an ordinary auditorium can reach as high as 6 s, which makes talking unclear and music noisy. Large unfurnished rooms with ceramic floors, plastered brick walls and gypsum ceilings are responsible for this long reverberation time.

Interior design preference also contributes to a lack of acoustic treatment. The limited choice of acoustic materials discourages architects (and interior designers) from applying them as interior elements. Available acoustic materials are relatively expensive and aesthetically uninteresting. The latter leads to the architects not wanting to have their interiors dominated by aesthetically boring materials. If absorptive surfaces are needed, the architects usually limit the areas of those surfaces.

Methods

This study used both a literature and an experimental method. The literature review explored the advantages and disadvantages of egg cartons as sound absorbers. The experiment was conducted at the Acoustic Laboratory at the Center for Research and Development of Housing and Settlements, Bandung. It was divided into two sub-experiments. The first sub-experiment was performed to obtain the sound absorption coefficient profile of common Indonesian egg cartons bought at an ordinary market. The second sub-experiment was conducted to obtain the sound absorption coefficient profile of the improved egg cartons, that is, EEC-D and EEC-W.

The experiment in Bandung used the ASTM C423-02 and International Organization for Standardization (ISO) 354 methods of sound absorption measurement.[22,23] It was conducted in a 135.07-m^3 sound-insulated concrete chamber with no parallel surfaces. A Brüel & Kjær two-channel building acoustic system was used, which consisted of an omnidirectional speaker type 4292, a power amplifier type 2734, an omnidirectional microphone type 4189, and a two-channel hand-held analyser type 2270. The microphone was calibrated using a calibrator type 4231. The omnidirectional speaker generated pink noise up to 110 dB. The microphone was used to measure the reverberation time at five locations. For each measuring location, 10 measurements were taken and were averaged. The sound absorption measurement of the common Indonesian egg cartons was taken in two steps: the first step without egg cartons and the second with 5.6-m^2 egg cartons placed on the floor. Each egg carton was 30 cm × 30 cm and was 4.5-cm thick. A total of 63 egg cartons were used to compose the 5.6-m^2 egg cartons. For EEC-D and EEC-W, the number of egg cartons was doubled, as they consisted of double-layered egg cartons. The NRC was calculated by averaging the absorption coefficients of frequency 250, 500, 1000 and 2000, while sound absorption average (SAA) was calculated by averaging the 12 one-third octave bands from 200 to 2500 Hz, respectively.

The sound absorption coefficients of the shredded rice straw paper, textile waste and rice straw were measured using a BSWA Tech impedance tube. It consists of two tubes (10 cm diameter for 50–1600 Hz and 3 cm diameter for 1000–6100 Hz), an MC3242 four-channel data acquisition and a PA50 amplifier.

The Sabine and Eyring-Norris formulas of reverberation time were used to calculate the sound absorption coefficients of EEC-D and EEC-W.[24–26]

Sabine's reverberation formula is as follows

$$T_{60} = \frac{0.161\,\mathrm{V}}{A + 4\,\mathrm{mV}} \tag{1}$$

$$A = \alpha S \tag{2}$$

where V is the room volume (m^3), A is the total room sound absorption (m^2), α is the Sabine sound absorption coefficient, S is the total surface area (m^2) and m is the constant of air sound absorption, as mentioned in ISO 9613-2.[27]

Eyring-Norris' reverberation formula is as follows

$$T_{60} = \frac{0.161\,\mathrm{V}}{A' + 4\,\mathrm{mV}} \tag{3}$$

$$A' = -S\left[\ln\left(1 - \alpha'\right)\right] \tag{4}$$

where α' is the Eyring sound absorption coefficient.

The Sabine formula is commonly used to determine the sound absorption coefficient, although it is not very accurate for highly sound absorptive materials. The Eyring-Norris formula is used to improve the accuracy. As guided by ASTM C423-02 and ISO 354, the calculation of the sound absorption coefficient can be done in a reverberant room. The total room sound absorption, A, can

Table 4. NRC and SAA.

	NRC	SAA
Common Indonesian egg cartons	0.32	0.33
EEC-D	0.60	0.59
EEC-W	0.54	0.54
Jayabell Type R15 No. 8	0.70	–
Armstrong Type Fine Fissured	0.50	–

be calculated using equation (1). The sound absorption value of the sampling material is the difference between the total sound absorption of the empty room and the one with sampling materials in it. Using equation (2), α can be found. The Eyring total room sound absorption, A', can be calculated using equation (4). Since $A = A'$, α' can be calculated using equation (5)

$$\alpha' = 1 - e^{-\alpha} \tag{5}$$

Results and discussion

The first experiment found that common Indonesian egg cartons have an NRC of 0.32 and a SAA of 0.33, which proves that they are not good absorptive materials (Table 4). However, with their highest sound absorption coefficient of 0.58 at 800 Hz (Figure 11), which is in the middle mid range (Table 2), the egg cartons do partially absorb sound energy in that narrow frequency range. Thus, covering a room's hard surfaces, such as plastered walls, with a large proportion of common Indonesian egg cartons will still lower the room's reverberation time in that narrow frequency range. This effect can give the impression to the general public that egg cartons are sound absorbers.

The second experiment found that EEC-D and EEC-W had higher sound absorption coefficients than common egg cartons at all frequencies (Figure 10). EEC-D and EEC-W, respectively, have an NRC of 0.60 and 0.59, which means that both materials can be considered sound absorbers. EEC-D has a slightly higher sound absorption coefficient than EEC-W at all frequencies, which makes it slightly better than EEC-W. EEC-D and EEC-W have maximum sound absorption coefficients of 0.77 at 500 Hz and 0.76 at 630 Hz, respectively, which are relatively close points. Their absorption coefficient curves are also similar. EEC-D has a sound absorption coefficient above 0.5 from 315 to 2500 Hz and EEC-W from 400 to 2000 Hz. Thus, both materials absorb lower mid-range to upper mid-range frequencies.

Figure 11 shows that EEC-D has a better upper bass absorption (160–300 Hz) than the common egg carton. This confirms Vigran's[18] statement that filling cavities with a porous absorber improves the lower sound frequency absorption. EEC-W's cavities were not fully filled with a porous material, which resulted in its upper bass absorption being lower than that of EEC-D.

Shredded rice straw paper, textile waste and cut rice straw have sound absorption coefficients >0.5 above 500 Hz. However, as seen in Figure 11, EEC-D and EEC-W can only take a small advantage of that potential. EEC-D and EEC-W only have a 0.1 higher sound absorption coefficient than the common egg carton above 2000 Hz, where both the EECs have around a 0.5 sound absorption coefficient, a minimum standard for a sound absorber.

Figure 12 compares common egg cartons, EEC-D and EEC-W, with two commercial acoustic panels. The common egg cartons cannot compete with the Jayabell Type R15 No. 8 (absorbing sound below 1 kHz) or the Armstrong Type Fine Fissured (absorbing above 1 kHz). However,

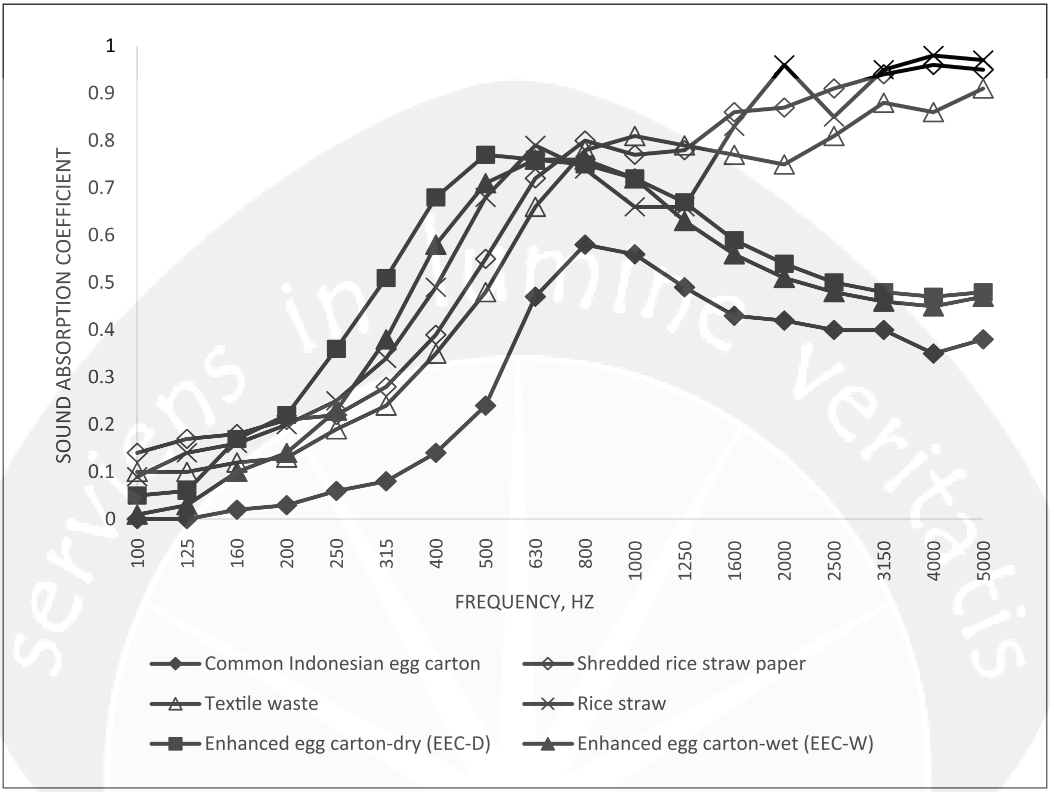


Figure 11. Sound absorption coefficient of common Indonesian egg cartons, EEC-D and EEC-W.

enhancing these egg cartons improves their sound absorption performance. EEC-D has sound absorption higher than Jayabell from around 630 to 4000 Hz and higher than Armstrong between 315 and 1250 Hz.

It is clearly shown in Figure 12 that EEC-D and EEC-W need improvement in absorbing the sound of frequencies below 500 Hz and above 1500 Hz if they are to compete with both manufactured acoustic materials. Referring to Table 1, coconut fibre (coir) can be added proportionately to EEC-D to improve the sound absorption of frequencies above 1500 Hz. Meanwhile, to improve the sound absorption of frequencies below 500 Hz, rice straw–polyurethane composite is a good candidate, although it will increase the price of EEC-D. A litre of polyurethane currently costs US$ 10.

Table 4 compares the NRC of the common Indonesian egg cartons, EEC-D and EEC-W, with the two manufactured acoustic panels. EEC-D has the highest NRC at 0.6 and SAA at 0.59 and therefore is, by definition, a sound absorber. Meanwhile, EEC-W has an NRC of 0.54 and SAA of 0.54. However, Table 4 should be used together with Figure 12, which shows that EEC-D's highest sound absorption coefficient is at 500 Hz.

From an acoustic point of view, EEC-D and EEC-W can be considered suitable for mosques and school auditoriums, thanks to their high-efficiency sound absorption at the middle mid range (Table 3). In these two types of buildings, hard surfaces will create long reverberation times for the dominant middle mid-range human voices and will create bad acoustic performance. EEC-D and EEC-W are able to shorten the reverberation time of the middle mid range and will enhance the quality of the room acoustics. For churches and music rooms, where the sound spectrum is broader,

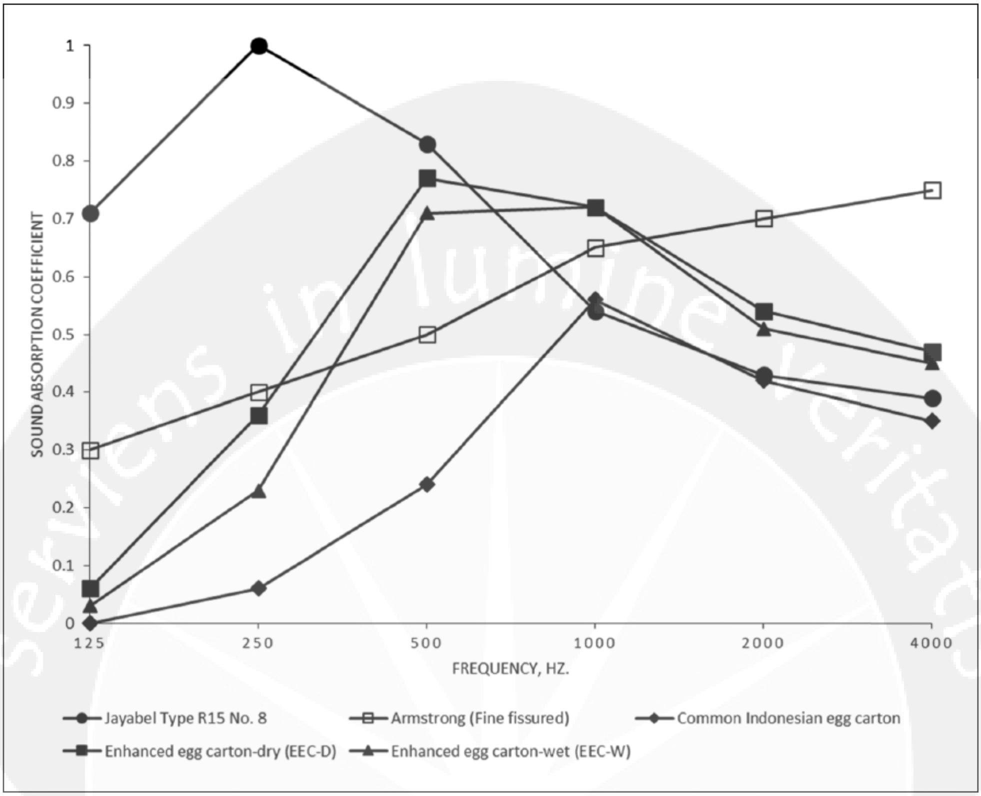


Figure 12. Sound absorption coefficient profiles of three egg cartons and two manufactured acoustic panels.

applying EEC-D or EEC-W should be done carefully, since it can result in too much absorption of the middle mid range, which creates an unbalanced sound.

The density of common Indonesian egg cartons, Jayabell, Armstrong, EEC-D, and EEC-W are, consecutively, 60, 792, 233, 63 and 122 kg/m^3. Seddeq[28] lists factors influencing sound absorption: fibre size, airflow resistance, porosity, tortuosity, thickness, density, compression, surface impedance, placement/position of sound absorptive and performance of sound-absorbing materials. Seddeq states that less dense materials absorb low frequencies (500 Hz), while denser materials absorb frequencies above 2000 Hz. EEC-W is denser than EEC-W. However, EEC-W and EEC-D have similar sound absorption coefficient curves and absorb lower mid-range to upper mid-range frequencies (315–2500 Hz). EEC-W is denser than EEC-W. The finding that EEC-W does not absorb more high sound frequencies than EEC-D might be caused by the loose bond between egg cartons and the fillers. This phenomenon needs further study to explain.

The experiments offer some other facts, as well, as follows.

1. EEC-D and EEC-W could easily be made using tools available at home, such as scissors, knives and a stove. This gives EEC-D and EEC-W the potential to be used in home industries.
2. EEC-D requires more time to put shredded rice straw paper and textile waste into small bags. It took 5 min to make one EEC-D module or 45 min for nine modules (1 m^2).

3. EEC-W requires more time to dry under the sun. It took 2 sunny days to make the EEC-W crispy dry. During cloudy and rainy days, it took 5 days for EEC-W to be dried using electric blowers.
4. EEC-W contains tapioca, which might attract insects.
5. EEC-D and EEC-W have not been tested as fire hazards. The nature of their recycled materials may mean that they are easily burned. A fire-resistant substance can be applied, but it will add to the cost. In climates where heaters are not needed, such as in Indonesia, the fire risk may be lower.
6. EEC-D and EEC-W have not been tested for mechanical impact endurance. Placing them on the upper parts of walls, 1.6 m above the floor, might avoid mechanical impacts from occupants' activities.
7. Used egg cartons are usually dirty and cannot be easily cleaned. Fabrics can be freely chosen to cover EEC-D and EEC-W without hampering their sound absorption performance.
8. In terms of cost, EEC-D and EEC-W have a much lower cost than manufactured acoustic panels. During the experiment, it was calculated that the cost of EEC-D and EEC-W was around US$ 2.00/m^2 and US$ 2.50/m^2, respectively. Both costs are for installed EEC-D and EEC-W. As a comparison, a manufactured acoustic panel (brand: Armstrong Type Fine Fissured, on hollow light metal frame), with an NRC of 0.6 and cost of US$ 10.00/m^2. All prices include labour costs. The lower costs of EEC-D and EEC-W are possible because the greatest portion of the materials, the recycled materials, can be obtained for free or at very low prices; textile waste and rice straw, the byproducts of garment production and rice fields are usually wasted.

Conclusion

This study has proven that through the use of free or inexpensive recycled materials (shredded rice straw paper and textile waste) and adopting low technology, common Indonesian egg cartons can be enhanced to become sound absorbers with an NRC of 0.6 and SAA of 0.59. The EEC-D absorbs more than 50% of sound energy from 315 to 2500 Hz or in the lower mid-range to upper mid-range frequencies. Although the study result is not as good as was expected at the beginning of the research (i.e. finding an acoustic material which was better than manufactured sound absorbers), the resulting EEC-D is a promising sound absorber to be used in situations where resources are limited and critical acoustic requirements are not mandated.

EEC-D needs further development to compete with manufactured acoustic materials produced by sophisticated technology. The better performance of EEC-D in absorbing the sound energy of lower mid-range to upper mid-range frequencies than that of the other two manufactured acoustic materials means that it can be regarded as a replacement for those two materials, particularly where sound frequencies at those ranges need to be absorbed, such as in buildings where human voices are the main noise sources. Further research is needed to improve the EEC-D's sound absorption coefficients for frequencies below 500 Hz and above 1500 Hz. For EEC-D, that future research can be more focused on finding the proportion of shredded rice straw paper, textile waste, coconut fibre (coir) and rice straw–polyurethane composite. However, to make it practical, further research into the fire safety, endurance and aesthetics issues of EEC-D is needed. EEC-D is also particularly promising from a sustainable points of view, so further research involving life cycle analysis can be conducted to investigate various alternate materials.

Declaration of conflicting interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship and/or publication of this article.

Funding

The author(s) disclosed receipt of the following financial support for the research, authorship, and/or publication of this article: This research is partially sponsored by the Universitas Atma Jaya Yogyakarta (UAJY), through Lembaga Penelitian dan Pengabdian kepada Masyarakat (LPPM); preparation space provided by the Laboratory of Architecture Technology Planning and Design of UAJY and the Center for Research and Development of Housing and Settlements (Bandung); and the monthly financial support provided by the Directorate-General of Higher Education of Indonesia, through the Lecture Certification Program (number 08234403106).

References

1. Antonio QR. Measurement of the sound-absorption coefficient on egg cartons using the tone burst method. In: *Proceedings of the 11th WSEAS international conference on Acoustics & music: theory & applications*, Iasi, 13–15 June 2010.
2. Asdrubali F, Schiavoni S and Horoshenkov KV. A review of sustainable materials for acoustic. *Build Acoust* 2012; 19(4): 283–310.
3. Ravandi M, Mardi H, Langari A, et al. A review on the acoustical properties of natural and synthetic noise absorbents. *Open Access Lib J* 2015; 2: 1–11.
4. Kassim U and Goh J. Recycle materials as Industrialised Building System (IBS) internal partition. *J Built Environ Technol Eng* 2016; 1: 330–334.
5. Kassim U and Goh J. *Standard test method for laboratory measurement of airborne sound transmission loss of building partitions and elements*. West Conshohocken, PA: ASTM International, 2016.
6. Kassim U and Goh J. Acoustic myths & realities: can egg carton be used as an acoustical treatment? Available at: http://www.acousticsfirst.com/eggc.htm (accessed 20 November 2016).
7. Carvalho APO. Sound absorption of egg boxes and trays. In: *Proceedings of internoise 2015*, San Francisco, CA, 9–12 August 2015.
8. Sim J, Zulkifli R, Tahir M, et al. *Jayabell noise absorption plasterboard*. Jakarta, Indonesia: Jayaboard (under Lafarge Boral Gypsum), 2017.
9. Sim J, Zulkifli R, Tahir M, et al. *Fine fissured*. Lancaster: Armstrong Building Products, 2017.
10. Sim J, Zulkifli R, Tahir M, et al. Recycled paper fibres as sound absorbing material. *Appl Mech Mater* 2014; 663: 459–463.
11. Ersoy S and Kucuk H. Investigation of industrial tea-leaf-fibre waste material for its sound absorption properties. *Appl Acoust* 2009; 70(1): 215–220.
12. Sari NP. *Pengukuran Karakteristik Akustik Ampas Singkong sebagai Bahan Penyerap Bunyi dengan Metode Tabung Impedansi Dua Mikropon*. Surakarta, Indonesia: Fakultas Matematika dan Ilmu Pengetahuan Alam, Universitas Sebelas Maret Surakarta, 2009.
13. Zulfian MSP. Kajian tentang Kemungkinan Pemanfaatan Bahan Serat Ijuk sebagai Bahan Penyerap Suara Ramah Lingkungan. *Rekayasa Kimia dan Lingkungan* 2009; 7(2): 94–98.
14. Mahzan S, Zaidi A, Ghazali M, et al. Investigation on sound absorption of rice-husk reinforced composite. In: *Proceedings of the Malaysian technical universities conference on engineering and technology*, Kuantan, Malaysia, 20–22 June 2009.
15. Kinsler LE, Frey AR, Coppens AB, et al. *Fundamentals of acoustics*. New York: John Wiley & Sons, 2000.
16. Allard J and Atalla N. *Propagation of sound in porous media*. Chichester: John Wiley & Sons, 2009.
17. Long M. *Architectural acoustics*. Amsterdam: Elsevier, 2006.
18. Vigran TE. *Building acoustics*. London: Taylor & Francis, 2008.
19. Everest FA and Pohlmann KC. *Mater handbook of acoustics*. New York: McGraw-Hill Education, 2009.
20. Zhang Y, Ghaly A and Li B. Physical properties of rice residues as affected by variety and climatic and cultivation conditions in three continents. *Am J Appl Sci* 2012; 9(11): 1757–1768.
21. Kuttruff H. *Room acoustics*. London: Elsevier, 2000.
22. Kuttruff H. *Standard test method for sound absorption and sound absorption coefficients by the reverberation room method*. West Conshohocken, PA: ASTM International, 2002.

23. Kuttruff H. *ISO 354:2003 acoustics – measurement of sound absorption in a reverberation room*. Geneva: International Organization for Standardization, 2003.
24. Cox TJ and D'Antonio P. *Acoustic absorbers and diffusers*. London: Spon Press, 2004.
25. Beranek LL. Analysis of Sabine and Eyring equation and their application to concert hall audience and chair absorption. *J Acoustic Soc Am* 2006; 120(3): 1399–1410.
26. McGrory M, Cirac DC, Gaussen O, et al. Sound absorption coefficient measurement: re-examining the relationship between impedance tube and reverberant room methods. In: Proceedings of acoustics 2012 Fremantle, Freemantle, WA, Australia, 21–23 November 2012.
27. McGrory M, Cirac DC, Gaussen O, et al. *ISO 9613-2:1996(en) acoustics – attenuation of sound during propagation outdoors – part 2: general method of calculation*. Geneva: International Organization for Standardization, 1996.
28. Seddeq HS. Factors influencing acoustics performance of sound absorptive materials. *Aust J Basic Appl Sci* 2009; 3(4): 4610–4617.