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Research Article

Acoustical Analysis of Insertion Losses of Ceiling Materials

Enobong Patrick Obot[1*], Rufus Chika Okoro[2], Daniel Effiong Oku[2], Christian Nlemchukwu Nwosu[1], and Michael Ugwu Onuu[1]

[1]Department of Physics, Alex Ekwueme Federal University Ndufu-Alike, Ebonyi State, Nigeria
[2]Department of Physics, University of Calabar, Cross River State, Nigeria

Abstract: This study concentrates on measuring, analyzing and recommending the ceiling materials most suited for the reduction of distinct frequency noise levels with focus on rain noise. A frequency analyzer has been used to measure and obtained accurate sound level (L_p) data of the rain noise outside, and inside five buildings with diverse acoustical ceiling materials in South Eastern Nigeria. It was done with and without the ceiling partition (or noise barrier) for the audio and narrow frequency band without contribution from other outdoor-related noise sources. Insertion losses of the ceiling materials were calculated using the data obtained from the measured L_p. Result obtained from the analysis indicated that the ceiling material found to effectively reduce the noise levels from external noise source. The type for speech reception threshold frequencies of more than 125 Hz and higher audiometric range was moabi wood with peak L_p of 21.20 dB at 500 Hz. While for lower frequencies where the ears are least responsive was plaster of Paris (POP) with peak L_p of 12.61 dB at 62.5 Hz. This makes "moabi wood" most suitable in lecture rooms, conference halls and large auditoriums as ceiling material, in consideration of its capability to provide notable attenuation of rain noise within the building. This is in accordance with several other studies done on this subject. In general, at much low frequencies and frequencies greater than 2k Hz significant reduction in the rain noise level was observed.

Keywords: Sound Enclosure, Acoustic Insertion Loss, Sound Pressure Level, Acoustic Ceiling Material, Frequency Analyser.

1. INTRODUCTION

The world is really noisy. Individuals are exposed to sounds twenty-four hours per day, seven days per week, twelve months per year – sounds they do not need, desire, or profit from. Every person continually fantasizes about living in a pleasant environment free of annoying noises [1]. Workers in loud industrial sites are subjected to continuous noise over the course of the workday. This unease could prompt some health disorders like heart issues, temporary or permanent hearing failure, internal tissue pain, nerve damage, and significantly higher circulatory strain in the long haul [2, 3]. According to World Health Organization (WHO), people exposed to prolong noise will adversely suffer hearing failure, sleep disturbance and even immune system problems [4]. Noise as one of the core air contaminants has a significant effect on living creatures, and the fast-industrial development and an ever-growing road traffic are the main factors [5].

The effect of acoustics on building's architecture can be seen over the centuries from the Roman amphitheaters to the contemporary structures, where people exhaust their flextime and free time. However, the major contrast between life in primeval Rome and life in the overcrowded urban towns is the prevalence of noise from a rising variety of sources, including factory, residents and traffic [6]. Acoustic enclosures are vast efficient methods of noise reduction to minimize noise generated from sources such as diesel engines, rain, turbines, air compressors and so on. Its performance is characterized by an insertion loss (IL), which can be defined as the variation in sound pressure levels at the receiver's end with and without the presence of a barrier (the enclosure walls in place), given that the source sound level is not altered [7].

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*Corresponding author: Enobong Patrick Obot <enobong_youngprof@yahoo.co.uk>

$$\mathrm{IL} = 10\log\left(I_1/I_2\right) = L_1 - L_2\ \mathrm{dB} \qquad (1)$$

where I_1 & I_2 are the intensities and L_1 & L_2 are the source sound pressure level and receiving end sound pressure level.

The sound pressure level at the measurement location resulting from the *i*th path can be written either with or without the partition in terms of the loss of the *i*th path insertion, IL_i as:

$$\mathrm{IL}_i = 10\log_{10} \sum_{i=1}^{n} 10^{-(IL_i/10)} \qquad (2)$$

Introducing subscripts to indicate cases 1 (without partition) and 2 (with partition), the total partition insertion loss ($\mathrm{IL} = L_1 - L_2$) is expressed,

$$\mathrm{IL} = 10\log_{10}\sum_{i=1}^{n_1} 10^{-(L_{1i}/10)} - 10\log_{10}\sum_{i=1}^{n_2} 10^{-(L_{2i}/10)} \qquad (3)$$

The acoustic enclosure insertion loss is resolved by the combination of source field movement and the wall panel vibrations. Bies and Hansen [8] determined a sole blockade indoors and outdoors insertion loss in accordance with "ISO 9613-2, ISO 10847, and ISO 11821". They found that in a higher reverberating condition, the blockades were ineffectual, but the indoor blockades performance enhanced by inserting specifically on the ceiling sound absorbing materials or by suspending ceiling assimilation baffles. Martinez-Orozco and Barba [9] investigated the in-situ performance of extant noise barriers using the indirect insertion loss technique outlined in the International Standard ISO 10847:1997. They performed the measurements at thirty sample locations, distributed among the three most prevalent forms of construction material (metal, concrete, and earthen berm walls). Their findings showed that the three different kinds of barriers had comparable insertion loss levels. The noise reduction effect was most effective in the 125 Hz – 8 kHz frequency band. Field measurements was conducted by May [10] on the balconies of a highway building. In spite of the fact that no balcony insertion loss calculation was made directly, these findings demonstrated that the balcony's ceiling reflection would greatly compensate the balcony's noise screening impact, and additionally the various reflections inside the balcony. Elden and Woloszyn [11, 12] used the pyramid tracing approach to investigate how the balcony ceiling and breastwork affected sound insertion loss. They also used a scale prototype to show that the configuration of the front parapet and the balcony's inclination and profundity could affect the balcony's overall sound insertion loss. The insertion loss of the balcony showed a rising pattern, they discovered, in conjunction with rising balcony profundity. No pattern was detected for either the angle of ceiling disposition or the impact of floor height on the insertion loss, which is most likely due to reflections from the "sensitive angle of incident". The insertion loss in the balcony was discovered to shift between 0.5 dB and 6 dB. Be that as it may, for balconies with depths of 1 m, 2 m, and 3 m respectively, the overall insertion loss when the front parapet was kept vertical, was found to be 2 dB, 4 dB and 6 dB [11]. An addition of 0.5 dB to 4 dB of noise reduction from a slant front parapet was also discovered [12]. Nonetheless, a 3-metre-deep balcony is by no means typical in a city filled with congested tall buildings. With the aid of simulations and a 1:50 scale ideal construction for a 16-storey building, Lee *et al.* [13] demonstrated the consolidated impact of front parapet configuration, ceiling tilt, and sound assimilation on noise reduction within an elevated building balcony. They utilized a sound-absorbing material made of 3 mm-thick polystyrene. They discovered a noise decrease of up to 23 dB, and described the noise reduction as the variation in balcony noise levels with and without the unique remedies mentioned above. On the balcony's rear wall, however, there was just a single measurement and consequently, the vulnerability in their analysis might be lofty. According to Rylander and Dunt [14], who conducted research on the subject of environmental noise control, noise levels can be decreased by installing effective noise barriers surrounding homes and entrance ramps. Application of noise barriers is one of the most pertinent mitigation strategies since reducing the sources of noise is a major concern for lowering ambient noise levels. Among other variable characteristics, noise barriers can be constructed from a variety of materials, as can their shapes or elevations [15-17].

Speech clarity is a concern in lecture rooms, conference halls, doctor's office, etc. It is a concern in our region where universities are built with lecture rooms without or with inferior ceiling material. More often than not, conference halls are built for their aesthetic value or cutting-edge ceiling design instead of the practicality of the ceiling material. Choices of ceiling materials and acoustical wall treatment have a significant effect on the noise level within this space. Statistical data on the sound pressure level within the building with and without a ceiling partition for the audio and narrow frequency band was obtained for the insertion losses of the ceiling materials to be analyzed and determine which one can be used to achieve a desired sound level within a building. The calculated insertion losses of the measurements for the acoustical ceiling materials are compared to confirm the accuracy of the calculation.

2. MATERIALS AND METHODS

Measurements were taken in five buildings with various acoustic ceiling materials as enclosure, as well as the appropriate instruments, digital sound level meter and real-time spectrum analyzer (Figure 1), required to assist in the measurements. The enclosures were about 4.66 m x 4.05 m (L x W) and the building dimensions about 3.58 m x 3.04 m x 2.95 m (L x W x H). Dimensions of the rooms (L x W) are different in each case. But similar acoustical problems exist in both small and large rooms, just on a different scale and level. Surface boundary reflections in small rooms can seriously affect the sound, particularly from side walls. The overall reverberation levels are impacted by large-room reflection problems. The building data/information is given in Table 1. Some sides of the buildings were surrounded with disposition of trees and vegetation, and the other side by other buildings. The particular types of materials for the buildings with moabi wood, plaster of Paris (POP), polyvinyl chloride (PVC), and asbestos ceiling materials (Figures 2, 3, 4 and 5) include reinforced concrete walls, tile floors, and normal (uncoated) aluminum glass windows. While that of the raffia palm ceiling material (Figure 6) is made up of mud walls, concrete floors, and wooden windows. The thickness of the building's wall was about 9" inches. The main objective has been to obtain statistical data on the sound pressure level within and outside the building with and without the ceiling partition (or noise barrier). Conclusions regarding the insertion losses of the ceiling materials would then be drawn.

2.1 Sound Level Meter (SLM)

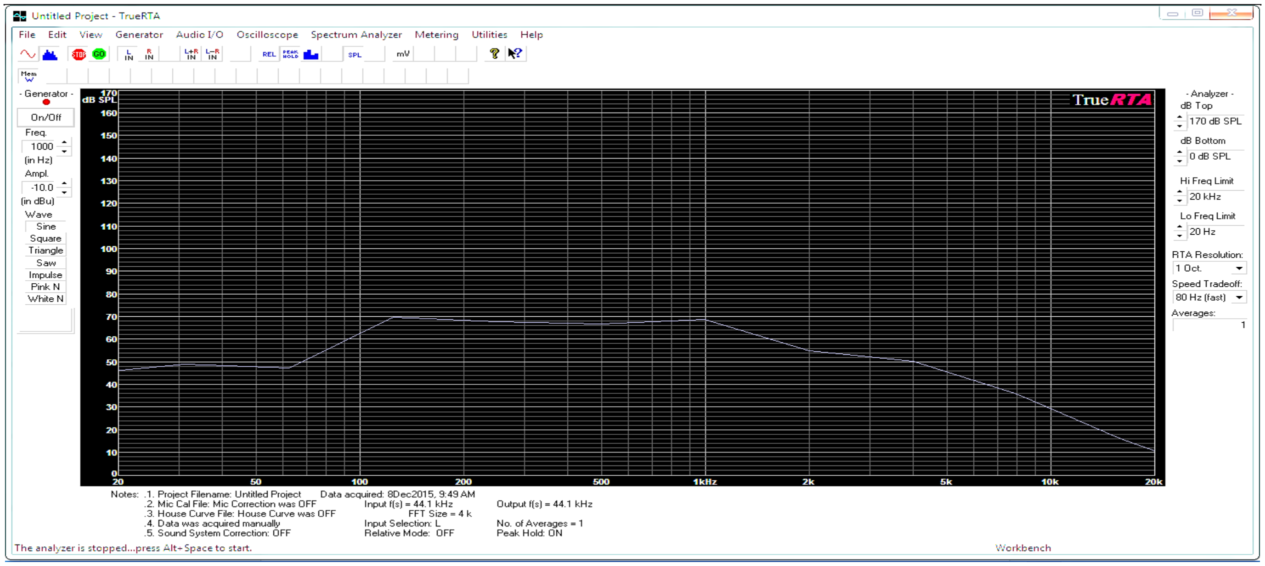
The Mastech digital SLM (model MS6700) with a measurement range of 30 dB to 130 dB and automatic ranging, a resolution of 0.1 dB, and a precision of ±1.5 dB, operates over a frequency response of 31.5 Hz to 8 kHz. It is a precision instrument used for the measurement of sound pressure level. It comprises of an array, a frequency response network range (weighting), a microphone, and an amplifier with graduated logarithm attenuator.

2.2 Frequency Analyzer

A real-time spectrum analyzer (RTA) allows precise measurement of the amplitude of the input signal versus the frequency enclosed by the analyzer's peak frequency scale. It is a software-based instrument used within the audio spectrum to analyze signals. This tool was installed in a personal computer with fundamental capabilities for sound input and output. A sound level meter, a low-distortion signal generator, a peak factor meter, a high-resolution real-time analyzer, and a double-trace oscilloscope are incorporated into the true RTA instrument.

Table 1. Building information

Building with ceiling materials	Dimension of the rooms (m^3)	Number of rooms	Interior description
Moabi wood	3.68 x 3.05 x 2.95	6	Normal residential rooms with reinforced concrete walls, tile floors and normal (uncoated) aluminum glass windows.
Plaster of Paris (POP)	4.20 x 3.87 x 2.95	6	Normal urban residential rooms with polished concrete walls, tile floors and normal (uncoated) aluminum glass windows.
Polyvinyl chloride (PVC)	3.63 x 3.00 x 2.95	5	Normal residential rooms with reinforced concrete walls, tile floors and normal (uncoated) aluminum glass windows.
Asbestos ceiling board	3.65 x 3.20 x 2.95	8	Normal residential rooms with reinforced concrete walls, tile floors and normal (uncoated) aluminum glass windows.
Raffia palm	2.75 x 2.10 x 2.95	4	Normal rural residential rooms with reinforced mud walls, concrete floors and wooden windows.



Freq. 1000 (in Hz)
Ampl. -10.0 (in dBu)

- Analyzer -
dB Top 170 dB SPL
dB Bottom 0 dB SPL
Hi Freq Limit 20 kHz
Lo Freq Limit 20 Hz
RTA Resolution: 1 Oct.
Speed Tradeoff: 80 Hz (fast)
Averages: 1

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Notes: .1. Project Filename: Untitled Project      Data acquired: 8Dec2015, 9:49 AM
       .2. Mic Cal File: Mic Correction was OFF          Input f(s) = 44.1 kHz          Output f(s) = 44.1 kHz
       .3. House Curve File: House Curve was OFF                   FFT Size = 4 k
       .4. Data was acquired manually                    Input Selection: L              No. of Averages = 1
       .5. Sound System Correction: OFF                  Relative Mode:  OFF             Peak Hold: ON
The analyzer is stopped...press Alt+Space to start.
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Fig. 1. True RTA audio frequency analyzer

Fig. 2. Moabi wood material

Fig. 3. Plaster of Paris

Fig. 4. Polyvinyl chloride material

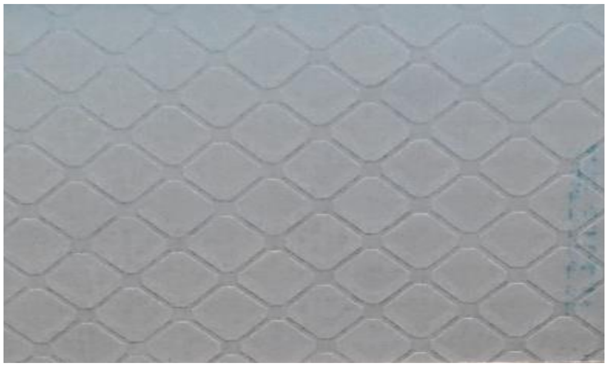

Fig. 5. Asbestos ceiling board

Fig. 6. Raffia palm material

2.3 Ceiling Materials

The measurements were carried out in five buildings with different acoustical ceiling materials. The materials specification is given in Table 2.

2.4 Measurement Method

For sound level measurements, a digital SLM and the RTA were used. The meter was synchronized

Table 2. Materials specification

Ceiling materials	Thickness (mm)	Mass per unit area (kg/m^2)
Moabi wood	10	0.0427
Plaster of Paris (POP)	10	0.0521
Polyvinyl chloride (PVC)	6	0.0081
Asbestos ceiling board	4	0.0096
Raffia palm	10	0.0062

with the RTA, and the one-octave band readings were taken. Measurements were made in four different rooms for each of the buildings at four different points, and the average values of the measuring points were used. Within the building, measurements were made prior to and during the rain. The sound level meter's weighting network was calibrated to "A" position and the meter's dynamic features calibrated to "slow" response. The microphone's axis of highest sensitivity was oriented towards the source of the noise, and all measurements were made at 3.5 m away from any vertical reflecting surface and a height of 1.5 m altitude. A windshield was used to protect and shield the most precious part of the sound level meter, the microphone, from external signal effects such as wind and electrical interference.

3. RESULTS AND DISCUSSION

3.1 Results for Moabi Wood

Figure 7 shows the measurements of the average noise level obtained and their characteristics within the moabi wood ceiling partition one-octave band. The first aspect observed is that without the partition, at most of the distinct frequencies, the ambient noise outside was attenuated within the building in the one-octave band. But with the partition, the building's ambient noise was reduced at all one-octave band distinct frequencies, with the highest attenuation occurring at 1 kHz, at 4.07 dB.

The noise level inside without the partition was higher at all one-octave band distinct frequencies when there was rain fall, relative to ambient noise inside without the partition, with a highest value of 86.63 dBA at 62.5 Hz. However, at all the distinct frequencies in the one-octave band, attenuation was observed with the partition, with a highest value of 21.20 dB at 500 Hz. One possible explanation for this observation is the spreading introduced by the building structure and interior [18].

3.2 Results for Asbestos Ceiling Board

In Figure 8, the same observation as in the case of moabi wood could be made. The difference

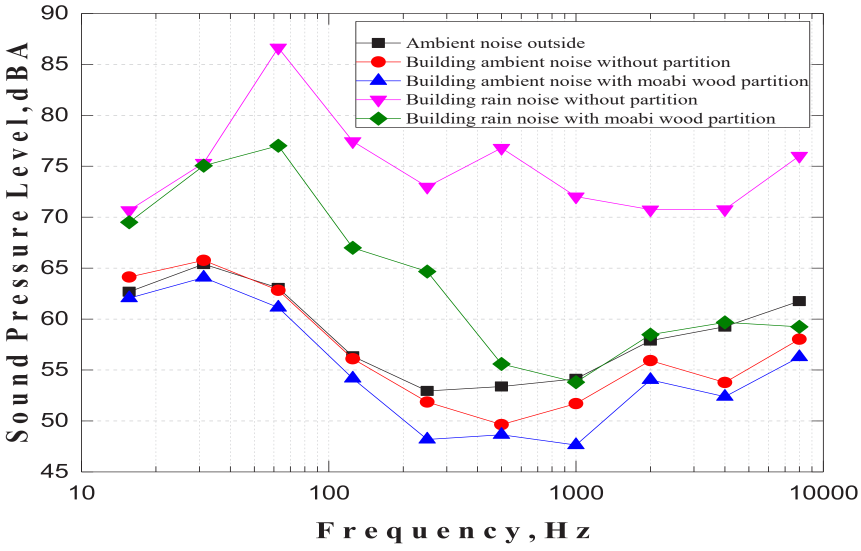

Fig. 7. Measurements of the average noise level for moabi wood

here was that, with the partition, at all one-octave band distinct frequencies, the building's ambient noise was not attenuated aside from 1 kHz and a considerably higher frequency spectrum. In other words, asbestos ceiling boards resonate the acoustic waves due to reflection, material composition, and spreading introduced by the building structure and interior. But at all the distinct frequencies in the one-octave band, attenuation was observed with the partition when there was rainfall with a highest value of 12.46 dB at 8 kHz, except at lower frequencies range of 31.2 Hz and below.

3.3 Results for Polyvinyl Chloride

Figure 9 shows the corresponding variations of the average measured noise level and their characteristics within the one-octave band for PVC ceiling partition. The results of PVC are similar to that of moabi wood. However, at all the distinct frequencies in the one-octave band, attenuation was observed with the partition when there was rainfall, with a highest value of 14.53 dB at 500 Hz.

3.4 Overall Experimental Results

Table 3 and Figure 10 show an overview of the calculated insertion losses for each ceiling materials based on the average measured rain noise level within the building, with and without the partition. The results of average noise level for each material investigated in the present study are given in appendixes (A to E).

3.5 Discussion of Results

As shown in Figures 7, 8 and 9, the noise level was attenuated by all the ceiling materials examined. For each ceiling materials, the insertion losses increase (in a particular case slightly) to a maximum value before decreasing and again increases with the frequency. At the initial stage in each of the ceiling materials, the system undergoes transient behaviors. From Table 3 and Figure 10, it is observed that at 15.6 Hz and 31.2 Hz asbestos ceiling board had the least insertion loss compared to others. As mentioned earlier, explanation was given for the insertion loss due to the composition of the material, reflection, and the spreading introduced by the building structure and the interior. At 62.5 Hz, in contrast to other materials, POP and raffia palm materials losses were slightly higher, but the differences were not notable. Again, apart from moabi wood which undergoes a little increment in insertion loss at 125 Hz, all the other materials undergo a substantial decrease in insertion loss. For other materials, except moabi wood which was higher at 250 Hz, the same pattern was encountered, although it also has a slight decrease. At 500 Hz, moabi wood has the highest value, as all materials witnessed a rise in insertion loss. Although its curve rises to a peak and then falls, its range of high attenuation is wider

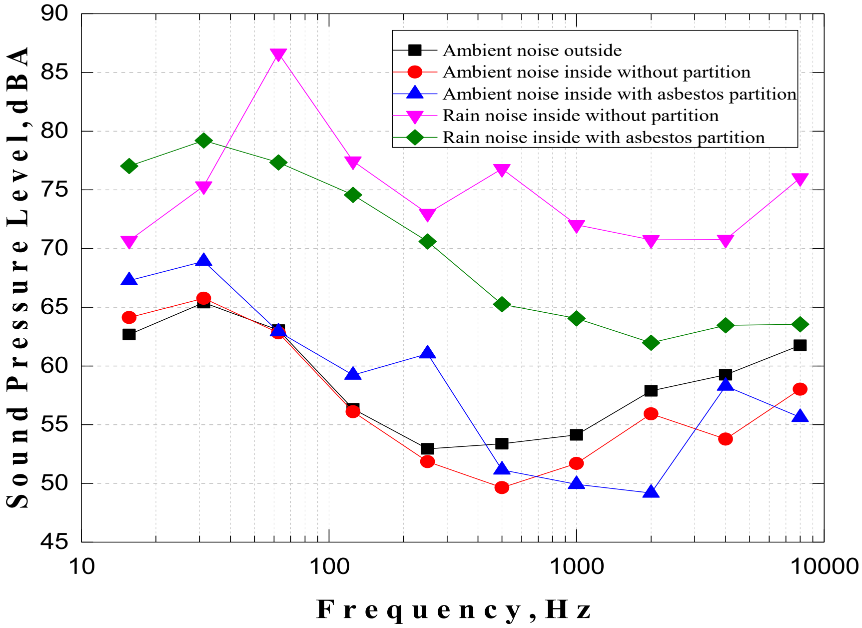

Fig. 8. Measurements of the average noise level for asbestos ceiling board

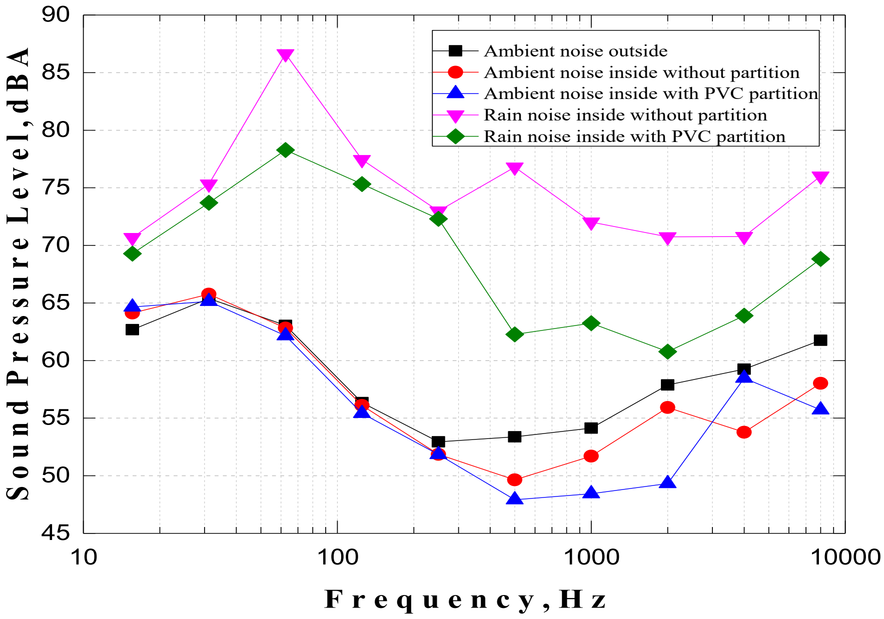

Fig. 9. Measurements of the average noise level for polyvinyl chloride

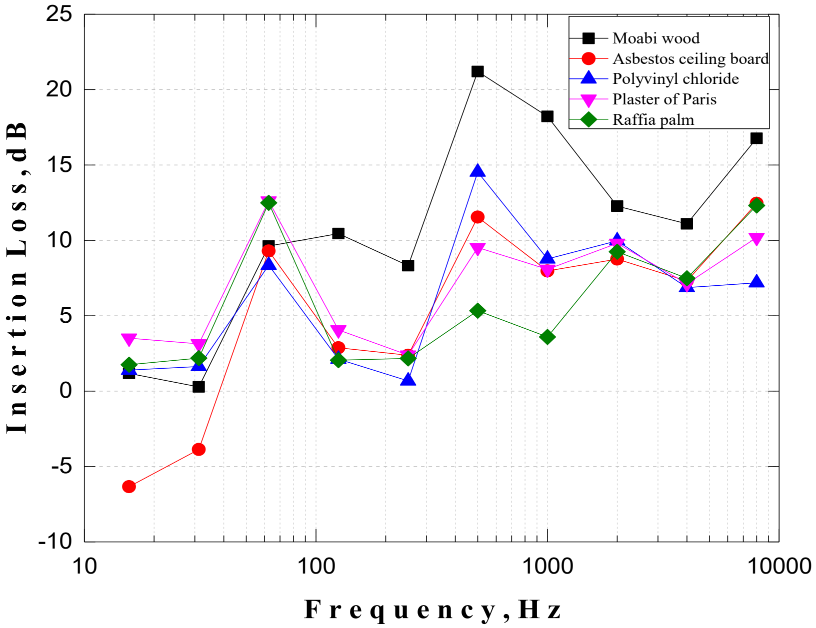

Fig. 10. Overall comparison results of insertion losses for the ceiling materials

than that shown by asbestos ceiling board, PVC, POP, and raffia palm materials. Their profiles of high attenuation are rather narrow, and confined to the middle range of the frequency spectrum. From 1 kHz to 8 kHz, moabi wood insertion loss was significantly higher than the other materials. In general, the curves are in sequence with noise criterion curve which shows that sound can be perceived at lower frequency with higher intensity of signal.

From these results, it has been perceived that the range of useful attenuation depends on the composition of the material, by weight or by thickness, microstructure of the material, and the spreading introduced by the building structure and interior. Results obtained show that, of all the ceiling materials examined, moabi wood has the best capability of attenuating sound, with a peak value of 21.20 dB from an external noise source of this type. This relates to the speech reception threshold frequency ranges of 500 Hz and higher audiometric frequency ranges. However, POP, which peaks at 62.5 Hz at 12.61 dB, is higher at lower frequencies

Table 3. Overall results of the calculated insertion loss per ceiling material

Frequency (Hz)	Insertion loss (dB) of the materials				
	Moabi wood	Asbestos ceiling board	Polyvinyl chloride	Plaster of Paris	Raffia palm
15.6	1.18	-6.34	1.39	3.51	1.75
31.2	0.28	-3.87	1.63	3.14	2.19
62.5	9.62	9.30	8.35	12.61	12.49
125	10.45	2.88	2.12	4.06	2.05
250	8.32	2.38	0.68	2.39	2.17
500	21.20	11.55	14.53	9.53	5.34
1000	18.22	7.97	8.77	8.08	3.59
2000	12.27	8.76	9.97	9.80	9.25
4000	11.10	7.31	6.87	7.13	7.49
8000	16.77	12.46	7.19	10.19	12.31

where the ears are slightly sensitive. Therefore, moabi wood can effectively be employed as ceiling material in lecture rooms, conference halls and large auditoriums in consideration of its capability to provide notable attenuation of rain noise level within the building. These results are in accordance with that of the work reported earlier by Lee *et. al*. [13].

The mean ambient noise level measured outside, adjacent to each room, and the room (with partition) mean ambient noise level measured were compared using the correlation coefficient, R. The overall computed correlation coefficient was approximately 0.9. This means that the ambient noise levels measured just outside the room and the ambient noise levels measured inside the room (with a partition) have a strong correlation.

4. CONCLUSIONS

Noise occurs when unwelcomed sounds encroach into the surroundings. Again, one is not only frequently greeted with a wide range of noise caused by rain when one stays in a shelter for safety, but also experiences varying degrees of frustration and discomfort from the same rain. In this study, measurements were taken with and without the ceiling partition (or noise barrier) to obtain sound pressure level statistical data outside and within the building. Conclusions were drawn regarding the insertion loss of the materials. Results from the measurements taken in five buildings with diverse acoustical ceiling materials in South Eastern Nigeria indicated a peak insertion loss of 21.20 dB with moabi wood. This relates to the speech reception frequency and other higher audiometric frequencies range. The insertion losses of the other ceiling materials examined show an increase in frequency, up to a maximum value, after which they fall and then rise again with further increases in frequency. Therefore, moabi wood can effectively be employed as ceiling material in lecture halls, conference rooms and large auditoriums. The correlation between the outdoor and indoor (with partition) measured ambient noise levels showed a close relation between the room sound pressure level recorded and the sound pressure level recorded just outside the room.

In general, a significant reduction of distinct frequency rain noise levels within the building was observed at much lower frequencies and other higher audiometric frequencies. The range of useful reduction depends on the composition of the material, by weight or by thickness, microstructure of the material, as well as the spreading introduced by the building structure and interior.

5. CONFLICT OF INTEREST

The authors declare no conflict of interest.

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APPENDICES

Appendix A. Result of average noise level measurement for moabi wood.

Frequency (Hz)	Ambient noise outside (dBA)	Building ambient noise without partition (dBA)	Building ambient noise with partition (dBA)	Building rain noise without partition (dBA)	Building rain noise with partition (dBA)
15.6	62.68	64.13	62.05	70.68	69.50
31.2	65.39	65.76	64.08	75.33	75.05
62.5	63.05	62.82	61.14	86.63	77.01
125	56.35	56.11	54.17	77.45	67.00
250	52.94	51.86	48.19	72.98	64.66
500	53.38	49.64	48.65	76.80	55.60
1000	54.13	51.70	47.63	72.02	53.80
2000	57.88	55.93	54.03	70.74	58.47
4000	59.26	53.78	52.38	70.77	59.67
8000	61.76	58.02	56.27	76.01	59.24
				R	**0.95**

Appendix B. Result of average noise level measurement for asbestos ceiling board.

Frequency (Hz)	Ambient noise outside (dBA)	Building ambient noise without partition (dBA)	Building ambient noise with partition (dBA)	Building rain noise without partition (dBA)	Building rain noise with partition (dBA)
15.6	62.68	64.13	67.28	70.68	77.02
31.2	65.39	65.76	68.91	75.33	79.20
62.5	63.05	62.82	62.93	86.63	77.33
125	56.35	56.11	59.23	77.45	74.57
250	52.94	51.86	61.04	72.98	70.60
500	53.38	49.64	51.16	76.80	65.25
1000	54.13	51.70	49.93	72.02	64.05
2000	57.88	55.93	49.18	70.74	61.98
4000	59.26	53.78	58.30	70.77	63.46
8000	61.76	58.02	55.63	76.01	63.55
				R	**0.66**

Appendix C. Result of average noise level measurement for polyvinyl chloride.

Frequency (Hz)	Ambient noise outside (dBA)	Building ambient noise without partition (dBA)	Building ambient noise with partition (dBA)	Building rain noise without partition (dBA)	Building rain noise with partition (dBA)
15.6	62.68	64.13	64.65	70.68	69.29
31.2	65.39	65.76	65.14	75.33	73.70
62.5	63.05	62.82	62.16	86.63	78.28
125	56.35	56.11	55.42	77.45	75.33
250	52.94	51.86	51.85	72.98	72.30
500	53.38	49.64	47.92	76.80	62.27
1000	54.13	51.70	48.44	72.02	63.25
2000	57.88	55.93	49.32	70.74	60.77
4000	59.26	53.78	58.47	70.77	63.90
8000	61.76	58.02	55.72	76.01	68.82
				R	**0.88**

Appendix D. Result of average noise level measurement for Plaster of Paris.

Frequency (Hz)	Ambient noise outside (dBA)	Building ambient noise without partition (dBA)	Building ambient noise with Partition (dBA)	Building rain noise without partition (dBA)	Building rain noise with partition (dBA)
15.6	62.68	64.13	63.83	70.68	67.17
31.2	65.39	65.76	66.50	75.33	72.19
62.5	63.05	62.82	62.28	86.63	74.02
125	56.35	56.11	51.51	77.45	73.39
250	52.94	51.86	49.98	72.98	70.59
500	53.38	49.64	48.53	76.80	67.27
1000	54.13	51.70	48.50	72.02	63.94
2000	57.88	55.93	49.36	70.74	60.94
4000	59.26	53.78	58.90	70.77	63.64
8000	61.76	58.02	55.81	76.01	65.82
				R	**0.92**

Appendix E. Result of average noise level measurement for raffia palm.

Frequency (Hz)	Ambient noise outside (dBA)	Building ambient noise without partition (dBA)	Building ambient noise with partition (dBA)	Building rain noise without partition (dBA)	Building rain noise with partition (dBA)
15.6	62.68	64.13	63.52	70.68	68.93
31.2	65.39	65.76	64.34	75.33	73.14
62.5	63.05	62.82	60.87	86.63	74.14
125	56.35	56.11	53.86	77.45	75.40
250	52.94	51.86	50.61	72.98	70.81
500	53.38	49.64	48.59	76.80	71.46
1000	54.13	51.70	48.55	72.02	68.43
2000	57.88	55.93	49.20	70.74	61.49
4000	59.26	53.78	58.06	70.77	63.28
8000	61.76	58.02	56.32	76.01	63.70
				R	**0.91**