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IMPROVING THE ACOUSTIC PERFORMANCE USING SUSTAINABLE MATERIALS
CASE STUDY: LECTURE ROOMS.

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ABSTRACT
This paper analyzes two Auditoria at the Faculty of Engineering, Helwan University, Cairo, Egypt. Based on the clarity of speech for educational facilities. This research was carried out on adapting the field survey to determine the architectural and acoustic measurements, followed by a digital simulation using CATT for both rooms. Sustainable treatments were provided to improve the sound environment of the learning process and were again tested using CATT. Analysis and simulation indicate that both rooms suffer from poor acoustics due to the surrounding area and the finishing materials selection. One possible solution to this problem is to use a new sustainable absorbent to maximize uptake, reducing excessive reverberation time to acceptable values, increasing early reflections and eliminating shadow areas that improve speech clarity for all receivers.

KEYWORDS: Acoustic performance, Speech intelligibility, Reverberation time, Ambient noise, Sustainable absorptive materials.

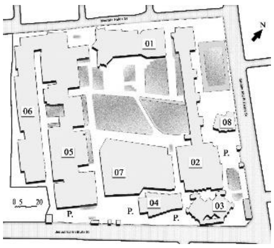
1. INTRODUCTION

Acoustic performance of lecture auditoria has attracted many researchers for its direct impact on the learning process in addition to the impact on the convenience of recipients and lecturers themselves [1]. Inadequate acoustic performance of any auditorium results from either room acoustics or signal to noise ratio that decrease because of high ambient noise or low early reflections energy [2]. There are a number of acoustic indicators that are used to assess the performance of any auditoria, particularly, occupied reverberation time (T_o), speech transmission index (STI) or useful to detrimental sound ratio (U_{80}) as a function of T [3], and ambient noise level (L_{eq}), because of its impact on the comfort of the recipients and also to avoid the sound problems that may affect the lecturers themselves, as indicated by some studies [1]. Speech intelligibility can be governed by many factors such as; speech transmission index (STI)) [2] [4], optimum reverberation time (T_{Opt}) [4], ambient noise level (L_{eq}) which should not exceed 35 dB to avoid distraction in learning facilities [3] [5].

The authors have experienced all along, either as students or lecturers, poor acoustic quality in the auditoria of the architecture department, Faculty of Engineering, Helwan University. Therefore, the authors intended to explore the rationale behind this issue and to advise a solution. Faculty of Engineering, Helwan University, Al-Mataria Branch is one of the oldest governmental educational institutions in Cairo, Egypt, and locates in densely populated urban area. The college covers about 52.000 square meters and includes six departments as depicted in Fig.1. The architectural department occupies building No. 1 in Fig. 1, which consists of five storeys and includes two typical auditoria. Namely, lecture room (LR) and drawings hall

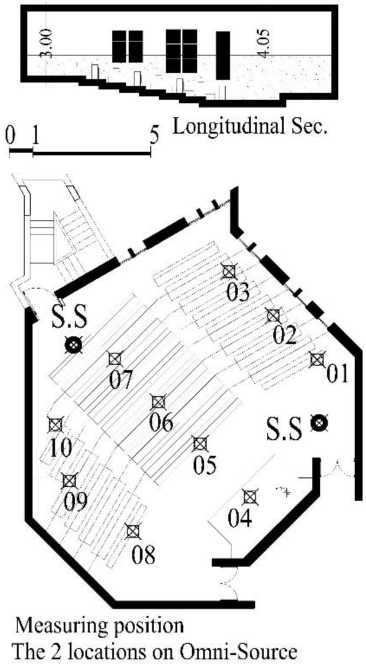
(DH). A previous study for the acoustic performance of the two major auditoria in the Faculty showed the poor acoustic quality of both of them because of high ambient noise levels as well their inadequate acoustic characteristics [6]. Thus, this paper focus on assessing the acoustic performance of the typical auditoria of the architectural department.

Lecture room (LR) is the typical auditorium in the department. It is of a 7-sided shape in which the seats are arranged diagonally, as shown in Fig. 2 (a). The floor slop is approximately 9^o, which corresponds to the minimum inclination required for the visibility. While, the drawing hall (DH) is one of ten typical drawing halls located in pairs on the five floors. It is a rectangular flat-floor hall, as shown in Fig. 2 (b). Both rooms rely on natural lighting and ventilation through open windows. The architectural features of both rooms are listed in Table 1.

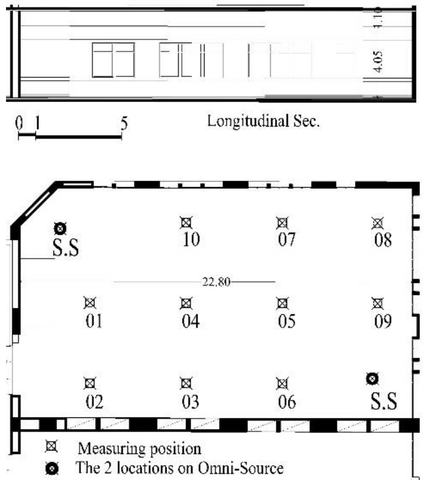


1 Architecture, Math and Physics Departments.
2 Department of automotive and locomotive, Library, Theatre and administration.
3 Civil engineering department Auditoria
4 Main auditorium
5 Civil Departments and Automotive & Locomotive Workshops
6 Mechanical Power Department and Laboratories.
7 New Building
8 Mosque

Fig.1. Layout of the Faculty of Engineering [6]



a. Lecture Room (LR)



b. Drawing Hall (DH)

Fig.2. Rooms' geometry and Omni source-microphone locations in the rooms

Table .1. The architecture features of rooms LR and DH.

	Room's sizes					
	Volume m^3	Area m^2	Perimeter m	W	L	H ave.
Room LR	587.76	161.8	51.6	14.5	13.25	3.10
Room DH	1237	302.5	72.43	13.30	22.8	4.05

eather Conditions			Statistical Information				
	Temp. °C	RH %	Net audience Area	No. of seats	V_P m^{3i}	A_P $^{ii}m^2$	T_{Opt}-500Hz
Room LR	27	43	64.8	162	3.70	0.40	0.53
Room DH	25	42	69.3	65	19	1.1	0.63

Sustainable materials will be implemented to improve sound quality in both rooms, as the scope of research and manufacturing of sustainable materials has recently expanded, the new sound materials have been studied and developed as an alternative to traditional materials. These materials are either natural, recycled or mixed. Its relevance to use in educational facility has two aspects; educational and functional (sound and aesthetics). The paper will demonstrate the suitability of material selected for both sides.

1.1 Literature Review

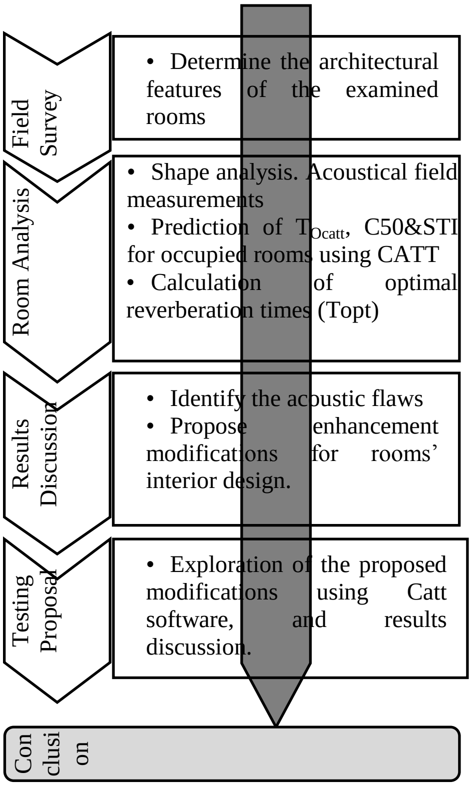
There were a lot of researches interested in studying the sonic environments in educational spaces using either computer programs to simulate the acoustical waves behaviors inside rooms or depending on real field measurements using manual tools. Putra et al [7] evaluated reverberation time in a class room using two methods: Sabine, Norris-Eyring, Milington formulas, and Autodesk Ecotect software to calculate T_o using other factors that have been ignored in the formulas. The result shows inconsistency between the T_o resulting from both methods. This was due to four main reasons: the space form complicity, different values of absorption coefficient for finishing materials, relative humidity and temperature, that affects the study results between the two methods. Alibaba and Ozdeniz [8] investigated the acoustical features for a multi-purpose hall that used for lectures, music performance and sports in the Eastern Mediterranean University, the hall suffers from echoes and long reverberation time that reaches (5 s), which is bad for speech and even for music. field measurement and ODEON simulation were used to compare the hall acoustical features with new four alternatives that used different materials to improve it. The alternatives were tested to find out the suitable solution, which was using fireproof pyramidal melamine plates for ceiling and front surface with different modifications, which result in reducing T to 0.52 as minimum and 2.16 as a maximum value which improved the sound criteria. Brüel&Kjær [9] Validate in their report a Lecture Hall Acoustics parameter using measured and simulated method using ODEON. The simulation results for T_o, STI were within 5% of the measured parameters in the mid frequencies, and larger differences were found in the higher frequencies. And the report aimed to validate the finding of using the simulation software in acoustic design and prediction not to suggest alternatives materials for the hall. Elkhateeb [10] used ODEON software as a tool to design a new lecture hall at Ain Shams University, to assist the learning process for faculty of law. The room was evaluated after construction in an unoccupied state using field measurements to calculate D50, STI, L, and T_o. then the researcher compares both results from field and designed simulation, and he concluded that the design achieved the required acoustical criteria for learning spaces for D50, STI, and T_o. Moreover, L did not match the design goals because open windows affected the ambient noise. For sustainable absorbers, other researches have investigated and tested the absorption coefficients of many ecological (natural) materials and its efficiency in comparing with the manufacture nonsustainable ones. Shiney [11] investigated the use of matt coir as sustainable materials in three auditoria for Bishop Moor College, India. The T_o was measured in the selected rooms and they find it was not suitable for rooms function due to the lake of absorbers. The researchers tried at first a traditional treatment of a cement plastered roof, then with the sustainable material coir matts for floor and walls ,they concluded after measurement that the second solution reduced T_o to fit the room function as the coir is a very good sound absorber, economic and sustainable. Asdrubali et al [12], demonstrated that even tropical plants used for the decorative purpose in the living buildings can also serve as good sound absorbers. Tropical plants, namely baby tears and fern shown to have average sound absorption coefficient of 0.9 from 900 to 1600 Hz. At low frequencies, the substrate soil is shown to be the main contributor for absorbing great amount of sound energy between 500 to 600 Hz. Bamboo, Kenaf, Acoustical Cotton, Wood Wool and other materials were tested to determine their physical properties and their sound absorption efficiency and the results showed that they have almost the same abortion as other common materials, Moreover, some of them were in the international markets now as a natural sound absorbers for green solutions [13] [14] [15] [16].

1.2 WORK OBJECTIVE

The work aims to analyze and evaluate the acoustic performance of the architectural department auditoria. The evaluation depends on field reconnaissance and measurements as well simulation. The acoustic indicators resulted from these steps are used to evaluate the performance, and to propose improvement solutions. Sustainable material will be used, and efficiency of these solution will be checked using simulation. The secondary purpose of selecting sustainable material, in particular, is to provide an experimental learning example to connect the undergraduate students with the real applications of such materials.

2 METHOD

The work method is established based on an analytical approach. Fig. 3. clarifies the



method, which comprises of four steps. Field reconnaissance to gather the information required on the examined rooms, as illustrated in Table 1. Second, assessing the speech quality based on room shape analysis as per the pattern of acoustic rays depicted in Table.2. as well different sound indicators T_o, L_{eq}, STI and C_{50}. Thus, L and reverberation time in vacant rooms (T_{Me}) were measured at the octave band centre frequencies according to ISO 1996-2 and ISO 3382-2 [17], [18]. Brüel&Kjear sound level meter including an Omni sound source (type 4296), a sound analyser (type 2260), and a power amplifier is utilized. Air temperature and relative humidity were captured.

Fig.3. Work method

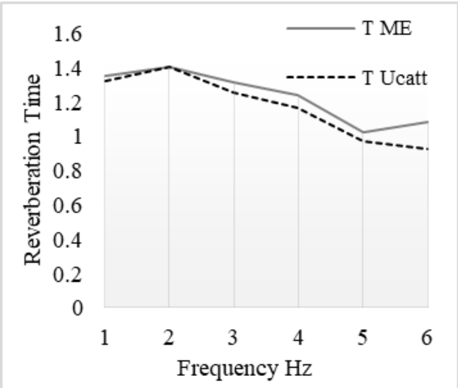
`Table .2. Different patterns as per geometric acoustics

Zone	Colour	Explanation
Hard		Zone received direct and 1st order late reflections
Fair		Zone received direct, early and 1st order late reflections.
Good		Zone received direct and 1st order early reflections only.
Shadow		Zone received only direct sound

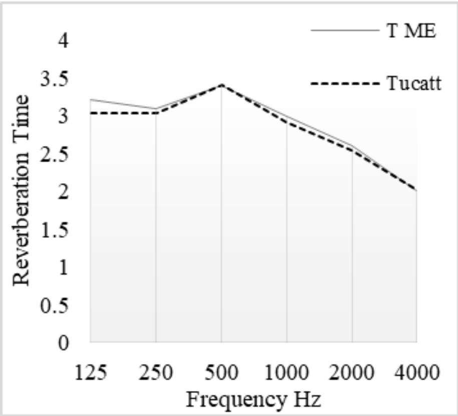
Simulation technique using CATT room acoustic software, version 8.0b, were used to estimate the occupied reverberation time, C50 and STI. The measured indicators, T_{Me} and L were an input to validate the simulation results, whereas position of the sound source, as well the locations and numbers of the receivers, were same as those utilized in the field measurements. Setups and simulation circumstances as well scattering coefficients are showed in Tables3 and 4. Fig. 4. clarifies a comparison T_{Me} gotten from field measurements versus vacant reverberation time (T_{Ucatt}) from CATT, the differences between the two curves of both rooms are negligible [19]. Then, both rooms are simulated occupied, in which the absorption coefficients (α) of all surfaces were kept same as the unoccupied case, except α of the seats that were replaced by audiences sitting on wooden seats [20].

Table.4. Scattering coefficients

Audience	Glass, terrazzo	Materials with rough surfaces
0.7	0.1	0.3



a. Room LR



b. Room DH

Fig 4 . coparison between the T_{Me} and T_{Ucatt} for both rooms.

Moreover, the optimum reverberation time (T_{Opt}) for both rooms were estimated using the followings equations. T_{Opt} at 500 Hz and higher were calculated using Eq. (1) [20]

$$T_{opt} = 0.3 \log \frac{V}{10} \ (s) \quad (1)$$

Table.3. Setups and simulation circumstances

Parameter	Value	Parameter	Value
Number of rays	18642 for lecture room 51956 for Drawing hall	Ambient noise level	Logarithmic average of real measurements in each room.

For the frequencies lower than 500 Hz, Eq. (2) ($T_{opt\ OBCF}$) was used:

$$T_{optOBCF} = nT_{opt}(s) \quad (2)$$

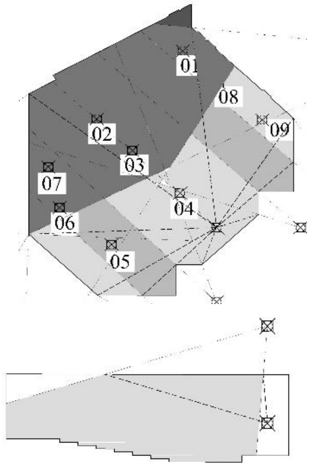
Eq. (3), is used to calculate *n*:

$$n = \frac{5.6716}{F^{0.2856}} \quad (3)$$

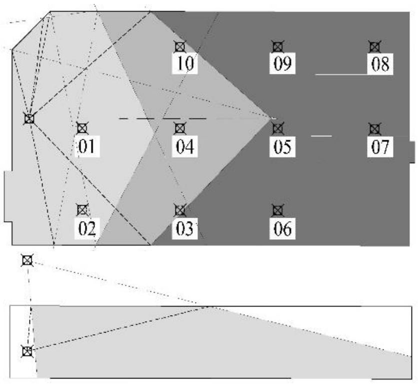
Finally, the results were analyzed to identify the acoustic flaws. Whereby, improvement solutions were proposed using sustainable materials, and the efficiency of these solutions were experimented using CATT.

2.1 Acoustic Features of the Examined Rooms

Ray diagram analysis based on geometric acoustics as depicted in Fig.5. clarified no sound defect from ceiling shape in both rooms, but nonhomogeneous distribution of early and late sound reflections because of wall shapes in both rooms. Moreover, DH room experienced flutter echo because of the parallel reflective walls. As per Table .2. [21] [22] each room includes 3 different acoustic zones: good, fair and hard. The good acoustic zone includes front seats, which receive a direct and early reflections from ceiling and nearby walls. The medium zone receives late reflections from walls as well early reflections from ceiling and walls. Whereas, the third zone receives first and second order late reflections from extent surfaces as well early reflections from ceiling.



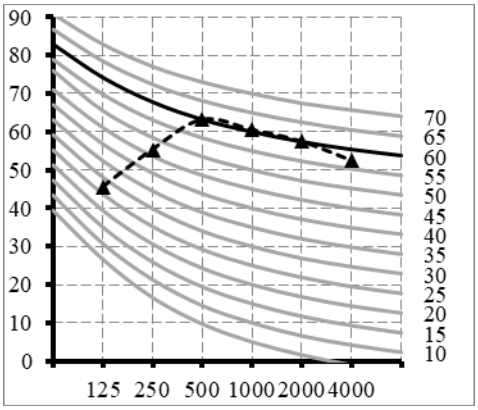
a. Room LR



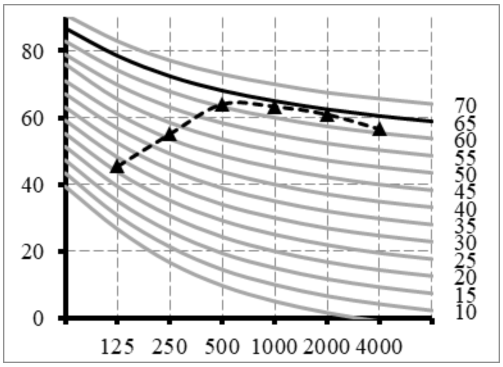
b. Room DH

Fig. 5. Plan and Longitudinal Sec. for Ray diagram distribution

In comparing the measured L with the standard noise level for learning spaces [5], it was found that L_{eq} in room LR is Nc-60 while it isN-65 in room DH where both values are exceeding the acceptable limits (Nc-35) at important frequencies for SI, as shown in Fig .6. This result is foreseen for the ambient noise that is penetrating the open windows used for ventilation.



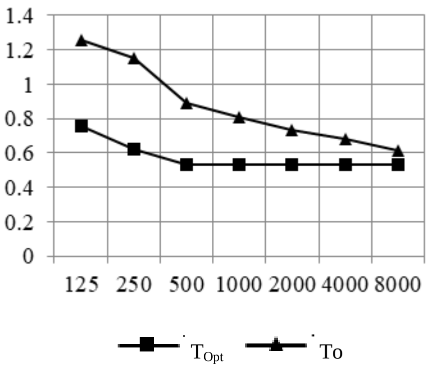
a. Room LR



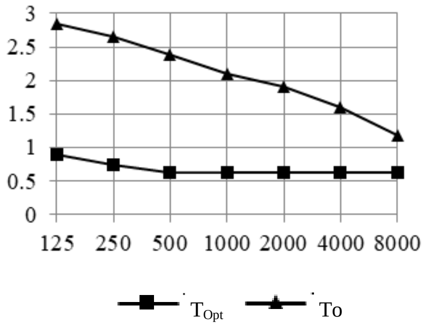
b. Room DH

Fig. 6. L_{eq} of both rooms indicated on NC

As seen in Fig.7. there is a significant difference between the occupied reverberation times T_o and the optimum reverberation T_{Optt} in both rooms. For room LR, T is higher than T_{Opt} by about 55% at low and mid frequencies, and 15% at high frequencies. While T_o in room DH is higher than T_{Opt} by about 250% at low and mid frequencies, and 85% at high frequencies.



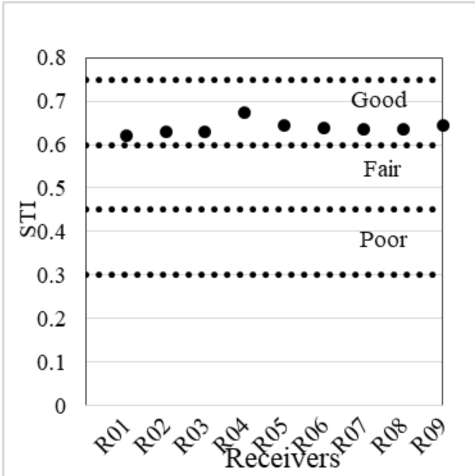
a. Room LR



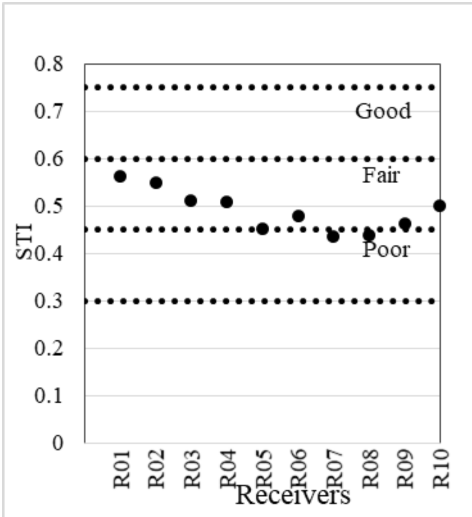
b. Room DH

Fig.7. Comparison between T_{OPT} and T_O for the unoccupied rooms

Fig.8. illustrated that STI values in room DH is worse than the other room. Most receivers in room LR lay in the good zone, as shown in Fig. 8(a), whereas the recipients are in fair/poor zones in room DH, Fig. 8(b). These results are in line with room shape analysis; the front recipients, No.4 and 9 in LR and No. 1 and 2 in DH receive the highest direct sound, early reflections from the near walls and ceiling as well late reflections from the distant walls. The other recipients receive abundant 1st late reflections from the distant walls, as well early reflections from the ceiling and side walls. These results are foreseen for the high T_o and L_{eq} in both rooms, while the excessive T_o in room DH justifies the glaring difference in the sound quality between the two rooms. Both rooms have low level of C50 because of the high L_{eq} and long reverberation time,Fig. 9



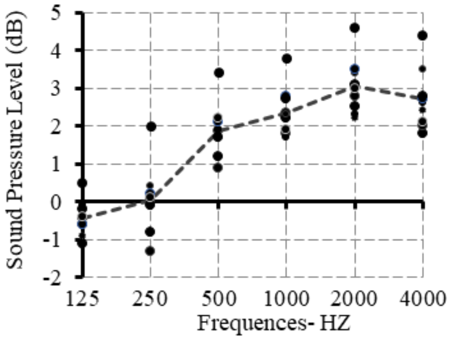
a. Room LR



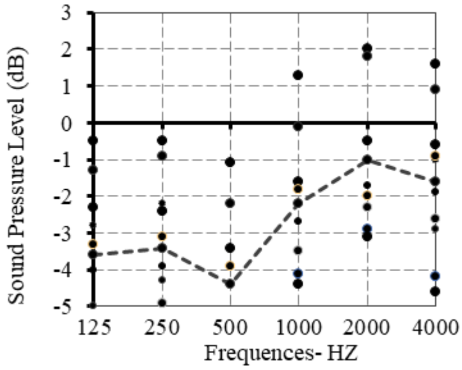
b. Room DH

Fig. 8. STI at rooms LR and DH

The average values of clarity in DH is less than -1 dB at all frequencies. While the average clarity in LR varied between 3 dB and -0.4 dB, the less values are at low frequencies for the absorption coefficient value at these frequencies, Fig. 9(a). Similar to STI, clarity in room DH is the most degraded as shown in Fig .9 (b).



a. Room LR

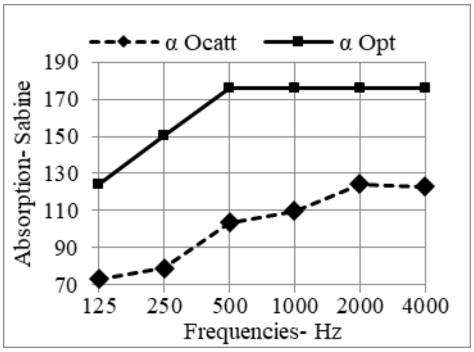


b. Room DH

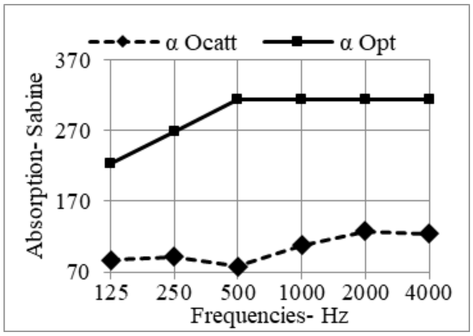
Fig.9. C50 Clarity in both rooms.

2.2 Discussion

As per the results in the above-mentioned topic, speech in the two rooms is not intelligible and their designs are not met the acoustic considerations for learning rooms. High ambient noise level that exceeds the recommended level by about 30 dB, particularly, at the frequencies essential for speech intelligibility. The available solution is to close the windows opened for the natural ventilation. High T_o in both rooms results mainly from the lake of suitable absorbing materials. While the volume per person (V_P) in room LR is compatible with DIN-18041 (3:6 m^3/seat) [23], this limit is exceeded in room DH by about 3 times making it acoustically worse. These flaws in room DH caused poor STI and negative values of C_{50}. So that the acoustic performance of room LR is less deficient. Consequently, finishing materials of the internal surfaces need be adjusted to absorb the late reflections, increase the early reflections and reduce excessive reverberation time to the optimal value. The absorption power in room LR to increase round about 1.7 times at all frequencies, Fig.10 (a). While for room DH, the total absorption power to be over its current values by about 2.7 at all frequencies except at 500 HZ which needs to be higher by about 4 times, Fig. 10 (b). It is worth mention that shape of the ceilings of both rooms are suitable where it did not cause any defects.



Room LR



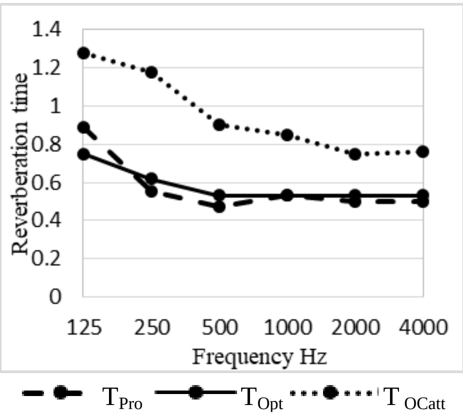
Room DH

Fig.10. The total absorption for T_{OCatt} and T_{opt}

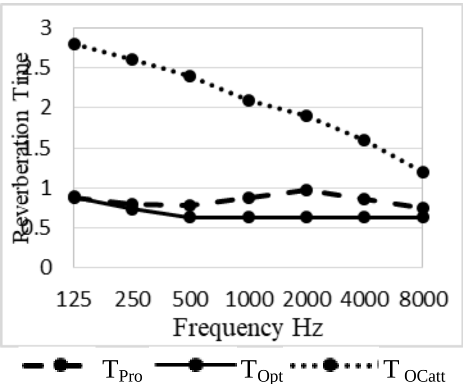
2.3 Proposed Solution for Enhancement

The results clarified that reducing the high ambient noise can’t be done so long as the rooms’ ventilation is relying on the windows, however, the alternate solution that is A/C system is not available for the cost wise. Thus, the ground of the proposed solution for both rooms is to replace the reflective materials at the rear surfaces by sustainable absorbents.

The results of the solution of each room were compared with the results for the base case. The comparison showed that the proposed solutions noticeably enhance the acoustic performance of both rooms. It is observed in



b. Room DH



b. Room DH

Fig.11. T for the current situation, optimal value and the proposed solution

Fig.11. that the values of reverberation time for the proposed solution at each room have decreased and become very close to the optimal values at all frequencies.

The suggested solution used EchoPanel which meet LEED requirements for green buildings, and manufactured from 100% of recycled plastic bottles, it is sustainable, recycled, and green. The absorption coefficient of selected panels met the acoustics requirements for both rooms. It varies from 0.25 with panels with no air gap, till 0.85 with 50mm air gap. It can be used for walls decoration or false ceilings, with thickness 7mm, 12mm and 24mm in a variety of colours, many prints and cuts Fig.12. [24] .

As a result of reducing T_o in the rooms, an obvious enhancement in the speech intelligibility at both rooms were obtained at all recipients who become in the good zone, Figs. 13(a), 14 (a). Due to the correlation between T_o and C50, the clarity has raised in a rage of 2-8 dB at room LR and 4-9dB at room DH.

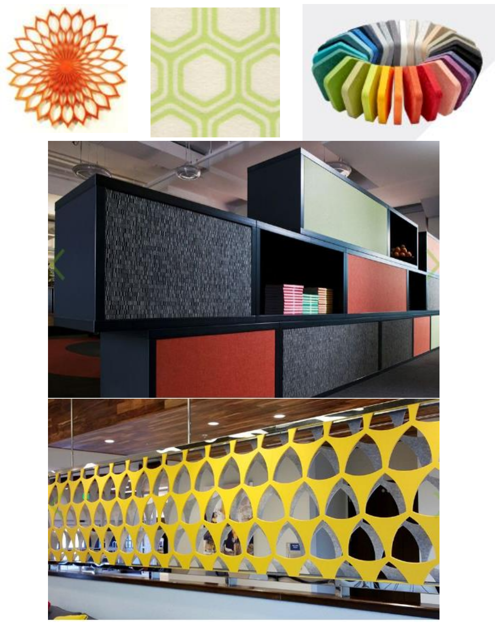
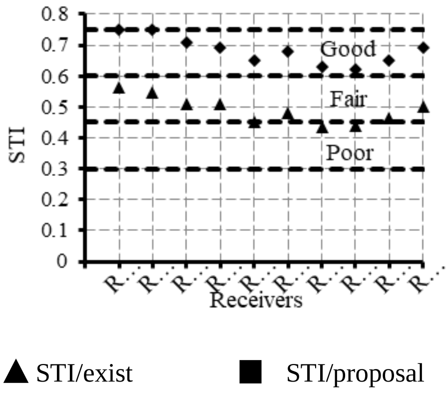
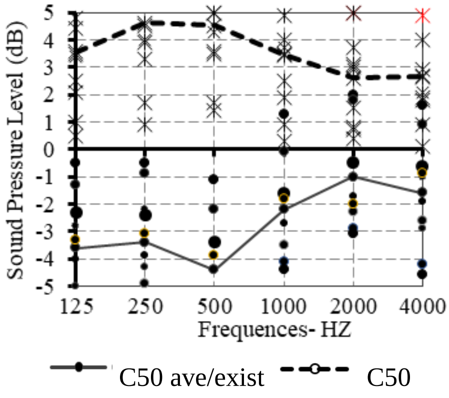


Fig.12. EchoPanel; patterns, cuts, and applications

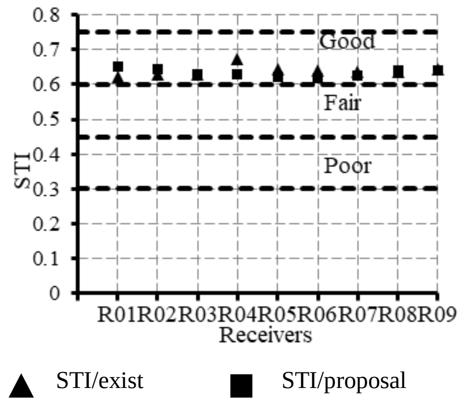


a. STI

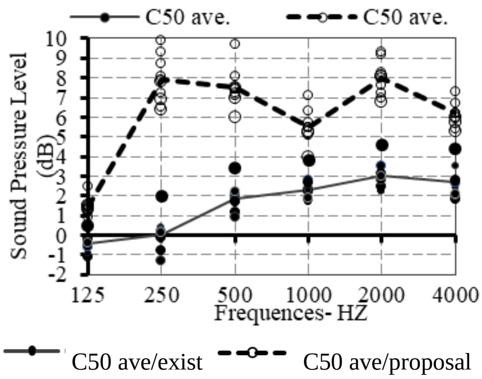


b. C_{50}

Fig.13. STI and C50 for room DH



a. STI



b. C50

Fig.14. STI and C50 for room LR

3 CONCLUSIONS

The outcomes of this study verify that using appropriate absorbents at the rear walls enhance the speech intelligibility inside the lecture auditoria, which decrease of late reflections and high reverberation time to the optimum value. Notwithstanding the above, the poor clarity and STI can't be enhanced without minimizing the ambient noise.

As per the field reconnaissance, almost all internal surfaces of the examined rooms are reflectors, in that both of them are high reverberant rooms. Room shape analysis based on the geometric acoustic illustrated that each room includes three acoustic zones, good, fair and hard. The parallel reflective longitudinal surfaces of room DH cause flutter eco, in that absorptive materials are required to partially add to eliminate this issue. The measurements showed that L (Nc-60& 65) in rooms LR and DH, respectively, are exceeding the maximum accepted level for lecture auditoria (Nc-35) by about 30 dB in the frequency ranges significant for speech intelligibility. Consequently, sound insulation of the windows is a restrict requirement to improve the acoustic performance of both rooms, which needs replacing the natural ventilation to A/C system. The analysis clarified that T_o in both rooms exceeds the optimum reverberation time at all frequencies, i.e. For room LR T_o is 55% higher than T_{opt} at low and mid frequencies, and 15% at and high frequencies. While T_o in room DH exceeds T_{opt} by about 250% at low and mid frequencies, and 85% at high frequencies, in that the worse results of room DH can be justified for its huge V_P which reach $19m^3/P$. Thus, C_{50}, STI are low, particularly for the extent recipients.

The analysis and discussion clarified that room LR needs about 1.7 times its recent total absorption at all frequencies. While room DH needs about 2.7 times at all frequencies except at 500 HZ at which needs about 4 times its recent total absorption at all frequencies. Enhancement solutions for the two rooms have been proposed and examined using CATT, in which the concept was to add an efficient sustainable absorbent for achieving the optimum reverberations time without affecting the useful reflections. The sound transmission class of the windows has improved as well. The proposals results showed that T_o in the examined rooms reduced to touch T_{opt} when two highly absorbents were covered the rear and back walls. Consequently, SI has improved in both rooms at all frequencies, in which STI values became good and clarity increased in a range of 2-8 dB at room LR and 4-9dB at room DH.

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دراسة حالة: تحسين الأداء الصوتي لغرف المحاضرات باستخدام مواد مستدامة

تحلل هذه الورقة قاعتي محاضرات في كلية الهندسة، جامعة حلوان، القاهرة. ركز البحث على استخدام المسح الميداني لتحديد القياسات المعمارية والصوتية، تليها محاكاة رقمية باستخدام CATT لكلا القاعتين. تم توفير علاجات مستدامة لتحسين البيئة الصوتية للعملية التعليمية وتم اختبارها مرة أخرى باستخدام CATT. يشير التحليل والمحاكاة إلى أن كلتا القاعتين تعانيان من ضعف الصوتيات بسبب ضوضاء المنطقة المحيطة واختيار مواد التشطيب. يتمثل أحد الحلول الممكنة لهذه المشكلة في استخدام مواد ماصة مستدامة جديدة لزيادة الامتصاص إلى الحد الأقصى وتقليل وقت الارتداد المفرط إلى قيم مقبولة وزيادة الانعكاسات المبكرة والقضاء على مناطق الظل التي تعمل على تحسين وضوح الكلام لكل المستقبلين.