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Classroom acoustics: a case study of the cost-benefit of retrofitted interventions

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It is known that classroom acoustics is important for effective learning. To this end, many countries have developed classroom acoustics standards. However, research shows that these standards are often not implemented. Research evaluating the implementation of classroom acoustic standards internationally concludes that successful implementation is driven by mandatory standards that are part of building codes and that the cost of compliance is a barrier. The study presented here explores the cost of upgrading classrooms to achieve a suitable reverberation time. The paper presents a case study in South Africa, where acoustic standards are generally not implemented and cost and know-how are barriers. The objective was to optimise the cost, acoustic benefit, and accessibility of acoustic interventions. Four different acoustic interventions were temporarily installed in a classroom, simulating floating sound-absorbing ceiling panels constituting 25% of the ceiling area. The weighted sum model was used to assess the suitability of each intervention, taking into account the cost, acoustic benefit (in terms of reverberation time) and ease of access to purchase the materials. The case study demonstrates that a noticeable improvement in acoustic conditions can be achieved without significant cost and provides a basis for further research to develop simple standardised design recommendations.

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1. INTRODUCTION

Classroom acoustics refers to the behaviour and quality of sound within a classroom. The quality of the acoustic environment is known to influence learning outcomes [1] and is therefore an important, yet often neglected, aspect of classroom design. It is known that appropriate classroom acoustics is important for effective teaching and learning. To this end, many countries have developed classroom acoustics standards. These standards recommend an unoccupied continuous equivalent sound level of between 35 dB and 40 dB and a reverberation time between 0.4 s and 0.7 s [2].

Despite these standards, research shows that they are often not implemented and that many classrooms have poor acoustics. Research evaluating the implementation of classroom acoustic standards internationally concludes that successful implementation is driven by mandatory standards that are part of building codes; the cost of compliance and practical guidelines are recognised as barriers [2].

This study aims to provide evidence to inform design guidelines and overcome cost and practicality barriers. The study was designed to explore the cost of various simple and easily accessible interventions that achieve suitable acoustic conditions in classrooms, particularly in terms of reverberation time.

A SOUTH AFRICAN CONTEXT

The study considers the acoustics of classrooms in South Africa, where acoustic quality is not a requirement of the National Building Regulations and therefore is not a mandatory design consideration for classrooms. The South African National Standard, The measurement and rating of environmental noise with respect to annoyance and to speech communication (SANS 10103:2008), is the only local standard that provides any reference to classroom acoustics but only in terms of design ambient noise levels (35 dBA). The standard is not mandatory and does not refer to reverberation time, which is a significant factor that influences speech clarity and noise.

The Minium uniform norms and standards for school infrastructure, published by the Department of Education, also provides a minimum background noise level a reverberation time of 0.6 to 0.7 seconds [3], but this is not enforced or monitored post-construction. Local case studies indicate that classrooms in South Africa do not meet standards in terms of ambient noise level or reverberation [4][5][6][7].

It is not clear why classroom acoustics receives little attention in South Africa, although anecdotal evidence indicates that it is perceived to be difficult and costly, requiring specialist input.

B STUDY CONTEXT

This study uses a recently constructed science centre as a case study site. The Albertina Nontiskelelo Sisulu Science Centre is located in the small rural town of Cofimvaba in the Eastern Cape, South Africa. It was commissioned by the National Department of Science and Innovation and is occupied by the provincial Eastern Cape Department of Education. The location is 75 km from the nearest big town and 168 km from the nearest city. The purpose of the Science Centre is to provide access to teaching spaces and resources for schools in the district. It includes offices, a small planetarium, a large exhibition hall, four standard classrooms and two teaching pods.

The building was constructed using innovative building technologies, rather than the conventional brick and mortar construction commonly used in South Africa. Although the building envelope is unconventional, the size and interiors are typical of classrooms in South Africa, with a floor area of 46 m2, with vinyl flooring, plastered and painted walls, and a gypsum ceiling. The reverberation time in the classrooms is noticeably high, making it difficult to hear or be heard if there is any other noise or disturbance in the classroom.

The experiment was carried out as part of a citizen science programme, which involves students from local high schools in real-life science activities. The recommendations of this study will be presented to the National Department of Science and Innovation, who commissioned the Science Centre, as a proposal to improve performance.

2. METHODOLOGY

The objective of this study was to optimise the cost, acoustic benefit and accessibility of acoustic interventions, answering the questions:

a. Which material is most effective in reducing reverberation time?
b. Which material is the most cost-effective?
c. Which material is most accessible to purchase?

The methodology used was experimental in nature, installing four different material interventions and measuring their impact on the reverberation time relative to a control case to establish which was the most effective. The control case was the existing classroom without interventions. The cost and availability of the materials were then factored into a weighted sum model to determine which material is optimal.

A EXPERIMENTAL SET-UP

To reduce reverberation time in the classroom, sound-absorbing materials were introduced. Considering that the walls are all taken up by windows, doors, and screens, treating the walls was not an option. The floor is vinyl sheeting and takes a lot of traffic and movement of the furniture, so it was also deemed impractical to treat the floors. This reflects the situation in most classrooms. It was decided to treat the ceiling area by installing panels containing sound absorbing material.

To minimise disruption, it was originally proposed that floating panels would be suspended from the existing ceiling, as illustrated in Figure 1. This was intended to become a permanent installation in each of the four classrooms with different sound absorbing materials installed in each. However, due to concerns about the ability of the existing ceiling structure to hold suspended panels, the construction of the experiment was changed to simulate a similar effect temporarily in one classroom.

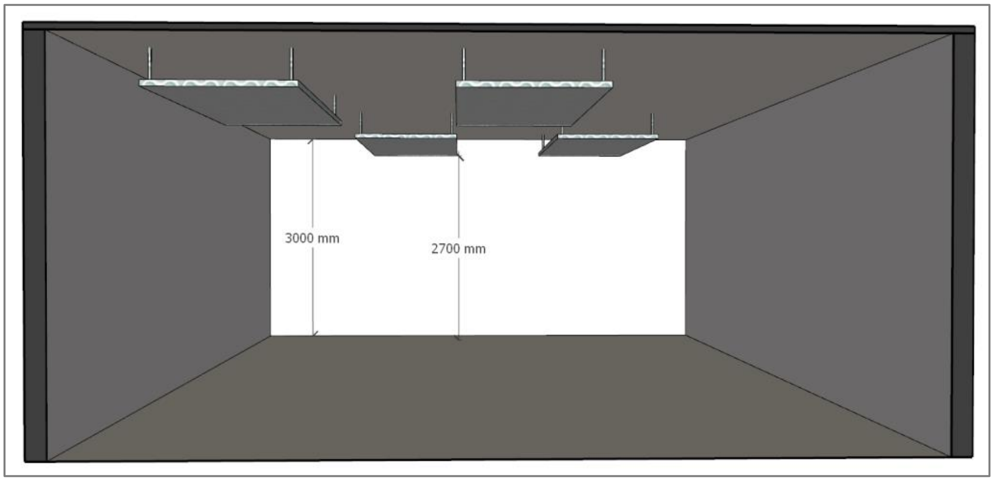

Figure 1. Illustration of proposed floating ceiling panels (author's illustration).

Temporary steel structures were erected on top of which aluminium frames were installed to hold the four intervention materials (see figure). Four aluminium frames of 2400 mm x 1,200 mm each were used, providing a total sound absorbing panel area of 11.52 m2 (25% of the ceiling area). One at a time, each of the four intervention materials was installed and the reverberation time was measured with each intervention.

The four materials used included acoustic ceiling tiles, representing a typical industry solution, and three do-it-yourself solutions using carboard egg cartons, thermal insulation batting, and sponge, all of which are easily available at regular retail stores. The detailed specifications of each are listed in Table 1.

Table 1. List of material interventions used.

Intervention material	**Specification**	**Installation description**
Material 1: Acoustic ceiling tiles	Tile size: 600 mm x 1200 mm x 15 mm (x 16 tiles) Weight: 5 kg/m^2 Sound reduction index: 31 dB Sound absorption NRC: 0.75	Number of tiles: 16 Total area: 11.52 m^2 These would normally be laid in T-hangers but for the purpose of this experiment they were laid loose, butting up against each other inside the aluminium frame.
Material 2: Thermal insulation batting	Isotherm™ PET thermal insulation batting Roll width: 1200 mm Thickness: 50 mm Weight: 0.54 kg/m^2 Density: 8.5 kg/m^3	Cut into 4 sheets of 2400 mm x 1200 mm Total area: 11.52 m^2 This flexible batting was laid inside the aluminium frames on top of thin polycotton fabric starched over the frame to provide a surface for the batting to rest on.
Material 3: Egg cartons	Size: 300 mm x 300 mm Weight: 1 kg/m^2	Total area: 11.52 m^2 128 egg cartons were laid inside the aluminium frames on top of thin polycotton fabric starched over the frame to provide a surface for the trays to rest on.
Material 4: Foam (not specialised acoustic foam)	Three-quarter bed mattress, medium density Size: 1880 mm x 1070 mm Thickness: 150 mm Weight: 3 kg/m^2 Density: 20 kg/m^3	4 mattresses were used. Total area: 8 m^2 The intention was to use a foam sheet of the same dimensions as the thermal insulation. However, foam of the same dimensions was not accessible in regular retail stores. Instead, a standards ¾ bed mattress was used, which was not the same size.

B ANALYSIS METHOD

Data were analysed to determine which material is the most efficient in terms of acoustic effect, cost, and accessibility. The weighted sum model was used to assess the suitability of each intervention, taking into account the cost, acoustic benefit (in terms of reverberation time), and ease of access to materials. This method is used for decision making when there are multiple criteria.

C MEASURING METHOD

The reverberation time was measured according to the methodology of the South African National Standard, SANS 3382-2:2014 (which adopts ISO 3382-2:2008). The minimum requirement for a survey method, assuming a simple geometry, is one sound source position, at least two microphone positions, and at least two decay measurements per microphone position.

In this study, three microphone positions were used. The locations were determined, according to SANS 3382-2, to be more than 2 m from the sound source, more than 1.5 m from any boundaries, and more than 1.5m away from each other, as shown in Figure 2.

An omnidirectional loudspeaker was placed in the corner of the room and remained in the same position throughout the procedure. For each measurement, four FFT time windows of 2.73 seconds each were averaged together. This provided a total of 10.92 seconds of pseudo-random pink noise for the integrated impulse response method. The background noise level was sufficiently low to produce enough level to record the decay time.

For each scenario, six measurement results were arrhythmically averaged together to provide overall comparative results.

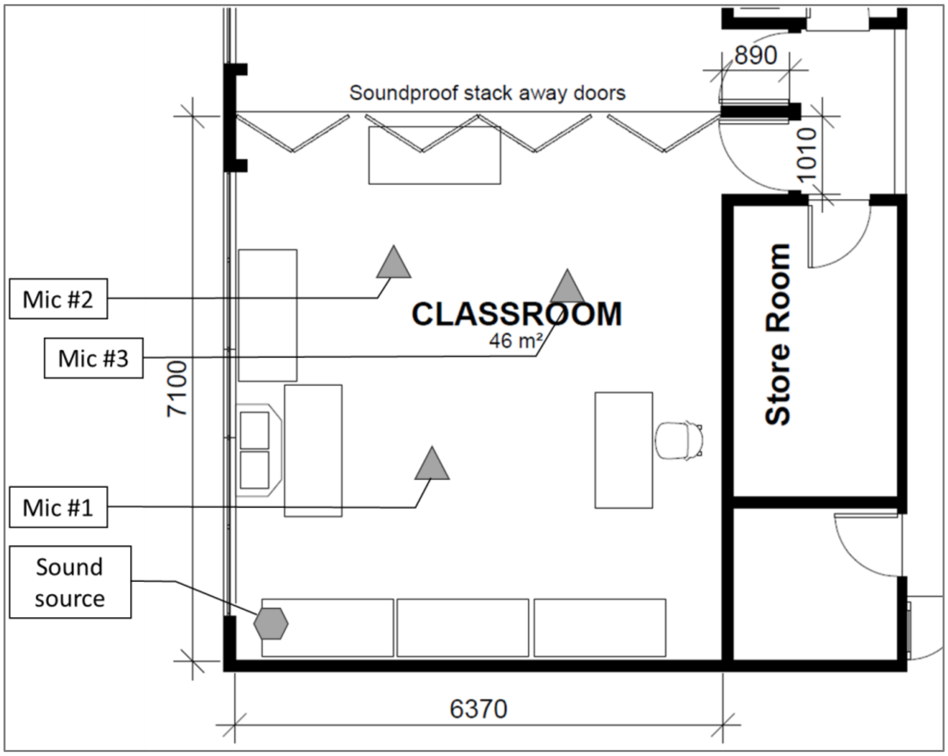

Figure 2. Diagram illustrating position of sound source and microphones

3. RESEARCH

A EXPERIMENT SET-UP

The experiment was set up according to the methodology. One of the four identical classrooms was selected as the case study location. Two fold-up steel structures (gazebos) were set up to support the aluminium panels and material interventions, as shown in Figure 3.

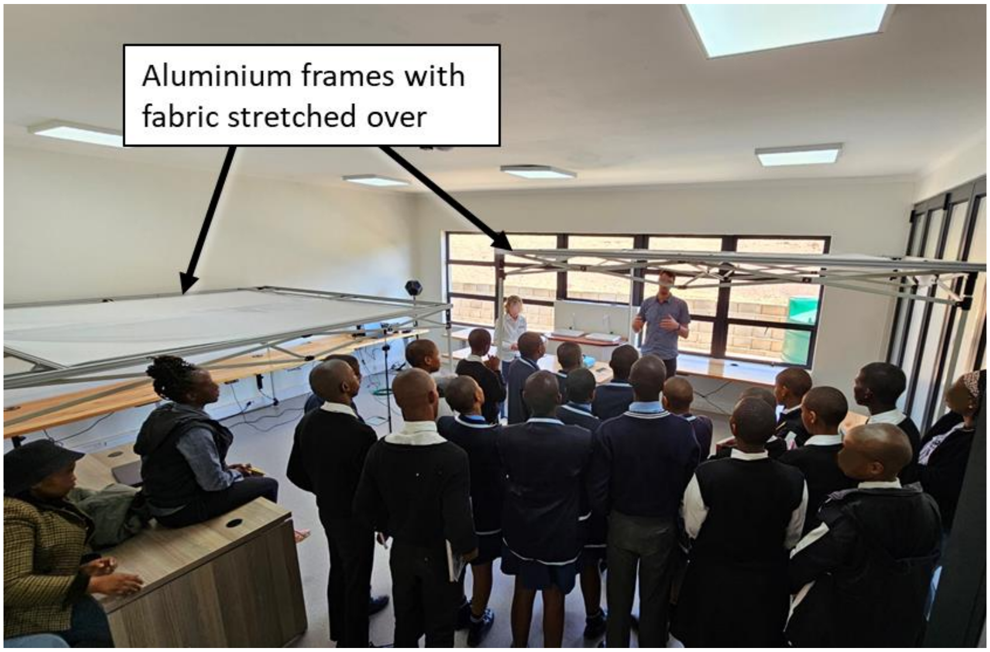

Figure 3. Photos of gazebos being set up in the classroom.

The gazebos were 3000 mm x 3000 mm each and were raised to a height of 2400 mm above floor level once the intervention materials had been installed; two aluminium frames of 2400 mm x 1200 mm each were placed on top of each gazebo, providing a sound absorbing panel area of 11.52 m2. Each material was installed within the aluminium frames, as shown in Figure 4.

Figure 4. Photos of each intervention being installed.

B ACOUSTICS RESULTS

I. REVERBERATION TIME

The baseline reverberation time was measured without occupants in the room, except for the measurement operator, and without interventions. This provided a control-case reverberation time (RT60) of 1 second on average, with the peak reverberation being 1.9 seconds at 250 Hz. A baseline was also measured with the fully occupied (25 people), resulting in RT60 of 0.7 seconds, demonstrating that the occupants make a significant difference in the reverberation time. However, to eliminate uncontrolled variables, all measurements with interventions were taken without occupants in the room. RT60 was measured for each material intervention. The results are shown in Table 2.

The results shown are an average reverberation time across the spectrum of 20 Hz to 20 kHz and show that the material resulting in the lowest (most favourable) reverberation time was the foam mattress, with a reverberation time of 0.6 seconds, which is within the recommended range of 0.4 to 0.7 seconds. When considering the average reverberation time, it is noted that the Isotherm, egg cartons, and acoustic tiles behave equally, also noting that the values are rounded to one decimal place. It should be noted that low frequency standing waves were present and that repeated readings could have provided different results.

Table 2. Average reverberation time for each condition over full spectrum.

CONDITION:	**Baseline (with students)**	**Baseline (empty)**	**Isotherm**	**Foam Mattresses**	**Egg cartons**	**Acoustic Tiles**
Reverberation time (RT60) (seconds):	0.7	1.0	0.8	0.6	0.8	0.8

The measured results at 1/3 octave band resolution are depicted in Figure 5.

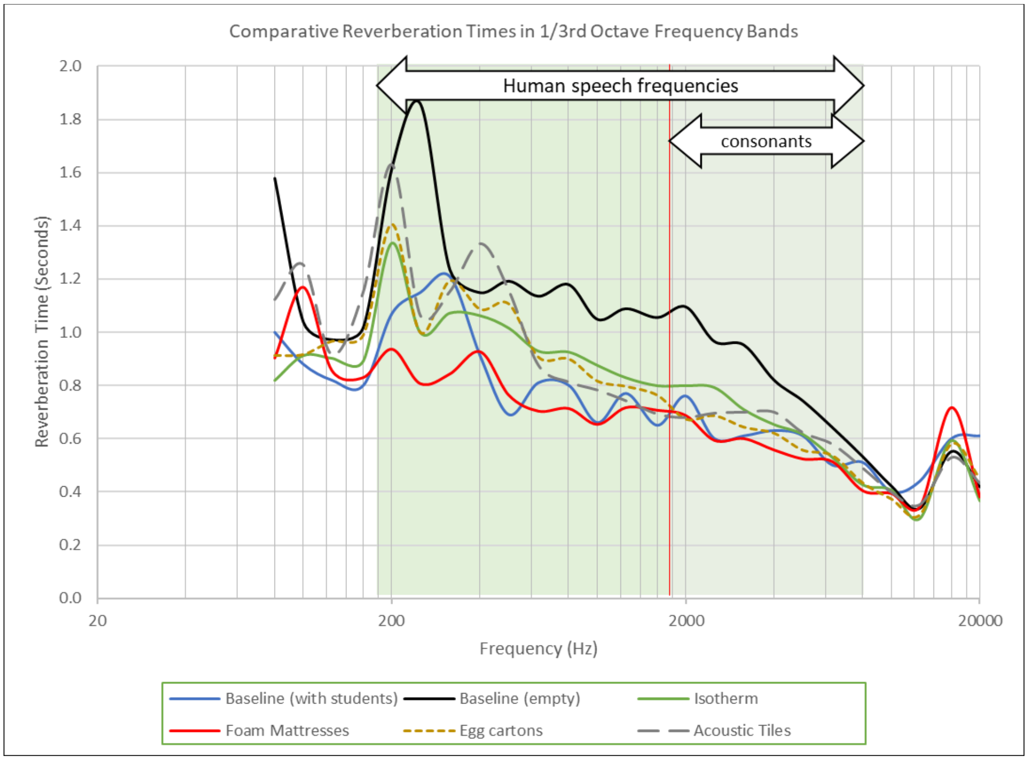

Figure 5. Graphic representation of measured reverberation time of each condition over frequency spectrum.

Considering that human speech range is 177 Hz to 5 654 Hz, and that consonants range is 1600 Hz to 5654 Hz, which influences speech clarity, it is necessary to consider the reverberation results in detail with reference to frequency.

As can be seen in the graph in Figure 5, the foam mattress performed the best in terms of lowering the reverberation time throughout the frequency spectrum, followed by the egg cartons. All four materials behaved similarly in the higher frequencies spectrum, but the foam mattresses performed significantly better at lower speech frequencies.

II. SPEECH TRANSMISSION INDEX

The speech transmission index (STI) is defined by IEC 60268-16:2011, and also the South African National Standard SANS 60268-16:2014, as an objective measure to predict the intelligibility of speech transmitted from a talker to a listener. STI is expressed as a value between 0 and 1 with 1 being perfectly clear transmission and 0 being very poor clarity. Despite limitations in the methodology, STI is a widely used metric to assess speech intelligibility and, since it is affected by reverberation, is also an indicator of the suitability of the room design in terms of geometry and material.

It is not surprising that the results of the STI measured in the room (see Figure 6) closely resemble the results of the reverberation time, with the foam mattresses producing the best STI (0.63) and the other three materials performing equally considering the full spectrum (0.59).

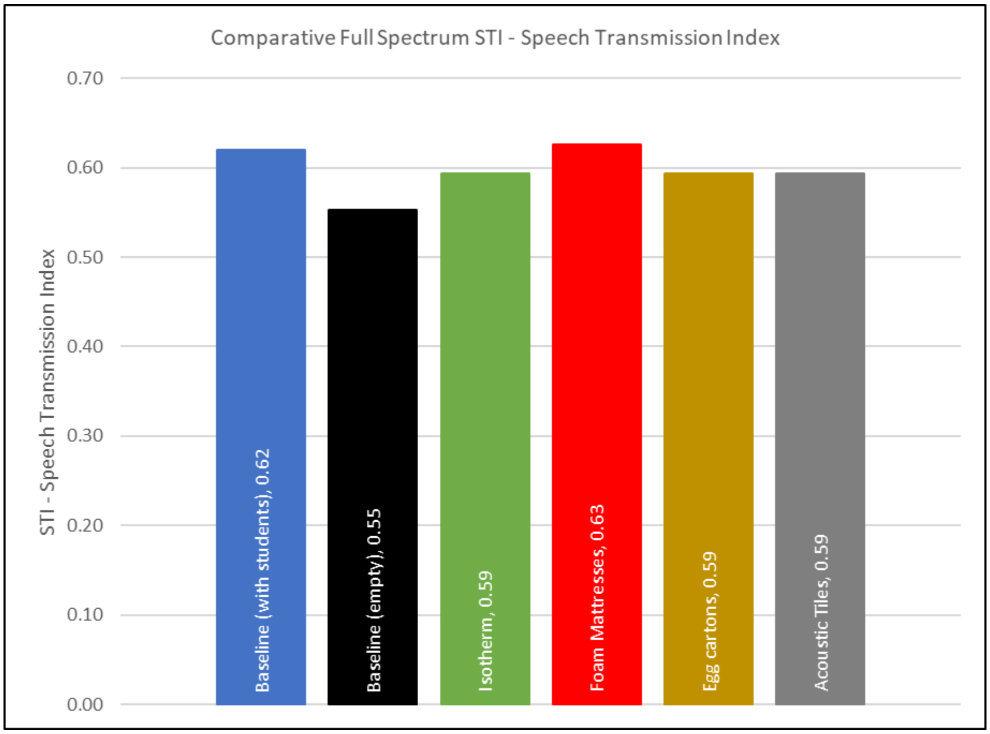

Figure 6. STI results measured for each material intervention relative to the baseline measurement(s).

Considering the STI per octave band, the foam performs best at lower frequencies and very similarly to the other materials at higher frequencies (see Figure 7).

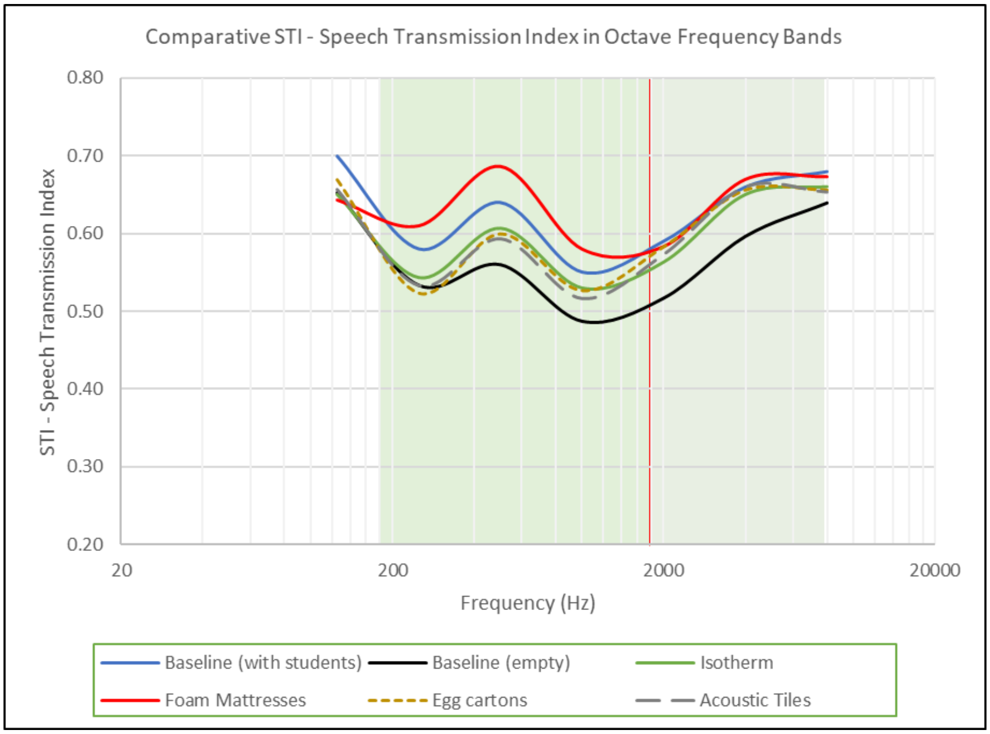

Figure 7. STI per octave band.

III. ABSORPTION COEFFICIENTS

Absorption in a room is directly related and indirectly proportional to the reverberation time in a room, since reverberation time is dependent on sound reflections, which is the opposite of sound absorption. Although one might assume that very low reverberation and very high absorption would result in very good STI, Nijs et al. suggest that overdamping (i.e., too much absorption) can negatively affect speech intelligibility and recommend a room absorption coefficient between 0.45 and 0.55 for a typical classroom [8].

The room absorption coefficient in the control case was 0.13, which is correlated with the high reverberation time experienced. With the material interventions, this changed to between 0.16 and 0.2 over the full spectrum (see Figure 8). It can be concluded that even with interventions, the room still showed an overall absorption coefficient that is not ideal for speech clarity. Again, the foam material intervention resulted in the best results when considering the full spectrum; however, when considering the performance per octave or third-octave bad, the Isotherm showed the highest absorption coefficient at high frequencies (see Figure 9).

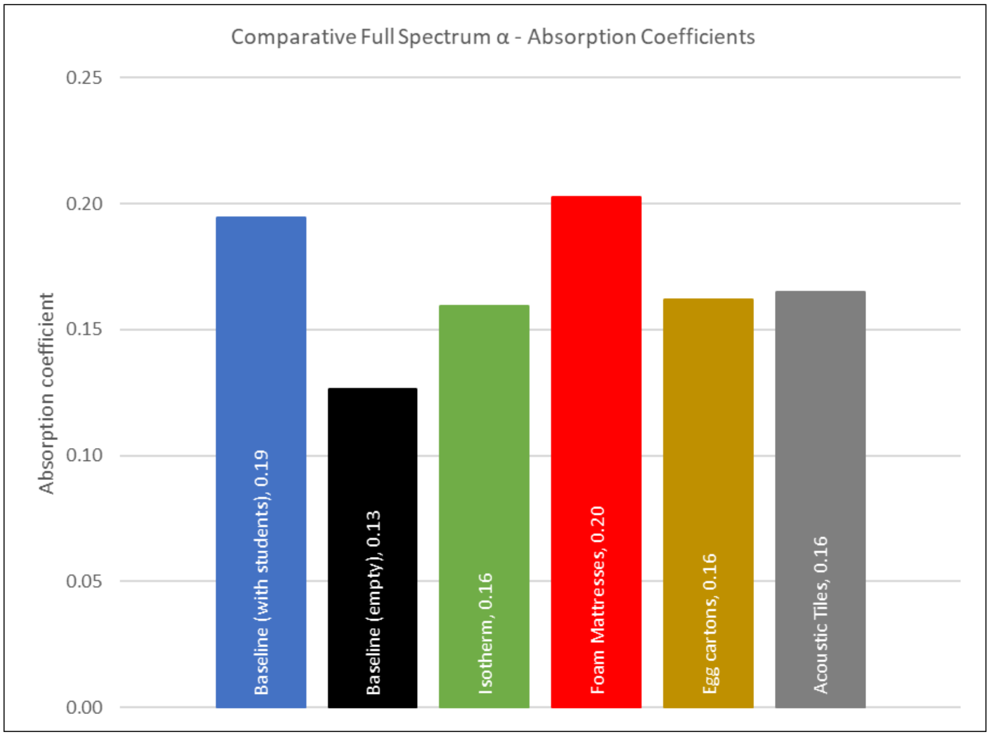

Figure 8. Absorption coefficient of each case over full spectrum.

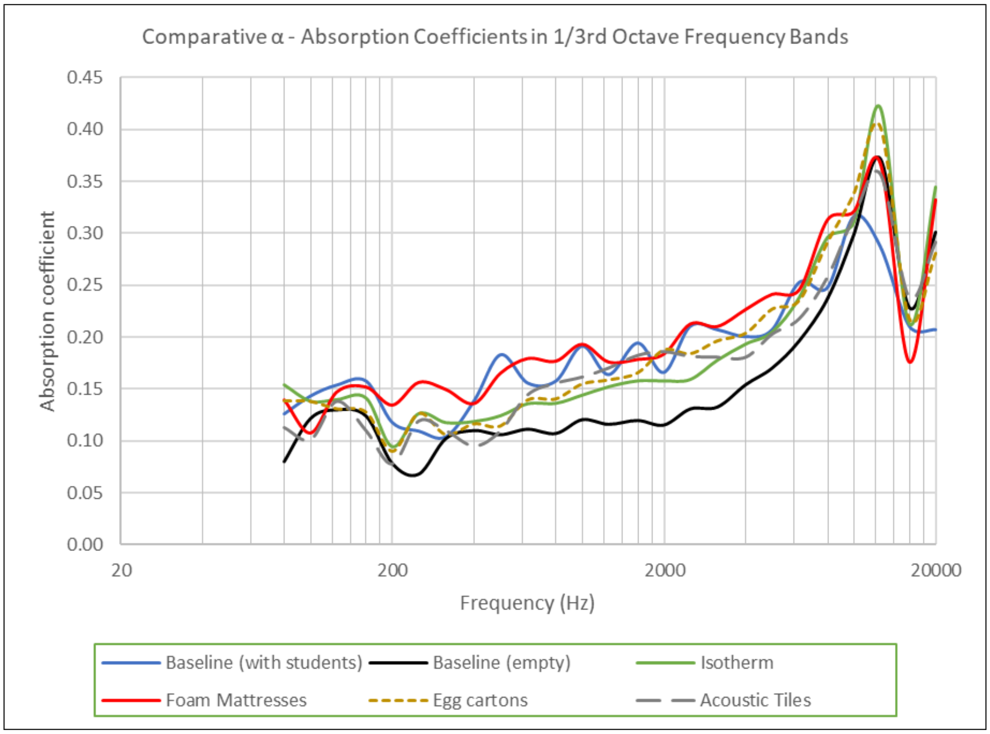

Figure 9. Absorption coefficients of each case in third-octave bands

C COST

The costs of each material are listed in Table 3. The cost has been reduced to a cost per square meter to allow a fair comparison, considering that the foam mattress area was less than the area for the other materials.

Table 3. Summary of cost of each material reduced to a cost per square meter.

MATERIAL	**Isotherm**	**Foam mattress**	**Egg cartons**	**Acoustic tiles**
Area (m^2)	11.52	8.05	11.52	11.52
Cost (ZAR)	R 549.00	R 1 960.00	R 256.00	R 4 191.52
Cost/m^2 (ZAR)	R 47.66	R 243.59	R 22.22	R 363.85

The most inexpensive material used was the egg cartons, at R 22.22 per square metre, relative to the most expensive material, which was the acoustic ceiling tiles as R 363.85 per square meter. Considering that egg cartons are potentially available at no cost as waste items, this makes egg cartons even more attractive.

D AVAILABILITY

The availability of materials was evaluated in terms of distance (straight-line radius) to supply and whether or not the product is available in a retail store or requires a special order and delivery.

Noting that availability and ease of access to materials may differ in different locations, this study considered how easy it was to source each material for use at the specific case study site.

Isotherm was ordered online from a nationwide retailer that has a footprint in most cities and large towns in South Africa. Although the Isotherm was actually purchased in Gauteng Province and transported to the site in the Eastern Cape (due to institutional procurement limitations), it could easily have been purchased by walk-in from the local hardware store, within a 2 km radius of the site.

Egg cartons were ordered online from a packaging company in Gauteng Province and transported to the site. A regional packaging supplier could also have been used within a 150 km radius. For the purpose of this exercise, it is assumed that egg cartons were purchased and not sourced from waste.

The intention was to use normal foam (not acoustic foam) of the same size and thickness as the Isotherm. However, it was difficult to find a supplier with stock and that could deliver so the material was substituted for foam mattresses that could be purchased by walk-in at a local retailer within a 5 km radius of the site.

The acoustic ceiling tiles were purchased via an online order from an acoustic solutions supplier. Despite their national footprint, the materials were delivered from their warehouse in Gauteng Province and transported to the site, within a 700 km radius of the site.

Each material was also evaluated for ease of access in terms of whether it could be purchased from a regular (walk-in) retail store or whether is needs to be ordered online and delivered. The results are included in Table 4.

Table 4. Tabulation of distance from supplier to site for each material.

MATERIAL:	**Isotherm**	**Foam mattress**	**Egg cartons**	**Acoustic tiles**
Radius of supply:	> 5 km	> 5 km	> 150 km	> 700 km
Available at walk-in retail:	Yes	Yes	No	No

E ANALYSIS

The findings summarised in Table 2, Table 3 and Table 4 were used to perform a weighted sum analysis. Each attribute was assigned an equal weighting of 0.25. All the attributes were considered non-beneficial (i.e. a lower value is desirable) because the objective was to find a solution that produces a low reverberation time, has a low cost, and a short distance to supply. Numerical values were assigned to the attribute of retail walk-in availability (Yes = 1, No = 2).

The values were normalised relative to the minimum values per attribute, as shown in Table 5, and multiplied by the weighting.

Table 5. Normalising values of attributes relative to minimum.

MATERIAL	**Reverberation time**	**Cost/m^2**	**Radius of supply**	**Walk-in availability**
weight	**0.25**	**0.25**	**0.25**	**0.25**
Isotherm	0.6/0.8	22.22/47.66	5/**5**	1/**1**
Foam Mattresses	0.6/**0.6**	22.22/243.59	5/**5**	1/**1**
Egg cartons	0.6/0.8	22.22/**22.22**	5/150	1/2
Acoustic Tiles	0.6/0.8	22.22/363.85	5/700	1/2

The performance score, which resulted from multiplying the normalised values by the weighting, and their ranking is shown in Table 6. Isotherm is ranked as the best overall performing material.

Table 6. Performance scores and ranking.

MATERIAL	**Reverberation time**	**Cost/m^2**	**Radius of supply**	**Walk-in availability**	**Performance score**	**Rank**
weight	**0.25**	**0.25**	**0.25**	**0.25**		
Isotherm	0.1875	0.12	0.25	0.25	0.80	1
Foam Mattresses	0.25	0.02	0.25	0.25	0.77	2
Egg cartons	0.1875	0.25	0.00833	0.125	0.57	3
Acoustic Tiles	0.1875	0.02	0.00179	0.125	0.33	4

4. DISCUSSION AND CONCLUSIONS

The case study demonstrates that a noticeable improvement in acoustic conditions can be achieved without significant cost and provides a basis for further research to develop simple standardised design recommendations.

Although the foam mattress performed the best in terms of reducing reverberation time, when all other factors are considered, such as cost and ease of access to materials, the PET batting, Isotherm, proved to be the optimal solution. The Isotherm did not achieve a reverberation time within the recommended range of 0.4 to 0.7 seconds, which, it may be argued, should disqualify it. However, in the critical speech frequencies, it achieved an average RT60 of 0.7 seconds. Although weight was not factored into the model, Isotherm is the lightest material tested, which is another aspect in its favour.

The foam mattress displayed the best acoustic performance, despite being smaller in area. This could be attributed to its inherent properties or it could be due to its thickness, being more than twice the thickness of any other materials tested. It is recommended that the experiment be repeated using foam with thickness and surface area matching that of the Isotherm.

The acoustic ceiling tiles performed poorly, which was unexpected since they are specifically designed to absorb sound. This could be due to the method of installation; acoustic tiles are usually installed as part of a fixed ceiling system, and as such, some of the sound absorption properties are achieved through panel absorption, rather than purely dissipative absorption.

The egg cartons performed better than expected, having little thickness. It is posited that the main property reducing reverberation is in this case is diffusion, due to the profiled shapes in the egg cartons.

In conclusion, it can be said that the acoustic condition of an existing classroom can be improved without a high-cost or disruptive construction. Provided that the ceiling battens are structurally able to support weight, floating sound absorbing panels can easily be fitted at a relatively low cost. Guidelines regarding the area, absorption coefficient, and construction details of such acoustic interventions should be developed and made easily available to designers and school planners to help improve the acoustics in classrooms, whether new or existing, and in so doing, support learning outcomes of the pupils.

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