Original Article

# The noise insulation properties of non-food-crop walling for schools and colleges: A case study

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**ABSTRACT** The use of sustainable materials in building design and renovation has been driven by government initiatives such as the Code for Sustainable Homes, BREEAM and other assessment techniques. This paper presents the results from *in situ* measurements of insulation against unwanted sound (noise) for a sustainable walling system that has much anecdotal commentary concerning its good sound-insulating qualities: straw bale walls. The case study building in which the measurements were conducted is the Genesis Centre, an educational facility in Somerset. Schools need to be acoustically effective buildings, as pupils and students need to concentrate to take part in the education process. Sound insulation measurements were undertaken according to ISO 140: 4 – 1998 and Approved Document E (ADE) procedure, or as close to these standards as possible given the 'as built' nature of the case study buildings. With due regard for the limitations that an *in situ* measurement case provides, the acoustical data collected from these tests suggests that it is possible for straw bale walls to achieve the minimum requirements of Part E with a range of values of 48–50 dB $D_{nT,w}+C_{tr}$. These results are also compared with guidelines related to acoustics in schools and robust details.

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**Keywords:** non-food-crops; straw bale walls; sound insulation; sustainable building materials; schools

## RATIONALE FOR SUSTAINABLE MATERIALS

Most construction materials used in the United Kingdom are mass produced in large-scale operations, often a great distance from their end use. Products such as bricks/blocks, cement and concrete contribute to environmental impacts through production/demolition/disposal processes. However, there are now certain drivers, many emanating from governmental initiatives that are having a major influence on construction theory and practice. Most are directly connected to the rise of the ethos of sustainable construction, (Desarnaulds *et al*, 2005) and the accepted need for reductions in global carbon dioxide ($CO_2$) emissions. This is articulated by the UK Government's commitment to targets to reduce greenhouse emissions from 25 per cent in 2025 to 60 per cent in 2050 (Dale, 2007). This can be seen as the result of efforts to meet the targets of the first stage of the Kyoto Protocol which is drawing to a close in 2012, at which point the United Kingdom has pledged to have reduced its $CO_2$ emissions by 12.5 per cent of 1990 levels (DEFRA, 2007).

Despite the existence of these drivers there are barriers (CIB, 1999) that stop construction professionals designing and constructing buildings that are appropriate to the needs of their end users and the planet as a whole. If practical, $CO_2$ and environmental savings could be achieved by using locally sourced natural materials for wall constructions (Jones, 2001). However, the dearth of credible data and the lack of a knowledge base that flows from experience with working with sustainable construction materials acts as a barrier to designers and other building professionals, concerning the use of more unusual but sustainable materials and details. Further barriers include market trends and also designers wishing to stick to what they know best (Braithwaite and Cowell, 2007). Recently, more specific data and knowledge are being disseminated with regard to the thermal and durability aspects of sustainable walling systems, (Goodhew *et al*, 2004) However, information related to the acoustic performance of these materials, is limited.

The aim of this article is to report the sound insulation properties of a sustainable construction technique, straw bale walling systems, using field measurements undertaken in a real building in a live and 'in use' situation. The case study building is a series of seminar rooms, relevant not only because of the large number of academic buildings currently being built, but also because of the sensitivity of the internal and external aspects of this use to good sound insulation. Performance aspects such as thermal comfort, $CO_2$ levels and ventilation, lighting, as well as acoustics have all been accepted to have a direct relation with student learning and well-being, making this a good choice of case study.

The results give an insight as to whether or not the tested materials achieve the requirements of Schedule 1 of the Building Regulations, 2000 (as amended by SI 2002/2872) and therefore, whether they are, in sound insulation terms, a viable alternative to more accepted modern methods of construction. Examples of these are described in Diagram 2.1 of Section 2 of Resistance to the Passage of Sound (DGLG, 2004).

## STANDARDS, LEGISLATION MEASURED VALUES AND GUIDELINES CONNECTED WITH THE STUDY

The work reported in this article measures airborne sound transmission from live examples. In order for the results to be credible and have any relevance to designers/specifiers, there are a number of procedures and guidelines that should be

**Table 1:** Minimum sound insulation performance values for separating walls

| *Position and type of partition* | *Standardised level difference, $D_{nT,w}$ (level in dB taking into account reverberation time) weighted for the third-octave band centred on the frequency of 500 Hz plus a correction factor $C_{tr}$ to take account of a specific sound spectra* |
|---|---|
| Separating walls between dwelling houses and flats | 45 dB $D_{nT,w} + C_{tr}$ |
| Separating walls between rooms for residential purposes | 43 dB $D_{nT,w} + C_{tr}$ |

followed. These include BS EN ISO 140 – 4: 1998, test method, BS EN ISO 717 – 1: 1996 for acquiring a single-figure result from the test measurements, and Annex B of ADE, Resistance to the Passage of Sound (DGLG, 2004) for procedure. The single-figure measured value uses the weighted standardised level difference, $D_{nT,w}$. $D$ denotes the difference, in decibels, between the average sound pressure level in the source room and the average sound pressure level in the receiving room. The subscript $nT$, refers to the level corresponding to absorption areas with respect to a reference absorption area of 10 m$^2$ and reverberation time in the receiving room with respect to a reverberation time of 0.5 seconds. The amount of reverberation in the receiving room will effect the rate at which sound will decay. A well furnished room will tend to absorb sound more quickly than a less well furnished room and impact upon the sound measurements. The subscript $w$ refers to the fitting of the measured results to a series of reference curves within 2 dB allowed in BS EN ISO 140 – 4: 1998. The measurements are weighted for the third-octave band centred on the frequency of 500 Hz, plus a correction factor $C_{tr}$ to take account of a specific sound spectra. When deciding whether the sound-insulating properties of the measured partition are acceptable or not, these will be compared to published minimum standards with the higher the $D_{nTw} + C_{tr}$ figure being deemed the better. The equipment to be used for the measurements complies with BS EN ISO 140 – 4: 1998 and IEC standards.

Part E of the UK building regulations is a necessary hurdle for most building works in the United Kingdom. The values that are relevant to new build separating walls are listed in Table 1.

The resultant mix of standards and legislative drivers will be used to reflect upon the measured sound insulation results within the discussion section of the article, and they need to be compared to appropriate measurements undertaken by other researchers.

## STRAW BALE WALLS AND SOUND

Previous work has been conducted by DELTA (Danish Electronic, Light and Acoustics), which undertook *in situ* measurements to ISO Standards upon an internal straw bale partition dividing two rooms (DELTA, 2001). The separate bales used in the DELTA study were 800 mm × 450 mm × 380 mm and were laid on edge with a coating of 40 mm of clay plaster on each face, providing a total wall thickness of approximately 460 mm. The DELTA study used an apparent sound index based upon the ratio of sound powers, rather than the difference in decibels as used in this study. The reported value of 46 (−2) dB $R'_w$ ($+C_{tr}$) (DELTA, 2001), was felt to be closer to 53–54 dB $R'_w$ if certain acoustical weaknesses had not existed. This conjecture is in part supported by a laboratory test undertaken by Dalmeijer, which provided a result of 53 dB $R$ ($R$ = Laboratory testing value), on a specimen of a 460-mm wide bale construction coated on one side with 25 mm clay plaster and 35 mm clay plaster on the other (Dalmeijer, 2006). Several anthologies

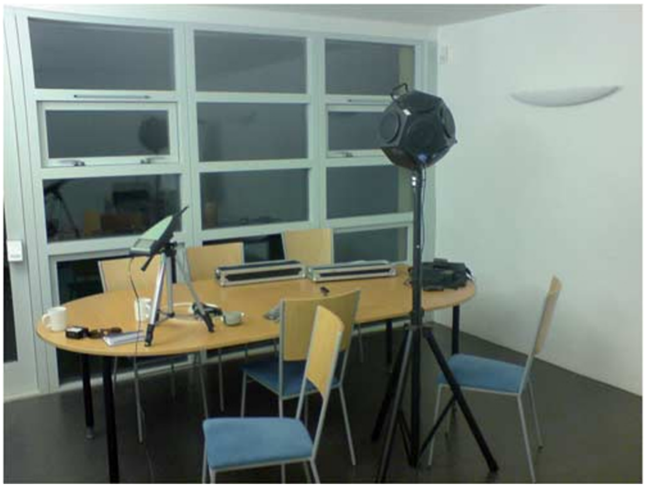

**Figure 1:** The audio analyser and the omni-power sound source.

of work devoted to the design and technical aspects of straw bale building quote some relevant sources. *Building With Straw* (Minke and Mahlke, 2005) refers to John Glassford at GrAT as stating that depending upon the frequency, a 45 cm thick straw wall, treated with appropriate render on both sides, gives a *noise level difference of 43–55 dB*. The exact conditions under which the measurements were taken is not comprehensively stated, but the figure does offer a general guide. The *Design of Straw Bale Buildings* (King, 2006) also quotes Glassford's work but eludes to Mass and Everback who measured the sound transmission of a *20 inch thick stuccoed wall of wheat and rye grass bales* with a resulting reduction of 59.8 dB. As the DELTA and Dalmeijer work has the accompanying detail of the conditions of the measurement, it is felt that this work should be used as a form of comparison.

## METHODOLOGY

A case study building that uses a straw bale walling system was selected as a space that allowed appropriate sound insulation measurements to be undertaken. The Genesis Centre at Somerset College of Arts and Technology is constructed according to current building regulations and is in use as an education space. This allows any measurements undertaken to be representative of other similar buildings. Field sound insulation measurements were carried out on two load bearing straw bale internal partition walls within the straw bale pavilion at the centre. The measurements were undertaken using a Bruel & Kjaer Modular Precision Analyzer Type 2260, an Omni-Power Sound Source Type 4296, a Power Amplifier Type 2716 (see Figure 1) and the Building Acoustics System Software. The measurements conformed to the procedure requirements set out in ISO 140-4: 1998 and Approved Document Part E: Annex B to mimic that of a professionally undertaken measurement.

ISO 140 refers to the field measurements of airborne sound between a receiving and source room (for more details of the receiving and source rooms used please see the next section). The measurements were taken using third-octave band filters with centre frequencies centred on 100 Hz through to 3150 Hz. Ten microphone positions were used, evenly distributed throughout each room. Reverberation time measurements were undertaken to allow a standardised level difference ($D_{nT}$), the difference in decibels in

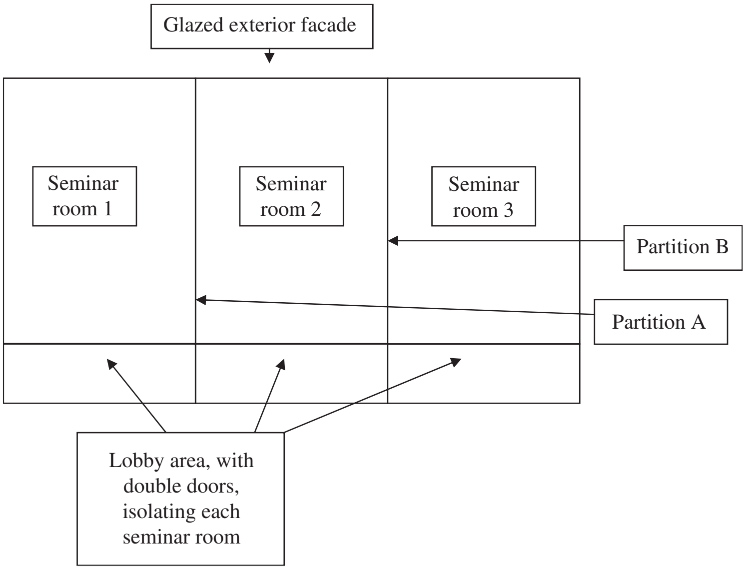

**Figure 2:** Diagram of the layout of the Genesis project straw bale seminar rooms.

the space and time average sound pressure levels produced in two rooms by one or more sources in one of those rooms to be calculated. The results from each measurement were investigated for evidence of weaknesses of sound-insulating properties at higher or lower frequencies. The final results were then used to compare with previous work and against the minimum requirements stipulated by the building regulations Approved Document Part E and other regulations pertaining to sound insulation standards for schools and educational buildings. By satisfying these requirements and limitations this investigation will test whether straw bale walling systems were acoustically a viable alternative to that of a traditional construction for use in educational building design.

## CASE STUDY BACKGROUND: THE GENESIS CENTRE

The Genesis Centre is a part of the Somerset College of Art and Design and was completed in 2005. It is a project that has had a number of sustainable building techniques incorporated into its design. These include an unfired clay block lecture hall, a timber framed office section, an unbaked earth enclosure and a straw bale pavilion. The main focus of the Genesis Centre was to show that sustainable materials could be used in the context of modern design. The locally sourced, wheat straw bale pavilion was constructed with load-bearing partitions. The partition constructions are inherently lightweight with one bale of straw weighing no more than 30 kg at the most and providing a face area of $0.35\,m^2$ on both sides. The layout of the straw bale seminar rooms is shown in Figure 2. Both the internal and external walls are constructed from straw bales, the internal walls are windowless, thus reducing the risk of sound propagating into the next room and providing an ideal subject for sound measurements.

Partition A divides two rooms, one with plastered internal surfaces, Seminar room 1 and another with flax board faced internal surfaces, Seminar room 2. Partition B divides Seminar room 2 from Seminar room 3. Seminar room 3 has flax board faced internal surfaces. The measurements undertaken have been labelled as Tests 1 and 2, and Tests 3 and 4. Tests 1 and 2 measure the sound insulation between Seminar room 1 (source) and 2 (receiving). Tests 3 and 4 measure the sound insulation between

**Table 2:** The construction details for each of the partitions

| *Partition* | *A* | *B* |
|---|---|---|
| Face in source room | Linopan flax board on timber stud framework (150 mm voids created by the framework) | Three coats of lime plaster |
| Main wall | 450 mm wide wheat straw bales | 450 mm wide wheat straw bales |
| Face in receiving room | Three coats of lime plaster | Linopan flax board on timber stud framework (150 mm voids created by the framework) |
| Total thickness | 630 mm | 630 mm |
| Approximate density | Mass 130 kg/m$^3$ (straw) | Mass 130 kg/m$^3$ (straw) |

Seminar room 2 (source) and 3 (receiving). An average value for each of the two measurements undertaken on each partition was obtained.

## RESULTS

The results are described for each of the partitions shown in Table 2 in turn, partition A then partition B. The results of the sound insulation measurements are detailed and followed by the appropriate reverberation measurements. Table 2 gives the construction details for each of the partitions indicating the different facing materials for the receiving and source room according to each of the measurements;

## PARTITION A: TESTS 1 AND 2

The overall figures for Test 1, Room 1–2 were 50 dB $D_{nT}+C_{tr}$ and for Test 2 Room 1–2 were 49 dB $D_{nT}+C_{tr}$ with an average of 49.5 dB $D_{nT}+C_{tr}$.

Figure 3 shows the $D_{nT,w}$ values at third-octave frequencies, the lowest at 100 Hz and the highest frequency at 3150 Hz. The first dip at 125 Hz may be attributed to the resonant frequency of either the flax board (in the source room) or the lime plaster (in the receiving room). There is also the possibility that this phenomenon could be caused by the flax board vibrating on its framework and increasing the amplitude of 125 Hz subjected to the straw bale wall. Straw may dampen some of the sound wave's energy, but it can only achieve a limited reduction over its wall thickness.

A possible method of controlling this effect would be to ensure that the framework was not touching the straw bales, thus reducing any transfer of sound. Further to this, a coat of clay plaster could be applied to the straw bales behind the flax board to increase the sound insulation at this frequency. Adding extra mass in the form of a clay coating will tend to increase the sound reduction level associated with the panel without increasing the risk of decay in the humidity sensitive straw.

Once the resonant drop (a fall in sound insulation dependent on the angle of incidence of the sound wave and the wall, (Szokolay, 2004)) has occurred, the partition's sound reduction performance recovers and its sound insulation value rises by 25 dB over three octaves.

When tracing the line in the graph for Test 2 it levels off earlier than that of Test 1. There may be a connection with the reverberation time (in the receiving room) at those particular frequencies on the plateaux (600–1000 Hz) as there appears to be a correlation between the sound reduction results of Test 2 in Figure 3 and the reverberation time results of Test 2 in Figure 4.

The next affected region of the sound insulation curve appears at the end of the measured scale, between 1600 and 2500 Hz. This is likely to be attributed to the partition's coincidence drop and may be connected to either the lime plaster or the flax

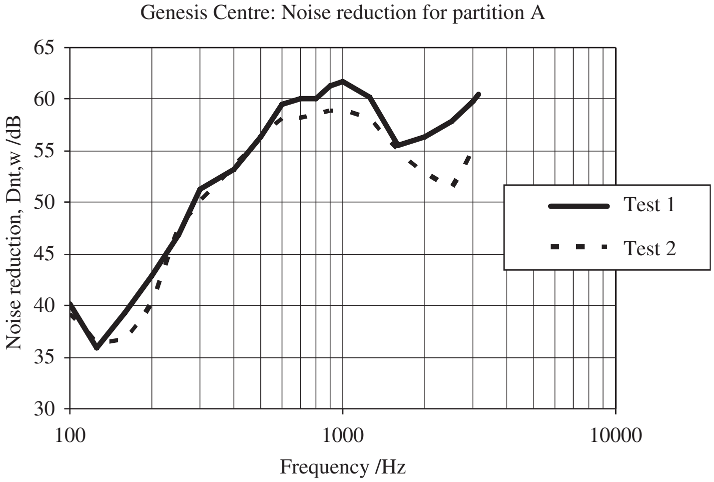

**Figure 3:** Sound insulation measurements for Tests 1 and 2.

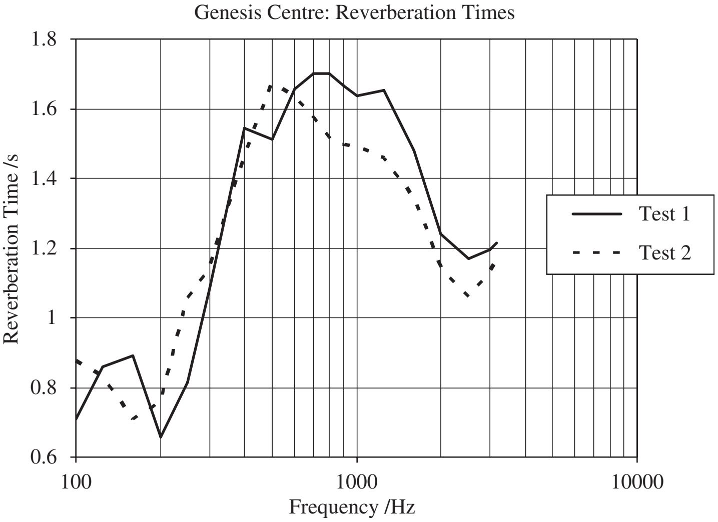

**Figure 4:** Reverberation time measurements for Tests 1 and 2.

board having larger wavelengths imposed on it, thus forcing the material to take on free bending waves and ultimately producing an increase in the amplitude of the waves (or a reduction in insulation values) (Purkis, 1966; BRE, 1994).

It is possible that the sheets of flax board and the gaps between them (see Figure 5) could be acting as a ventilated cavity wall and therefore altering any critical frequencies.

## PARTITION B: TESTS 3 AND 4

The overall weighted standardised level difference for Test 3, Room 2–3 was 50 dB $D_{nT}+C_{tr}$ and for Test 4 Room 2–3 was 48 dB $D_{nT}+C_{tr}$ with an average of the two readings of 49 dB $D_{nT}+C_{tr}$

In Figure 6 it can be seen that the Test 3 results are similar to those of Test 1 and 2 with a drop of sound insulation at 125 Hz, whereas the Test 4 line shows a rise.

**Figure 5:** The flax board partition in Seminar room 1, gaps are visible between the boards.

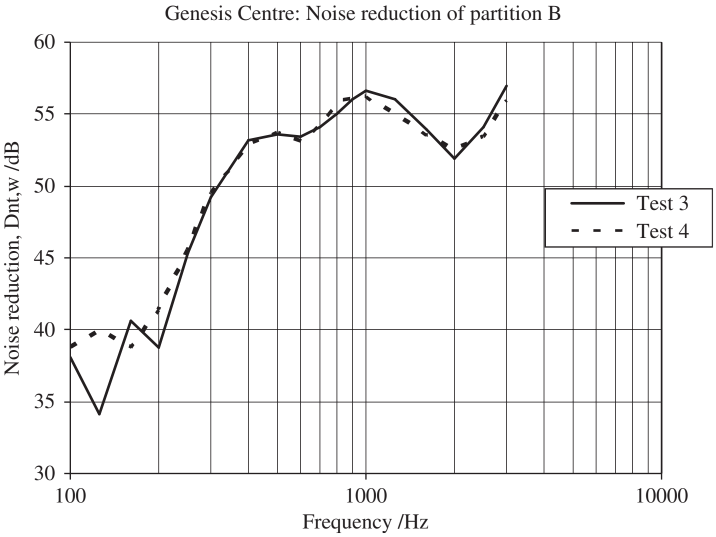

**Figure 6:** Sound insulation measurements for Tests 3 and 4.

Although the materials are presented in the reverse order to that of the previously tested partition, (see Table 2) it would seem that a resonance drop around this area is inherent to the design of the wall, although further measurements would be required to confirm this.

The line in the Test 3 graph (Figure 6) shows a more prominent drop at 125 Hz than those seen in Test 1 and Test 2. Logically the flax board may be producing the resonance, as the effect of it is likely to be slightly more pronounced when the flax board is in the receiving room.

After the resonance frequency region has been passed, the sound insulation curves of both tests rise to 15 dB in just over one octave (around 200–400 Hz), but then level off dropping in both cases by some 1–2 dB. Although the cause of this drop cannot be conclusively explained, it is logical that the flax board is the cause.

In summary, the observations can be due to the flax board on the receiving room side of the partition being excited by the oblique waves from the source room thus allowing

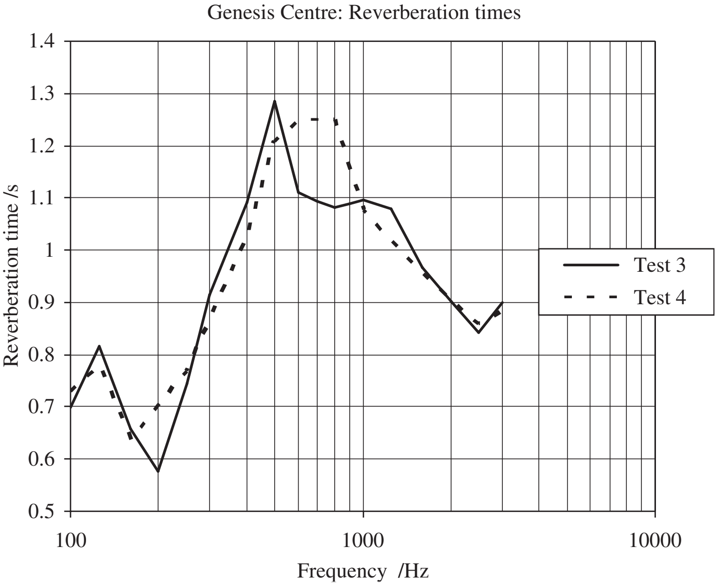

**Figure 7:** Reverberation time measurements for Tests 3 and 4.

the critical frequency to influence the insulations of the partition as a whole. Fortunately, the sound absorbance of the internal face of the straw provides good acoustic dampening capabilities that are likely to have reduced the transmission of much of this particular frequency, thus the dip is small and largely inconsequential to the overall performance of the partition.

Figure 7 shows the reverberation time measurements for Tests 3 and 4, which peak at approximately 1.20 seconds. It can be seen that there is a significant drop in the reverberation times in comparison to those of the plastered room, Room 2. For example, in Tests 1 and 2 the approximate peak results are around 1.60 seconds. The results reflect that this room has more absorbent surfaces than the previously tested room, possibly because the flax board is less dense and made from vegetal fibres. Despite this, the room lined with flax board still appears to experience greater reverberation (possibly flutter echoes) between 500 and 1600 Hz, but not as noticeable as those experienced in the plastered room. This effect may partly be ascribed to the room shape, hard parallel surfaces and a lack of absorbent materials to 'soak up' the sound.

Overall the sound reduction curves for these two measurements run almost in line with that of the ISO reference curve. This shows that there is an increase of slightly less than 25 dB across the whole frequency range; this is in line with the Mass Law rule that sound insulation will increase by around 5 dB per octave.

## DISCUSSION

The results for partition A (Rooms 1–2) provide an average result of 49.5 dB $D_{nT,w}+C_{tr}$ and the results for partition B (Room 2–3) achieve 49 dB $D_{nT,w}+C_{tr}$. Despite the resonance and coincidence effects visible in all the graphs, this is a respectable value that would indeed satisfy the required performance standards set out in the UK building regulations ADE.

It is not practical, for many reasons, to have straw bales as the surface of a partition wall within a functioning modern building; thus, some form of covering is needed for the bales to maintain the many expected performance criteria. It is therefore preferable that a

**Table 3:** Comparison of Genesis sound insulation measurements, with related criteria and measurements

| *Genesis results* | *ADE requirement* | *Robust details* | *Other case studies* |
|---|---|---|---|
| 49 dB average | 45 dB separating | 52 dB average E – WM – 1 | 53 dB ($R$) Dalmeijer |
| 53 dB ($R$) average | 40 dB ($R$) partitions | 52 dB average E – WM – 4 | 46 dB ($R'_w$) DELTA |
| 53 dB ($R'_w$) average | | 53 dB average E – WM – 6 | 52 dB ($R'_w$) DELTA |
| 51 dB ($D_w$) | | | 53 dB ($R'_w$) DELTA Predicted |

**Table 4:** Table from Building Bulletin 93 that gives acceptable sound levels between class rooms and other areas of a school (DfES, 2003)

| *Values=dB* $D_{nT\,(Tmf,\,max),\,w}$ | *Low activity noise* | *Medium activity noise* | *High activity noise* | *Very High activity noise* |
|---|---|---|---|---|
| High noise tolerance | 30 | 35 | 45 | 55 |
| Medium noise tolerance | 35 | 40 | 50 | 55 |
| Low noise tolerance | 40 | 45 | 50 | 50 |
| Very low noise tolerance | 45 | 50 | 55 | 60 |

surface covering such as lime plaster or flax board is used. However, it is likely that air gaps in the surface covering are contributing to a reduction in the overall sound insulation of such partitions. Further measurements would be required to optimise the use of sustainable surface coatings to allow such partitions to achieve even higher sound insulation values.

Table 3 allows a comparison between the measured results of this study, legislation, guidelines and by others. The results of the sound insulation figures conducted for this study are given as a single-figure average from all of the measurements taken on both partitions. Unless otherwise stated the values within the table are given as $D_{nT,w} + C_{tr}$.

As can be seen from Table 3, the partitions have exceeded the minimum performance values required by law to function as a separating wall (in terms of acoustic insulation). At an average level, the measurement is 4 dB higher than that required by the current UK building regulations, thus providing adequate protection against a wide spectrum of airborne noise. If improvements were made to the acoustic design of the partitions and the rooms, it is likely that further airborne sound insulation could be introduced. The partition construction is inherently lightweight with one bale of straw weighing no more than 30 kg at the most and presenting a wall face area of 0.35 m$^2$ on each side. Despite this relatively low mass, the straw bale-measured sound insulation exceeds standard requirements of educational buildings.

If a partition is able to pass the separating wall test, it is probably capable of also passing the ISO partition wall test. The $D_{nT}$ value can be adjusted to that of an $R$ value (which denotes a laboratory measured value) and an $R'$ value (Apparent Sound Reduction Index used in some other non-UK countries as a performance standards), as well as $D$ and $D_n$. The partition would have little problem passing the 40 dB $R$ minimum requirement.

Table 4 shows a number of values that are available from the DfES guidance for acoustic insulation standards in schools. Building Bulletin 93 also provides a method of calculation that enables a $D$ result to be adjusted to a value that has significance, in light of the specific reverberation time requirements of certain areas within a school. The upper row in Table 4 refers to the activity taking place in an educational space within a source room and the column on the left as the level of tolerance in the receiving room. The value required is $D_{nT\,(Tmf,\,\max),w}$. This basically means that the reverberation time has been adjusted against a standard reverberation time for a required room type (much the same as the $D_{nT}$ calculation, but with a different standard reverberation time). The calculation is given as this:

$$D_{nT(Tmf,\max),w} = D + 10\log\frac{T}{Tmf,\max}\,\mathrm{dB}$$

where, $D$ = level difference; $T$ = reverberation time; $Tmf$, max = standardising reverberation time for rooms in schools (DfES, 2003)

When an average $D$ result of 51 dB is adjusted using a number of standard reverberation times (provided in Table 1.5 of the DfES document), a number of final values can be produced for comparison against the values given in Table 4. These values provide results of 54 dB $D_{nT(Tmf,\max),w}$, 53 dB $D_{nT(Tmf,\max),w}$ and finally 50 dB $D_{nT(Tmf,\max),w}$.

These results show that there may be scope to use this type of straw bale design within the construction of schools and nurseries. All the values achieved either perform as well as or better than 11 of the 16 performance criteria described in Table 4. The only values that could not be achieved by this type of construction were those where activity noise in the source room is very high or in a source room where the activity noise is high, but the receiving room tolerance level is low. All other situations, such as high activity noise/medium tolerance or low tolerance/medium activity noise, are within the performance capabilities of the material. Therefore, straw bale partitions could successfully be used within school buildings; thus offering the specifier or building designer a practical alternative material encompassing appropriate sound and thermal insulation values with intrinsically low embodied energy.

## CONCLUSIONS AND RECOMMENDATIONS

In light of the collected results for the straw bale walls at the Genesis Centre (with due regard to the inconsistencies noted), the study has shown that 450 mm straw bale walls with a flax board on studwork cladding to one side and three coats of lime render to the other (with an overall thickness of 630 mm) will pass the minimum requirements of Part E of the Building Regulations, 2000 (as amended).

Further analysis allowed the results to be measured against the performance requirements for walls in schools. It was found that this form of construction would also perform well in this context by managing to achieve 11 of the 16 recommended minimum values (even when standardised to a number of different reverberation times).

The analysis of the measured sound insulation and reverberation values showed a correlation between similar constructions/samples, which may indicate that the results are connected and could be further investigated when further tests were undertaken on the same partition walls (or any other straw bale construction). The measured values do not achieve the average results for any of the Robust Detail Ltd examples, but these have been heavily tested and modified to produce good sound insulation. With some future investigation into the reduction of resonance and coincidence patterns inherent to the surface materials it is possible that the sound insulation of this construction type could be further improved.

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