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The Effects of Mass-Air-Mass Resonance on the $R_W + C_{tr}$ Performance of Wall Systems

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ABSTRACT

The Building Code of Australia (BCA) forms part of the National Construction Code (NCC) and stipulates a minimum requirement for inter-tenancy walls between dwellings expressed in terms of "$R_W + C_{tr}$ *not less than 50*" for airborne noise (BCA, 2019).

Inter-tenancy walls come in a range of configurations, including lightweight plasterboard wall systems (with timber or steel studs), pre-cast concrete walls, concrete block walls (core-filled and unfilled), Autoclaved Aerated Concrete (AAC) panels and brick walls. In these latter wall systems, the walls are generally finished with a layer of plasterboard on both sides, either direct (daub) fixed, fixed on furring channels or on a separate stud.

This paper presents some laboratory test results conducted by USG Boral on AAC block and core-filled lightweight masonry block wall systems. The results are analysed in terms of the effect of the Mass-Air-Mass resonance on the $R_W + C_{tr}$ of the wall system. Injudicious / poor / unlucky choice of air cavities and plasterboard weight can result in Mass-Air-Mass resonances that can significantly reduce the $R_W + C_{tr}$ performance of the wall system, so that even though additional weight is added to the wall system it never-the-less reduces the $R_W + C_{tr}$ value.

1 INTRODUCTION

The effect of the Mass-Air-Mass resonance and its ability to reduce the sound transmission loss is relatively well known to most acoustic consultants and others in the building industry. However, the magnitude of the effect on the $R_W + C_{tr}$ performance of masonry wall systems with a cavity to each side is often not appreciated.

A cavity to each side of a masonry wall (or AAC panel) is desirable as it allows for services to be easily run in the wall (electrical, data, plumbing etc). Cavity sizes are usually nominated based on the types of services to be accommodated rather than acoustic requirements. This form of construction is very common in many parts of Australia. Unfortunately, this type of approach often results in undesirable Mass-Air-Mass resonances that significantly reduce the $R_W + C_{tr}$ performance of the wall system, often to less than the BCA minimum requirement of $R_W + C_{tr}$ 50 d**B** for inter-tenancy walls between sole-occupancy units.

The following paper provides some analysis of laboratory tests on wall systems with gypsum plasterboard lining to each side of a central masonry panel (core-filled lightweight concrete block and AAC panels) in terms of the Mass-Air-Mass resonance of these systems.

2 MASS-AIR-MASS RESONANCE

The Mass-Air-Mass (MAM) resonance of a double or cavity wall system is a well know phenomenon and has been taken into account in many theories of sound transmission loss. The resonance has the effect of reducing the sound transmission loss at the Mass-Air-Mass (f_{mam}) resonant frequency and is given by the following equation;

$$f_{mam} = \frac{1}{2\pi}\sqrt{\frac{\rho_0 c^2 (m_1 + m_2)}{d m_1 m_2}} \qquad (1)$$

Where ρ_0 is the density of air (kg/m^3), c is the speed of sound in air (m/s), d is the distance between the two wall leaves (m) and m_1 and m_2 are the surface densities of the wall leaves (kg/m^2) respectively.

The formula is based on the simple mass spring system consisting of two masses connecting by a spring. As applied to wall systems, the spring is the air cavity between the two wall leaves and the respective masses are the surface densities of each wall leaf.

When insulation is added, the f_{mam} resonant frequency is found to be reduced. Narang (Narang, 1993) has suggested that the reason for this is that the sound propagation through the insulation in the cavity is isothermal rather than adiabatic which introduces a factor of $\frac{1}{\sqrt{1.4}}$ and so reduces the f_{mam} resonant frequency by about 15.5%.

Depending on the choice of values for the above variables, slight differences may be found in the literature but Equation (1) appears to be the most accepted form for calculating the f_{mam} resonant frequency.

3 AAC AND PLASTERBOARD WALL SYSTEMS

Davy and others (Davy et al, 2017) have reported on the acoustic performance of Autoclaved Aerated Concrete (AAC) panels for a number of different systems with gypsum board lining to both sides of the panel, either directly adhered, on furring channels or on separate steel studs, with and without insulation in the cavity.

A total of 27 tests were conducted at the CSIRO acoustic testing laboratories in Clayton, Melbourne, in June, October and November 2016. The AAC panels were 75 mm thick tongue & groove panels with a nominal stated density of 510 kg/m^3 (nominal surface density of 38.2 kg/m^2). The gypsum plasterboard lining was 13 mm thick with various surface densities (7.2 kg/m^2, 8.5 kg/m^2 and 10.5 kg/m^2).

The intention of the tests was to determine the acoustic performance of these systems, preferably achieving $R_W + C_{tr}$ 50 dB, within an overall wall width of 243 mm.

The following section summarises some of these findings and highlights the effect of the f_{mam} resonant frequency on the overall acoustic performance of a number of these wall systems.

A typical configuration for these wall systems, acting as an inter-tenancy wall between sole occupancy units (SOUs) and therefore requiring an acoustic performance of not less than $R_W + C_{tr}$ 50 dB is –

- 13 mm gypsum plasterboard on
- 28 mm furring channel to create a 30 mm cavity
- with or without insulation
- 75 mm thick AAC panel
- 20 mm (minimum) gap
- 64 mm (typically) steel stud
- Insulation in the cavity
- 13 mm gypsum plasterboard

This provides a cavity for services to each side of the AAC panel and the minimum 20 mm gap provides a discontinuous construction (which is required in some circumstances to comply with the BCA).

Figure 1 shows the laboratory measured sound transmission loss curves of a number of wall systems with a 30 mm cavity on one side of the AAC panel created by use of a furring channel (with and without insulation) and 112 mm cavity on the other side, created by using a 64 mm steel stud and 48 mm gap (with 110 mm thick glasswool insulation (11 kg/m^3) in both cases). A schematic diagram is shown in the figure that shows the general arrangement.

The red lines show the test results with no insulation in the 30 mm cavity. The dashed red line shows the results using a lighter 13 mm gypsum board (7.2 kg/m^2) and the solid red line shows the results with a heavier 13 mm gypsum board (8.5 kg/m^2). In both cases, the result was $R_W + C_{tr}$ 49 dB, although the system with the heavier board was very slightly higher at most frequencies (the differences were greater below 100 Hz).

Since this result is just below the BCA requirement of $R_W + C_{tr}$ 50 dB, it would be tempting to assume that adding insulation to the furring channel side of this system would be sufficient to increase the acoustic performance to achieve $R_W + C_{tr}$ 50 dB.

However, adding insulation to the furring channel side of these systems (25 mm thick glass wool with a density of 24 kg/m^2) actually *reduces* the acoustic performance to $R_W + C_{tr}$ 46 dB for the lighter gypsum plasterboard system (7.2 kg/m^2) and $R_W + C_{tr}$ 48 dB for the heavier gypsum plasterboard (8.5 kg/m^2).

Figure 1 shows that adding the insulation into these systems increases the acoustic performance between 160 Hz and 500 Hz, but *reduces* the acoustic performance below 125 Hz.

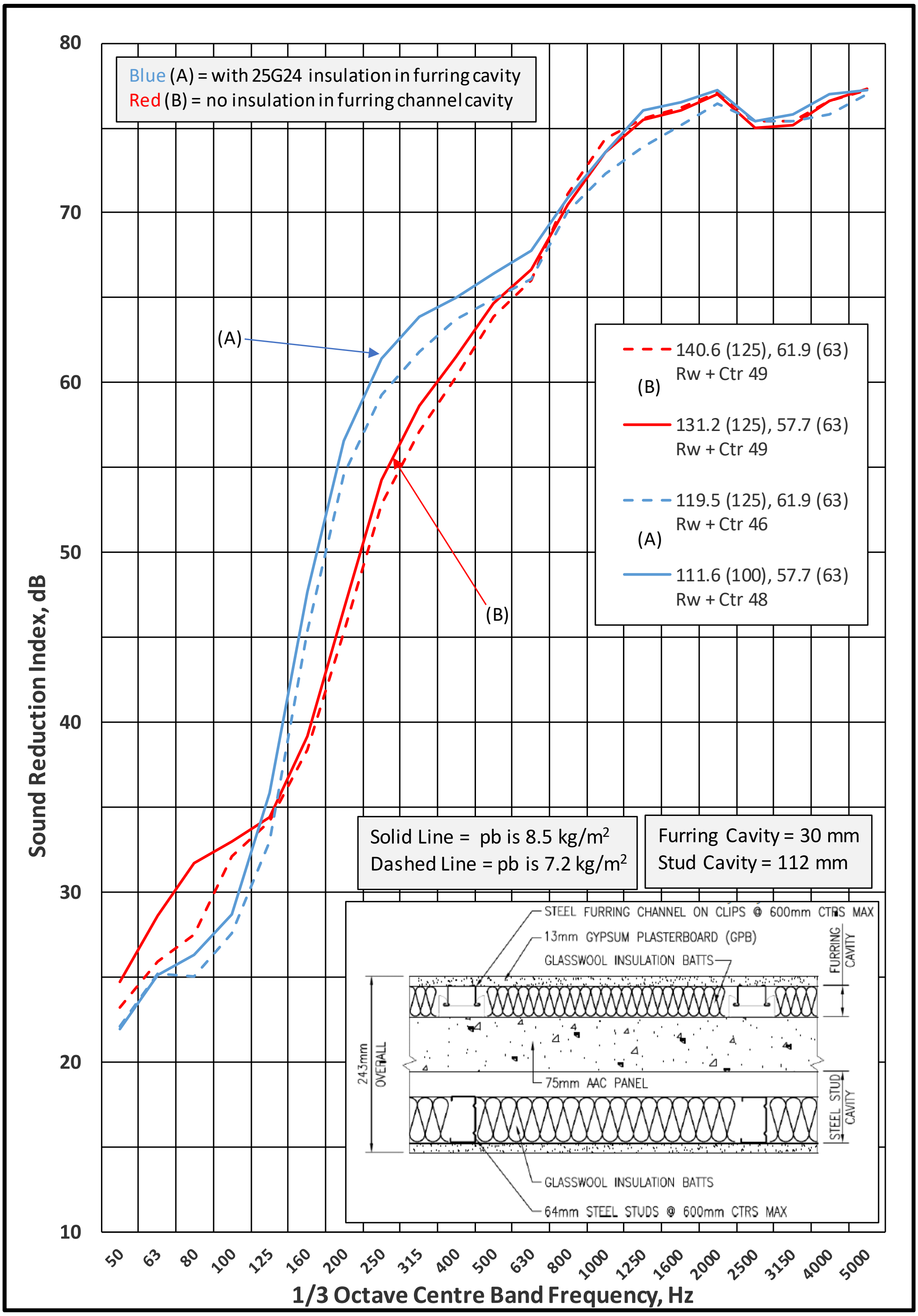

Figure 1: Laboratory measured sound transmission loss of AAC and gypsum plasterboard wall system with a 30 mm cavity to one side and 112 mm cavity to the other side.

Figure 1 also shows the calculated f_{mam} resonant frequency for the smaller cavity (higher frequency) and the larger cavity (lower frequency) with the associated 1/3 octave band in brackets. For the purposes of this exercise, it has been assumed that the resonant frequency of each cavity is associated with the panels/lining to each side of the cavity and that there are no interactions with the cavity system on the other side of the AAC panel (ie, two double panel systems rather than a single triple panel system).

The curves clearly show the reduction in the f_{mam} resonant frequency with the addition of acoustic insulation in the 30 mm cavity. It is less clear that the calculated f_{mam} resonant frequency correlates to a dip in the curve. There is a clear dip at 125 Hz as predicted by the calculation for both curves with no insulation (red curves) for the higher resonant frequency, but there is no apparent dip at 63 Hz. With the insulation in the cavity, the dips are at lower frequencies and although the solid blue line has a dip at 100 Hz, the blue dashed line seems to have a larger dip at 80 Hz or 100 Hz, rather than 125 Hz, as predicted by the MAM calculation.

It is possible that since there are two resonant frequencies relatively close to each other in the case of the system with insulation in both cavities (blue lines), that they cannot be clearly independently identified, or, contrary to the assumption, the central AAC panel is not sufficiently heavy compared to the gypsum linings (38.2 kg/m^2 compared to 7.2 kg/m^2 and 8.5 kg/m^2) and the system should not be analysed as two separate two mass systems, but a more complicated triple mass (two spring) system.

The calculation of the f_{mam} resonant frequency is useful in identifying potential issues associated with the impact on the acoustic performance of the wall system at low frequency, which in turn can have a significant influence on the overall $R_W + C_{tr}$ value. In the example above, given that the initial system without insulation in the furring channel cavity achieved $R_W + C_{tr}$ 49 dB, it would be tempting to assume that adding insulation in this cavity would increase the acoustic performance slightly and so meet the BCA requirement of $R_W + C_{tr}$ 50 dB. Adding insulation actually made the $R_W + C_{tr}$ value lower (although there was an improvement in many other frequencies). In addition, it is noted that the weight of the gypsum board did not make a significant difference to the acoustic performance.

4 MASONRY AND PLASTERBOARD WALL SYSTEMS

Another set of laboratory tests were conducted on a similar system but using a core-filled masonry wall as the central panel. This construction is common in Queensland and parts of NSW where the 190 mm thick lightweight concrete block wall is core-filled with concrete to create a structural wall with a nominal surface density of 360 kg/m^2. These walls are usually constructed with furring channels to each side for services. A separate stud to one or both sides is often not preferred as the wall width becomes unfeasibly large.

The tests were conducted in September 2017 at the CSIRO acoustic testing laboratories in Clayton, Melbourne, and consisted of a number of different configurations including, daub fixing gypsum plasterboard, steel studs and furring channels, with and without insulation.

Figure 2 shows the sound transmission loss curve for a number of results, including the base masonry wall with no linings. This base wall achieved $R_W + C_{tr}$ 49 dB (black line), and it is tempting to believe that the BCA requirement of $R_W + C_{tr}$ 50 dB may be achieved by adding a layer of plasterboard (on a furring channel for convenience) to one side of this wall.

The dashed blue line shows the test results when a layer of 13 mm gypsum plasterboard (7.2 kg/m^2) is daub fixed to one side and fixed to 28 mm furring channels on the other side of wall (to create a 30 mm cavity), with no insulation in the cavity. The acoustic performance *reduces* to $R_W + C_{tr}$ 45 dB. Again, it may be expected that adding insulation to the furring channel cavity would increase the acoustic performance to $R_W + C_{tr}$ 50 dB.

The solid blue line shows the result with the same construction as the dashed blue line, but with insulation in the furring channel cavity (25 mm thick glass wool of density 24 kg/m^3). The acoustic performance is almost identical to the previous result but shows an improvement at 125 Hz, 160 Hz and 200 Hz, but a reduction at 100 Hz. The overall performance increases only slightly to $R_W + C_{tr}$ 46 dB, which is still well below the base masonry wall.

By adding the same furring channel construction (with insulation) to the other side of the masonry wall, the result shown by the green curve is obtained. There is a significant improvement (increase) in the sound transmission loss at the 200 Hz 1/3 octave band and above, a slight decrease at 125 Hz and a significant reduction at 100 Hz. This is sufficient to reduce the overall $R_W + C_{tr}$ of the wall system to 42 dB.

This same wall system was re-tested using a heavier gypsum plasterboard, which was 13 mm thick with a density of 8.5 kg/m^2. The result is the red line shown in Figure 2, which is almost identical to the result using the lighter gypsum plasterboard (7.2 kg/m^2) and also achieved $R_W + C_{tr}$ 42 dB.

Analysis of the f_{mam} resonant frequency of these systems shows that the system with the cavity to one side only and no insulation (dashed blue line) had a f_{mam} resonant frequency of 130.3 Hz which is in the 125 Hz 1/3 octave band. The curve has a sharp reduction at this frequency, and smaller reductions to each side.

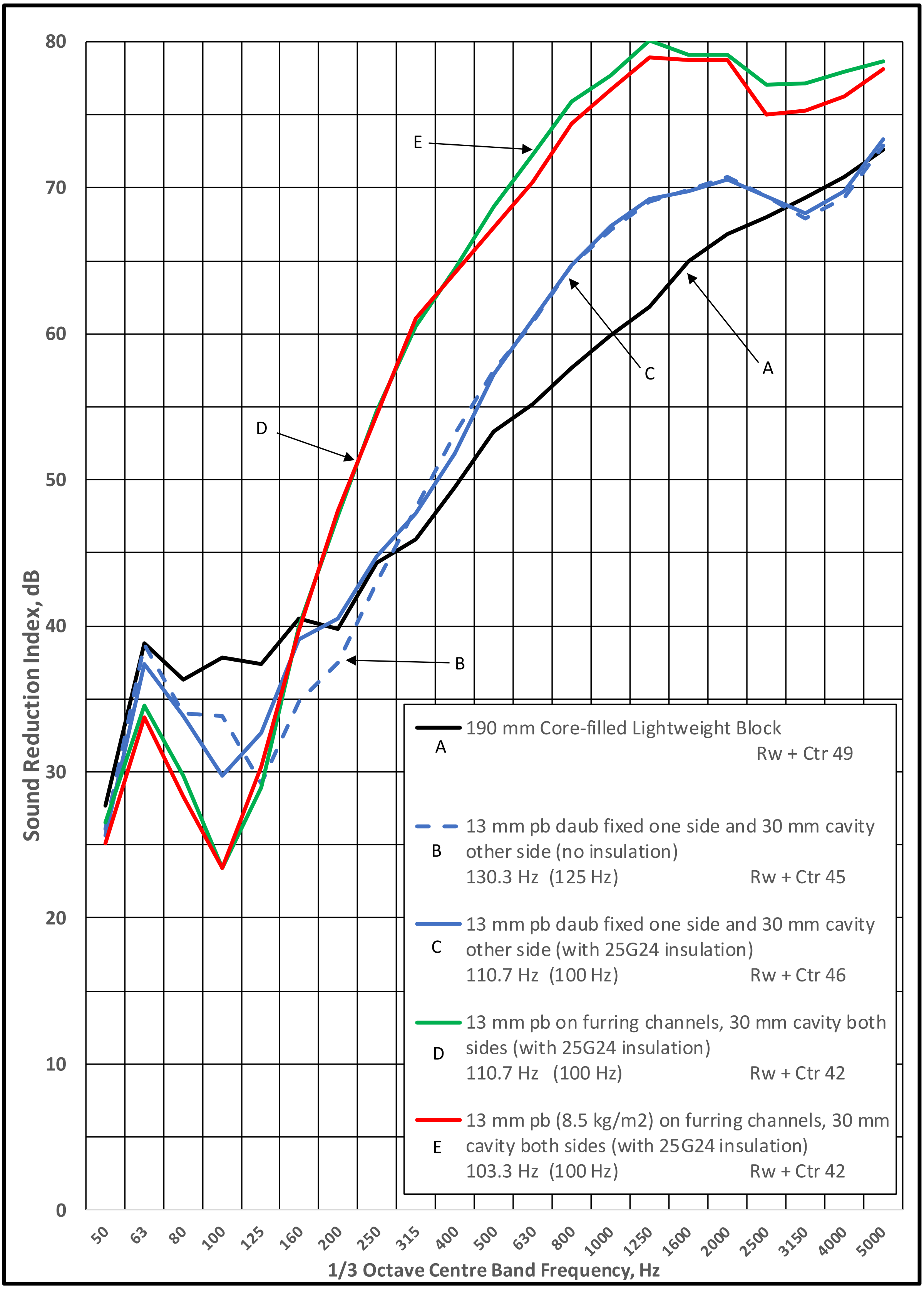

Figure 2: Laboratory measured sound transmission loss of core-filled lightweight block with 13 mm gypsum board daub fixed or on 28 mm furring channels to each side of the block wall, with and without insulation.

Adding insulation to the cavity reduces the f_{mam} resonant frequency to 110.7 Hz (in the 100 Hz 1/3 octave band), and the result is the solid blue line which is almost identical to the dashed blue line, but with the f_{mam} dip moved across to the 100 Hz 1/3 octave band.

By adding the same construction (furring channel, gypsum board and insulation) to the other side of the masonry wall and creating a symmetrical system, the result shown by the green line was obtained. This shows a large increase in the acoustic performance at 200 Hz and above, but the f_{mam} resonant frequency dip at 100 Hz appears to be twice as deep. So, even though most frequencies improved, the reduction at 100 Hz meant that the $R_W + C_{tr}$ value dropped by 4 dB.

Repeating this test with a heavier board did not significantly alter the f_{mam} resonant frequency. The resonant frequency only moved from 110.7 Hz to 102.1 Hz, and since this too is within the 100 Hz 1/3 octave band the overall acoustic performance was very nearly identical.

These results are in line with the findings from others, especially as shown by Warnock (Warnock, 1991), who has shown this effect on concrete block walls, including the additional reduction in acoustic performance at the Mass-Air-Mass resonant frequency when lining on one side of the block wall is replicated on the other side.

5 DISCUSSION OF RESULTS

The effect of a f_{mam} resonant frequency at or around 100 Hz on the $R_W + C_{tr}$ of a wall system has been demonstrated in the above test results. The relationship between the acoustic performance, $R_W + C_{tr}$ as a function of the Mass-Air-Mass resonance frequency cannot easily be demonstrated in the set of measurements with the AAC block as there were two cavities that were not the same (non-symmetrical systems), so even though there may have been a significant detrimental effect of one cavity having a resonance at or around 100 Hz, this may have been negated, at least in part, by having the second cavity well below 100 Hz.

Figure 3 shows the f_{mam} resonant frequency of the smaller cavity and the resultant $R_W + C_{tr}$ of the wall system, for the aggregate of all of the AAC panel wall systems tested in this series of tests (30 mm, 43 mm and 58 mm, with or without insulation, and different gypsum board weights, 7.2 kg/m^2, 8.5 kg/m^2 and 10.5 kg/m^2).

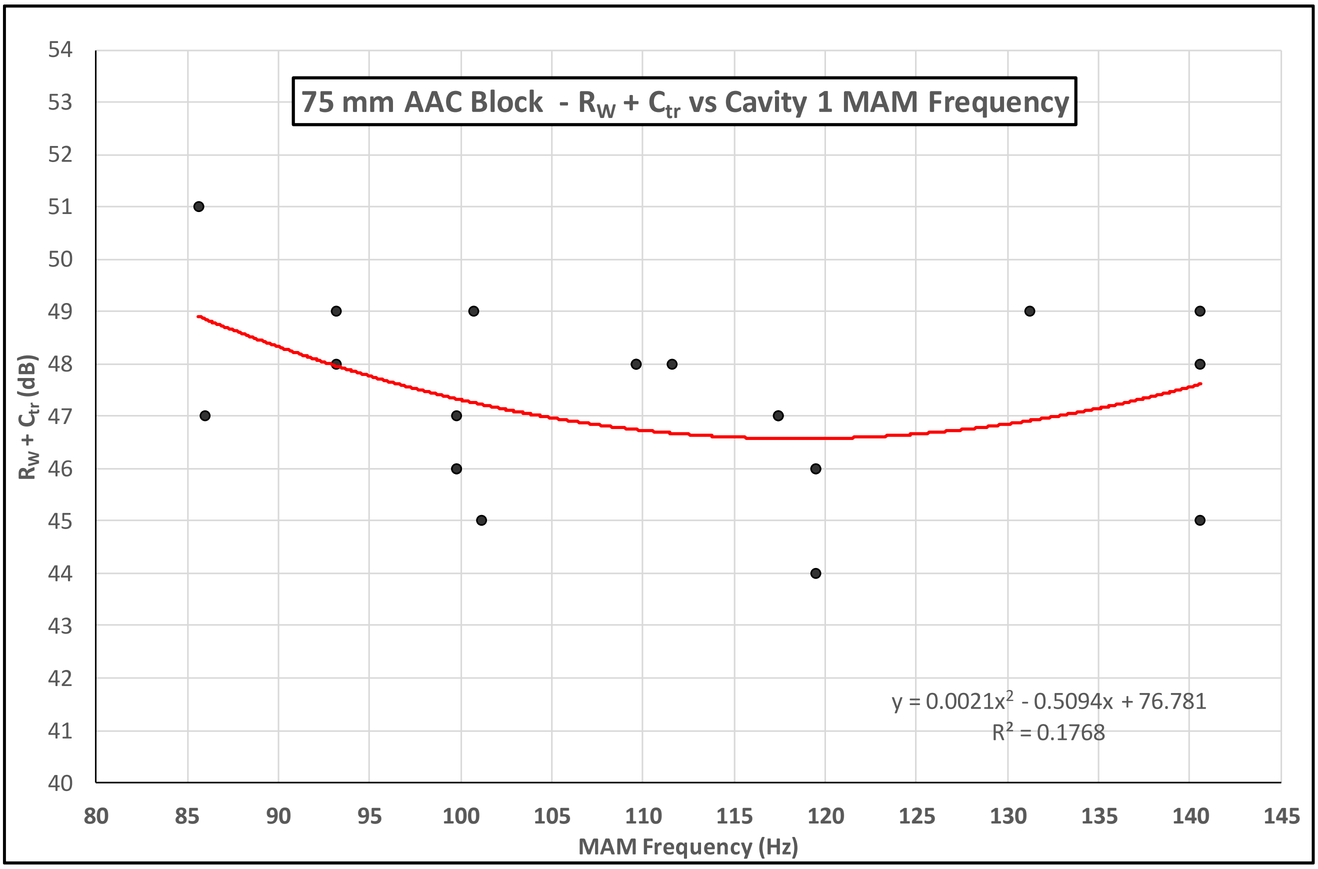

Figure 3: Mass-Air-Mass resonant frequency (Cavity 1) vs measured $R_W + C_{tr}$ of AAC wall systems.

Although there is not a strong relationship and a large spread of results for any given resonant frequency, Figure 3 shows that lower R_W + C_{tr} values are expected for f_{mam} resonant frequency between approximately 98 Hz - 125 Hz than for frequencies above or below this range. Figure 4 shows the same information as Figure 3, but plots the R_W + C_{tr} as a function of the f_{mam} resonant frequency of the second, larger, cavity.

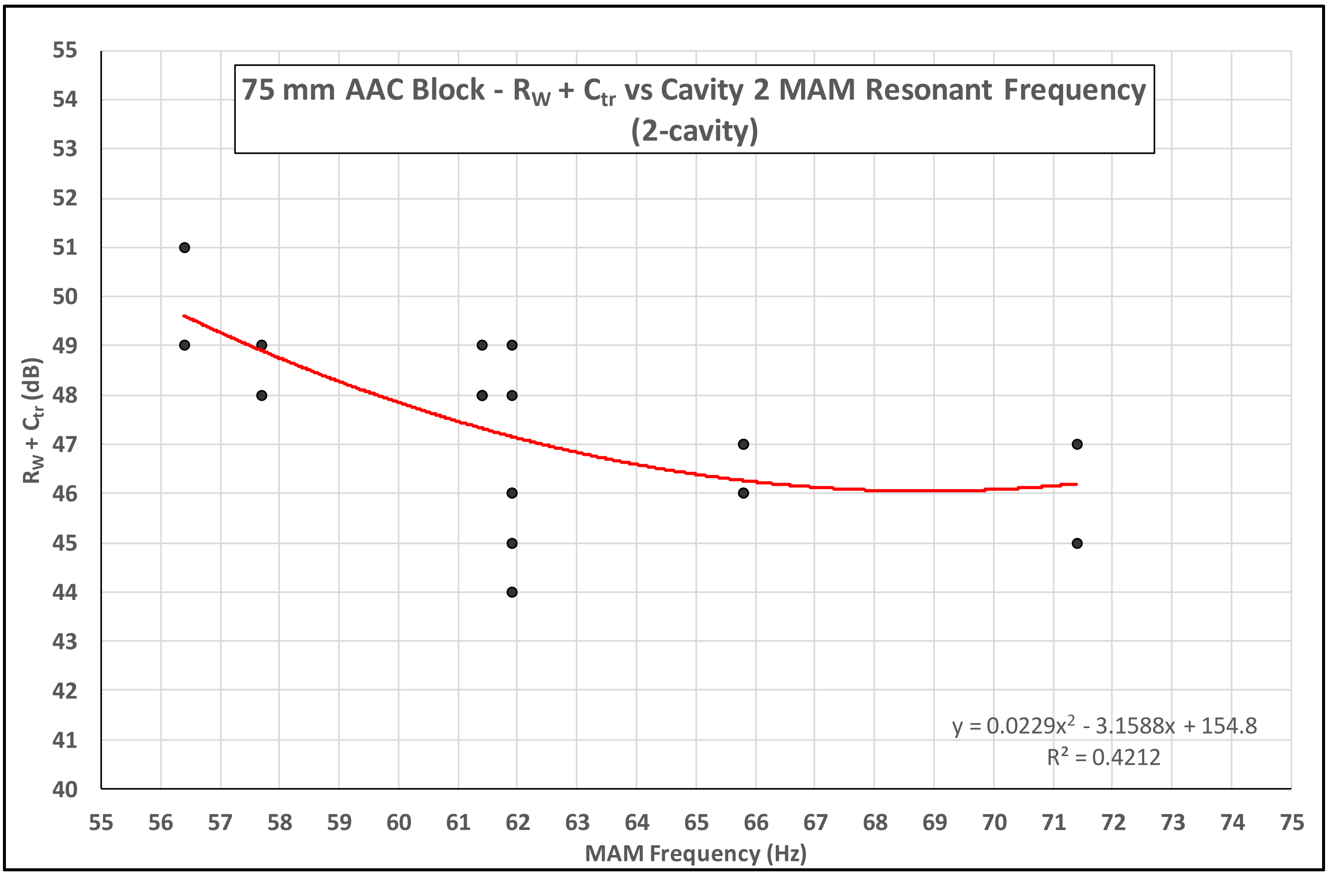

Figure 4: Mass-Air-Mass resonant frequency (Cavity 2) vs measured R_W + C_{tr} of AAC wall systems.

The larger cavity has lower f_{mam} resonant frequencies, and again, although there is a spread of results, the trend seems to indicate that the acoustic performance reduces as the f_{mam} resonant frequency increases (presumably towards 100 Hz).

Figures 5 and 6 show the same aggregated results for core-filled masonry wall systems. These systems contained both symmetrical and non-symmetrical systems with 13 mm lightweight and standard gypsum board, (7.2 kg/m^2, 8.5 kg/m^2) with cavities to one or both sides, with furring channels or separate steel studs and with and without acoustic insulation in the cavities.

There is a spread of results once again, but there seems to be a clearer trend showing that R_W + C_{tr} values seem to reach a minimum when the Mass-Air-Mass resonant frequency is between 100-110 Hz.

Within the set of masonry wall tests, there were four tests that had symmetrical configurations and which are shown in Figure 7. This figure shows a very strong relationship between the f_{mam} resonant frequency and the R_W + C_{tr} value of the wall system, possibly because the system is symmetrical and so the acoustic performance at the resonant frequency “doubles up”.

Symmetrical systems are usually preferred as they are easier to build, but these results show that if a f_{mam} resonant frequency at or around 100 Hz is created, the R_W + C_{tr} value can be reduced much more significantly than would generally be expected. It is easy to create a system that has a Mass-Air-Mass resonant frequency around 100 Hz using a combination of typical plasterboard surface densities and typical cavity depths to each side of a masonry (or AAC). In many cases, this can occur inadvertently and a system that is expected to achieve the minimum BCA requirement of R_W + C_{tr} 50 dB, may in fact be significantly below this standard.

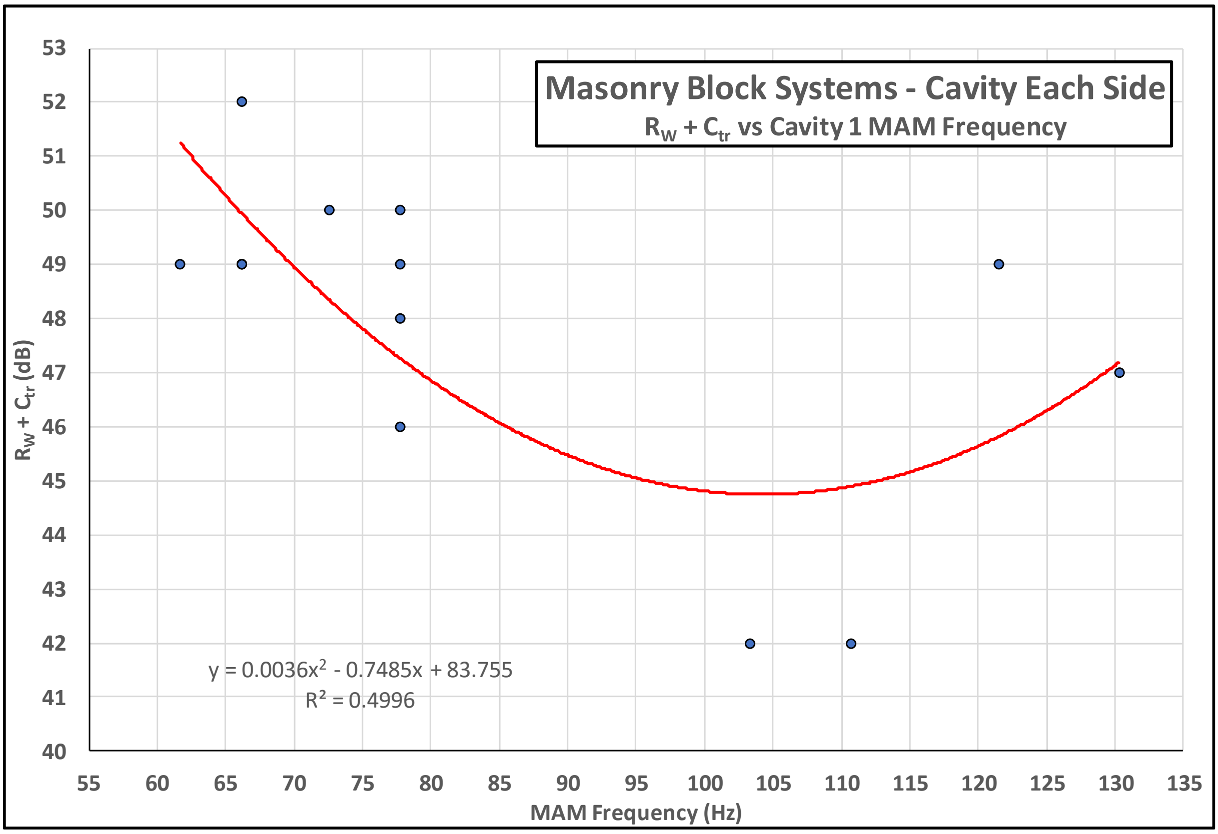

Figure 5: Mass-Air-Mass resonant frequency vs measured $R_W + C_{tr}$ performance of masonry walls - Cavity 1.

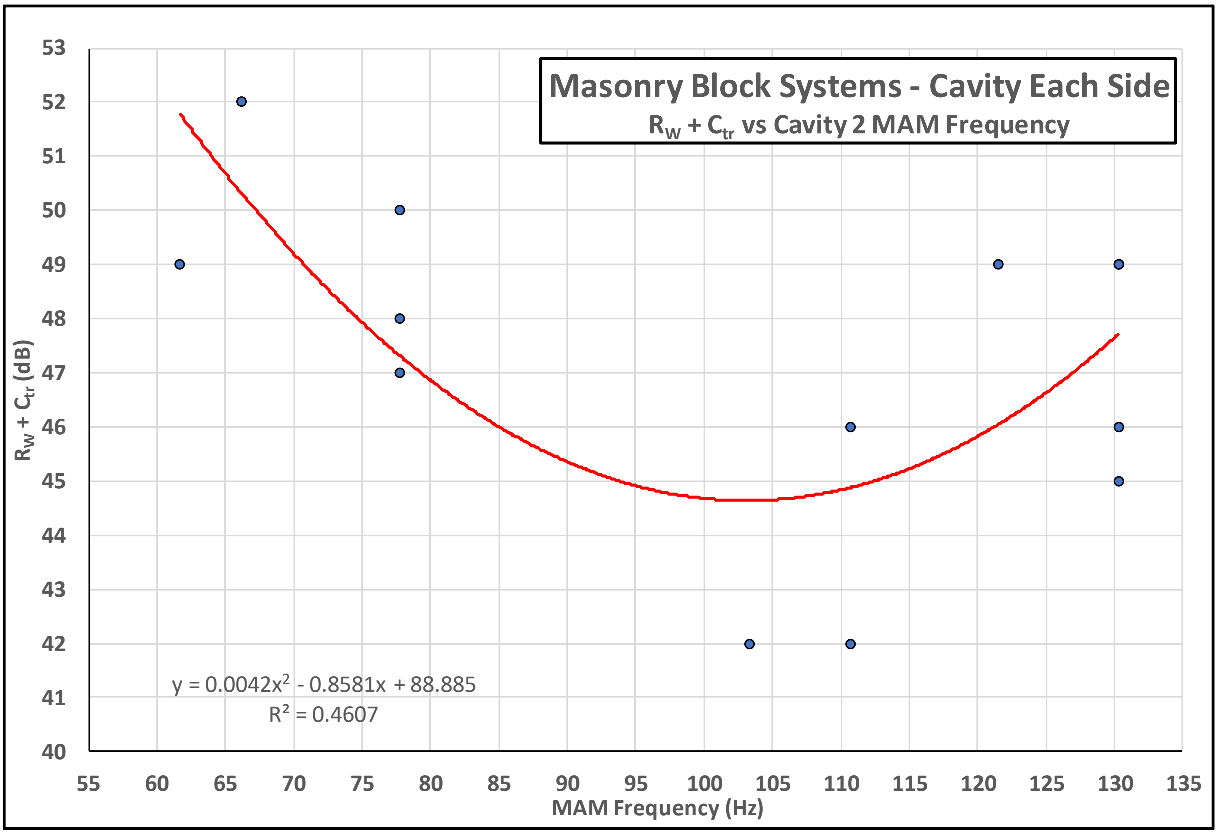

Figure 6: Mass-Air-Mass resonant frequency vs measured $R_W + C_{tr}$ performance of masonry walls - Cavity 2.

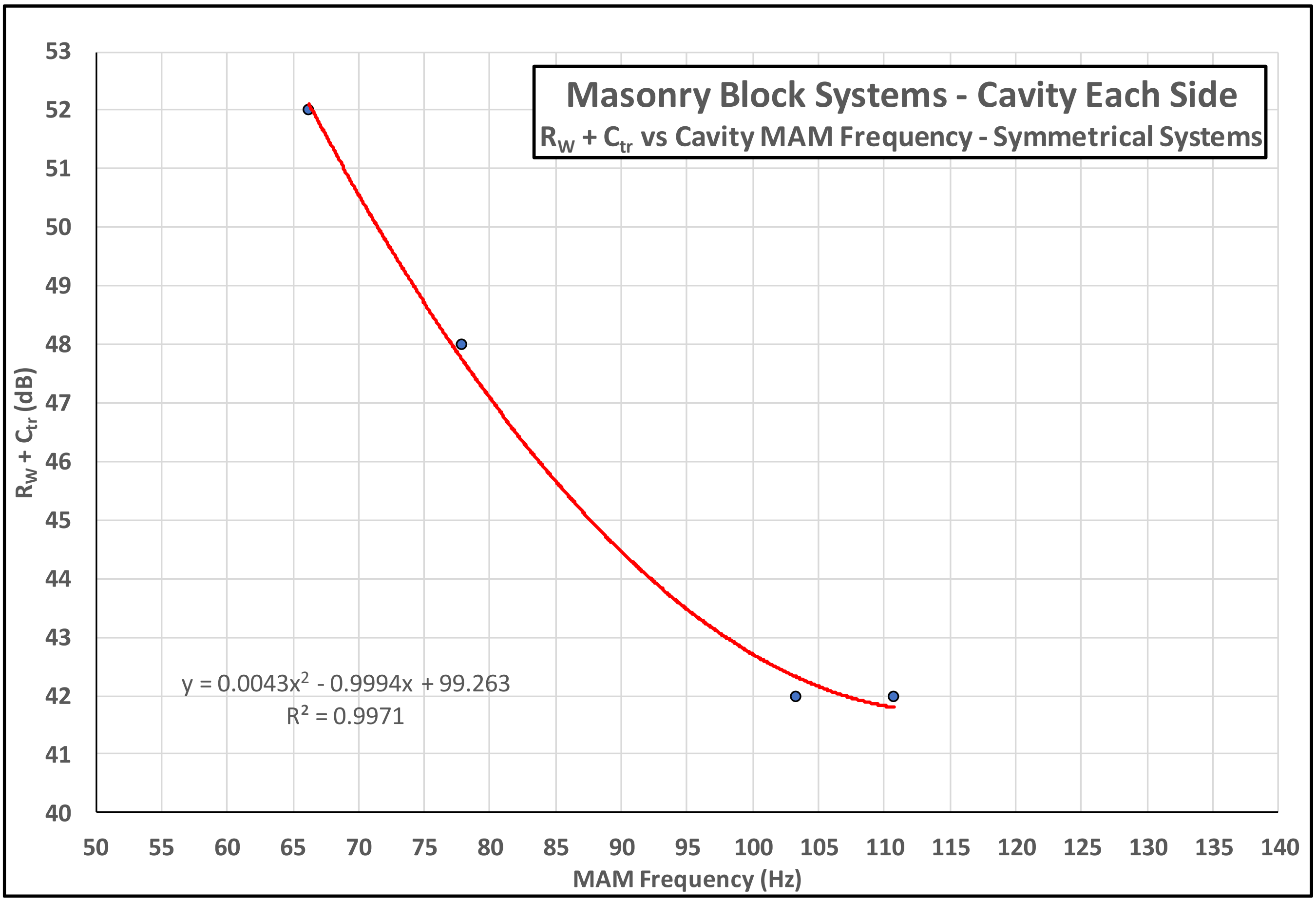

Figure 7: MAM resonant frequency vs measured $R_W + C_{tr}$ performance of masonry walls - symmetrical systems.

The results also indicate that to achieve $R_W + C_{tr}$ 50 dB with a masonry wall system with plasterboard lining and symmetrical cavities to each side, the f_{mam} resonant frequency should be below approximately 70 Hz. Although the data suggests that as the resonant frequency increases past 110 Hz, the $R_W + C_{tr}$ values begin to improve, there no tests on these systems to show that this improvement increases to $R_W + C_{tr}$ 50 dB or more.

A potential issue in designing a wall systems with a high Mass-Air-Mass resonant frequency, is that these systems require relatively narrow cavities (eg 10 mm for 13 mm thick, 8.5 kg/m^2 plasterboard to achieve an f_{mam} resonant frequency of 208 Hz, which may or may not be sufficiently high). In practice, under site conditions, it is very difficult to accurately control small cavity depths and relatively small variations in the cavity could result in significant changes in the resonant frequency and therefore in the $R_W + C_{tr}$ result. Also, cavities in the order of 10-15 mm may not be practical/desirable, and services generally require cavities in the order of 30-50 mm. Further tests will be required to determine systems that provide both an appropriate services cavity and consistently achieve $R_W + C_{tr}$ 50 dB or more.

Currently, to consistently achieve the minimum BCA requirement of $R_W + C_{tr}$ 50 dB, it is recommended that a larger cavity is incorporated (min 50 mm cavity, or separate stud) and a heavier plasterboard lining or multiple plasterboard layers are used.

The sensitivity of the $R_W + C_{tr}$ value on low frequency has been noted previously (eg Smith et. al, 2007) which take into account either individual changes to each 1/3 octave band on the $R_W + C_{tr}$ value or multiple frequency changes. For certain wall systems, such as the test results reported in this paper, the sensitivity to the acoustic performance at 100 Hz is very high. So much so that at least one acoustic laboratory often reports this sensitivity to their clients. The sensitivity of the $R_W + C_{tr}$ value to the sound transmission performance at 100 Hz is sometimes 0.90 or more. A figure of 0.90 means that for every 1 dB increase in the sound transmission loss at 100 Hz, the

$R_W + C_{tr}$ value increase by 0.90 dB. This is almost a 1:1 correspondence which shows that the acoustic performance at 100 Hz is very much lower than the rest of the sound transmission loss spectrum (compared to the reference curve). Corrections to the R_W (C_{tr} value), in the order of -15 to -17 are common for these systems.

The results also show that even relatively heavy wall systems, such as the masonry wall system reported here with a surface density of more than 360 kg/m^2, may still not achieve the minimum BCA standard of $R_W + C_{tr}$ 50 dB if there are linings applied to both sides that have a Mass-Air-Mass resonant frequency at or around 100 Hz.

Given that these and similar systems generally achieve an R_W value in the high 50's or low 60's, it may be a valid question as to whether a single value requirement in terms of $R_W + C_{tr}$ ($D_{nT,w} + C_{tr}$) is the most appropriate method of measuring the BCA performance requirement to "*prevent illness or loss of amenity to the occupants*" of sole-occupancy units (BCA, 2019). Especially if compliance with this requirement means that the large reduction in acoustic performance is moved to a higher or lower frequency. Smith et. al. (Smith et. al., 2007) have previously raised the question of whether the $R_W + C_{tr}$ (or $D_{nT,w} + C_{tr}$) on its own is sufficient to effectively provide a sustainable environment and whether a combination of R_W (or $D_{nT,w}$) and $R_W + C_{tr}$ (or $D_{nT,w} + C_{tr}$) would be more appropriate, although this too may entail other complications.

6 CONCLUSIONS

The laboratory sound transmission loss tests on AAC panel and masonry wall systems with plasterboard lining to one or both sides may exhibit a strong Mass-Air-Mass resonance at or around 100 Hz that significantly reduces the $R_W + C_{tr}$ performance of the overall wall system. The tests show that wall systems that would otherwise be expected to easily comply with the BCA requirement of $R_W + C_{tr}$ 50 dB, may actually be significantly below this minimum requirement. This is true of even relatively heavy wall systems. The examples provided are by no means unusual constructions, but common constructions used throughout the building industry.

Calculation and analysis of the Mass-Air-Mass frequency (which can be easily calculated) can provide useful information on the potential impact of lightweight linings to relatively heavy central panel or wall, on the overall $R_W + C_{tr}$ performance of the system.

Symmetrical systems with the same Mass-Air-Mass resonant frequency to each side cavity compounds the issue, resulting in a deeper reduction of the sound transmission loss at the resonant frequency.

The acoustic performance of non-symmetrical systems are more difficult to predict due to the potential interaction of two resonant dips at low frequency.

Based on the limited test data, it is recommended that wall systems with cavities are designed so that the Mass-Air-Mass resonant frequency is less than approximately 70 Hz.

ACKNOWLEDGEMENTS

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REFERENCES

Building Code of Australia: Volume 1: Section F5.5 Sound Insulation Rating of Walls. May 2019. Commonwealth of Australia and the States and Territories. Australian Building Codes Board.

Davy, J.L, Debevc, M and Blanc, C, 2017. 'The Sound Insulation of Autoclaved Aerated Concrete Panels Lined with Gypsum Plasterboard'. INTER-NOISE and NOISE-CON Congress and Conference Proceedings, Inter-Noise17, Hong Kong CHINA, pp. 691-701(11)

Narang, P.P, 1993. 'Effect of fiberglass density and flow resistance on sound transmission loss of cavity plasterboard walls', Noise Control Engineering Journal, Vol 40, No. 3, 215-220, (1993).

Smith, R.S, Macdonald, R, Lucock, D, Mackenzie, R. K, 'Sensitivity Analysis of ISO 717-1Spectrum Adaptation Terms'. Proceedings of the Institute of Acoustics, pp. 139-146, Vol. 29, Pt. 3, 2007.

Warnock, A.C.C., 1991. 'Sound Transmission Through Concrete Blocks with Attached Drywall', Journal of the Acoustical Society of America, Vol. 90, No. 3, September 1991.