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ORIGINAL ARTICLE

# Airborne Sound Insulation of Sandwich Partition Panels and Masonry Constructions for Noise Control

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**Abstract:** The paper reports the airborne sound insulation characteristics of sandwich partition panels and masonry constructions tested in Reverberation chambers for their applications as doors, noise barriers or enclosures for traffic and machinery noise control. The study presents the rarely reported sound insulation characteristics of various types of sandwich constructions available commercially. The measurement uncertainty in sound transmission loss determination using Reverberation Chamber method is reported. The sound insulation of various dry wall systems utilizing vapor barriers, GI blocks, Tecsound sheets, Asbestos and non-Asbestos sheets, Stainless, Aluminum, Plastic and transparent sheets and various damping materials and double glazing's is reported in the study that can be helpful in the development of optimal sandwich constructions of enhanced acoustic performance accomplishing the desired noise level reductions. The study suggests that sandwich constructions utilizing the various Gypsum and Tecsound sheets can provide enhanced sound insulation characteristics.

**Keywords:** Sound insulation; Reverberation chamber; Sound transmission loss; Coincidence dip; Resonance

## 1. Introduction

Airborne sound insulation of multilayered sandwich constructions has been always a grey area of research amongst the building manufacturers and researchers for developing sandwich configurations providing enhanced acoustic performance. The prime considerations for design of sound insulative material are the building elements, viz. the walls, windows, roof, ceilings and exterior facade. Thus, a proper treatment of the building elements would considerably reduce the outside noise exposure and protect the residents from hazards of noise pollution. Also, the development of highly insulative doors, noise barriers and machinery noise enclosures can be very instrumental in noise control solutions. The dry wall technology that has emerged in past two decades has numerous advantages compared to the masonry constructions as: speed of installation is much faster than masonry constructions; lighter in weight, higher sound insulation and fire resistance, and less heat convection. The sound insulation provided by the drywall constructions can also be significantly enhanced by combination with masonry constructions for its suitability for building facades [1]. However, the dry wall constructions sometimes suffer from poor low frequency sound insulation which can be compensated by sandwich construction involving sound absorbing materials, using double stud walls or resilient channels, etc. [2]. The airborne sound insulation is measured in Reverberation Chambers by ascertaining the difference of sound pressure level in the source and the receiving room. There are varied single-number ratings, viz. Sound Transmission Class (STC), Weighted sound reduction index ($R_w$) and spectrum adaptation terms $C$, $C_{tr}$ used for describing the sound insulation properties of partition wall panels. The STC value is defined as sound transmission loss value where the STC contour intersects the 500 Hz line [3, 4]. The better the STC of materials, higher the sound insulation it provides. Similarly, the weighted sound reduction index, $R_w$ is used to facilitate the comparison of sound insulation performance of different materials in European continent [5]. There had been various studies reported on enhancing the STC/$R_w$ of sandwich constructions. Also, analytical models facilitate the prediction of single-number ratings in many cases [6–9].

The light weight dry wall partition systems are used widely consists of GI steel frame, encased with gypsum plasterboards on either side attached through self-drilling

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drywall screws [10]. Structurally decoupling the drywall panels from each other (by using resilient channel, steel studs, a staggered-stud wall, or a double stud wall) can yield modest improvements in STC as revealed in some previous studies [11–17].

This present paper presents the sound insulation characteristics of various types of sandwich constructions available commercially. Such a comprehensive study focused on analyzing the sound insulation characteristics at 1/3rd octave band frequencies of various materials has been rarely reported. Also, the use of some materials like Tecsound sheets embedded in sandwich constructions, damping materials, vapor barriers, etc., in developing sandwich constructions of higher sound insulation had been not much reported. The sound insulation of various dry wall systems utilizing vapor barriers, GI blocks, Tecsound sheets, Asbestos and non-Asbestos sheets, Stainless, Aluminum, Plastic and transparent sheets and various damping materials and double galzing's is reported in the study that can be helpful in the development of multi-layered sandwich constructions of enhanced acoustic performance accomplishing the desired noise level reductions. Such multi-layered constructions can be used in doors, noise barriers or enclosures for traffic and machinery noise control [18, 19]. The study also presents the calculation of measurement uncertainty in sound transmission loss evaluation of acoustical materials in frequency range of 100 Hz to 5 kHz.

## 2. Airborne Sound Insulation Measurements and Uncertainty

Sound transmission loss measurements were carried out by means of placing sample in a window opening between two reverberation rooms and calculating sound pressure levels in 1/3rd octave band at 125–4000 Hz frequency range. In this method, one measurement microphone is placed in source room and other microphone is placed in receiving room. When sound generates by the reference source and incident on building material mounted on the wall with specific dimensions, it gets reflected, absorbed and transmitted. The measured microphones present in source room and receiving room are used to record the sound pressure levels within the rooms. The various instruments used for airborne sound insulation measurements are the Reference Omnipower Sound Source Type 4292-L Optimum, B&K Power Amplifier Type 2734, Sound level analyzer Type 2270, AKG PT 470 Wireless Bodypack Transmitter and Measurement Microphone Type 4189 traceable to the national measurement standards of sound pressure level are shown in Fig. 1. The Reverberation Chambers dimensions are: 6 m × 6.5 m × 7 m, cut-off frequency: 100 Hz with source room volume: 257 m$^3$ and receiving room volume: 271 m$^3$ as shown in Fig. 2. The dimensions of the wall specimen window are 930 mm × 630 mm. The diffusivity of the room is prior checked so to ensure the standard deviation of sound pressure level at different positions in the room is less than ± 1.0 dB. These sound pressure levels in source room and receiving room are used to calculate the Sound Transmission Loss (STL) at 16 different frequencies in range 100 Hz to 4 kHz as [3]:

$$\mathrm{STL} = L_{\mathrm{p1}} - L_{\mathrm{p2}} + 10 \times \log\left(\frac{RT_{\mathrm{R}} \times A_{\mathrm{S}}}{0.161V}\right) \quad (1)$$

where $L_{\mathrm{P1}}$: Sound Pressure level in source room; $L_{\mathrm{P2}}$: Sound Pressure level in receiving room; $RT_{\mathrm{R}}$: Reverberation time in receiving room; $A_{\mathrm{S}}$: Sample Area; $V$: Source room volume. Sound Transmission Class is derived from Sound transmission loss values in 1/3rd octave band from 125 to 4000 Hz at 16 standard frequencies. These values are plotted with a standard reference contour provided by ASTM E413-87 and adjusting the standard contour on measured curve at 500 Hz to determine the Sound Transmission Class (STC) value at contour intercept at 500 Hz [4]. The weighted sound reduction index, $R_{\mathrm{w}}$ and spectrum adaptation terms are calculated as per ISO 717-1 [5]. Table 1 shows the factors affecting the measurement uncertainty in sound transmission loss measurements with a coverage factor of $k = 2$ as per the *Guide to the Expression of Uncertainty in Measurement* [20]. The sensitivity coefficient of unity is assumed for each component contributing to the uncertainty of measurement in sensitivity determination. The evaluated expanded measurement uncertainty in sound transmission loss measurements ranges between ± 1.5 to 2.0 dB in frequency range 100–4000 Hz, which is at a coverage factor $k = 2$ and which corresponds to a coverage probability of approximately 95% for normal distribution

## 3. Results and Discussion

The typical sound insulation of a material can be broadly classified in different regions: stiffness and damping controlled; mass controlled region and co-incidence effect region [21]. At lower frequencies, the stiffness of the panel of the panel resonances affects the sound insulation of the material. At lower frequencies, stiffer the material, the better is the transmission loss [22]. The middle frequency range shows the linear dependence of sound transmission loss on the mass of the construction and as such the sound transmission loss increases with the frequency at the rate of 6 dB/octave. In the higher frequency range, co-incidence dip is observed at the critical frequency that occurs when the wavelength of the sound in air coincides with the

**Table 1** Measurement uncertainty in sound transmission loss measurements in reverberation chambers

| Source of uncertainty | Probability distribution | Divisor | Uncertainty contribution (dB) for frequencies in 1/3rd octave band | | | | |
|---|---|---|---|---|---|---|---|
| | | | 100 Hz and 125 Hz | 160 Hz $\leq f \leq$ 315 Hz | 400 Hz $\leq f \leq$ 500 Hz | 500 $< f \leq$ 2.5 kHz | 3.15 $\leq f \leq$ 5 kHz |
| Repeatability of sound pressure level | Normal | $\frac{s(L_i)}{\sqrt{n}}$ | 0.51 | 0.51 | 0.45 | 0.46 | 0.29 |
| Repeatability and reproducibility of reverberation time | Normal | $\frac{s(T_i)}{\sqrt{n}}$ | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 |
| Uncertainty due to microphone and preamplifier calibration | Normal | $\frac{u(\delta L_i)}{2}$ | 0.06 | 0.06 | 0.06 | 0.08 | 0.08 |
| Uncertainty due to dual channel analyzer calibration | Rectangular | $\frac{u(\delta L_{\text{anal}})}{\sqrt{3}}$ | 0.30 | 0.30 | 0.30 | 0.30 | 0.30 |
| Uncertainty due to calibration of area and volume of reverberation room | Rectangular | $\frac{u(\delta S)}{\sqrt{3}}$ | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 |
| Environmental conditions | Rectangular | $\frac{u(t_i)}{\sqrt{3}}$ | 0.30 | 0.30 | 0.30 | 0.30 | 0.30 |
| Resolution of Reverberation Time reading | Rectangular | $T_{\text{res}}/2\sqrt{3}$ | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 |
| Residual factors viz., background noise in receiving room, boundary conditions, influence of source positions, meteorological conditions, absorption in receiving room, flanking transmission | Rectangular | $\frac{U_{\text{residual}}}{\sqrt{3}}$ | 0.46 | 0.29 | 0.29 | 0.29 | 0.46 |
| Deviations from ideal diffuse sound field and deviations in SPL due to dips associated with low frequency resonances (flexural and mass-air-mass) and co-incidence dips | Rectangular | $\frac{U_{\text{dips}}}{\sqrt{3}}$ | 0.46 | 0.29 | 0.17 | 0.17 | 0.46 |
| Errors in spatial averaging, diffuse incidence of sound field | Rectangular | $\frac{U_{\text{diffuse}}}{\sqrt{3}}$ | 0.29 | 0.17 | 0.17 | 0.29 | 0.29 |
| Expanded uncertainty ($k$ = 2, 95% confidence level) in dB | | | 2.00 | 1.60 | 1.50 | 1.60 | 1.80 |

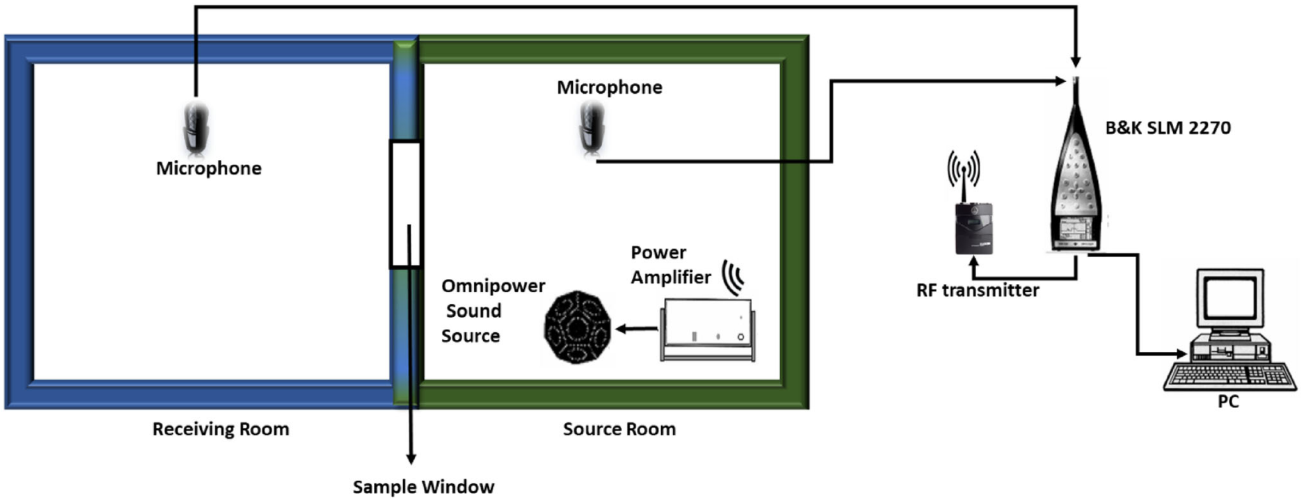


**Fig. 1** Set-up of airborne sound insulation measurements in reverberation chambers

**Fig. 2** Pictorial view of reverberation chambers used for airborne sound insulation measurements and diffusers installed for ensuring sound diffusivity at CSIR-National Physical Laboratory, New Delhi

structural wavelength [2, 21–28]. Above the critical frequency, the insulation curves exhibit slopes with an inclination close to 9 dB/octave [26]. The sound reduction index for the plane waves assuming grazing incidence follows the mass law [27] described as:

$$R = 20\,\mathrm{Log}\ (Mf) - 47\,\mathrm{dB} \quad (2)$$

where $M$ is the mass per unit area of panel in kg/m$^2$ and $f$ is frequency in Hz. This equation predicts an increase in the sound reduction index of about 6 dB for each doubling of the mass per unit area [27]. The sound insulation of various dry wall systems utilizing vapor barriers, GI blocks, Tecsound sheets, Asbestos and non-Asbestos sheets, Stainless, Aluminum, Plastic and transparent sheets and various damping materials and double Galzing's is discussed.

### 3.1. Polycarbonate Sheets

Polycarbonate sheets are environmental friendly and used widely as noise barriers and enclosures as they possess higher stiffness, UV protection, thermal insulation and are light-weight. Figure 3 shows the sound transmission loss characteristics of the various polycarbonate sheets tested in the Reverberation chambers. It can be observed that these sheets encounter low frequency dip in frequency range of 160–315 Hz and higher frequency coincidence dip at 2 kHz. Table 2 shows the details and measured STC and $R_w(C,\ C_{tr})$ of different Polycarbonate Sheet. It can observed that the STC/$R_w$ values lies between 19 and 21 which suggests the need of exploring the suitability of sandwich polycarbonate sheets can provide better sound insulation rather than single sheets.

**Table 2** Details and measured STC and $R_w(C, C_{tr})$ of different polycarbonate sheet

| Sr. no | Sample ID | Details of partition panels | STC | $R_w$ ($C$, $C_{tr}$) |
|---|---|---|---|---|
| | P1 | 12-mm-thick Polycarbonated Noise Barrier (Inner cells are hexagonal in section) | 19 | 19(− 2, − 5) |
| | P2 | 12-mm-thick Polycarbonated Noise Barrier (Inner cells are rectangular in section) | 21 | 21(− 1, − 4) |
| | P3 | 10-mm-thick Hollow Polycarbonate Sheet (2 wall structure) | 20 | 20(− 2, − 4) |

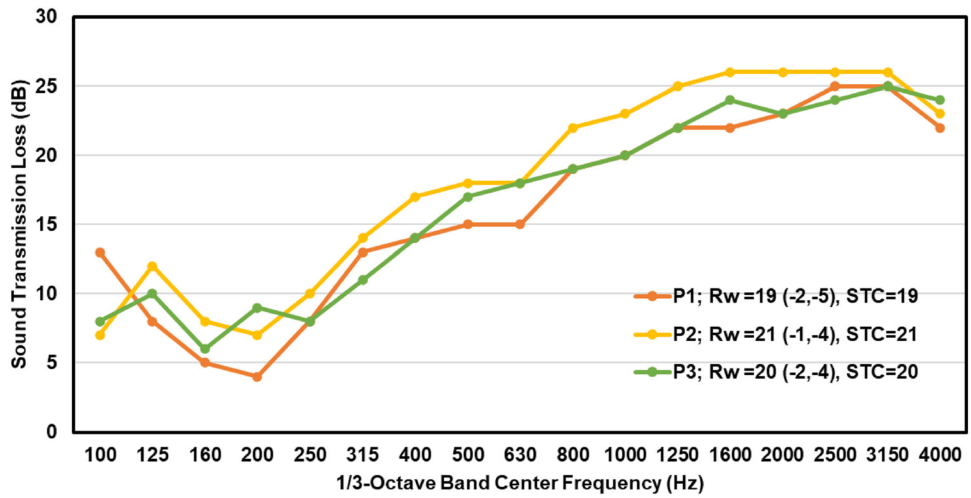


**Fig. 3** Sound transmission loss of different polycarbonate sheets

### 3.2. Sandwich GI Metal Stud Dry Wall System with Vapor Barrier

A vapor barrier is generally a plastic or foil sheet that provides damp proofing and resists the diffusion of moisture through the partition wall. Table 3 shows the details and measured STC and $R_w(C, C_{tr})$ of different sandwich GI Metal stud dry wall system with vapor barrier. Figure 4 shows the sound transmission loss characteristics of the various sandwich GI Metal stud dry wall system with vapor barrier tested in the Reverberation chambers.

### 3.3. Gypsum Sandwich Partition Panels

The various sandwich gypsum constructions tested in the Reverberation chambers are tabulated in Table 4. Figure 5 shows the sound transmission loss characteristics of the various sandwich gypsum partition panels tested in the Reverberation chambers. The weighted sound reduction index, $R_w$ of sandwich gypsum constructions lies between 40 and 48, while the $R_w + C_{tr}$ values lie between 31 to 39 dB. The addition of steel studs with gypsum boards each side interestingly enhances the low frequency sound

**Table 3** Details and measured STC and $R_w(C,C_{tr})$ of different Sandwich GI Metal stud dry wall system with vapor barrier

| Sr. no | Sample ID | Details of partition panels | STC | $R_w$ ($C$, $C_{tr}$) |
|---|---|---|---|---|
| | V1 | 124-mm-thick wall with 0.90-mm-thick GI metal studs, comprises Vapour barrier + 12.7 mm special polymerized fibre glass mesh based cement board + cement board one side with 4-mm-thick Basecoat and other side 15 mm Fire block board | 41 | 41(− 3, − 8) |
| | V2 | 124-mm-thick wall with 0.90-mm-thick GI metal studs, comprises Vapour barrier + 12.7 mm special polymerized fibre glass mesh based cement board + cement board one side with 4-mm-thick Basecoat and other side 15 mm Fire block board including All Purpose Jointing Compound (APJC) compound + Metal frame cavity filled with Glass wool of 50 mm thick and density 24 kg/m$^3$ | 43 | 42(− 1, − 7) |
| | V3 | 154-mm-thick dry wall System with 0.90-mm-thick GI metal studs, comprises Vapour barrier, 1 × 15 mm Fire Bloc Board + 12.7 mm special polymerized fibre glass mesh based cement board + cement board with 4-mm-thick Basecoat and other side 2 × 15 mm Fire Block Board including APJC compound + Metal frame cavity filled with Rockwool of 50 mm thick and density 48 kg/m$^3$ | 45 | 44(− 2, − 8) |
| | V4 | 154-mm-thick dry wall System with 0.90-mm-thick GI metal studs, comprises Vapour barrier, 1 × 15 mm Fire Bloc Board + 12.7 mm special polymerized fibre glass mesh based cement board + cement board with 2–3-mm-thick Base flex/Basecoat and other side 2 × 15 mm Fire bloc board including APJC compound + Metal frame cavity filled with Rockwool of 75 mm thick and density 64 kg/m$^3$ | 43 | 42(− 3, − 8) |

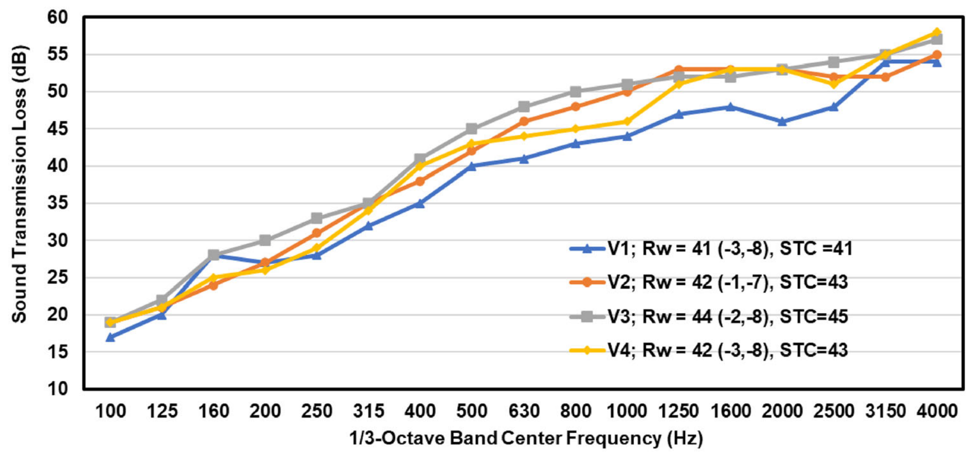


**Fig. 4** Sound transmission loss of different sandwich GI metal stud dry wall system with vapor barrier

**Table 4** Details and measured STC and $R_w(C, C_{tr})$ of different Gypsum sandwich partition panels

| Sr. no | Sample ID | Details of partition panels | STC | $R_w$ ($C$, $C_{tr}$) |
|---|---|---|---|---|
| | G1 | 122 mm dry wall partition consist Gyproc 70 mm C-stud + two layers of certified 12.5-mm-thick Gypboard + Plain boards on either side of metal framing. Ceiling channel & board strip above to be wrapped with double layer of 70µ Self Adhesive Low Density Polyethylene (LDPE) moisture barrier film. 70 mm GypSteel ULTRA Noggin channel at horizontal joint of board & 50 mm Glass Wool insulation of density 20 kg/m$^3$ | 41 | 40(− 2, − 8) |
| | G2 | 12 mm Gypsum sheet + 2 mm Insound barrier (high-density, highly viscoelastic synthetic soundproofing membrane) + Inrock (Resin bonded slab consist of long fine fibres spun from molten natural rocks, bonded with a thermosetting resin slab) 140 × 50 plain + 2 mm Insound barrier (9 mm) | 45 | 45(− 6, − 14) |
| | G3 | 12 mm Gypsum sheet + Insound barrier 4 mm + In airfill 8 mm + Inrock 150 × 25 + Insound barrier 2 mm + Inrock 140 × 50 Foil Scrim Kraft (glass reinforced Aluminium Foil) | 43 | 43(− 3, − 8) |
| | G4 | 14 mm Gypsum board bottom side + 90 mm steel stud + infilled glass fiber of density 25 kg/m$^3$ | 43 | 42(− 4, − 10) |
| | G5 | 13-mm-thick Gypsum board + 90 mm steel studs + infilled glass fiber of density 40 kg/m$^3$ + back side two Gypsum boards (13 mm thick inside and 12 mm thick outside) | 48 | 48(− 3, − 9) |

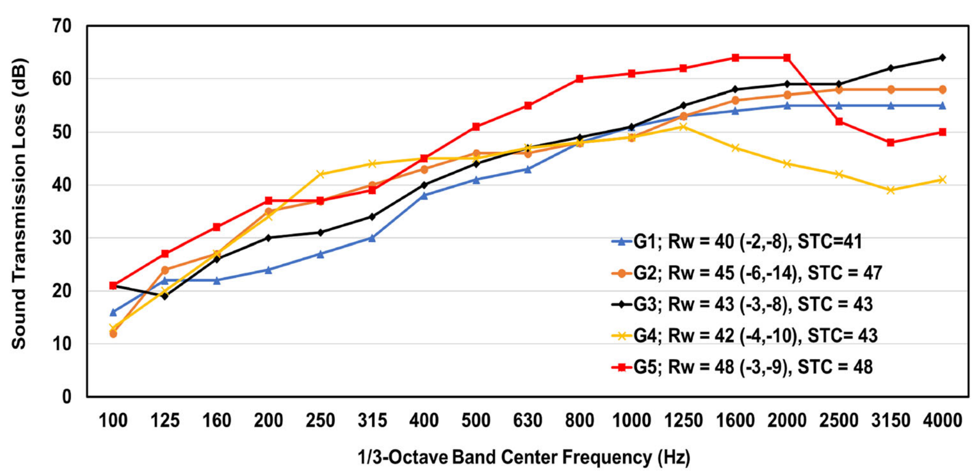


**Fig. 5** Sound transmission loss of different gypsum sandwich partition panels

**Table 5** Details and measured STC and $R_w(C, C_{tr})$ of different AAC blocks

| Sr. no | Sample ID | Details of partition panels | STC | $R_w$ $(C, C_{tr})$ |
|---|---|---|---|---|
| | A1 | 150-mm-thick AAC block of density 550–650 kg/m$^3$ | 44 | 44(− 2, − 5) |
| | A2 | 230-mm-thick AAC block | 48 | 48(− 2, − 6) |
| | A3 | 200-mm-thick AAC block with 12 mm Plaster on both side | 46 | 45(− 2, − 7) |
| | A4 | 229-mm-thick brick wall with 3 mm plaster | 41 | 41(− 3,− 7) |
| | A5 | 75 mm nominal thick V panel (A) consist of aerated light weight concrete core material sandwiched between two facing fibre cement sheets of thickness 5 mm | 32 | 31(− 2,− 5) |

insulation characteristics, but at higher frequencies (> 2 kHz) a coincidence dip is observed.

### 3.4. Autoclaved Aerated Concrete (AAC) Blocks

The various AAC block constructions tested in the Reverberation chambers are tabulated in Table 5. Figure 6 shows the sound transmission loss characteristics of the various AAC block constructions tested in the Reverberation chambers. The $R_w$/STC of AAC block constructions varied in range of 32–48, while the $R_w + C_{tr}$ values lie between 26 and 42 dB. AAC blocks suffer from low frequencies dip in range 160–315 Hz and higher frequency dip at 2 kHz. It can be observed that a widely used 200 mm thick AAC Block with 12 mm plaster on both sides shows a low frequency resonance dip at 250 Hz and a high frequency coincidence dip at 3.15 kHz and shows an $R_w + C_{tr}$ value of 38 dB. A 230 mm thick AAC Block has fairly high sound insulation in the entire frequency range and shows an $R_w + C_{tr}$ value of 42 dB.

### 3.5. GI Blocks

The various GI blocks constructions tested in the Reverberation chambers are tabulated in Table 6. Figure 7 shows the sound transmission loss characteristics of the various GI blocks constructions tested in the Reverberation chambers. The $R_w$/STC of GI blocks constructions varied in range of 31–40, while the $R_w + C_{tr}$ values lie between 26 and 34 dB.

### 3.6. Tecsound Sheets

Tecsound sheets are polymer based, asphalt free, high density synthetic sound proofing membrane sheet included with a self-adhesive layer embedded in sandwich

**Fig. 6** Sound transmission loss of AAC blocks

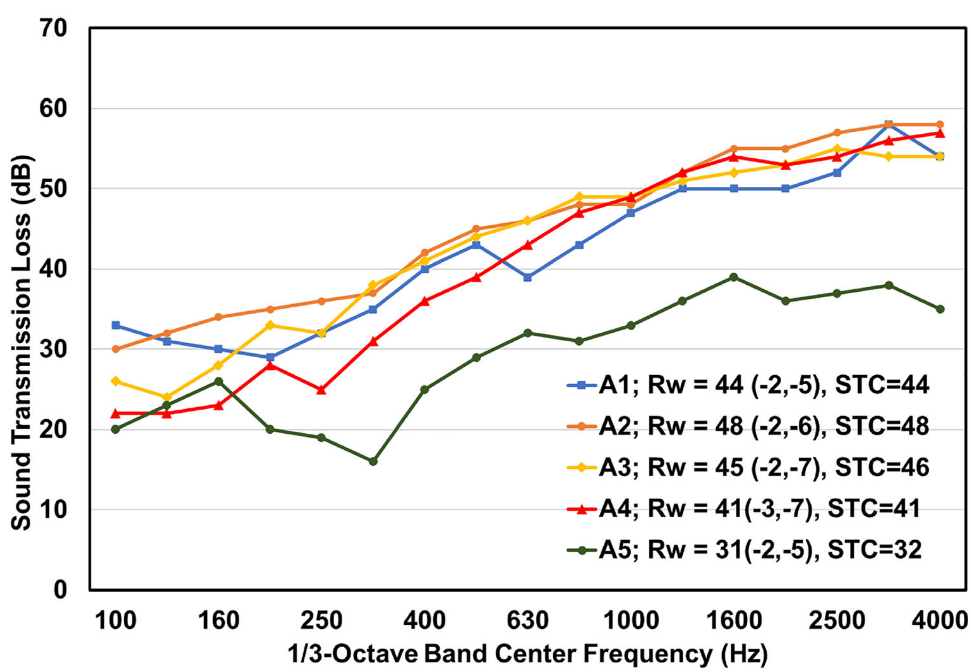

**Table 6** Details and measured STC and $R_w(C, C_{tr})$ of different GI blocks

| Sr. no | Sample ID | Details of partition panels | STC | $R_w$ ($C$, $C_{tr}$) |
|---|---|---|---|---|
| | GI1 | 1 mm PPGI (pre-painted galvanized Iron) + 75 mm Rockwool (R/W)-64 kg/m$^3$ + 1 mm perforated GI | 31 | 31(− 1, − 5) |
| | GI2 | 1 mm PPGI + Tecsound-35 (polymer-based, asphalt-free, high density synthetic soundproofing membrane) + 100 mm R/W-96 kg/m$^3$ + 1 mm perforated GI | 36 | 35(− 1, − 6) |
| | GI3 | 3 mm CR sheet + Tecsound-70 + 100 mm Rockwool-64 kg/m$^3$ + 1 mm GI perforated sheet | 40 | 40(− 2, − 6) |
| | GI4 | 1 mm Pre-coated outer sheet + 50 mm Mineral Wool (M/W)-80 kg/m$^3$ + 2 mm GI intermediate sheet + 50 mm M/W- 60 kg/m$^3$ + 0.8 mm perforated GI inner perforated sheet | 38 | 37(− 2, − 7) |
| | GI5 | 1.5 mm GI Sheet + 3 mm EPDM (Ethylene Propylene Diene Monomer) + M/W—100 kg/m$^3$ + 1.0 FGT Paper + 1.0 mm GI Perforated Sheet | 38 | 38(− 2, − 6) |
| | GI6 | 75-mm-thick Noise Barrier Panel consists of 1 mm GI Perforated sheet with 5 mm hole diameter 8 mm Triangular Pitch + Mineral wool of 100 kg/m$^3$ density, 75 mm thick covered with Fiber Glass cloth + 1 mm PPGI Outer sheet | 36 | 35(− 2, − 7) |
| | GI7 | 75-mm-Thick Acoustic Panel consist of 1 mm GI perforated sheet with 5 mm hole diameter 8 mm triangular pitch + Mineral Wool of 100 kg/m$^3$ density (75 mm thick) + 1.5 mm S235 JR (un-alloyed structural steel) outer sheet | 33 | 33(− 2, − 6) |

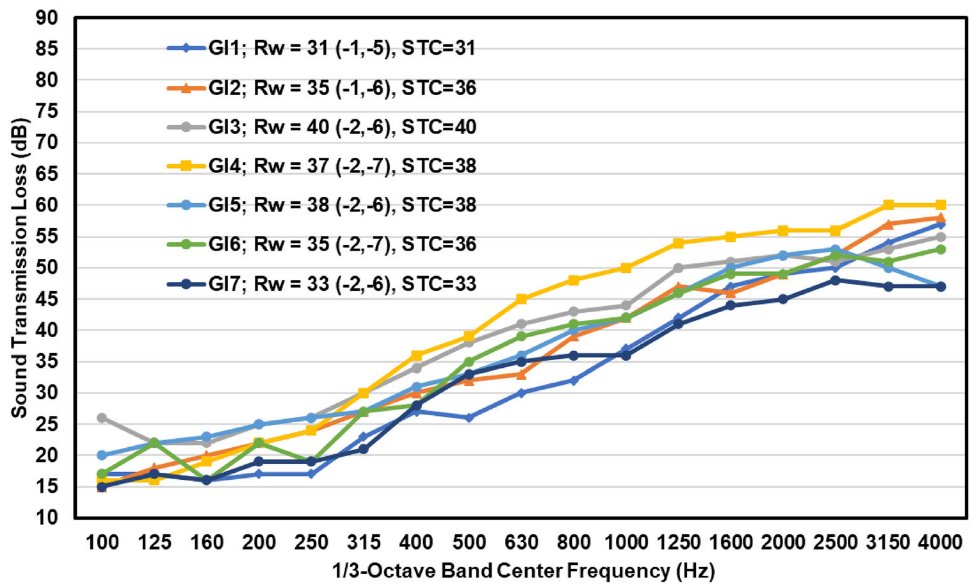


**Fig. 7** Sound transmission loss of different GI blocks

constructions. The various Tecsound sheet constructions tested in the Reverberation chambers is tabulated in Table 7. Figure 8 shows the sound transmission loss characteristics of the various Tecsound sheet constructions tested in the Reverberation chambers. The $R_w$/STC of Tecsound sheet constructions varied in range of 35–48, while the $R_w + C_{tr}$ values lie between 29 and 39 dB. The low frequency dips are significantly controlled using these sheets, while coincidence dip at higher frequencies in observed in some cases.

## 3.7. Green Materials

The various Green material constructions tested in the Reverberation chambers were the agri-bio panels made of natural agri-residue sugarcane bagasse, bamboo composites, teak wood, ply board and sandwich type composite sound reducing door panel (Table 8). Figure 9 shows the sound transmission loss characteristics of the various Green material constructions tested in the Reverberation chambers. The $R_w$/STC of Green material constructions varied in range of 29–37, while the $R_w + C_{tr}$ values lie between 24 and 32 dB.

**Table 7** Details and measured STC and $R_w(C, C_{tr})$ of different Tecsound (polymer-based, asphalt-free, high density synthetic soundproofing membrane) sheet embedded in sandwich constructions

| Sr. no | Sample ID | Details of partition panels | STC | $R_w$ ($C$, $C_{tr}$) |
|---|---|---|---|---|
| 1 | T1 | 1-mm-thick lamination on 12 mm W/P Plywood + 2-mm-thick Tecsound + 50 mm × 50 mm wooden Baton frame filled with 50 mm/500 Grams per Square Metre (GSM) wool + 14 mm plywood | 45 | 45(− 3, − 9) |
| 2 | T2 | 1-mm-thick lamination on 14 mm Plywood + 2-mm-thick Tecsound + 37 mm × 50 mm wooden Baton frame filled with 50 mm / 500 GSM wool + 2.5 mm Tecsound + 37 mm × 50 mm wooden Baton frame filled with 37 mm/ 500 GSM wool + 14 mm plywood | 48 | 47(− 2, − 8) |
| 3 | T3 | 1-mm-thick lamination on 12-mm-thick Plywood + 5-mm-thick Tecsound + 7 mm wooden Baton with wool 7 mm thick/500 GSM wool | 44 | 43(− 3, − 9) |
| 4 | T4 | 12 mm cement fiber board + 50 mm × 50 mm wooden baton frame filled with 50 mm 500 GSM wool + 5-mm-thick Tecsound | 46 | 45(− 4, − 11) |
| 5 | T5 | 1-mm-thick laminated 12 mm waterproof plywood + 2-mm-thick Tecsound + 50 mm × 50 mm wooden baton frame filled with 50 mm / 500 GSM wool + 14 mm plywood | 45 | 45(− 3, − 9) |
| 6 | T6 | 1 mm laminated 14 mm plywood + 37 mm × 50 mm wooden baton frame with 50 mm/ 500 GSM wool + 2.5 mm Tecsound + 37 mm × 50 mm wooden baton frame filled with 37 mm/500 GSM wool + 14 mm waterproof plywood | 48 | 47(− 2, − 8) |
| 7 | T7 | 1-mm-thick laminated 12-mm-thick plywood + 5-mm-thick Tecsound + 7 mm wooden baton with wool 7 mm thick/500 GSM + 14-mm-thick plywood | 44 | 43(− 3, − 9) |
| 8 | T8 | 5-mm-thick Tecsound + 14 mm 100 density FR grade foam + 1 mm aluminium foil | 35 | 34(− 1, − 5) |
| 9 | T9 | 8-mm-thick plywood + 5-mm-thick Tecsound + 8-mm-thick plywood | 38 | 38(− 2, − 5) |

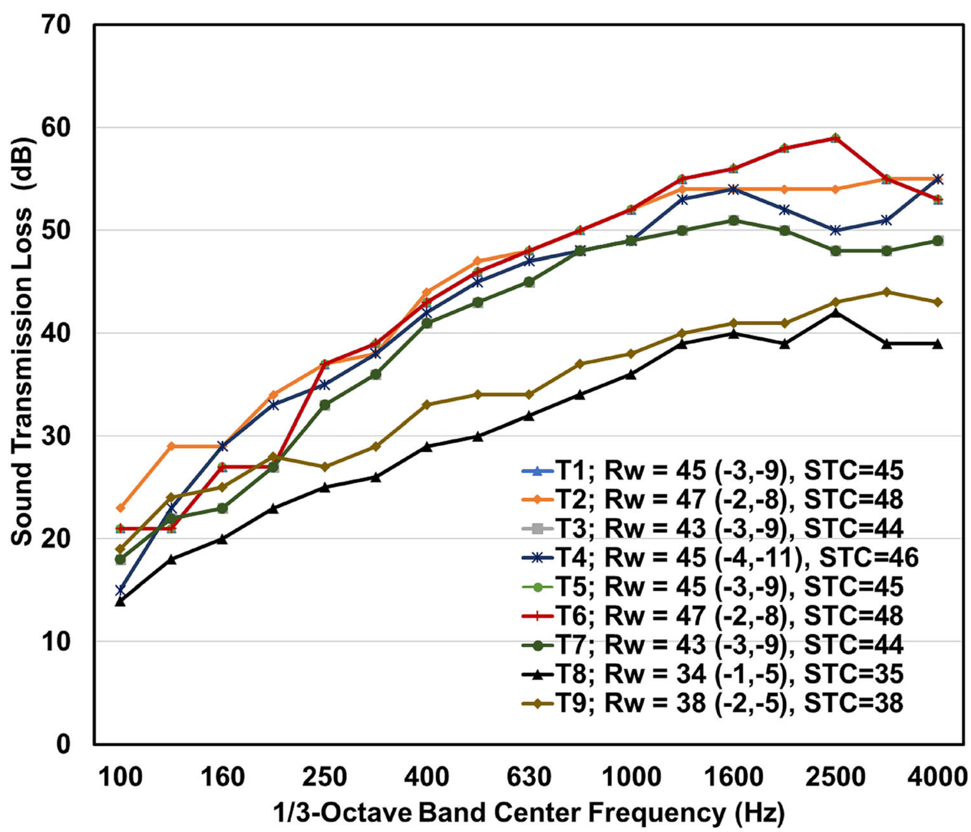


**Fig. 8** Sound transmission loss of Tecsound sheets embedded in sandwich constructions

**Table 8** Details and measured STC and $R_w(C, C_{tr})$ of different Green materials

| Sr. no | Sample ID | Details of partition panels | STC | $R_w$ $(C, C_{tr})$ |
|---|---|---|---|---|
| | GM1 | AgriBio panels made of natural agri-residue sugarcane bagasse | 29 | 29(− 2, − 5) |
| | GM2 | 20-mm-thick Bamboo Composites | 37 | 37(− 1, − 4) |
| | GM3 | 16-mm-thick teak board | 36 | 35(− 1, − 6) |
| | GM4 | 72-mm-thick sandwich type composite sound reducing door panel including Ist class Burma Teak wood frame. The frame of shutter face panels are 12-mm-thick Marine Ply board and 4-mm-thick Teak Veneer bonded with marine ply board. The Core of Door shutter is filled with resin bonded Glasswool | 34 | 34(− 2, − 5) |
| | GM5 | 16-mm-thick plywood board | 36 | 37(− 2,− 5) |

**Fig. 9** Sound transmission loss of green material partition panels

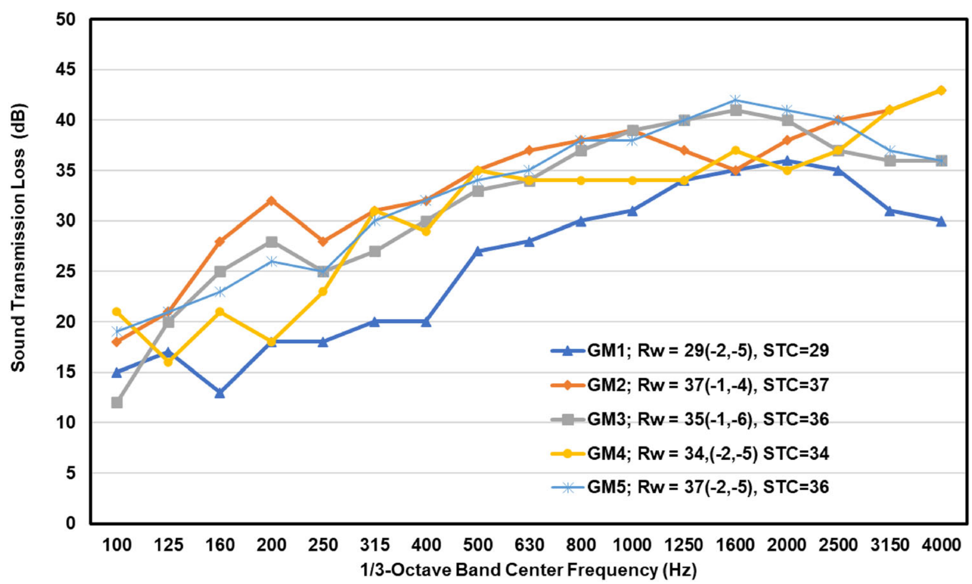


**Table 9** Details and measured STC and $R_w(C, C_{tr})$ of different asbestos and non-asbestos sheets

| Sr. no | Sample ID | Details of partition panels | STC | $R_w$ $(C, C_{tr})$ |
|---|---|---|---|---|
| | AS1 | 75-mm-thick asbestos panels | 36 | 37(− 2, − 5) |
| | AS2 | 100-mm-thick non-asbestos (high impact polypropylene, (HIPP) sheets) consisting of two non- asbestos cellulose cement based facing sheets of 5 mm thick and filled with light weight aerated concrete of 90 mm thick in between | 44 | 44(− 2, − 6) |
| | AS3 | 75-mm-thick non-asbestos sandwich wall panel consisting of two non- asbestos facing sheets of 4.8 mm thick and filled with light weight concrete core of 65.4 mm thick in between | 39 | 38(− 2, − 7) |

### 3.8. Asbestos and Non-asbestos Sheets

The various Asbestos and Non-Asbestos sheet constructions tested in the Reverberation chambers are tabulated in Table 9. Figure 10 shows the sound transmission loss characteristics of the various Asbestos and Non-Asbestos sheet constructions tested in the Reverberation chambers. The $R_w$/STC of Asbestos and Non-Asbestos sheet constructions varied in range of 36–44, while the $R_w + C_{tr}$ values lie between 32 and 38 dB. A 75 mm thick Asbestos sheet construction shows the dip at various frequencies in the entire measurement frequency range, while a 100 mm thick non asbestos sandwich construction shows enhanced sound insulation characteristics registering a dip at 160 Hz and 4 kHz.

**Fig. 10** Sound transmission loss of different asbestos and non-asbestos sheets

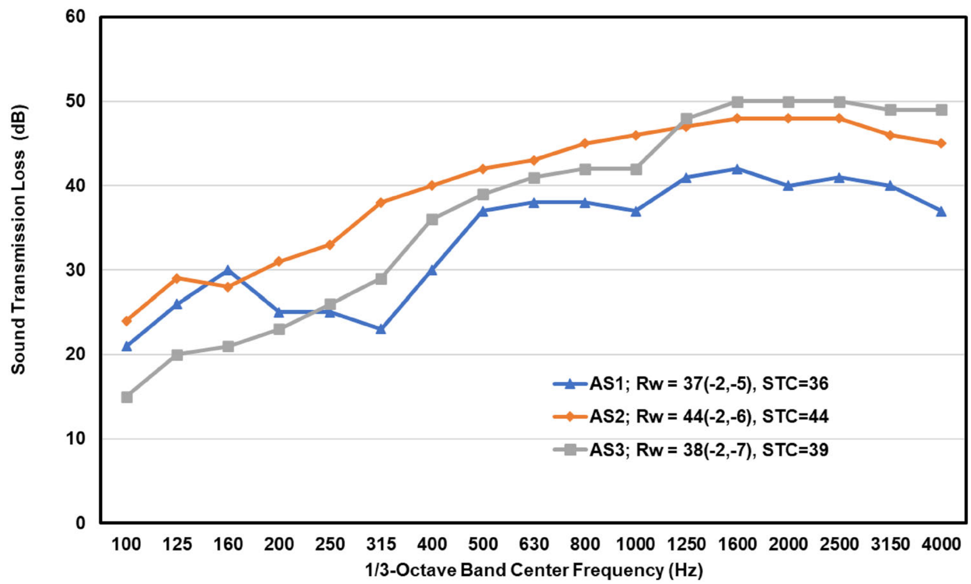


**Table 10** Details and measured STC and $R_w(C, C_{tr})$ of different stainless, aluminium, plastic and transparent sheets

| Sr. no | Sample ID | Details of partition panels | STC | $R_w$ ($C$, $C_{tr}$) |
|---|---|---|---|---|
| | SAP1 | 2-mm-thick layer with PU based 2 component sound insulating paint coated on 2-mm-thick MS Panel | 36 | 36(− 2, − 8) |
| | SAP2 | 1.5-mm-thick layer with PU based 2 component sound insulating paint coated on 2-mm-thick MS Panel | 36 | 36(− 2, − 4) |
| | SAP3 | 100-mm-thick Steel Acoustic Panel consisting of 16 Standard Wire Gauge (SWG) CRCA sheet on Front face and other side face laminated with GI perforated sheet, Acoustic insulation material (sound dampening & absorbing) filled in between | 50 | 50(− 2, − 6) |
| | SAP4 | P.U. sound/dampening Insulating paint coated on Mica with Polyester polyol and Polymethylene | 36 | 36(− 3, − 7) |
| | SAP5 | 3-mm-thick Aluminium Composite Panel (ACP) sheet (Alubond USA FR A2 (exterior fire retardant Panels with over 90% Stone core sandwiched between two layers of aluminium composite with Magnesium Hydroxide), ACP Thickness-3 mm, Color code—ALS 140, Color Name – Bone White, Al Skin thickness – 0.5 mm both side, Alloy – 5005A H42, Coating—Polyvinylidene fluoride (PVDF)) | 30 | 30(− 2, − 6) |
| | SAP6 | 5 mm Plastic Sheet | 27 | 27(− 2, − 5) |
| | SAP7 | 12-mm-thick Plastic Waste Tile | 35 | 35(− 1, − 6) |
| | SAP8 | 10-mm-thick Transparent Sheet | 19 | 19(− 1, − 3) |
| | SAP9 | 2.5 mm sprayed layer of paint on a 2-mm-thick Steel plate | 39 | 39(− 2, − 6) |

### 3.9. Stainless, Aluminium, Plastic and Transparent Sheets

The various Stainless, Aluminium, Plastic and Transparent Sheet constructions tested in the Reverberation chambers are tabulated in Table 10. Figure 11 shows the sound transmission loss characteristics of the various Stainless, Aluminium, Plastic and Transparent Sheets constructions tested in the Reverberation chambers. The $R_w$/STC of Stainless, Aluminium, Plastic and Transparent sheet constructions was observed to vary in range of 19–50, while the $R_w + C_{tr}$ values was observed in range of 16–33 dB. It can be observed that in case of 3 mm thick Aluminum Composite Panel (ACP) sheet widely used, the low frequency dip at 250 Hz and at high frequency dip at 4 kHz are observed.

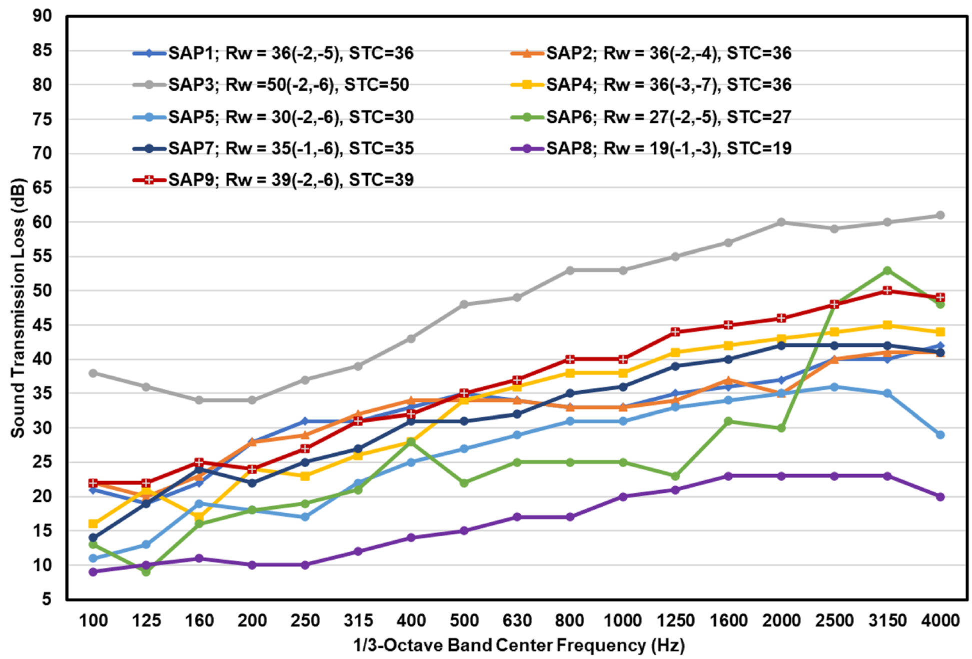


**Fig. 11** Sound transmission loss of stainless, aluminium, plastic and transparent sheets

**Table 11** Details and measured STC and $R_w(C, C_{tr})$ of different partition panels of various damping materials and other sandwich constructions

| Sr. no | Sample ID | Details of partition panels | STC | $R_w$ ($C$, $C_{tr}$) |
|---|---|---|---|---|
| | DM1 | 53-mm-thick Barrier with 50 mm accosound 3 mm butyl rubber dampener | 32 | 32(− 1, − 3) |
| | DM2 | 50-mm-thick metallic acoustic panel for noise barrier laminated with one side 1.2-mm-thick plain precoated sheet & other side 1.0-mm-thick perforated precoated sheet with infill sound dampening material combined with soft and flexible elements supported by Aluminum honey comb | 34 | 34(− 2, − 6) |
| | DM3 | 46-mm-thick Acoustic Door Shutter consists of Rockwool of 96 kg/m$^3$ filled between 3 mm thickness of Vinyl barrier and 1.2 mm GI Sheet both sides | 30 | 30(− 1, − 4) |
| | DM4 | 4 mm Insound barrier + Extruded polystyrene insulation board 50 mm | 31 | 31 (− 1, − 3) |
| | DM5 | Light Gauge Steel Frame (LGSF) wall with 9 mm + 6 mm HD Fibre Cement Board (FCB) at external face and 8 mm FCB + 12.5 mm Gypsum board at inside face with 100 mm Rockwool density 48 kg/m$^3$ | 36 | 36 (− 2, − 3) |
| | DM6 | 118-mm-thick modular metal wall cladding/paneling/Partition System consists of rigid PVC coated/powder Coated GI sheets backed with acoustic insulations and covered with powder coated GI sheet | 40 | 39 (− 4, − 10) |
| | DM7 | 100 mm thick of Acoustic Enclosure (consists of 0.6 mm perforated GI Sheet + 100-mm-thick Rockwool of density 120 kg/m$^3$ + 1.6 SWG Sheet) | 37 | 37 (− 2, − 7) |
| | DM8 | Front and back with 2 mm CRCA sheet + 12 mm absorptive wool and 5 mm high density board, at 69 mm thickness 2 mm high density board placed and in between front and back Rockwool of 96 kg/m$^3$ density inserted in the air-gap of 50 mm | 33 | 32(0, − 2) |
| | DM9 | 15-mm-thick calcium silicate based tile of density: 350 to 375 kg/m$^3$ | 32 | 32(− 2, − 5) |
| | DM10 | 62-mm-thick acoustical door consists of 12 mm calcium silicate board /4 mm sdm single layer/12 mm hdf/1 mm laminate 1 side and back side 4 mm sdm 2 layers/12 mm calcium ciliate board /12 hdf/1 mm laminate, all square edges 8 mm wooden beading | 44 | 43 (− 1, − 6) |

### 3.10. Partition Panels of Various Damping Materials and Other Sandwich Constructions

The details of the partition panels of various damping materials and other sandwich constructions tested in the Reverberation chambers are tabulated in Table 11. These constructions involve the sheets made of Butyl rubber dampener, vinyl barrier, calcium silicate based tiles, Fibre Cement boards. The sandwich constructions employing the cold rolled closed annealed steel sheet suffers from low

**Fig. 12** Sound transmission loss of different partition panels of various damping materials

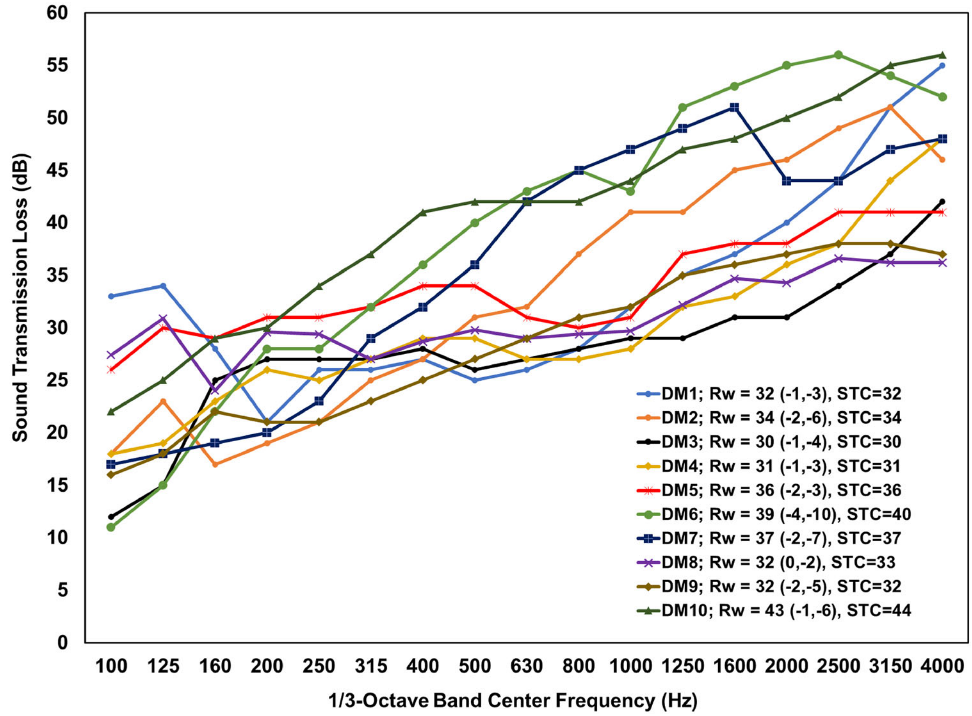


**Table 12** Details and measured STC and $R_w(C, C_{tr})$ of double glazed windows

| Sr. no | Sample ID | Details of partition panels | STC | $R_w$ ($C$, $C_{tr}$) |
|---|---|---|---|---|
| | TG1 | Double Glazed window with 10-mm-thick toughened glass on front side and 12.52-mm-thick laminated glass on back; Aluminium frame of size 100 mm × 25 mm; 62 mm air-gap between two glasses | 41 | 40(− 3, − 9) |
| | TG2 | Double Glazed window with 10-mm-thick toughened glass on front side and 12-mm-thick toughened glass on back; Aluminium frame of size 100 mm × 25 mm; 62 mm air-gap between two glasses | 38 | 38(− 2, − 5) |
| | TG3 | Double Glazed window with 10-mm-thick toughened glass on back side and 12-mm-thick toughened glass on front; Aluminium frame of size 100 mm × 25 mm; 62 mm air-gap between two glasses | 36 | 36(− 2, − 5) |

frequency dip at 160 Hz and coincidence dip at 2 kHz. Also, the Light Gauge Steel Frame (LGSF) suffers from low frequency sound insulation dip observed at 160 Hz. Figure 12 shows the sound transmission loss characteristics of the various damping and other sandwich constructions tested in the Reverberation chambers. It was observed that the $R_w$/STC of these constructions varied in range of 30–40, while the $R_w + C_{tr}$ values lie between 27 and 37 dB.

### 3.10.1. Double Glazed Windows

The details of the double glazed windows tested in the Reverberation chambers are tabulated in Table 12. These constructions involve the 10 mm and 12 mm toughened glass. Figure 13 shows the sound transmission loss characteristics of the double glazed windows. It can be observed that the $R_w$ varied from 36 to 40 for the double glazed windows. The 10(62)12 mm double glazed window shows a dip at 1.25 kHz, while the 12(62)10 mm double glazed window shows dip at 1 kHz and 1.25 kHz. It can be also observed that the back panel thickness has major role as compared to the front panel thickness as in case of 12(62)10 mm double glazed window, the $R_w$/STC is higher than 10(62)12 mm double glazed window. This may be attributed to the reduction in the co-incidence dip due to increased back pane thickness [29–31]. The co-incidence dip has been observed to shift to the lower frequencies as the back pane thickness is increased [25].

## 4. Conclusions

The paper reports the airborne sound insulation characteristics of sixty three sandwich partition panels and masonry constructions tested in Reverberation chambers for their applications as doors, noise barriers or enclosures for traffic and machinery noise control and for developing the

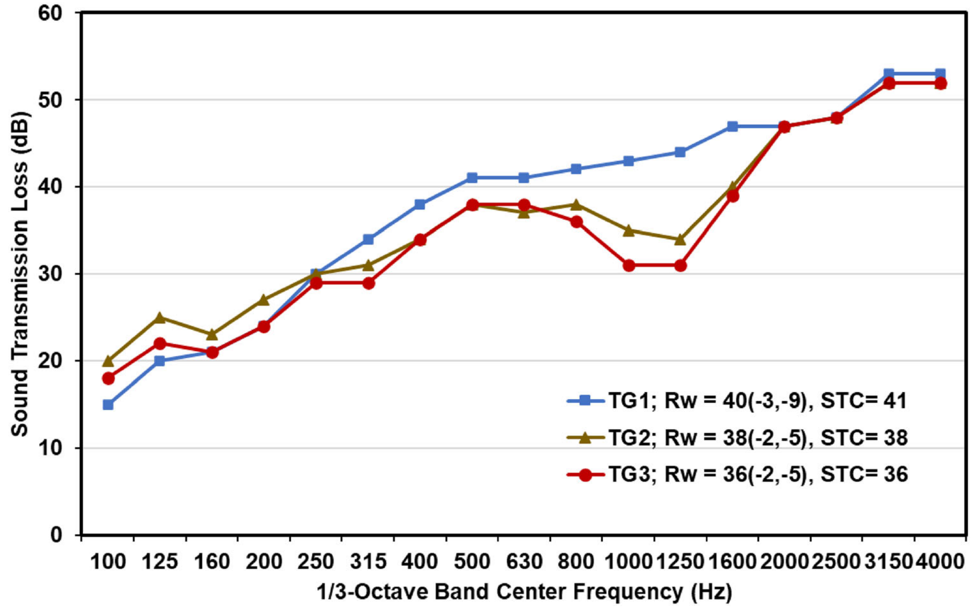


**Fig. 13** Sound transmission loss of double glazed windows

canopies for Diesel Generator Sets used widely in industries and commercial zones in Indian scenario and also for window glazing's. The study presents the rarely reported sound insulation characteristics of various types of sandwich constructions available commercially. The sound insulation of various dry wall systems utilizing vapor barriers, GI blocks, Tecsound sheets, Asbestos and non-Asbestos sheets, Stainless, Aluminium, Plastic and transparent sheets and various damping materials and double glazing's is reported in the study. The following conclusions are derived from the present study as follows:

1. The expanded measurement uncertainty in sound transmission loss measurement ranges between ± 1.5 an 2.0 dB in frequency range 100–4000 Hz, which is at a coverage factor $k = 2$ and which corresponds to a coverage probability of approximately 95% for normal distribution
2. The study suggests that sandwich constructions utilizing the various Gypsum and Tecsound sheets can provide enhanced acoustic performance comparable to the masonry constructions. The weighted sound reduction index, $R_w$ of sandwich gypsum constructions lies between 40 and 48, while the $R_w + C_{tr}$ values lie between 31 and 39 dB. The weighted sound reduction index, $R_w$ of sandwich Tecsound constructions lies between 34 and 47, while the $R_w + C_{tr}$ values lie between 29 and 39 dB.
3. The weighted sound reduction index, $R_w$ of masonry constructions, AAC blocks tested lies between 31 and 48, while the $R_w + C_{tr}$ values lie between 26 and 42 dB. AAC blocks suffer from low frequencies dip in range 160–315 Hz and higher frequency dip at 2 kHz.
4. The experimental results suggest that the polycarbonate sheets offer less sound insulation as the weighted sound reduction index, $R_w$ lies between 19 and 21, while the $R_w + C_{tr}$ values lie between 14 and 17 dB. These sheets suffer from poor low frequency sound insulation as low frequency dips are observed in lower frequencies from 160 to 250 Hz. Thus, sandwich constructions for polycarbonate sheets can be considered for accomplishing the desired noise level attenuation.
5. The $R_w$/STC value of double glazed windows tested in Reverberation chambers is observed to be enhanced with increasing the back pane thickness attributed to the reduced co-incidence dip.

Thus, the present study can be helpful in the development of optimal sandwich constructions of enhanced acoustic performance accomplishing the desired noise level reductions. Future efforts shall focused on developing sandwich constructions involving gypsum board, Tecsound sheets and fiber cement boards for developing sandwich constructions of enhanced acoustic insulation. Future efforts are also targeted in enhancing the low frequency diffusion characteristics in Reverberation chambers for evaluating the sound transmission loss characteristics in the measurement frequency range below 100 Hz.

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