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Design considerations of building elements for traffic and aircraft noise abatement

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The paper presents various design aspects based on exhaustive review of previous studies done so far and presents a database and design aspects of sandwich material combinations for applications in building elements, including various wall and roof constructions to combat traffic and aircraft noise. The paper includes a series of laboratory experiments carried out in Reverberation chambers at NPL for characterizing the sound insulation properties of sandwich dry wall partition panels in conjunction with the laboratory results published on masonry and drywall sandwich constructions by various researchers. The work provides an extensive database and physical understanding of theoretical phenomena proposed in previous studies for design and development of better sound insulative sandwich drywall constructions for their applications in building facades, walls, ceilings and doors for abatement of traffic and aircraft noise in Delhi city and tries to assimilate all the design guidelines in a cause and effect analysis diagram. The present work also envisages the significance and need of stricter building regulations w.r.t sound insulation of building elements for new residential projects planned especially in vicinity to airport or road traffic in India.

Keywords: Traffic noise, Aircraft noise, Dry wall constructions, Acoustics

1 Introduction

Transportation noise has emerged as a serious problem in Delhi city. The alarming increase in vehicular population and excessive use of horns have become havoc for the society causing serious annoyance amongst the community. Residents near the vicinity of airports or dwellings under directly the funnel zone of aircraft are the major sufferers and thus proper measures have to be undertaken to prevent the exterior noise entering inside the dwellings. Noise pollution can cause annoyance and aggression, hypertension, high stress levels, tinnitus, hearing loss, sleep disturbances and other harmful effects. The source-path-receiver concept of noise propagation has to be concentrated primarily on designing innovative sandwich constructions on the receiver i.e. dwellings, not only of aesthetic appeal but also of less cost. The main consideration for design of sound insulative material is 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 and protect the residents from hazards of noise pollution. The laboratory experiments, thus, shall serve as a benchmark for these investigations as in practical situations it is very difficult to characterize the sound insulation and absorption properties of materials. There are various laboratory method documented in literature for such measurements. Transmission loss (TL) is a performance of sound insulation measured in reverberation chambers. Sound Transmission Class (or STC) is an integer rating of how well a building partition attenuates airborne sound[1]. The method compares a family of numbered contours with one-third octave band TL data covering the one-third octave bands from 125 to 4000 Hz. The number of the contour that best fits the data gives the STC rating. The better the STC of materials, better sound insulation it provides. This integer rating is widely used to rate interior partitions, ceilings/floors, doors, windows and exterior wall configurations in USA. In practice, the Sound Transmission Class (STC) of laboratory samples represents optimum conditions, and is rarely achieved in actual construction. Field Sound Transmission Class (FSTC) evaluates the in-situ sound-insulating properties of building elements. It quantifies sound isolation between two rooms and the performance of a partition installed in the interior of a building. FSTC is a function of background noise levels, room volumes, surface areas, sound absorption values and spectral content of the sound source. A single number descriptor called weighted sound reduction index[2] R_w is used to facilitate comparison of the performance of different element in European continent. R_w contours consist of a horizontal segment from 1250 to 3150 Hz, a middle segment increasing by 5 dB from 400 to 1250 Hz and a low frequency segment increasing by 18 dB from 100 to 400 Hz. R_w rating of an element is determined by plotting the one-third octave band level of the element and comparing it with R_w contours. The R_w contour is shifted vertically until the curve falls mainly below the contour and the sum of the deficiencies below the contour over the 16 one-third octave bands does not exceed 32 dB is met. When the R_w contour is shifted to meet these criteria, the R_w rating is given by the value of the contour at 500 Hz. This uses a slightly different frequency range (125-4000 Hz for STC versus 100-3150 Hz for R_w) and excludes a limitation of no point more than 8 dB below the rating curve in any one-third-octave band as prescribed in STC. The laboratory investigations in determining the sound transmission characteristics of acoustical materials are instrumental in devising innovative material combinations to be used in dwellings for traffic and aircraft noise abatement. The present work attempts to focus on design aspects w.r.t building elements for strengthening the facades, walls, ceilings, doors and windows for acoustical comfort of residents in dwellings.

Sound transmission loss measurements in the present work are made in accordance in Reverberation chambers at National Physical Laboratory[3]. The source room has a volume of 257 m^3 and receiving room of 271 m^3. Test specimens are mounted in an opening of 1 m^2 between the source and receiving room. The sound pressure in both the rooms is measured using two condenser microphones (B&K 4165) and a real time analyzer (Norwegian, 830). The standard 1/3-octave bands are measured with center frequencies from 100 to 4000 Hz. Adequate diffusion exists in chambers while conducting the measurements. The transmission loss is calculated as:

$$TL = L_1 - L_2 + 10 \log_{10}(S/A) \text{ dB} \qquad \ldots (1)$$

where L_1 and L_2 are the average sound levels (dB) in the source and receiving room, S is area of panel and A is total absorption of the receiving room. The sound absorption[4] measurement is carried out according to ASTM C-423 Standard Test Method for Sound Absorption and Sound Absorption Coefficients by the Reverberation Room Method' at NPL. A loudspeaker with uniform spherical radiation suspended at a height of 2.5 m above the floor is used as a sound source in one corner of reverberation chamber of volume 260 m^3, surface area 240 m^2 and average reverberation time of 6 s. A band of random noise is used as a test signal and turned on long enough for the sound pressure level in the room to reach a steady state and decay rate is estimated by a Graphic level recorder. The absorption of the reverberation room is measured as both before and after placing a specimen of sound absorptive material in the room. A minimum six number of decay measurements for each frequency band is acquired. At least one loudspeaker position and three microphone positions with two readings in each case are used. The material is kept on rigid floor so as to get an exposed sample area of 12 m^2. The sound absorption coefficient is calculated and correction for boundary absorption is also applied. The evaluated uncertainty in measurement of sound absorption coefficient is ±5% at a coverage factor k=2 and probability of approximately 95% for a normal distribution.

2 International Guidelines

The low frequency noise annoyance has been a motivating factor in development of spectrum adaptation terms C and C_{tr} in ISO 717-1 standard[5]. The spectrum adaptation terms have been included to take into account the different spectra of noise sources: C and C_{tr} (corresponding to pink noise and road traffic noise) for airborne sound insulation. The standard covers the correction values C_{tr} which are to be applied when a representative urban traffic noise is assumed as the loading noise. A comparative study of legal sound insulation requirements in 24 countries in Europe was carried out which revealed significant differences in the descriptors and levels[6]. The main criteria for airborne sound insulation between dwellings followed in some European countries is presented in Table 1. Nordic countries have detailed regulations and higher values in comparison to other countries. INSTA Standard prepared by Norwegian council for building standardization specifies a sound classification system with four classes A, B, C and D for dwellings and its outdoor areas. In Finland, Norway, Sweden and Lithuania, Class C refers to the legal requirements and Classes A and B define higher levels of acoustical comfort. The following criteria have been suggested as standard for legal requirements based on a comprehensive study and literature survey by Rasmussen[7].

$$D_{nT,w} + C_{50\text{-}3150} \geq 55 \text{ dB} \qquad \ldots(2)$$

$$L'_{nT,w} + C_{I,\,50\text{-}2500} \leq 50 \text{ dB} \qquad \ldots(3)$$

Table 1 — Airborne sound insulation between dwellings. Main criteria in sound classification schemes in Europe[6]

Country	Airborne sound insulation between dwellings – Main class criteria in dB				
	Class A NL: Class 1 DE: Class III FR: N/A	Class B NL: Class 2 DE: Class II FR: QLAC	Class C NL: Class 3 DE: Class I FR: QL	Class D NL: Class 4 DE: N/A FR: N/A	Class E NL: Class 5 DE: N/A FR: N/A
Denmark	$R'_w + C_{50\text{-}3150} \geq 63$	$R'_w + C_{50\text{-}3150} \geq 58$	$R'_w \geq 55$	$R'_w \geq 50$	N/A
Finland	$R'_w + C_{50\text{-}3150} \geq 63$	$R'_w + C_{50\text{-}3150} \geq 58$	$R'_w \geq 55$	$R'_w \geq 49$	N/A
Iceland	$R'_w + C_{50\text{-}3150} \geq 63$	$R'_w + C_{50\text{-}3150} \geq 58$	$R'_w \geq 55$	$R'_w \geq 50$	N/A
Norway	$R'_w + C_{50\text{-}3150} \geq 63$	$R'_w + C_{50\text{-}3150} \geq 58$	$R'_w \geq 55$	$R'_w \geq 50$	N/A
Sweden	$R'_w + C_{50\text{-}3150} \geq 61$	$R'_w + C_{50\text{-}3150} \geq 57$	$R'_w + C_{50\text{-}3150} \geq 53$	$R'_w \geq 49$	N/A
Lithuania	$R'_w + C_{50\text{-}3150} \geq 63$ or $D_{nT,w} + C_{50\text{-}3150} \geq 63$	$R'_w + C_{50\text{-}3150} \geq 58$ or $D_{nT,w} + C_{50\text{-}3150} \geq 58$	R'_w or $D_{nT,w} \geq 55$	R'_w or $D_{nT,w} \geq 52$	R'_w or $D_{nT,w} \geq 48$
Netherlands*	$D_{nT,w} + C \geq 62$	$D_{nT,w} + C \geq 57$	$D_{nT,w} + C \geq 52$	$D_{nT,w} + C \geq 47$	$D_{nT,w} + C \geq 42$
Germany** (Multi storey)	H: $R'_w \geq 59$ V: $R'_w \geq 60$	H: $R'_w \geq 56$ V: $R'_w \geq 57$	H: $R'_w \geq 53$ V: $R'_w \geq 54$	N/A	N/A
Germany (Row)	$R'_w \geq 68$	$R'_w \geq 63$	$R'_w \geq 57$	N/A	N/A
France***	N/A	$D_{nT,w} + C \geq 56$	$D_{nT,w} + C \geq 53$	N/A	N/A

*Classes 1,2,3,4,5; ** Classes III, II, I;
*Classes QLAC, QL, DE-Germany, FR-France, NL-Netherlands, Row = Row Housing, H = Horizontal, V = Vertical

where $D_{nT} = L_1 - L_2 + 10 \log(T/T_0)$ ...(4)

$$D_n = L_1 - L_2 + 10 \log(A/A_0) \quad \ldots(5)$$

where L_1 and L_2 are average sound pressure level in source and receiving room, respectively, S the area of separating element, A is equivalent sound absorption area in receiving room; $A = 0.16\ V/T$, where V is volume of the room, A_0 is reference absorption area; $A_0 = 10\ m^2$, T is reverberation time in receiving room, T_0 is reference reverberation time; for dwellings T_0 = 0.5s, L_i is the impact sound pressure level in receiving room when floor under test is excited by standardized impact source.

$$L'_{nT} = L_i - 10 \log(T/T_0) \quad \ldots(6)$$

The basic descriptors $D_{nT,w}$ and $L'_{nT,w}$ correlate better with subjective evaluation for performance of airborne and impact sound insulation. The German standard [8] (DIN 4109) mentions the R_w requirement of 40 for exterior walls in case of ambient L_{Aeq} ranging from 66 to 70 dB(A). The R_w value requirements are incremented by 5 dB in case the L_{Aeq} values are incremented by 5 dB(A). The Manhattan standard for residential constructions also prescribes an STC of 39 for exterior walls for a noise level reduction of 25 dB, which is incremented by 5 in case of noise level reductions requirement is incremented by 5 dB.

The term R'_w refers to weighted sound reduction index, $D_{nT,w}$ is weighted normalized level difference, $L'_{nT,w}$ is weighted standardized impact sound pressure level and L'_{nT} is standardized impact sound pressure level. In USA, STC (Sound Transmission Class) is used for airborne sound insulation values of building elements and IIC (Impact Insulation Class) is used for impact sound according to FHA (Federal Housing Administration) criteria[9]. The FHA uses three grades for acoustical environment as presented in Table 2, which allows its criteria to be applied to a wide range of urban developments, geographic locations, economic conditions and other factors. Grade II is applicable to largest percentage of multifamily construction and can be used as basic guide. In Indian context, STC is widely used term. However, with growing international trade for building materials and technology, the scientific investigations are to be focused considering both the metrics followed in European and American continent for better harmonization. The present work attempts to evaluate TL in terms of both the metrics.

Table 2 — Airborne and impact sound insulation of building elements[9] in USA

Building element	Grade I	Grade II	Grade III
Wall	STC >55	STC>52	STC>48
Floor	STC >55 IIC> 55	STC>52 IIC > 52	STC>48 IIC > 48

3 Design Aspects

The resonant response including flexural and mass-air-mass resonances of the partition panels is major culprit for decrement in transmission loss at low frequencies particularly. Flexural resonant response is damping-controlled and thus minimized by increasing damping of the panel, while mass-air-mass resonance is controlled by the thickness of the individual panels and the distance between them. The larger the space or heavier the materials, the lower is the frequency at which the resonance occurs. The frequency of mass-air-mass resonance is calculated as[10]:

$$f_{\text{mam}} = \frac{1}{2\pi} \times \sqrt{\frac{1.8\rho_0 c_0{}^2 (m_1 + m_2)}{d m_1 m_2}} \quad \ldots (7)$$

where m_1 and m_2 are surface masses of layers in kg/m^2, ρ_0 is 1.18 kg/m^3 and c_0 is 343 m/s. Designing for mass-air-mass resonance of 50 Hz makes the optimum use of wall or floor materials. Filling the cavity with absorptive materials will increase the TL significantly. At frequencies above the mass-air-mass resonance, the effect of air cavity is to increase the TL significantly. Apart from the mass-air-mass resonance frequency; coincidence frequency also plays a pivotal role in controlling the sound transmission through partition panels. At coincidence, the mechanical impedance of the plate equals to the bending impedance, leading to large vibration at the resonance. The resonance dip due to coincidence effect usually begins about an octave below the critical frequency. In case of thick panels, a shear wave predominates the bending waves when panel is thicker than a wavelength. When shear frequency falls below the critical frequency for materials such as concrete slabs and brick or masonry walls, there is no coincidence dip and shear mechanism lowers the TL even below that as is observed at 200 Hz in case of a 6 inch concrete slab[11]. If shear frequency is greater than coincidence frequency, the shear wave impedance eventually becomes lower than bending impedance. The shear wave impedance limits the slope of TL line above the shear-bending frequency to 6 dB per octave. The sound reduction index for the plane waves assuming grazing incidence follows the mass law[11]described as:

$$R = 20 \log(Mf) - 47 \text{ dB} \quad \ldots (8)$$

where M is the mass per unit area of panel in kg/m^2. Eq. (8) predicts an increase in the sound reduction index of about 6 dB for each doubling of the mass per unit area. The sound reduction index of partition panel of area S_{Struct} with slit of area S_{Slit} can be calculated as[12]:

$$R = 10 \log_{10} \frac{S_{\text{Struct}} + S_{\text{Slit}}}{S_{\text{Struct}} 10^{-R_{\text{Struct}}/10} + S_{\text{Slitt}} 10^{-R_{\text{Slit}}/10}} \quad \ldots (9)$$

where R_{Struct} is sound reduction index of partition panel of area S_{Struct} and R_{Slit} is sound reduction index of slit. The sound reduction index of slit shaped apertures is calculated by Gomperts model[13] that requires the shape of regular slit as input data. The sound reduction index of slit is the highest just before the slit resonance and lowest at slit resonances; which occurs at wavelength corresponding to integral multiples of half depth of slit. Hongisto[14] pointed about these resonances occurring above 2000 Hz for typical doors. At frequencies below the frequency where the panel is half wavelength thick, the TL approaches that of panels without a hole. The sound reduction required through building elements depends upon the existing ambient noise levels in that area and expected Noise Level reductions for acoustic comfort of residents. Table 3 presents the Sound Transmission Class (STC) requirements for various building elements on basis of specified Noise Level Reduction as recommended by Metropolitan Council, Minnesota[15]. It can be observed that these guidelines are consistent with the theoretical calculations for expected Noise level reductions from a building element for a particular value of STC of material. To overcome the difference between the field and laboratory performance, it is recommended to select a wall or floor/ceiling system rated at 5 STC points above the level of sound attenuation required based on Dunn's observations[16] related to comparison of dBA reductions for aircraft and traffic noise with STC rating for 104 different building elements. It was concluded that aircraft noise and traffic noise on an average is attenuated by 4.6 and 6 dB less than numerical value of appropriate STC rating. Dunn's average values of 5 and 6 dB were used as corrections to table of STC values in Australian standards

4 Materials and Methods

It is difficult to insulate buildings against transportation noise because wall cavities are only effective in increasing sound insulation above mass-air-mass resonance frequency. The architectural aspects play a vital role in combating the outside

Table 3 — STC rating required for building elements[15]

Specified Noise Level reduction dBA	Required STC rating needed for compliance			
	Roof-Ceiling	Walls	Windows	Doors
20	40	40	30	20
25	45	45	35	25
30	50	50	40	30
35	55	55	45	35
40	60	60	50	40

noise apart from the material applications. The living rooms should be designed such that the traffic facing part of the dwelling is reserved for bathrooms, toilets etc. In areas not directly beneath the flight paths, the building orientation can sometimes be used to screen windows from aircraft noise. The most common weak links are windows, doors, ventilation openings and other cracks and openings. Proper measures undertaken to deal with the important elements of design of the building skin viz., glazing (glass thickness, double pane design etc.), roof material, caulking standards, chimney baffles, exterior door design, attic ventilation ports and mounting of wall air conditioners can be very effective in providing the acoustic comfort to residents in the dwellings. The material application and method of installation plays an equally important role in curtailing the traffic and aircraft noise. Apart from the conventional masonry constructions used widely in Indian dwellings, stud wall technology has gained its importance in recent years although these have significant structural resonances in low frequency region. However, stud walls can equal or outperform the level of noise insulation provided by masonry walls if designed properly. The conventional use of brick walls offers a good sound insulation and thus is a good choice for common portions in dwellings. Laboratory results[17] with different thickness of conventional building material is shown in Fig. 1. It can be observed that a high STC value of more than 45 is achieved in all the cases. Figure 1 also interprets the corresponding $R_w(C, C_{tr})$ as per ISO 717 standard.

Guillen *et al*[18]. showed that masonry-air cavity-brick walls built with clay or concrete blocks and 40 mm thick hollow brick leaves gives higher sound reduction index than the wall built with perforated brick and 70 mm thick leaf due to location of critical frequency. The experimental observations also revealed that masonry-air cavity-gypsum walls had higher sound reduction index than masonry-air cavity-brick ones. Binici[19] pointed out the compressive strength and sound insulation of fiber reinforced mud bricks to be higher than concrete bricks. The material used for fiber reinforced mud bricks was clay, cement, basaltic pumice and gypsum as stabilizers and plastic fiber, straw and polystyrene fabric as fibrous materials. High STC and good low frequency performance can be achieved with masonry walls. Concrete blocks or precast or cast-in-place concrete of same weight gives similar performance. Concrete block walls have wall board applied to each face as finishing material. If wall board is resiliently mounted, increasing airspace and adding absorptive material between concrete and wall board, the TL is enhanced and STC value over 60 can be obtained[20]. To ensure mass-air-mass resonance is below 80 Hz, the air space between single layer of wall board and concrete block should be at least 60 mm; for a double

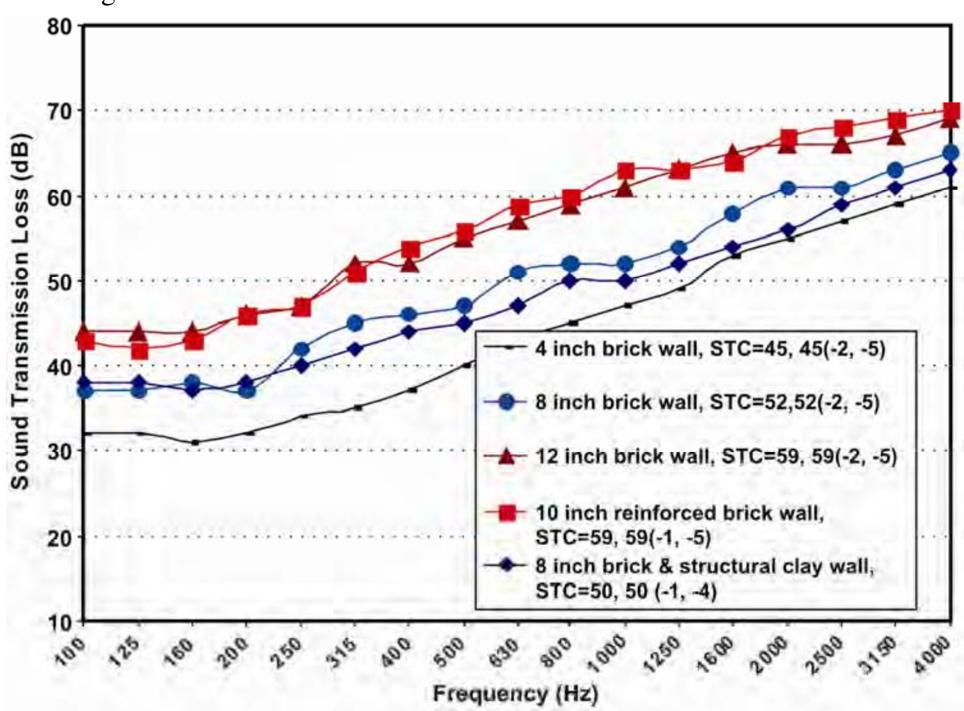

Fig. 1 — Sound transmission through various brick wall constructions used conventionally in dwellings[17]

layer of wall board, the space[20] may be as small as 35 mm. Fig. 2 shows the sound insulation characteristics of concrete wall sandwich constructions[21] for achieving a higher sound insulation. The STC of concrete block construction could be empirically predicted[21] in terms of block weight (kg) as:

$$STC = 0.5 \times \text{Block weight} + 39 \quad \ldots(10)$$

The abbreviation G16-Con 190 (SS65) GFB65 G16 indicate 16 mm dry wall applied to one side of a 190 mm concrete block wall supported on 65 mm steel studs with 65 mm of glass fibre butts in the cavity. On the other side, one layer of 16 mm dry wall is supported on 65 mm steel studs. RC 13 indicates 13 mm resilient channels applied to one side of 190 mm block wall and other side attached one layer of 16mm dry wall. The conventional use of brick and concrete masonry constructions for dwellings offers a good solution for noise abatement. However, dry wall technology has significantly gained importance especially in developed countries attributed to the light weight constructions (around 8 to 10 times) leading to non-messy faster construction time, high thermal insulation, excellent passive fire protection and aesthetic appeal also.

Gypsum, calcium silicate dehydrate ($CaSO_4.2H_2O$) has gained importance since past two decades and is widely used for dwellings in form of sandwich constructions. Gypsum plaster is advantageous as being a green material; shrinkage crack free surfaces, durability; light weight and reduced plastering time by seventy per cent as compared to conventional sand cement plaster can be achieved. 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 an STC with good low-frequency transmission loss as well. Bravo *et al.*[22] showed that thin air layer between gypsum boards causes a decrease in sound reduction index due to mass-air-mass resonance. A damping layer of bitumen based membrane improved the coincidence dip. Glass wool rolls and batts are very effective in causing the resonance frequency of light weight cavity walls to shift the lower frequencies resulting in higher sound insulation. The shift of resonance of mass-spring-mass system to lower frequency is caused by reduced dynamic stiffness of cavity filled with glass wool and reduced negative influence of standing waves. Non-load-bearing steel studs typically made from 24 mm gauge sheet steel are usually resilient enough to provide adequate mechanical decoupling between layers of gypsum board applied to both sides[20]. For load bearing steel studs, good results have been obtained through use of resilient channels. Lin and Garrelick[23] showed that when the two layers are not rigidly connected, the system has no longer primary structural resonance.

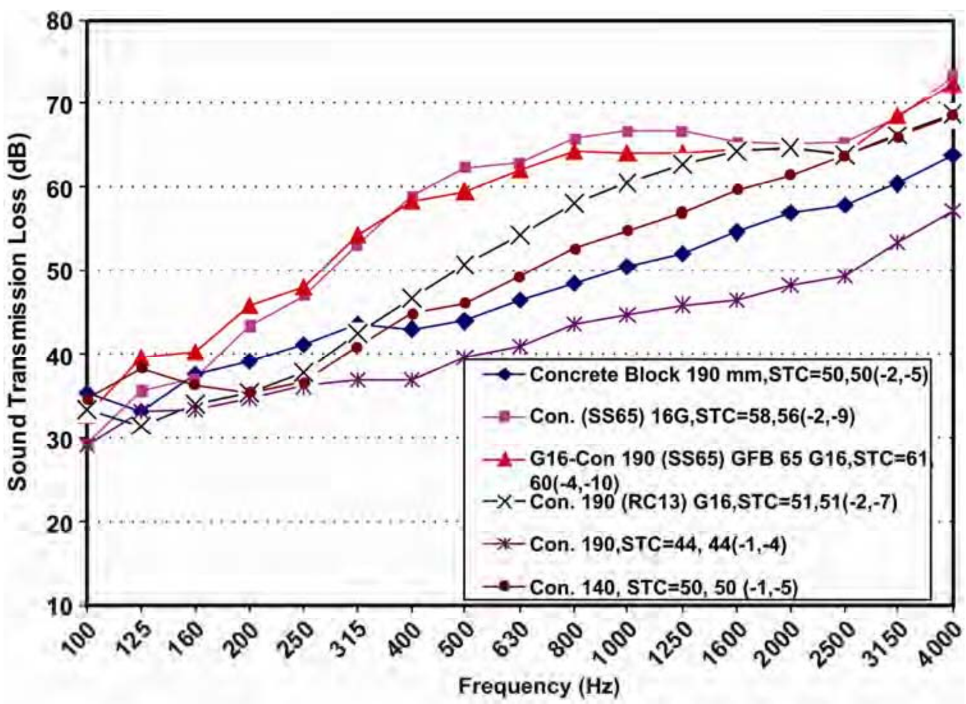

Fig. 2 — Sound transmission through various concrete block constructions[21]

Resilient furring channels separate the gypsum board from framing members thereby eliminating a direct path for transmission of vibration and noise. These channels act as shock absorber as they stiffen the vibrations coming from either side of walls. However, for this case the two surface layers are still coupled by stiffness of air cavity and a mass-air-mass resonance occurs[24]. The frequency of this resonance is modified by addition of stiffness of resilient channels. The coincidence dip is often of less practical importance as it occurs at a frequency where sound transmission loss is quit high. Stud spacing[25] is more important determinant in overall performance of exterior walls. Increasing stud size for both metal and wood studs result in modest STC increase. 25 gauge steel studs will provide approximately 3 STC point increase for each doubling of stud size, while wood studs provide 1 to 2 STC point increase for each doubling of stud size[26]. The most effective way for studs and resilient furring partition is to have them both spaced at 610 mm on centre. Varying the stud size from 305 to 406 mm and 610 mm reduce the resonance dip from 200 to 125 Hz and 80 Hz. Bradley[24] pointed out that adding resilient channels eliminate the primary structural resonance at 125 Hz and introduce modified mass-air-mass resonance at 63 Hz.

The staggered stud construction with resilient channels have significantly improved low frequency performance. Although the surface masses are similar, the staggered stud walls have lower stiffness because they do not include the added stiffness of resilient channels leading to mass-air-mass resonances in lower frequency region. When resilient channels are added to staggered stud wall system, further improvement is obtained[24]. A double studded wall is two separate rows of studs, top and bottom plates installed and separated from each other. Staggered or double studded walls will structurally decouple or mechanically separate two sides of walls and thus improve sound insulation characteristics. An ideal cavity partition would have no structural connection between the layers. Filling the cavity with absorptive material can increase the transmission loss substantially when cavity is large. Fig. 3 shows the sound absorption coefficient of inexpensive and readily available rockwool in Indian market of varied densities ranging from 48 to 144 kg/m^3.

It can be observed that NRC value increases with density. The normal incidence sound absorption coefficient of rockwool has been correlated by researchers as a function of non- dimensionless parameter, $\rho_0 f/R$, where ρ_0 is density of air and R is flow resistivity of bulk material. Uris[27] measurements indicate that for frequencies below 1250 Hz, the sound reduction index can be increased by reducing rockwool density. Over this frequency range, there are no differences on sound reduction index between rockwool densities The addition of drywall to surface of concrete block wall creates a cavity behind the drywall which will resonate at a frequency[21] $f_{\text{mam}} = 60/\sqrt{md}$. Adding sound absorbing materials to cavity behind dry wall lower the resonance frequency $f_{\text{mam}} = 43/\sqrt{md}$ and behaviour of air cavity changes from adiabatic to isothermal.

The most effective approach in attaining high sound transmission loss in stud or joist construction is to use two layers of material, one on each side of stud

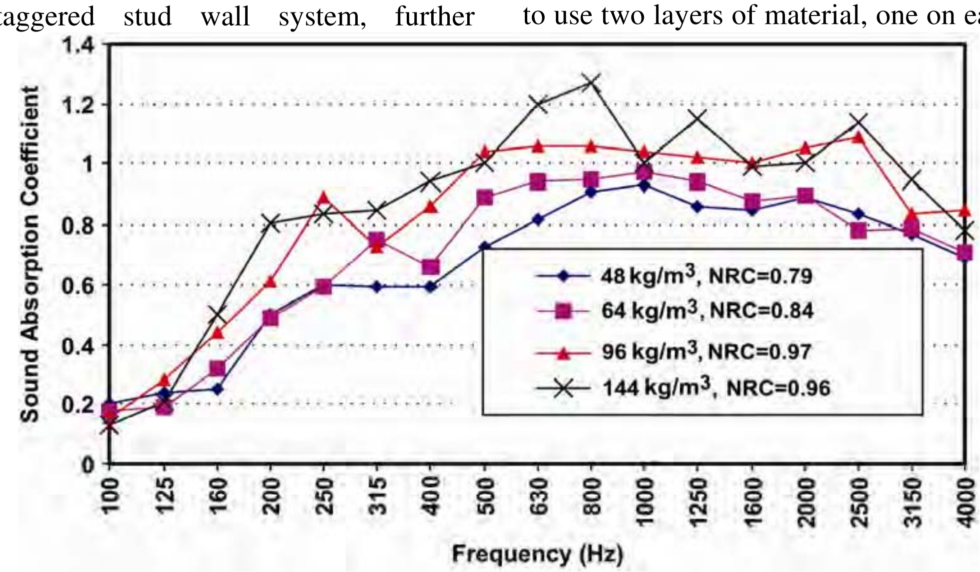

Fig. 3 — Sound absorption coefficient of rockwool of varied densities

or joist. The location of screws used to fasten gypsum board to resilient channels also play a crucial role. Craik and Smith[28,29] suggested that if screw spacings are less than half bending wavelength of waves on gypsum board, they behave as a continuous line and if more than a half bending wavelength as a discrete point. When the connection between the gypsum board and frame behaves as points, then structural coupling is proportional to number of nails and increasing the number of screws will increase the structural transmission. In double leaf walls, the measured sound reduction index is higher when screws were at 600 mm centers than at 300 mm centers[30]. The regression equation based on experimental observations on 360 walls formulated by Warnock[31] for empirically predicting STC and R_w through gypsum board walls can be used to predict the performance of partition panel without testing it.

$$\text{STC}= -69.7+33.5\times\log_{10}M_g+32.2\log_{10}d-7\times10^{-4}R +0.017S_{oc};\ r^2=0.903 \quad \ldots(11)$$

$$R_w=-60.3+29.5\times\log_{10}M_g+32.2\log_{10}d-2.1\times10^{-4}R +9.2\times10^{-3}S_{oc};\ r^2=0.92 \quad \ldots(12)$$

where M_g is total mass per unit area of gypsum board layers (kg/m^2), d is cavity depth in mm, R is flow resistance of sound absorbing material (mks rayls) and S_{oc} is stud spacing (mm). The standard error estimates are 2.0 and 1.6 dB, respectively.

The laboratory evaluation of sandwich gypsum constructions reveals a higher sound reduction index which can be accomplished by proper design as shown in Fig. 4. A metal stud of 102 mm thick partition consisting of one tapered layer of 15 mm thick fire line Gypboard on either side of 70 mm stud places at 610 mm centre to centre in 72 mm floor and ceiling channel with joists staggered and 50 mm glass wool of density 24 kg/m^3 inserted in cavity tested in laboratory showed an improved sound insulation characteristics at higher frequencies. Another partition panel comprising of 198 mm thick metal stud partition of two tapered edge layers of 12.5 mm thick Gypboard on either side of 146 mm studs placed at 610 mm center to centre in 148 mm floor and ceiling channels with joist staggered and 50 mm thick glass wool 24 kg/m^3 inserted in cavity was tested. It can be observed that such combination proved to be quite beneficial in both low and high frequency range. Another combination of 264 mm thick metal stud fire wall comprising of three layers 15 mm thick fire line Gyp board and 300 mm thick metal stud wall comprising of three layers of 15 mm thick fire line Gyp board and 100 mm of glass wool 32 kg/m^3 inserted in cavity also showed a high STC value although a mass-air-mass resonance dip at 200 Hz was registered. A comparison of the lightweight constructions as compared to the masonry construction was further drawn as shown in Fig 5. A 132 mm thick metal stud partition consisting of two tapered layers of 15 mm thick plain Gyp board on

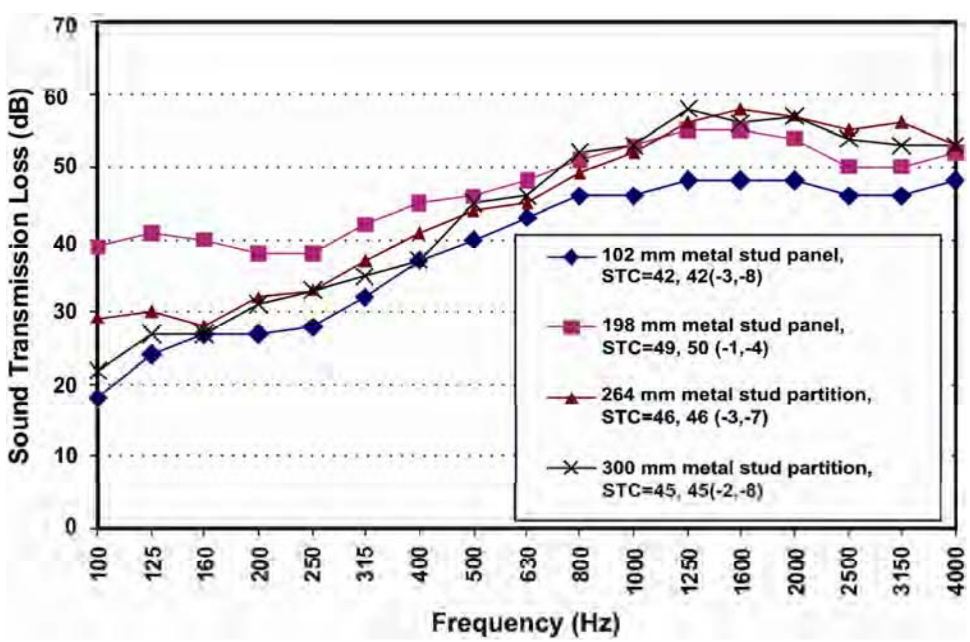

Fig. 4 — Sound transmission through various sandwich gypsum wall constructions

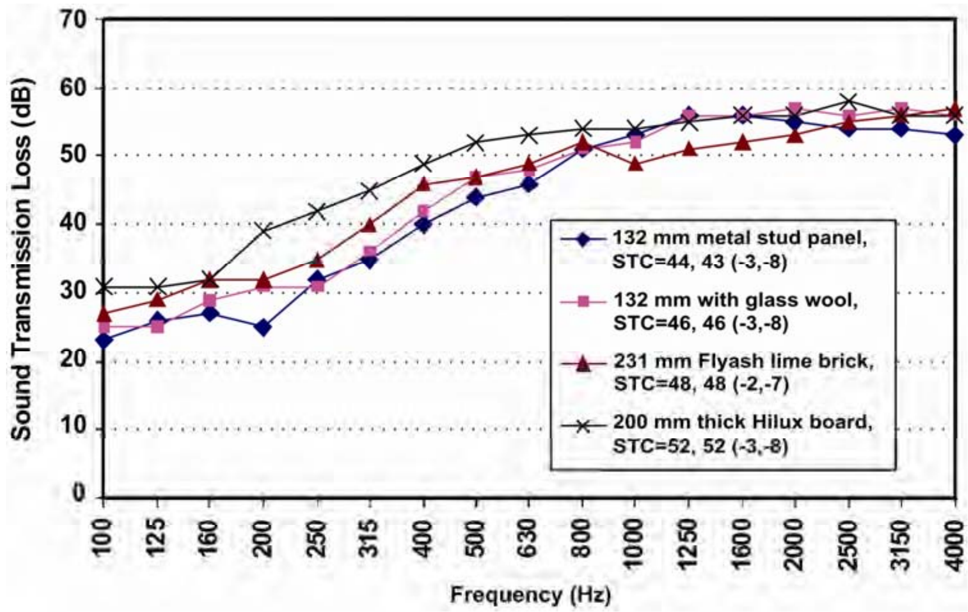

Fig. 5 — Sound transmission through various sandwich wall constructions

either side of 70 mm suds placed at 610 mm center to centre in 72 mm floor and ceiling channel with joists staggered and another same combination with 50 mm thick glass wool 24 kg/m^3 inserted in cavity showed a high STC value.

Another partition wall construction of 231 mm thick comprising of Fly ash lime bricks of size 231×110×70 mm and 10 mm cement plaster on facing side registered significantly improved insulation characteristics. A very high STC was observed with a 200 mm thick partition consisting of 12 mm thick Hilux calcium silicate board and 10 mm Hicem board on either side of twin 48 mm stud holding 50 mm glasswool (48 kg/m^3) and at center being 56 mm air gap. Thus, the dry wall construction can outperform the masonry constructions with inclusion of absorptive materials in air cavity. For single stud walls, adding extra mass by doubling layers usually leads to modest improvements with increments[24] that approximate 10 log(M/M_0). Laboratory experimentation[32] confirm the modest improvements in STC of such sandwich constructions with inclusion of resilient furring channels, addition of absorptive materials and increasing the number of gypsum layers. Fig. 6 shows the benefits of resilient furring channels, non load bearing steel studs, addition of glass fiber batt and increasing the mass by incrementing the gypsum layers.

The configuration I and II shows the relative increase in STC with increasing the thickness of conventional masonry constructions. The configuration III is 132 mm thick metal stud partition comprising of two tapered layers of 15 mm thick Gypsum board on either side of 70 mm studs placed at 610 mm centre to center in 72 mm floor and ceiling channel with joists staggered. Addition of glass fiber batt of 24 kg/m^3 increases the STC value by 2 points.

The IV material combination[32] shows the increments in STC value for a 38×89 mm wood stud at 400 mm o.c with 90 mm mineral fiber batt in cavity and 12.5 mm Gypsum boards on each side. It can be observed that addition of resilient furring channels at 600 mm oc increase the STC value by 8 points and with a further addition of two Gypsum boards on each side, the value increases substantially by 22 points. A similar laboratory experimentation[32] for wood studs at 600 mm oc with 65 mm glass fiber batts and 12.5 mm gypsum board on each side revealed 11 points increase in STC value. In case (VI) of a 31×92 mm, 25 gauge (0.5 mm) non load bearing steel studs[32] at 400 mm oc with 89 mm glass fiber batt and 12.5 mm gypsum board on each side, the STC value increases up to 10 points with further addition of Gypsum boards. The use of load bearing steel studs of varying thickness results in maximum 2 points increase in STC. The experimental observations concluded by Warnock[33] serve as best guidelines in design of sandwich constructions:

- mass-air-mass resonance has a great deal of effect on STC, and much more on low frequency sound transmission loss;

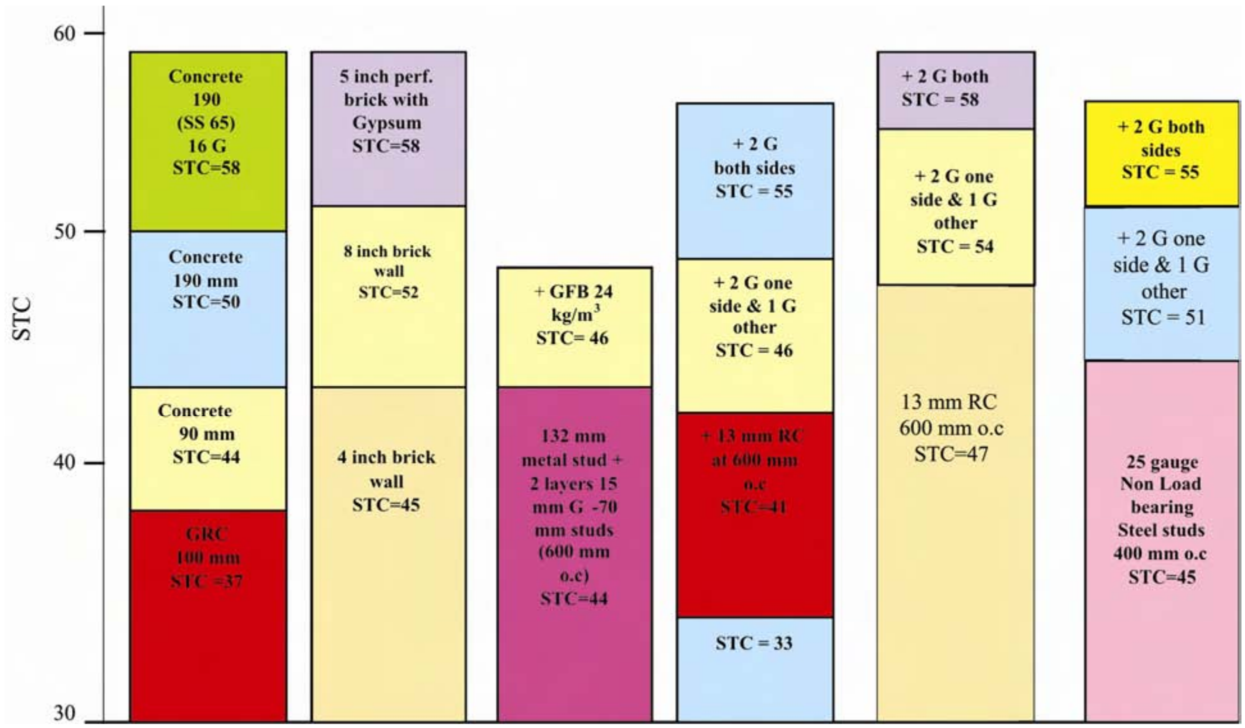

Fig. 6 — Increments in STC (Sound Transmission Class) value in masonry and drywall constructions upon addition of various options (resilient furring channels RC 13, 2 Gypsum board on one side and one on other, 2 Gypsum board on both sides, Non load bearing steel studs, addition of glass fiber batt)

- the greater the airspace, the lower the mass-air-mass resonance and the greater the STC; addition of sound absorbing material lowers mass-air-mass resonance;
- the use of resilient connections instead of rigid supports increases high frequency performance but the STC rating may be still controlled by low frequency behaviour;
- if adding a layer on one side causes a detrimental resonance, then adding a similar layer on the second side makes the resonance worse.

In designing of floor/ceiling system, both impact and airborne noise has to be controlled. Providing independent joist to support ceiling is the best solution. For obtaining an STC appreciably above 50, the upper layer of floor[20] should have mass per unit area of at least 50 kg/m^2. The floating floor gives the greatest amount of sound and vibration insulation although it is extremely expensive. A suspended ceiling can also provide better reduction of structure-borne noise due to the decoupling of the construction and the area above called the plenum space can contribute in improving the absorption characteristics of the room. An isolation clip or hanger is used to support the steel grid and gypsum board ceiling. Isolation elements are typically fiber glass pads, neoprene pads or for low frequency sound isolation springs. Ceiling isolation systems should be used in conjunction with floor isolation and high STC walls to achieve complete acoustical privacy. Reducing the structural connections across the floor/wall junction (wall with double row of studs) and adding a heavy floor topping such as 38 mm concrete provides effective solution[33]. Soft or resilient surface layers on floor provides a better cushioning effect. Changing the orientation of floor joist is also instrumental as floor framing that runs perpendicular to separating wall transmits more flanking sound than framing that runs parallel[34] Less flanking via the ceiling/ceiling path can be expected when joists are parallel to the wall. Fig. 7 shows the sound transmission loss characteristics of commercial metal stud partitions available in Indian market for floor/ceiling applications. An 122 mm thick metal stud partition comprising of two tapered 12.5 mm thick plain Gypboard on either side of 70 mm studs placed at 610 mm centre to center in 72 mm floor and ceiling channel with joists staggered and 2 mm thick Veneer finish plaster on board side registered an appreciable coincidence dip as compared to similar 97 mm thick and 102 mm thick metal stud partition with tapered

15 mm plain Gypboard. A Kalzip roofing manufactured by M/s Polybond Organics, Bangalore widely used in airports consisting of Kalzip 65/400, 0.9 mm thick Aluminium sheet with Stucco embossed finish with 50 mm thick mineral wool (96 kg/m^3) and 50 mm thick mineral wool (120 kg/m^3) inserted, vapour control 0.2 mm thick polyurethane film and 0.7 mm thick galvanized steel sheet with 25 microns polyester coated type trapezoidal panel applied in ceilings tested showed an appreciable sound reduction at high frequencies.

Innovative designs also prove to be fruitful in attenuating noise apart from the material and installation methodology. Quirt[35] reported the A-weighted noise reduction of aircraft noise by three type of roof-ceiling structures. A flat built-up roof had a noise level reduction of 44 dBA, a peaked roof with ventilated attic 51 dBA and a peaked roof with non-ventilated attic had a 54 dBA aircraft noise reduction. Cook[36] reported improvement in TL at medium and high frequencies and eliminations of coincidence dip on addition of 74 mm layer of high density mineral fiber in attic space of roof ceiling of 6 mm thick corrugated asbestos panels. The attenuation of ceiling transmitted flanking sound depends upon the sound transmission and absorption characteristics of ceiling panels and the acoustical leakage through plenum which can be controlled using the absorptive materials. The application of absorptive materials over the ceilings and walls reduces the reverberant sound fields developed in the room during to any additional noise sources. Fig. 8 shows the sound

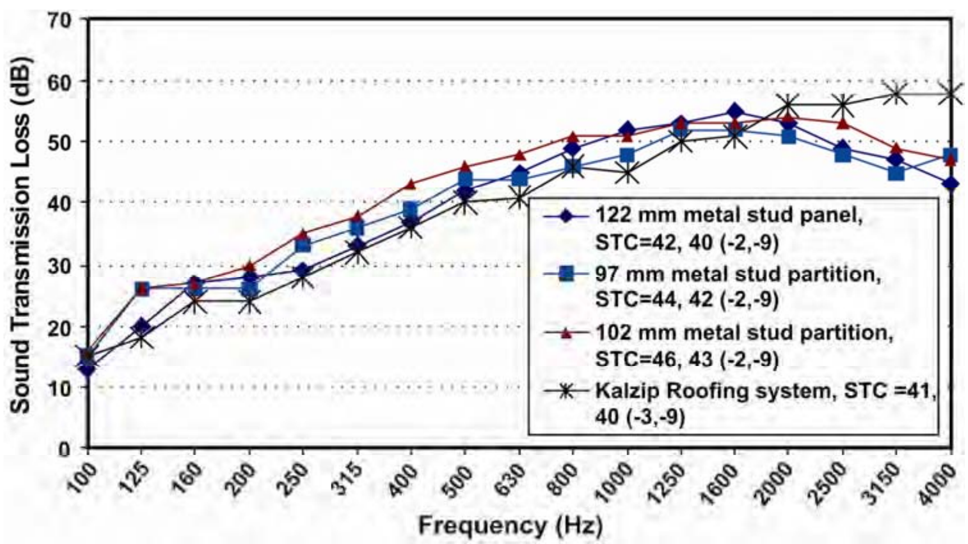

Fig. 7 — Sound transmission through various sandwich ceiling constructions

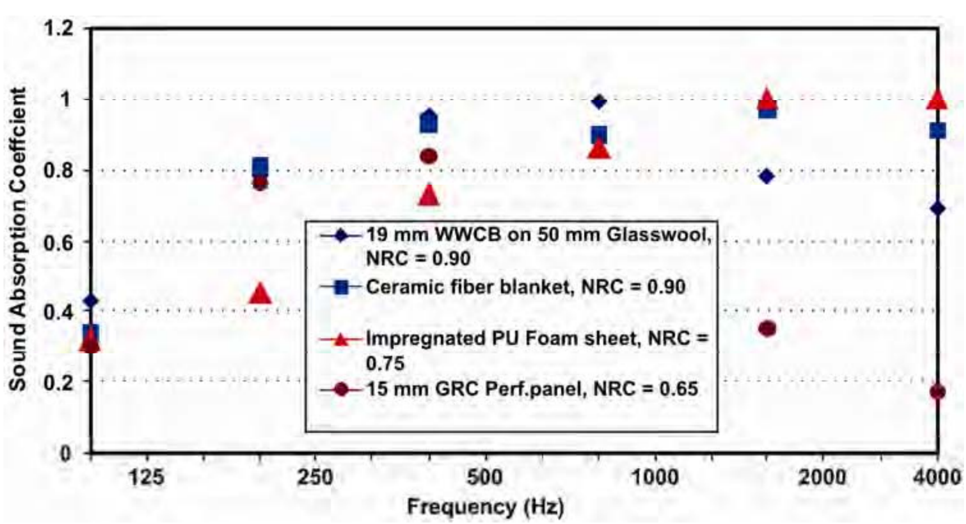

Fig. 8 — Sound absorption coefficient of various suspended ceiling tiles

absorption coefficient of the various suspended tiles tested. An impregnated PU foam sheet 25 mm thick with aluminium foil laminated on 50 mm air cavity was observed to provide good absorption at higher frequencies. It can be observed that 19 mm wood wool cement board on 50 mm glass wool (32 kg/m^3) provides an improved sound absorption coefficient in entire frequency range. Experimental results reveal that 38 mm ceramic fibre blanket of density 96 kg/m^3 shows a very high sound absorption characteristics especially at high frequencies as compared to 15 mm thick GRC perforated panel mounted on 50 mm thick glass wool of 32 kg/m^3 density. The laboratory experimentation of wide variety of absorbing materials has revealed that with increasing the thickness of porous soft materials, absorption coefficient attains the maximum value at 500 Hz, which is maintained uniformly at higher frequencies also. On covering the absorbing materials with aluminium foil of 0.15 mm thickness, it behaves like a resonant membrane with maximum absorption in low frequency range. Perforated panels spaced away from solid backing provide a widely used practical application of cavity resonator principle for control of reverberant noise. The increase in open area (perforated 30%) not only shifts the resonance frequency but also provides uniformly a higher value of absorption coefficient over a wider frequency range.

Acoustically doors are even weaker than windows and more difficult to treat attributed to the sealing characteristics. The alternative solution is to place

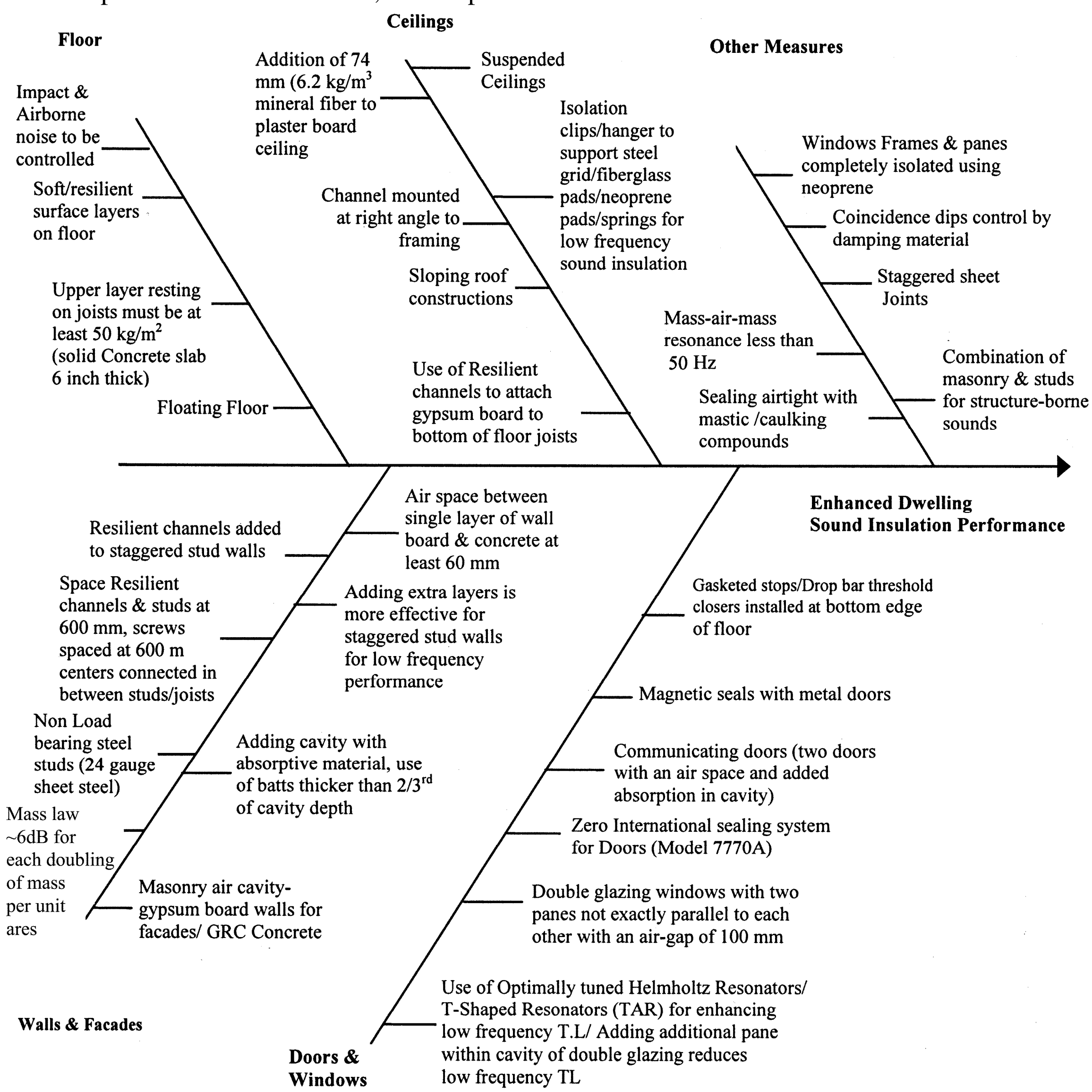

Fig. 9 — Cause and effect analysis diagram for enhancing dwelling sound insulation performance

them in more shielded areas. Rubber or neoprene gaskets between the floor and frame, use of magnetic seals, installation of gasketed stops or drop bar thresholds; communicating doors[20] (two doors with airspace between) prove to efficient ways in enhancing the sound insulation characteristics of doors. The application of double glazing windows can significantly reduce the outside traffic noise. Increasing the thickness of cavity in double glazing, leads to enhanced sound insulation characteristics. The design features enhancing the sound transmission loss of building elements are summarized in a cause and effect diagram is shown in Fig 9. Resilient channels with staggered stud walls, spaced at a 600 mm and screws attached at 600 mm with absorptive material in the cavity and increasing the depth of cavity prove to be optimum solution for combating the low frequency noise especially. Adding extra layers for staggered constructions are instrumental in accentuating the low frequency performance. Adding mass, decoupling by breaking the path of vibration via resilient channels, providing absorption and proper sealing are effective measures for restricting the airborne sound from sound from passing through walls and floors and preventing flanking transmission. The metal stud dry wall constructions discussed can be used in exterior applications also for achieving the desired objectives. Brick veneer, masonry blocks or stucco exterior walls constructed air tight with all joints caulked air tight in conjunction with dry wall constructions inside the building provides one of the best solutions in achieving the desired noise level reductions.

5 Conclusions

The present work highlights the importance of drywall light weight constructions for application in dwellings and provides a database of various material combinations available in Indian market and the regulations required for building elements to combat the low frequency noise radiated by vehicular traffic and over flying aircrafts. Apart from understanding the physical principles behind accentuating the sound insulation characteristics of sandwich partition panels, economics and readily availability in market is a challenge before acoustical engineers for implementation of design to seek desired objectives. It can be inferred from the exhaustive literature survey carried out that not only the material combinations, but also the practical installation is crucial for preventing the flanking transmission and achieving high STC values. It is also envisaged that stricter building codes w.r.t sound transmission class requirements for building elements shall be implemented and strictly enforced in National Building Code of India for new residential projects to provide acoustic comfort to the residents from outside noise. The technological advancement in building sciences for adapting for light weight construction materials with high strength and rigidity and improved sound insulation characteristics has to be thus brought in persistent use in Indian dwellings rather than relying on massive masonry constructions for tackling the adverse effects of ever-growing transportation noise in metro cities like Delhi.

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