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Performance evaluation of autoclaved aerated concrete and brick masonry buildings: A case study in north Indian climatic region

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ABSTRACT

The present work evaluates a detailed study of thermal, acoustic, water tightness, indoor air quality and day time illuminance of auto claved aerated concrete (AAC) walls and brick masonry buildings. Both the buildings are ground plus one storey with anarea of 1100 sq. ft. The water tightness test was performed under simulated rain fall condition of 210 mm per / hour continuously for 5 hours on AAC building. Parameters *viz.*, ambient and indoor temperature, thermal transmittance, thermal admittance, *etc.*, are recorded and analysed for period for April to Mayand December to January month. The temperature plot shows the maximum temperature inside the building does not exceed 32°C and relative humidity (R.H.) less than 60% for both the buildings. Noise isolation values at frequencies ranging from 100 Hz to 4000 Hz are noted with maximum of 35-40 and 45-55 dBA for porous concrete and brick masonry walls.

1. INTRODUCTION

Climate change and rising temperature is a global issue which needs to be addressed very effectively. In today's scenario, nearly 50 per cent of the global population resides in urban areas, which is responsible for the major amount of greenhouse gas emissions[1-4]. Due to the rising temperature, the cost of comfortable living has also increased. Buildings, either commercial or residential, are responsible for nearly more than 40 per cent of the energy consumption[5]. In harsh climatic conditions, external aids are required for a comfortable living which in turn are responsible for greenhouse gas emissions. In a report published by the Ministry of Statistics and Program Implementation of Government of India, the majority of electricity consumption in India is accounted to industrial and domestic sectors[6]. Out of this total consumption, 24 per cent of the electricity is consumed for domestic household purposes, and the industrial sector is responsible for nearly 42 per cent of electricity consumption. The demand for energy is likely to increase three fold by the year 2025. The indoor comfort which involves, thermal, air conditioning and artificial daylighting accounting for major greenhouse gases (GHG) emission. To lower the energy consumption in domestic households, which accounts for a major share of electricity consumption, well-planned houses having sufficient interior daylighting, new construction materials, proper ventilation, and external cooling/heating should have a mandatory feature.

Regarding the thermal and acoustic comfort of a building, engineered structural materials are being utilised in building materials that can provide sufficient thermal comfort against the harsh ambient environment. Most common thermally insulated materialsare fiberglass, foam, glass wool and mineral wool[7-9]. To minimise the solar radiation into a building, optimum window area must also be taken into account[10-12]. The above mentioned thermally insulated materials are not building blocks but are fillers to minimise ambient heat in the houses. Usually the building walls comprises of brick masonry with additional layer of plasters on outside and inside. The thermal conductivity of masonry brick wallsand concrete varies from 0.5 to 1.7 W/m. K[13]. The rat trap model is also employed in brick masonry wall construction techniques which helps in thermal comfort against ambient high temperature fluctuations. Instead of using brick masonry construction practices, light weight composites materials comprising of porous lightweight materials, cement fibre boards *etc.*, are being utilised in current time which improves thermal performance of a building and thereby contributing to energy efficient buildings. In this regard, autoclaved aerated concrete (AAC) blocks is one of the most promising material in the construction field. Features *viz.*, low density of 550-650 kg/m^3, thermal conductivity of 0.11-0.19 W/m.K. and fire resistant properties make AAC blocks it as good construction material for thermal comfort. Despite having advantages, drawback *viz.* high water absorption capacity can degrade its material properties[14-17].

A lot of interesting research work on environmental impacts assessment on various types of Australian buildings have been done by Vivian W. Y. Tam and co-workers. They have studied the development of building optimization models which helps in minimizing the overall energy consumption and also reduce the greenhouse gas emissions. Similar type of energy consumption, thermal comfort study based on window to wall ratios have also been done by Vivian W. Y. Tam and co-workers and described elsewhere in detail[35].

The northern part of India which falls under composite climate which experiences both harsh summer and winter climatic conditions. The AAC infilled building may be of great potential as far as energy efficient building designs are concerned with some added modifications like optimizing the window size, reflective coating on the roof top *etc*. Major portion of the heat is transmitted through ceiling in daytime. On the other hand, AAC blocks as an acoustic barrier to outside noise has a sound transmission class (STC)of 40-45 dB as compared to concrete wall which has a STC rating of 52 dB[18]. The present study investigates the thermal, acoustic and water leakage performanceof ground plus one storey building of AAC and composite brick masonry building.

2. METHODOLOGY

2.1 Materials and methods

The AAC building has been constructed from AAC blocks of 600 mm × 230 mm × 150 mm blocks with inner and outer mortar layer of 18 and 12 mm respectively. Whereas, the brick wall building comprises of bricks and concrete blocks as construction materials. The west facing wall is a double layer wall with rat trap model with an air gap of 80 mm and total wall thickness of 230 mm. Inset of Figure 4 shows the model of rat trap bond employed in the brick layer construction.

2.2 Thermal comfort measurement

The constructed AAC and brick masonry buildingswere tested for temperature difference for outside and inside walls, ambient and inside room temperature, relative humidity on ground plus storey building of 1100 sq. ft. area. Table 1 shows the physical properties of AAC blocks and related thermal conductivity values.

Table 1. Physical properties of AAC blocks and related thermal conductivity values[15, 19].

Physical parameters	Values
Temperature and relative humidity at the time of testing	41ºC 17% R.H
Blocks in wall construction	AAC blocks, 150 mm thick
Density	550-650 kg/m^3
Total wall thickness	180 mm (including plaster)
Glass window thickness	5 mm
Room area	3 m × 2.6 m
Window area	1.8 m × 1.4 m
Thermal conductivity of AAC block	0.11- 0.15 W/ m. K
Thermal conductivity ofmortar	0.5 - 1.2 W/m.K
Thermal conductivity of brick	0.6-1.0 W/m.K
Thermal conductivity of single window glass pane.	0.8 W/ m. K
Test location	Roorkee (IN), composite climate zone.

The wall and ambienttemperatures measurement for both the buildings was done by an infrared thermometer Fluke 64 MAX having a temperature range of -30°C to 600°C with an accuracy of ± 1.5°C. According to Guide for Heat Insulation of Non-Industrial Buildings IS 3792 -1978, no heating or cooling aids are used during the measurement. For relative humidity measurement TESTO THERM Hygrometer 6400 was used with an accuracy of ± 2 per cent of R.H value. The R.H. measurement was done under various conditions *viz.* ambient R.H., no ventilation, single sided and cross ventilation for AAC building. The wall temperatures, inside temperaturesand relative humidity were recorded at 1-hour interval for 24-hours and over the period of seven days' in the month of April to May and December to January month. The thermal transmittance (U-value) measurement of AAC block and brick walls were measured by Testo 635 U-value meter. The measurement is based on the formula which can be described as:

$$U = \alpha \frac{T_{in} - T_{surface,in}}{T_{in} - T_{out}}$$

where, α is 7.69 W / m^{2}K, T_{in} inside room temperature, $T_{surface,in}$ is inside room surface temperature, T_{out} is outside ambient temperature[32].

2.3 Acoustic comfort and indoor air quality measurement

Sound level meter Class I, CESVA SC-420 was used for the measurement of outdoor-indoor noise around the AAC and composite brick wall building. Asound source (CESVA AP 602) with pink noise of

Table 2. Acoustical parameter details of AACand brick walls blocks and instrumental details[18, 19].

Physical parameters	Values
Temperature and humidity at the time of testing	42ºC 19% R.H
Sound transmission class (STC) rating of AAC block (porous concrete)	44 dB
STC rating of concrete block 100 mm thickness	52 dB
STC rating of brick wall with plaster (8 inches)	45 to 55 dB
Ambient noise at the time of testing	65 to 75 dB
Measuring range of sound level meter	30 dBA to 130 dBA
Accuracy	± 1.1 dB at 1 kHz
Resolution	0.1 dB
Operating condition	0 to 40ºC, 10-80% R.H

audible frequencies over the range of 100-5000 Hz was used. A multi face dodecahedron speaker (CESVA FP 122 complying to ISO-3382-1 and ISO 3382-2 standard) was used to amplify the noise to a level of 100-115 dB. Table 2 shows the acoustical parameter details of AAC and other building blocks and other relevant instrumental details.

Indoor air quality (IAQ) inside the AAC building of room area 3 m x 2.6 m with three-person occupancy for 10 minutes was recorded under zero and cross ventilation condition. Testo 400 was used for CO_2 level measurement. The CO_2 measurement limit for Test 400 sensor is 0 to 5000 ppm. The current CO_2 level in Roorkee in at 423 ppmand the safe limit is 400 ppm in the residential areas. Microscopy images of AAC block and cement sand mortar as plaster were captured by MIRA TUSCAN 3 field emission scanning electron microscope (FE-SEM).

2.4 Water tightness test

The water tightness test is done under a simulated rain condition of 210 mm per hour. Sprinklers used in firefighting were installed on the roof and the front walls. The deflector of the sprinklers creates

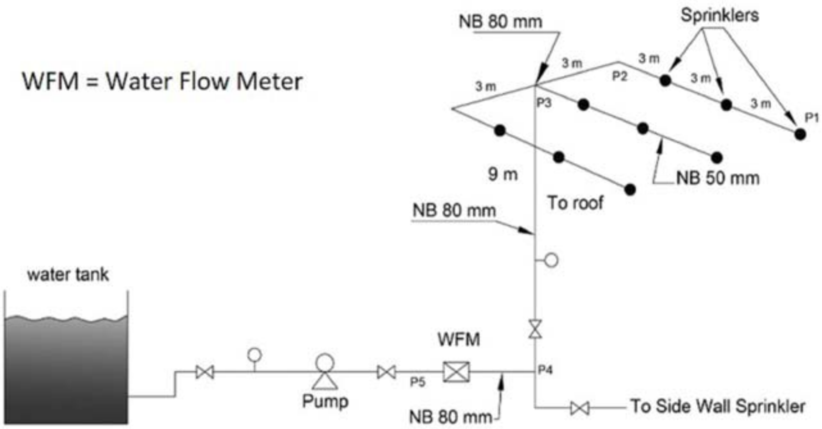

Fig. 1. Single Line Diagram of Setup.

Fig. 2. View of water tightness test setup and actual testing at AAC building.

a uniform spray pattern over the roof.The water from water tank was supplied to the sprinklers through a 180 liters per minute pump having 50 m head. The sprinklers on the roof and on the front wall can be activated one at a time or simultaneously. Pressure gauges were installed at different locations in addition to the water flow meter to measure the water flow rate. The water was recycled to prevent its wastage. The single line diagram (SLD) of setup is shown in Figure 1. Whereas, Figure 2 shows the view of water tightness test setup and actual water testing facility in building. The whole building was subjected to a flow rate of 210 mm/hour for a continuous period of 5 hourswhich is representative of a cloud burst phenomenon.In addition, the drain pipes on the roof were blocked to accumulate the water on the roof. The ponding depth was kept 50 cm. The ponding was done for a period of 15 days as seen in Figure 2.

2.5 Daytime illuminance measurement

The daytime light intensity measurement inside the AAC buildings *viz*. ground floor room, first floor room, lavatory, stairs *etc.* was done by LUX intensity meter (LX 1020 BS). The data were recordedduring daytime of the summer season. No internal illumination was done at the time of measurement.

3. RESULTS AND DISCUSSION

3.1 Thermal studies

Figure 3 shows the satellite images of AAC building at CSIR-CBRI campus where thermal, humidity acoustic, water tightness test and indoor air quality and illuminance measurement are done.

Figure 4 and 5 show the directional faces and rooftop/ceiling images of AAC and brick wall building at CSIR-CBRI Roorkee.

Fig. 3. Satellite images of CSIR-CBRI Roorkee and AAC and brick wall building site.

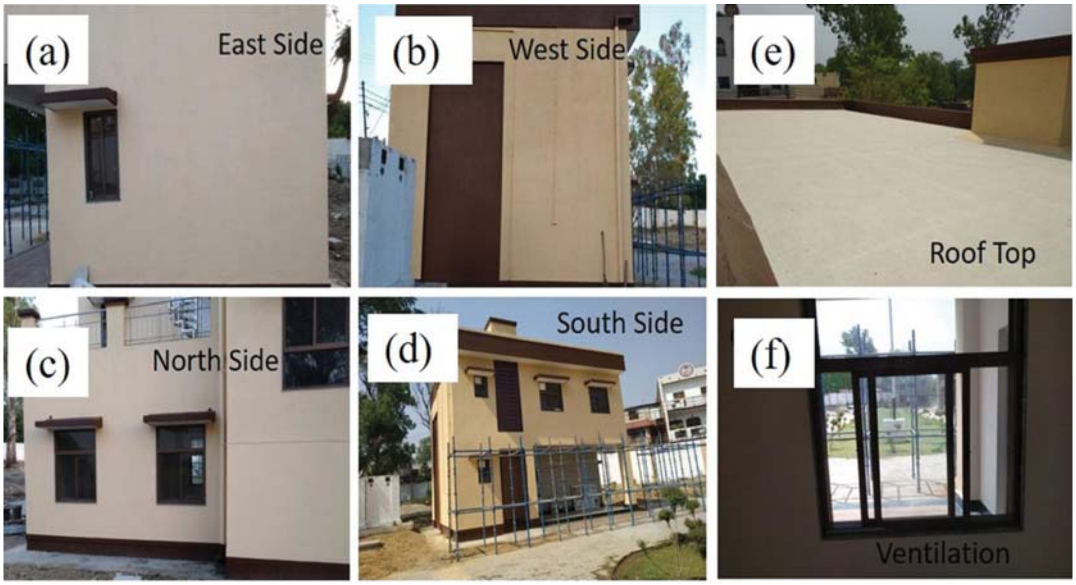

Fig. 4. Directional faces, roof top and ventilated view of AAC building.

Fig. 5. Directional faces of brick wallbuilding.

Figure 6 and 7 show the surface wall temperatures (both inside and outside) of the all the directional faces of AAC and masonry brick wall building namely east, west, north and south recorded for peak

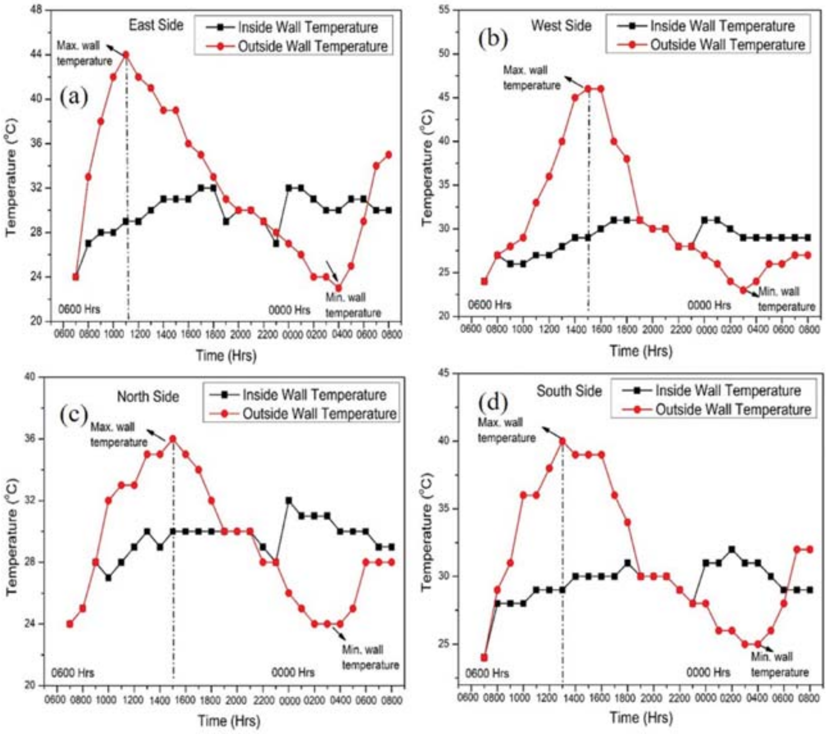

Fig. 6. Wall temperature variation of AAC building facing towards (a) east, (b) west, (c) north and (d) south side.

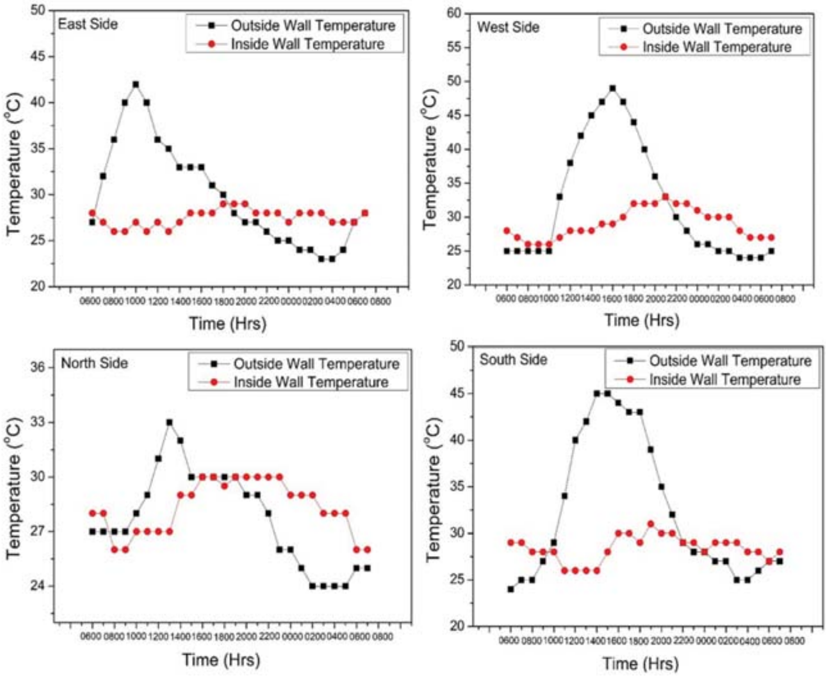

Fig. 7. Wall temperature variation of brick masonry building facing towards east, west north and south side.

summer season (April to May). From Figures 6 and 7 it is evident that outside wall temperature reaches to a maximum of 45-50°C for east and west facing walls at 1100 and 1500 hours approximate respectively. Whereas, for north and south direction, the outside wall temperature has reached to 35-45°C. The inside wall temperature of all the directional faces does not exceed 30-32°C for AAC building and 27-30°C for brick masonry building. Both outdoor and indoor temperatures in Figure 6 and 7, follow a sinusoidal naturewith maximum temperature at daytime and minimum temperature peak at night hours. The outside and inside wall temperature differences for all directions of AAC building and ambient/indoor temperature plot for AAC is shown in Figure 8. The directional wall temperature difference is maximum

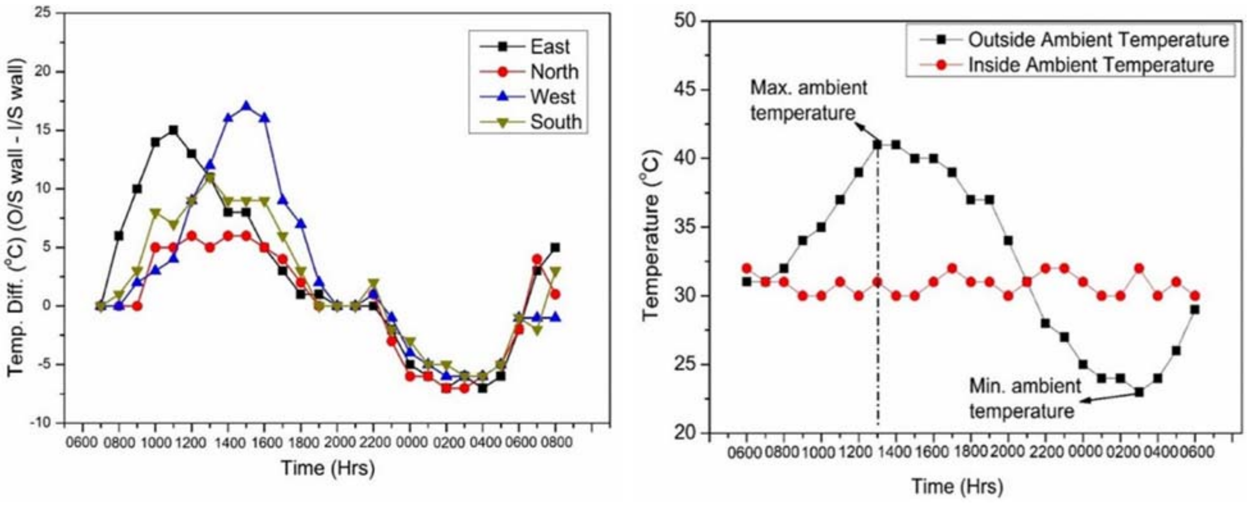

Fig. 8. Temperature difference of outside and inside wall variation of all directional faces for AAC building and ambient and indoor temperature of AAC building.

during day time with value in the range of 5-15°Cand minimum of -5°C in the night time suggesting that outside wall temperatures are lower than inside wall temperature. The temperature difference curve also follows sinusoidal behaviour. This is because of heat entrapment through the glass windows in the rooms with no ventilated conditions. The AAC and brick masonry building has an indoor temperature of 28-32°C and 27-30°C respectively. Brick masonry building has slightly cooler indoor temperature as compared to the AAC building. This may be attributed to an air gap in the rat trap wall model which result lower inside room and wall temperatures.

Figures9 and 10 show the average surface wall temperatures for peak winter season. Both The temperature plot reveals that outside maximum temperature reaches up to 15-20°C while inside wall surfaces attains a minimum temperature of 10-12°C.

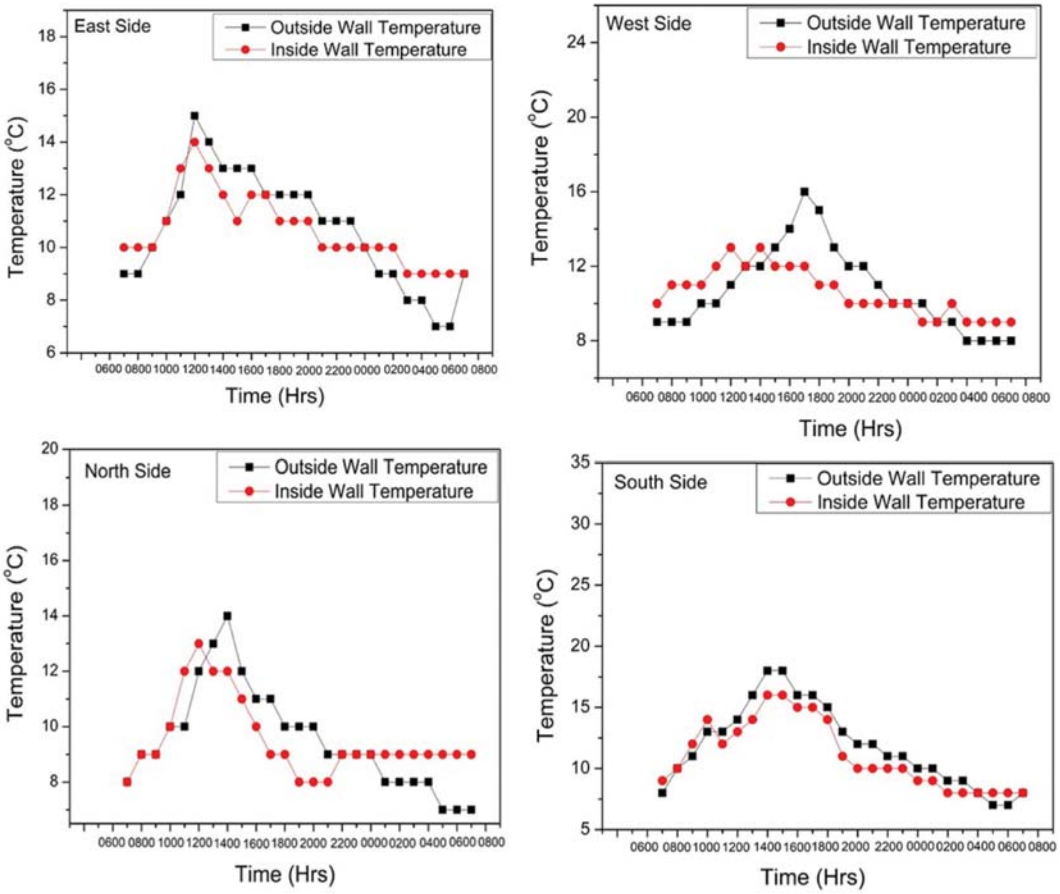

Fig. 9. Temperature Plot for AAC building for winter season.

The low value of indoor wall and room temperature as compared to outdoor wall/ambient temperature is due to low thermal conductivity of AAC block. The outside and insidecement mortar layer and air voids in the AAC block can be viewed as a composite panel. The thermal conductivity of air is around 0.01 W/m.K which further enhances the thermal insulation. Therefore, the overall thermal parameters inside the building are much lower than outdoor parameters. The porous nature of surface mortar layer and AAC block can be confirmed from FE-SEM images from Figure 11.

The indoor temperature for AAC building is found to be 28-32°C which is slightly higher than values mentionedin National Building Code of India (NBCI). For a comfort living inside a building, the optimum indoor temperature should be around 24-27°C[20, 21].

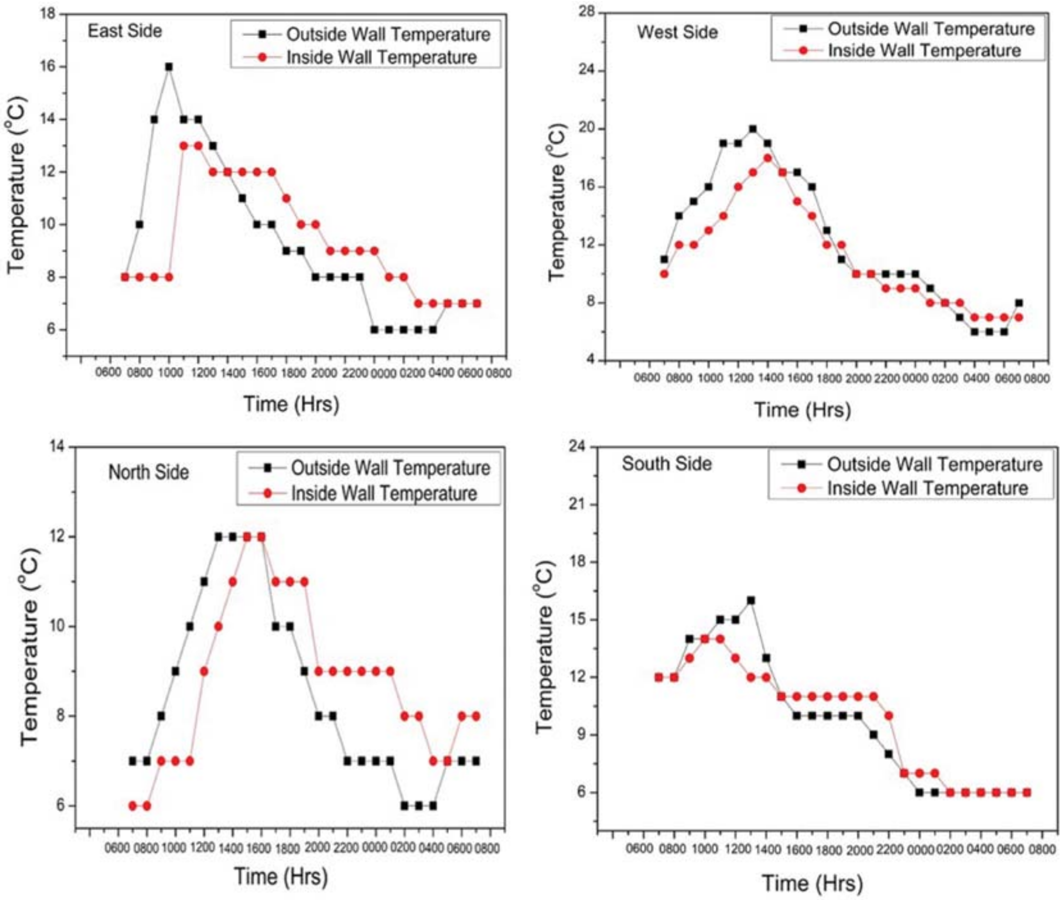

Fig. 10. Temperature Plot for brick masonry building for winter season.

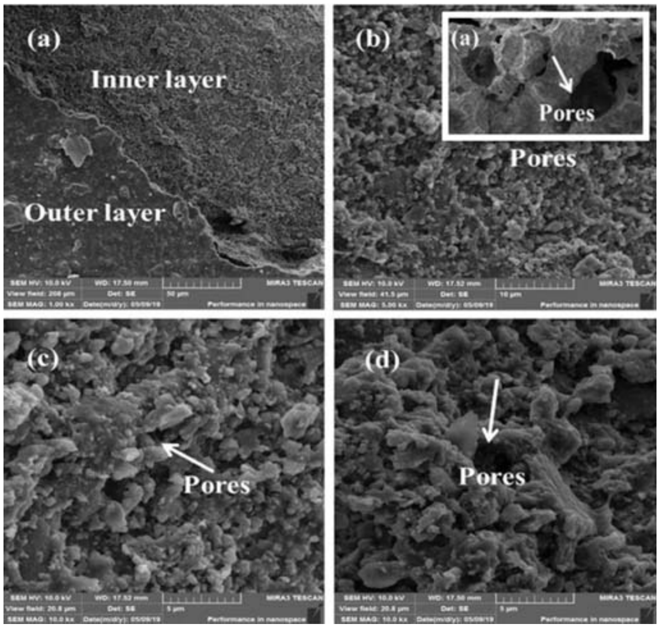

Fig. 11. FE-SEM Images of Cement Plaster and inset shows the porous nature of AAC blocks.

The mechanism of heat transfers between outdoor atmosphere and walls of AAC and brick masonry buildings is assumed to one to be dimensional and non-steady state. Figure 12 shows the representation of 1-dimension heat conduction through a AAC wall. As mentioned earlier, the wall consists of two mortar layers and AAC blocks sandwiched in between.

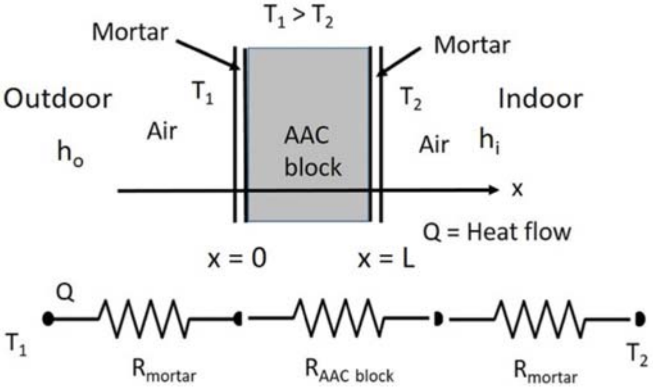

Fig. 12. Schematic of heat conduction and thermal resistance model of a plane wall.

The one dimensional (1-D) transient heat conduction can be written as[22, 23]:

$$\rho c_p \frac{\partial T}{\partial t} = k \frac{\partial^2 T}{\partial x^2} \tag{1}$$

where, parameters: k, ρ, and C_p are the thermal conductivity, density, the specific heat capacity of the building wall materials, respectively.

Considering the temperature *(T)* is the function of time *(t)* and distance (thickness x), equation 1 can be further written as

$$\frac{\partial T}{\partial t} = \alpha \frac{\partial^2 T}{\partial x^2} \tag{2}$$

where, the thermal diffusivity is defined by $\alpha = \frac{k}{\rho Cp}$ and it is expressed in m^2/sec. The thermal diffusivity may be defined as rate at which thermal disturbance propagates in the material and is a thermo-physical property.

U-value, thermal admittance and other thermal parameters for AAC and brick masonry walls with mortar finishing have been listed in Table 3.

Table 3. Various calculated thermal parameters of AAC Buildings.

	Time lag (hrs)	D.F	Thermal damping (%)	Thermal admittance (W/m^2K)	U value (W/m^2K)	TPI
AAC wall	4	0.18	32	6.19	1.5-1.8	25
Brick masonry wall (with rat trap bond)	4	0.33	35	11	2.2-2.4	25

3.2 *Thermal admittance calculation of AAC and brick masonrybuilding for cyclic temperature variations*

Thermal admittance (Y) values of both the buildings is analysed and presented in Table 3. Basically, it is a measure a material's ability to absorb heat from, and release it in space over a period of time. Thermal admittance is expressed in W/(m^{2}K), where the higher the admittance value, the higher the thermal storage capacity.Typical admittance values based on a 24-hour temperature cycle.

For AAC homogeneous slab of finite (150 mm) thickness, subject to sinusoidal temperature variations (for 24 hours) θ_{si} and θ_{so} on its internal and external surface, respectively. Let si θ and so θ be the mean values, whereas $<\theta_{si}>$ (mean value) and $<\theta_{so}>$ (mean value), and θ_{si} cyclic and θ_{so} cyclic are the respective cyclic fluctuations around the mean value.

The cyclic heat fluxes denoted by *qi* and *qo* occurring on the two surfaces of the slab can be written in the following form (3) as a function of the surface temperature in unidirectional conductive heat transfer through the slab thickness in the usual direction to its surfaces:

$$\begin{matrix}\theta_{si}\\ \theta_{si}\end{matrix}(Cyclic)=\begin{bmatrix} z_1 & z_2\\ z_3 & z_4\end{bmatrix}\begin{matrix}\theta_{so}\\ q_{so}\end{matrix}(cyclic) \tag{3}$$

The elements of the transmission matrix can be calculated as follows[24]:

$$z_1 = z_4 \cosh\ (t+it) \tag{4}$$

$$z_2 = \frac{\sin h(t+it)}{\xi(1+i)} \tag{5}$$

$$z_3 = \xi.(1+i).\sinh(t+it) \tag{6}$$

Two parameters appearing in the definition of the matrix, namely the cyclic thickness *t* and the thermal effusivity ξ, defined in Equations (5) and (6) relates to thermal properties of the material with slab thickness *L* and the period *P* of the cyclic energy transfer may be written as:

$$t = \sqrt{\frac{\pi}{P.3600}.\frac{\rho.c}{\lambda}.L^2} \tag{7}$$

$$\xi = \sqrt{\frac{2\pi.\lambda.\rho.c}{P.3600}} \tag{8}$$

where ξ is thermal effusivity in J. m^{-2}. K^{-1} s$^{0.5}$, ρ is density of the material, *c* is specific heat capacity in *J.* Kg^{-1}. K^{-1} and *P* is number of period hours.

The transmission matrix *Z* of the multi-layered wall is obtained through the product of the matrices related to each layer, including the transmission matrix containing the film resistance:

$$\begin{bmatrix} z_1 & z_2\\ z_3 & z_4\end{bmatrix} = \begin{bmatrix} 1 & R_{si}\\ 0 & 1\end{bmatrix} \Pi_1^n \begin{bmatrix} z_1 & z_2\\ z_3 & z_4\end{bmatrix}\begin{bmatrix} 1 & R_{so}\\ 0 & 1\end{bmatrix} \tag{9}$$

The thermal admittance function *Y* can be written as $\frac{Z_4}{Z_2}$

For AAC block λ = 0.2 W/m.K, *L* = 150 mm, *c* = 1000 J. Kg^{-1}. K^{-1}

The values of Z_4 and Z_2 is calculated by equations 11 and 12 by MATLAB coding are 6.87 and 1.346 respectively. The value of thermal admittance (Y) for AAC block wall is ~6 W/m^{2}K and brick masonry wall with rat trap bond, is found to be ~ 11 W/m^{2}K.

Other thermal parameters viz., time lag (Φ) which can be defined asthe time difference between the temperature maximum at the outside and inside when subjected to periodic conditions of heat flow[25].

The time lag can be defined as:

$$\Phi = t_{T_{in(\max)}} - t_{T_{out(\max)}} \tag{10}$$

where, $t[T_{in\ (max)}]$ and $t[T_{out\ (max)}]$ are the time of day when the inside and outside surface temperatures reach maximum.

Decrement factor which describes the indoor and outdoor temperature swings is the ratio of the maximum outside and inside surface temperature amplitudes. It may be written as:

$$DF = \frac{T_{in(\max)} - T_{in(\min)}}{T_{out(\max)} - T_{out(\min)}} \tag{11}$$

where $T_{in(max)}$, $T_{in(min)}$, $T_{out(max)}$ and $T_{out(min)}$ are maximum inside surface temperature, minimum inside surface temperature, maximum outside surface temperature and minimum outside surface temperature respectively of wall under consideration.

Thermal damping or decreased temperature variation is a characteristic dependent phenomenon based on the thermal resistance of the material used in the structure. It can be written as

$$D = \frac{T_o - T_{in}}{T_o} \times 100 \tag{12}$$

where T_o and T_{in} are maximum outside and inside wall temperatures, respectively.

The thermal performance index (TPI) of a building depends on heat gained by the building through steady-state and periodic part[25].

$$TPI \ may \ be \ written \ as : (T_{is} - \ 30)12.5 \tag{13}$$

where T_{is} the maximum peak inside surface temperature.

The above mentioned thermal parameters *viz.* time lag, decrement factor, thermal damping, U-value and thermal performance indexfor AAC block walls and brick masonry building and are listed in Table 3. A similar study on conventional and alternative wall systems have been done by Balaji and co-workers described elsewhere in detail[22, 23]. They have studied thermal aspects *viz.*, decrement factor, thermal diffusivity, time lag for individual wall systems.The low values decrement factor obtained for both buildings indicate the ability to suppress the indoor temperature swings as compared to the outdoor temperature variations. Whereas, the high values of thermal admittance depict the nature of energy storage capability and lower indoor temperature fluctuations. AAC infill blocks have also high thermal admittance because of mortar layer on the both sides of the wall.

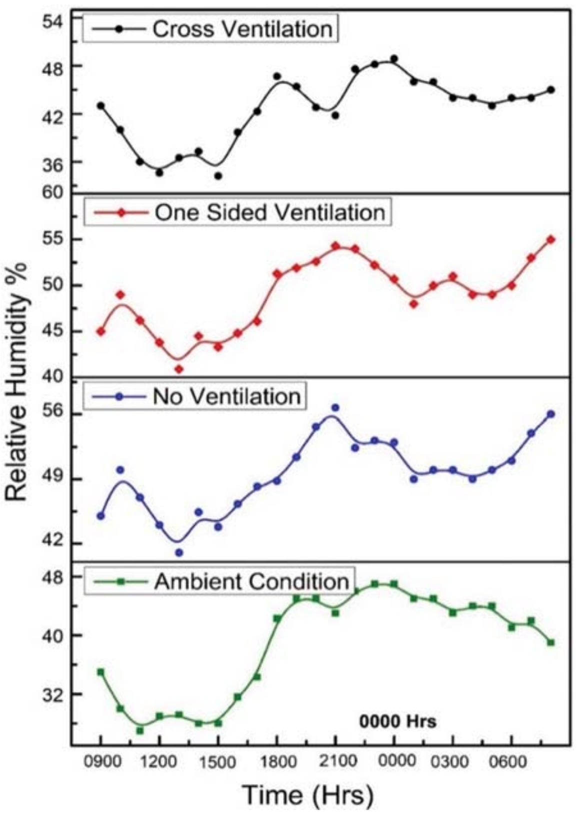

Fig. 13. Relative Humidity Variation in AAC Building.

Figure 13 shows the relative humidity of AAC building room with various ventilated and ambient conditions. It is evident from the figure that in no ventilation and one sided ventilation condition the R.H. level is about 60 percent. Whereas, for ambient and cross ventilation the relative humidity values falls under 50 per cent. Therefore, cross ventilation is required for a low value of humidity for a comfort living. According to NBCI 2016, the maximum humidity level for comfort living should lie in range of 30-60% of R.H. Similar values of R.H. (~ 50%) have also been obtained for brick wall buildings.

3.3 Outdoor - indoor transmission loss

Regarding acoustic isolation of AAC building, with an outside noise source of 100-105 dB, indoor noise level in both the buildingsis measured. Figure 14 shows the sound isolation of outdoor to indoor noise level of AAC and brick masonry building. The noise reduction data is collected at 1/3 octave center frequency band over the range of 100 - 4000 Hz.From the Figure 14, it can be seen thatthe brick wall structure provides a better sound isolation (47 dB) as compared to AAC wall structure (40 dB) for outside noise.According to national building code of India (NBCI) the optimum noise level values for apartment and homesis 35-40 dB. The inside noise values of AAC buildings lies between 60-65 dB. As evident from the values, the noise isolation values are higher than the values prescribed in NBCI 2016. With proper noise isolation methods and materials, the optimum noise levels inside the buildings can be achieved.

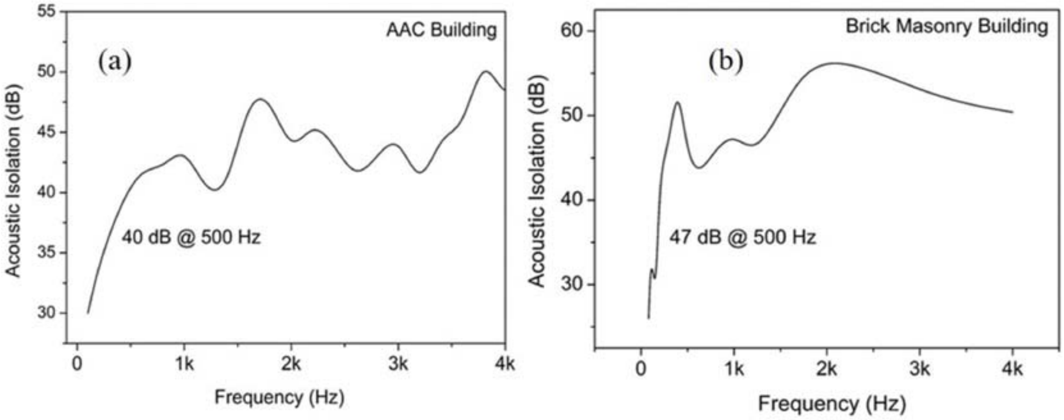

Fig. 14. Sound isolation of AAC and brick masonry building.

Sound isolation(transmission loss) depends upon surface density, thickness and damping of the material.High dense and stiffed material shall have more sound isolation as compared to porous materials.

Stiffness of a material may be defined as:

$$S = 0.083\ (Eh^3 / 1\text{-}v^2) \qquad (14)$$

where E, h and v are Young's modulus, thickness, and Poisson's ratio, respectively[26].

According to ASTM standard 1332 - 16, the outdoor - indoor rating (OITC)for sound attenuation of AAC and brick masonry building has been calculated and found to be 37 and 41 dB respectively[33,34].

3.4 Water tightness test

Regarding water tightness test, the thermal imaging after 7 and 15 days of ponding is shown in Figure 15 and 16 which shows very less or minimum water ingress inside the walls[27-30].

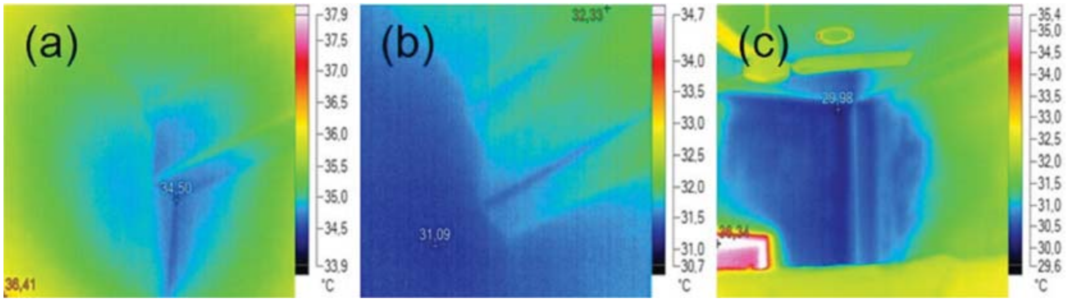

Fig. 15. Thermal imaging (a) Before Ponding at ground floor
(b) after 7 days Ponding (c) after 15 days ponding.

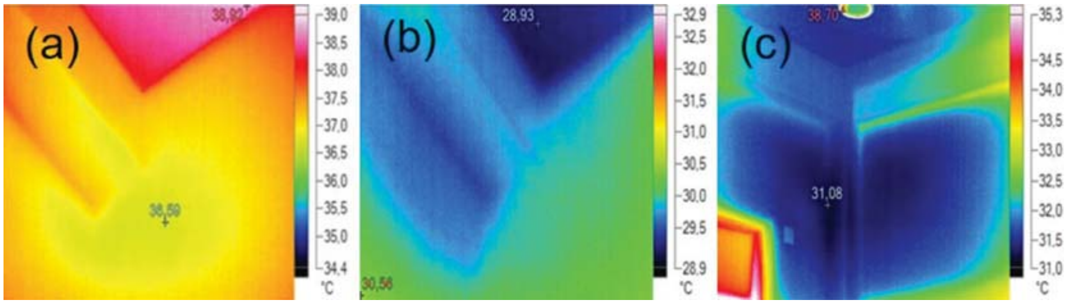

Fig. 16. Thermal Imaging (a) Before Ponding at first floor (b) after 7 days ponding (c) after 15 days ponding.

As evident from the Figure 15(a) and 16(a), before ponding the thermal scanning shows higher temperatures of the respective building section. The same portion of the AAC building shows lower temperature after ponding for 7 and 15 days at first floor as shown in Figures 15 and Figure 16 (b) and (c). This may be attributed to some of the water leakage in to the structure from the roof topdue to presence of minor cracks.

3.5 Indoor air quality and daylight illuminance

The indoor air quality monitoring of AAC building is shown in Figure 17. The CO_2 level in the present study has been monitored under different ventilation scenario. It is evident from the figure that upon the three occupants in the room, the CO_2 level rises from 420 ppm to 850 ppm within 10 minutes with no ventilated condition. After 10 minutes of measurement, the CO_2 levelalmost remains constant after single sided ventilation. Further CO_2 level drops to ambient level when cross ventilation is maintained in the room. The maximum permissible CO_2 level for indoor buildings is 400-1000 ppm. Above 1000 ppm, drowsiness and poor air quality is considered[31]. Proper ventilation must be maintained at all the times to maintain the indoor CO_2 level below 1000 ppm.A similar values of CO_2 level with same number of occupants of equal room volume has been observed for brick masonry buildings.

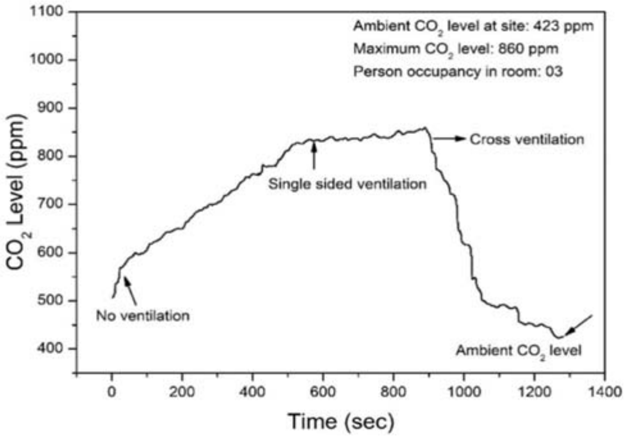

Fig. 17. Indoor air quality of AAC Building Room.

The illuminance measurement at various places inside the AAC and brick masonry buildings without any internal illumination is shown in Table 4.

Table 4. Daytime interiorilluminance values of AAC buildings.

Building	AAC	Brick masonry Illuminance(lux)
Ground floor	770	300
Kitchen	410	420
Lavatory	230	260
Stairs	1160	1380
First floor	1010	960

According to NBCI 2016, the range of service illuminanceshould lie between 200 - 750 lux. Whereas, for lavatories, the range of illuminance values should be over the range of 50-150 lux. As evident from the Table 4, the illuminance values inside both the buildings during the daytime lighting is meeting the criteria as mentioned in NBCI. Therefore, with the proper ventilation techniques, the illumination values inside the AAC and brick wall masonry building has the potential of energy saving during the daytime.

4. CONCLUSION

The thermal, acoustic, water tightness, indoor air quality and illuminance study of AAC and brick masonry buildings materials have been studied and presented. The water tightness study shows no significant leakage inside the building as evident by thermal scanning of walls and ceiling/rooftop. Thermal performance of the AAC walls with mortar finishing and brick masonry building with rat trap bond exhibit good thermal insulation in the summer time with average outside and inside temperature being 40-45 °C and 27-32°C respectively. The relative humidity level less than 60 % for cross ventilation condition in the room without any heating or cooling aids being used during the measurement. According to NBCI 2016 the optimum inside room temperature should be 24-27 °C and R.H % should be less than 60 % for a comfortable living. The inside room temperatures are slightly higher than the recommended values. The transmission lossvalues lie in the range of 35-40 dB for AAC building and 45-50 dB for brick masonry building. The OITC values of AAC and brick masonry buildings are 37 and 41 dB respectively. The noise isolation values are slight less than the values mentioned in NBCI.With proper noise reduction techniques viz. proper sealing of door and window frames with sound insulation materials, the optimum values may be achieved. Overall, the AACand rat trap brick masonry walls both provide a good thermal comfort and may definitely contribute to energy saving in the buildings.

5. ACKNOWLEDGEMENT

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Strategic noise mapping of Mumbai city, India: a GIS-based approach

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ABSTRACT

Indian cities are facing an enormous challenge in terms of noise pollution due to rapid urbanization, industrialization and poor traffic conditions. Evaluation and monitoring of noise pollution is a very complex task because of the heterogeneous noise generating sources, mixed land use pattern, a representative number of noise monitoring sites, display of noise level, noise monitoring protocol and handling of so many city information on a common platform. In view of these, the Geographical Information System (GIS) based strategic noise maps are very useful for hotspot analysis monitoring the noise level during day and night time for working and non-working days. Using these maps city planners can make strategy, to control the noise level in the city, and authorities can implement the rules and regulations about noise pollution. Thus, strategic noise maps are crucial for measurement and control of noise pollution in the city.

1. INTRODUCTION

An atmospheric pressure variation in a medium such as air is defined as a sound. The oscillation of pressure difference can be sensed by the human ear, so we feel the sound. Sound is an essential part of our life but unwanted and unpleasant sound is considered as noise because of its negative impact on the excellence of life. Assessment and monitoring of the urban acoustic environment is a serious challenge in the present decade[1]. Noise in the environment is a serious problem in metro cities[2,3] and considered as a public health problem[4]. Environmental noise pollution has been recognised as an increasing universal complication over the last few years mostly due to the increasing use of vehicles in cities[5]. Rapid urbanization and industrialization create huge noise pollution in the urban area[6,7,8,9,10,11,12]. Vehicular traffic including railway and air traffic plays a significant role to create major noise pollution in the urban area[13,14,15,16,17,18,19,20]. In this situation, noise mapping is necessary to assess the noise status of the entire city. Noise maps are an actual demonstration of the present and probable level of noise emanation based on one specific or multi sources of noise[21]. A strategic noise map is a key component to assess noise exposure of a particular area, from various noise sources like road, railway and air traffic. Strategic noise maps are also helpful to control the noise level of the city, hotspot identification and town planning[22]. In India, metro cities are facing an immense challenge in terms of noise pollution. Vehicular traffic noise

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plays an important role to increase the noise level of the city. Central Pollution Control Board (CPCB) reported in 2017 that Mumbai is the worst violated city in terms of noise[24]. In view of that, a strategic noise mapping would be a necessary measure to assess the noise pollution of the city. Extensive noise monitoring and critical analysis, as well as interpretation of the data, are essential to generate the noise map, which precisely portrays the existing condition of the noise level of the city[25].

GIS is a proven technique to display the variation, distribution and to assess the temporal changes of spatial data. GIS-based modeling tools are very popular and efficient to prepare a noise map that helps in policy making and regulation of noise pollution. For prediction and propagation of the sound level GIS software plays a significant role[22,23] to establish a relationship between spatial and non-spatial data and identify the critical zones. Therefore, considering different noise generating sources and land use pattern of the city an attempt has been made to generate strategic noise map of Mumbai city that will help to assess the noise exposure of entire city, hotspot and risk zone identification during day and night time of working and non-working days.

2. STUDY AREA

Mumbai is situated in the west-coast of India. The geographical setting of the study area is 72°46'30" to 72°58'30" E and 18°52'30" to 19°16'00" N, with the areal coverage of 512 sq. km. The city is known as financial as well as commercial and entertainment capital of India. In view of global finance flow, it is one of the top ten world's commerce centre that provides occupation for a large number of population. Mumbai comes under tropical dry and wet climate with average annual temperature and precipitation of 27.2°C and 2167 mm respectively. The city is connected by National Highway (NH-3, NH- 4, NH-8, NH-17, NH-222), Eastern expressway, Western expressway, Mumbai-Pune expressway, Mumbai-Nasik, Mumbai-vadodara expressway, Chhatrapati Shivaji International Airport, Mumbai Port and Jawaharlal Nehru Port Trust (JNPT). The city is highly urbanized with 70% of the built-up area and highly populous as 12.4 million population as per the census of 2011. Details of the study area along with noise monitoring locations are represented in Fig. 1.

3. MATERIALS AND METHODOLOGY

The methodology implemented in the present research work is divided into four sections, Section I is about the creation of the database, Section II describes data collection, Section III describes the data analysis and Section IV deals with the development of noise map of the city based on the ambient noise level measured at uniformly distributed monitoring sites.

3.1 Section I : Creation of thematic database

In order to conduct effective noise monitoring and mapping in a synchronised manner, city boundary, transportation system, land use pattern are incorporated as the different thematic data set. In this study noise monitoring locations were identified based on transport, industrial and commercial activities and housing colonies and silence zone. Transportation network like railway (98 km), expressway (48 km), national highway (43 km), major road (244 km) and minor road (745 km); Land Use Land Cover (LULC) of the city were generated to prepare the strategy for noise monitoring locations in consultation with Maharashtra Pollution Control Board (MPCB) and Municipal Corporation of Greater Mumbai (MCGM). LULC plays a crucial role to categorize the industrial, commercial, residential and silence zone of the city. The total numbers of 55 locations were selected for the monitoring of noise level and details about the sites are described in Table 1.

3.2 Section II : Data collection

Data collection was the most crucial part of this research work to carry out every kind of geo-spatial data analysis. Primary and secondary types of data were used in this study. In order to assess the ambient noise level in the environment, noise monitoring was carried out in identified locations for 48 hours considering working and non-working days using calibrated type-1 sound level meters in fast response

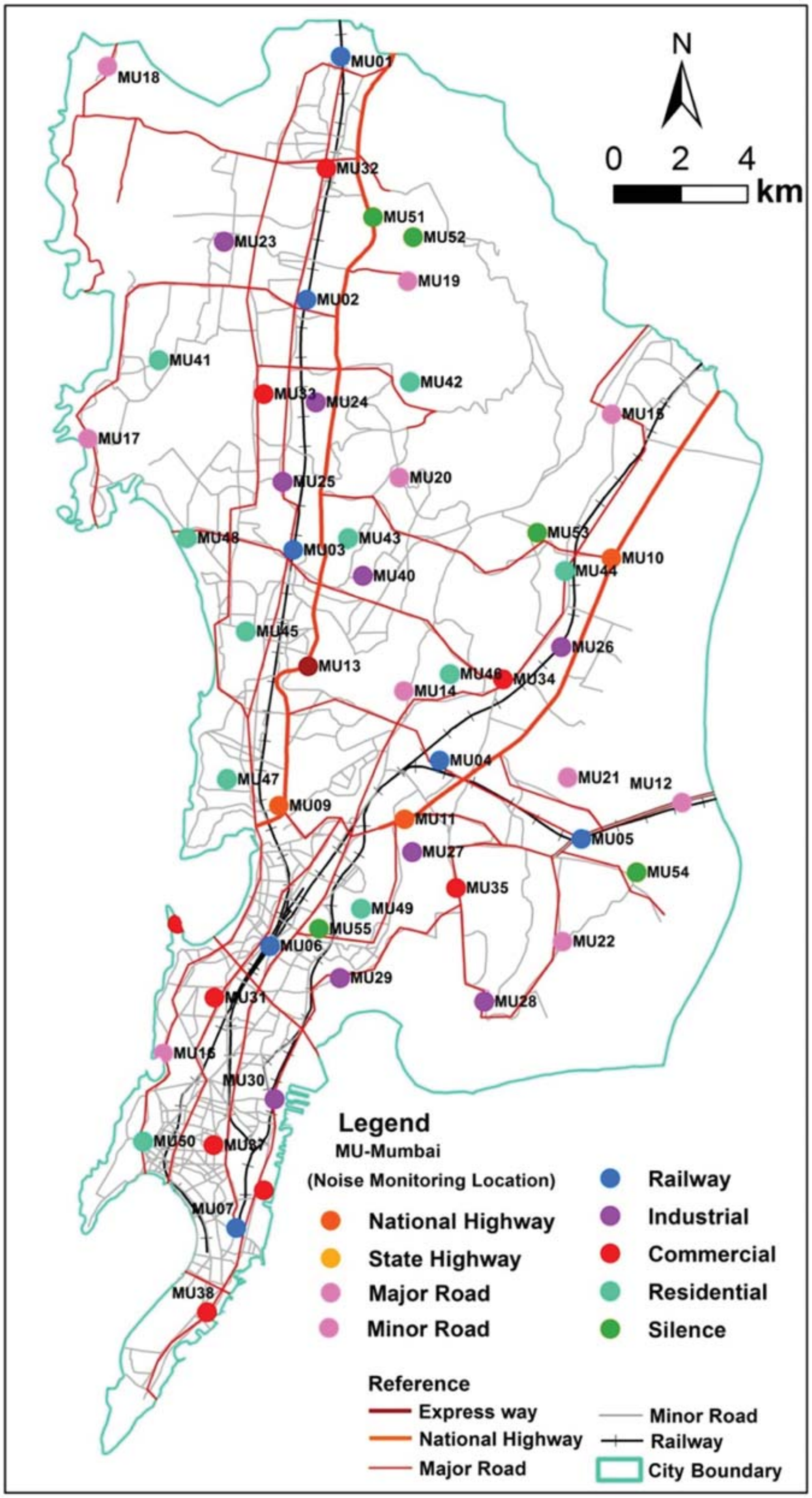

Fig. 1. Noise Monitoring Locations

Table 1. Details of noise monitoring locations in Mumbai city.

Noise source and receptors	No	Monitoring Ids	Descriptions
Railway	6	MU01, MU02, MU03, MU04, MU06, MU07	Chatrapati Shivaji Terminus, Western Railway line, Dadar Central, Malad East, Lokmanya Tilak Terminus, HF Society
National Highway	4	MU08, MU09, MU10, MU11	Jogeshwari and NH3 Junction, Suman Nagar Highway, National Highway 8 / Penkar Pada, National Highway 8
Expressway	2	MU05, MU12	Panvel expressway, Sion-PanvelExp/Octroi Naka
Major Road	5	MU13, MU14, MU15, MU16, MU17	Santacruz Road, Vile Parle Road, Goregaon Mulund Link Road, Dr. Annie Besant Road / NEERI, Madh Marve Road
Minor Road	5	MU18, MU19, MU20, MU21, MU22	BARC area, Uttan Road (Vegetation nearby), Aarey Road, Near Adasa Nagar, Damupada Road near Green Hills
Commercial	08	MU31, MU32, MU33, MU34, MU36, MU37, MU38, MU39	Saat Rasta, Mahalaxmi, Borivali Market, Fish Market / Goregaon, Ghatkopar (w), Worli Fort / Old passport Office, Chor Bazaar, Colaba Market, Victoria Docks
Industrial	10	MU23, MU24, MU25, MU26, MU27, MU28, MU29, MU30, MU35, MU40	Charkop Industrial Estate, Royal Pack Industries, Sanjivan Industries, Godrej and Boyce Plant, Trombay Industrial Area, Tata Power Trombay Thermal Plant, BPCL Terminal, Britania Industries Limited, Chembur, Chakala Industry
Residential	10	MU41, MU42, MU43, MU44, MU45, MU46, MU47, MU48, MU49, MU50	Ambujwadi Slum Area, Krishna Society, Madhukunj Society, Chandan Nagar, Cumbala Hill, Govind Nagar, Pali Village, RatanKunj, Antop Hill, Nehru Nagar slum area
Silence	05	MU51, MU52, MU53, MU54, MU55	Sanjeevan Hospital, Sanjay Gandhi National Park, Borivali, IIT Bombay, Mankhurd Shivaji Nagar, Institute of Chemical Technology

mode with 'A' frequency weighting and one-second data logging. Noise meters were mounted on a tripod stand 1.5 m above the ground level and wind ball was used to reduce the wind effect[26]. According to noise pollution rules[27] noise levels need to be measured separately for day time (06:00 hrs. to 22:00 hrs.) and night time (22:00 hrs to 06:00 hrs) due to noise level standards.

3.3 Section III : Data analysis

This section comprises data analysis, which was carried out from the field monitoring as mentioned in the previous section. The noise monitoring is analysed for maximum (L_{max}), minimum (L_{min}), equivalent (L_{eq}) noise level during day and night time over a given period of working and non-working days. Apart from these, L90 was also analysed, it represents the noise level that exceeded 90% of the time about a particular area. L_{90} index generally used to display the background noise environment at the monitored location in the city.

3.4 Section IV : Development of noise map

Development of noise map using GIS is a pivotal work to assess the noise exposure of the city. In view of that, this segment deals with the procedure of generation of spatial and strategic noise map using the digital status of the transportation activities, noise monitoring locations along with observed noise levels. GIS platform provided the development of the noise map in the vicinity through geospatial modeling based on the limited number of sample points. Noise maps are generated using Triangulated Irregular Networking (TIN) model with the help of the spatial analysis tool of ArcMap software. The spatial analysis describes the pattern and geographical expression of geospatial data in terms of mathematical and geometrical aspects that is also known as locational analysis[26]. Interpolation technique is one of the popular and useful practices about spatial analysis extension. It provides a set of modeling tools and generates statistics of geospatial data. TIN model is very efficient for interpolation technique to generate continuous surface data using discrete spatial point and line data. After the creation of TIN it was converted into raster format using natural neighbour tool to slot in breaklines into the interpolation[28,29,30,31].

4. RESULTS AND DISCUSSION

4.1 Noise level

To conduct an efficient noise monitoring for Mumbai city, Noise Pollution (Regulation & Control) Rules 2000[27], Amendment 2010 is followed which narrate the day time and night time standards. Silence zone is referred to as an area such as hospitals, educational institutions; Government offices and religious places. To monitor the noise level of the city 55 locations were identified to install the sound level meter. Equivalent noise level of all the points throughout day and night time on working and non-working days are summarized in Table 2 also represented the noise level of every transport and land use category along with the prescribed standard (Noise Amendment Rules, 2017)[32] for different land use zones, which is helpful to assess the comparison between measured noise level and prescribed noise standards. It is observed that the noise level of the railway is higher at day time than the night time for working and non-working days. The same observation is also found for expressway, national highway. Higher L_{eq} value was found at major road and minor road for day and night time for working day as compared with the non-working day. It is also observed that L_{eq} value is higher in the day time than the night time for the industrial zone and it exceeded the prescribed permissible limit at some locations. Commercial zones are crossing the prescribed noise limits at few identified locations. Similarly, in a residential area, the noise level at all the sampling locations are above from the specified standards at day time and night time for both working and non-working days, which is the serious concern to maintain the state of the life. In case of silence, the zone noise level was found to be always above the specified standards at day time and night time respectively for working and non-working days. The reasons behind this exceedance may be due to most of the silence zones are actually having a mix of several land types hence it is difficult to

Table 2. Summary of noise levels in Mumbai city.

Category	**Noise Level Range dB (A)**				**Permissible Noise Limits dB(A)**	
	Working Day		**Non-working Day**			
	Day	**Night**	**Day**	**Night**	**Day**	**Night**
Railway	73.8-95.3	64.2-86.8	72.2-94.3	64.5-90	No limits	prescribed
National Highway	76.8-89	72.3-81.2	76.5-91	71.1-81.9		
Express Highway	77-80.9	72-75.1	76-78.2	71.7-76.7		
Major Road	72.2-91.6	73.9-86.2	69.6-88.7	69.2-86.9		
Minor Road	67.9-87.1	59.9-80.2	58.9-84.2	57.5-78.3		
Commercial	71.4-92.1	66.7-77.6	70.9-90.3	66-75.3	65	60
Industrial	66.1-94.3	63.2-83.8	68.6-94.5	61.3-83.4	75	70
Residential	70.8-94.3	60.6-89.8	70.1-94.3	61.7-79	55	45
Silence Zone	75.1-81.4	63.4-74.5	69.5-74.5	64.2-71	50	40

maintain the prescribed limits. Further, the most significant factor for exceeding noise level in the city is honking irrespective of road types, day and night time and whether honking is really required. It was also observed that even during congestion conditions and high traffic density, people use the horn, which won't serve the purpose to make the traffic smooth.

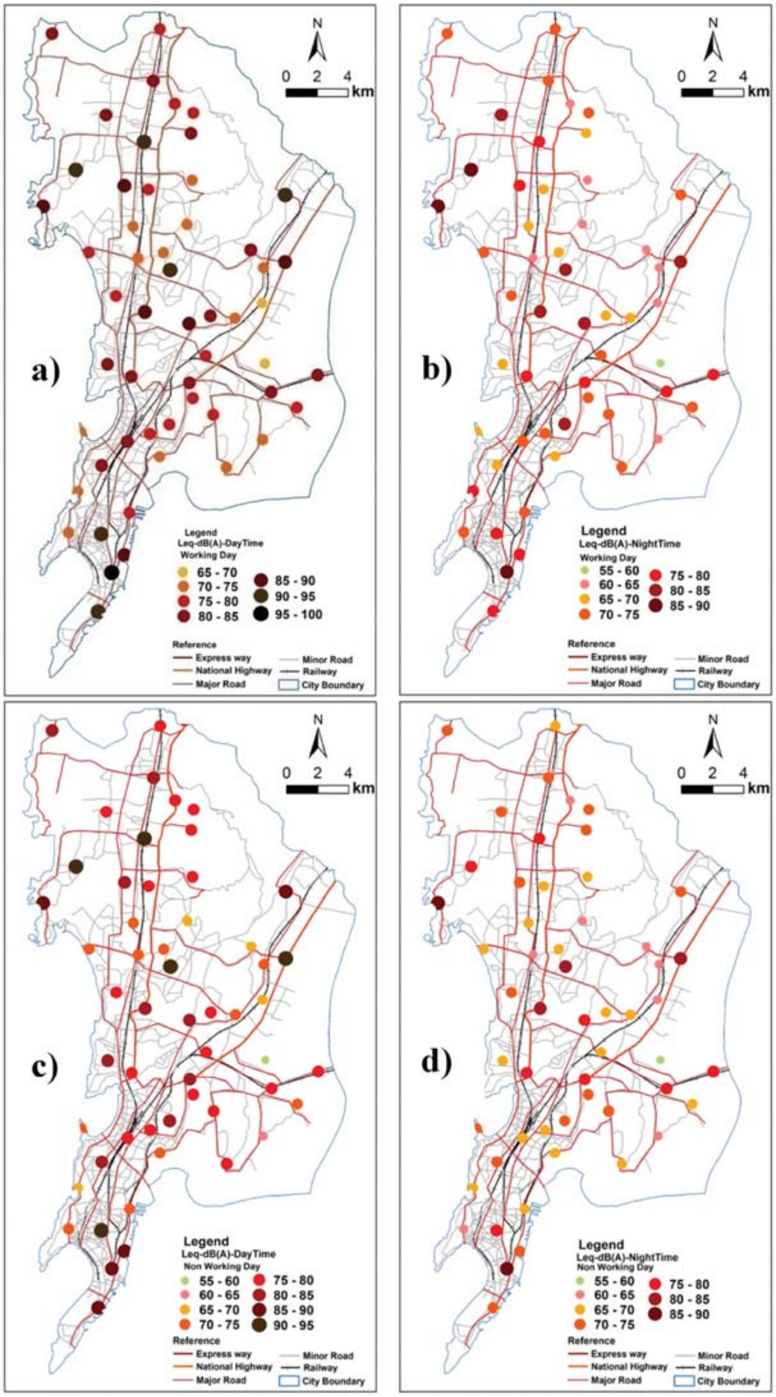

Fig. 2. Spatial noise map, (a) working day - day time (b) working day - night time (c) non-working day - day time (d) non-working day - night time

4.2 Spatial noise map

Spatial noise map is a special kind of noise map which shows the noise exposure of the particular location. To prepare this spatial noise map L_{eq} value was symbolized according to the noise level of the particular point. Using ArcMap10.5 software graduated symbols from quantities option and value field was considered as L_{eq} value of working and non-working day and night time. In this study spatial noise map is showing by different size of the circle based on the intensity and colour of the circle varying from dark green to black. Dark green, small circle represent lower noise level and black colour biggest circle represent the highest noise level in the city.In this study spatial noise maps were created for day time and night time for working and non-working day, as shown in Fig. 2 (a,b,c,d) respectively. These maps depict the distribution of noise level in the city to assess the overall noise pollution considered noise sources and receptors.

During day time of working day minimum and maximum values of equivalent noise is observed as 66.1 dB (A) at MU26 (Godrej and Boyce Plant) and 95.3 dB (A) at MU7 (Chhatrapati Shivaji Terminus) respectively. During night time, minimum and maximum values are observed as 59.9 dB (A) at MU21 (Near Adasa Nagar Residential area) and 89.8 dB (A) at MU41 (Ambujwadi Slum Area) respectively. In case of the non-working day, minimum and maximum values of equivalent noise are observed as 58.9 dB (A) at MU21 (Near Adasa Nagar Residential area) and 94.5 dB (A) at MU40 (Chakala Industrial Area (MIDC)) respectively. During night time, minimum and maximum values are observed as 57.5 dB (A) at MU21 (Near Adasa Nagar Residential area) and 90.0 dB (A) at MU7 (Chhatrapati Shivaji Terminus) respectively.

4.3 Strategic noise map

Strategic noise map which is an innovative approach to assess the noise level for the entire city is a state of the art that depicts the noisy environs. The strategic noise maps are generated based on the L_{eq} of 55 noise monitoring locations and associated noise levels using geospatial analysis. These noise maps show noise variation by different shades of green, red and in-between colours are used to portray the scenario of noise in the city. The dark green colour area in the map shows less noisy areas whereas yellow to red coloured patches represents more noisy areas. Strategic noise map has a great significance to control the noise level and city planning[33]. Thus, these strategic noise maps are helpful to observe the scenario of noise exposure of the city, hot spot analysis and city planning. The strategic noise maps of day time and night time for working and non-working days are shown in Fig. 3 (a,b,c,d) respectively. Variation in noise level during day time and night time for working and non-working days,and area coverage can be easily assed through through strategic noise maps. To clearly understand noise exposure, the noise level has been categorised into 5 ranges as<50, 50-60, 60-70, 70-80 and >80 dB(A) with area cover as summarised in Table 3.

It is observed that 41.7% of the city area in the day time is coming under the noise exposure level of 70-80 dB(A) but for night time it is about 17.6% of the area. While during non-working day highest area cover (29.7%) comes under the noise level of 60-70dB(A) but 41.3% area is under this range for the night time, which shows that the non-working

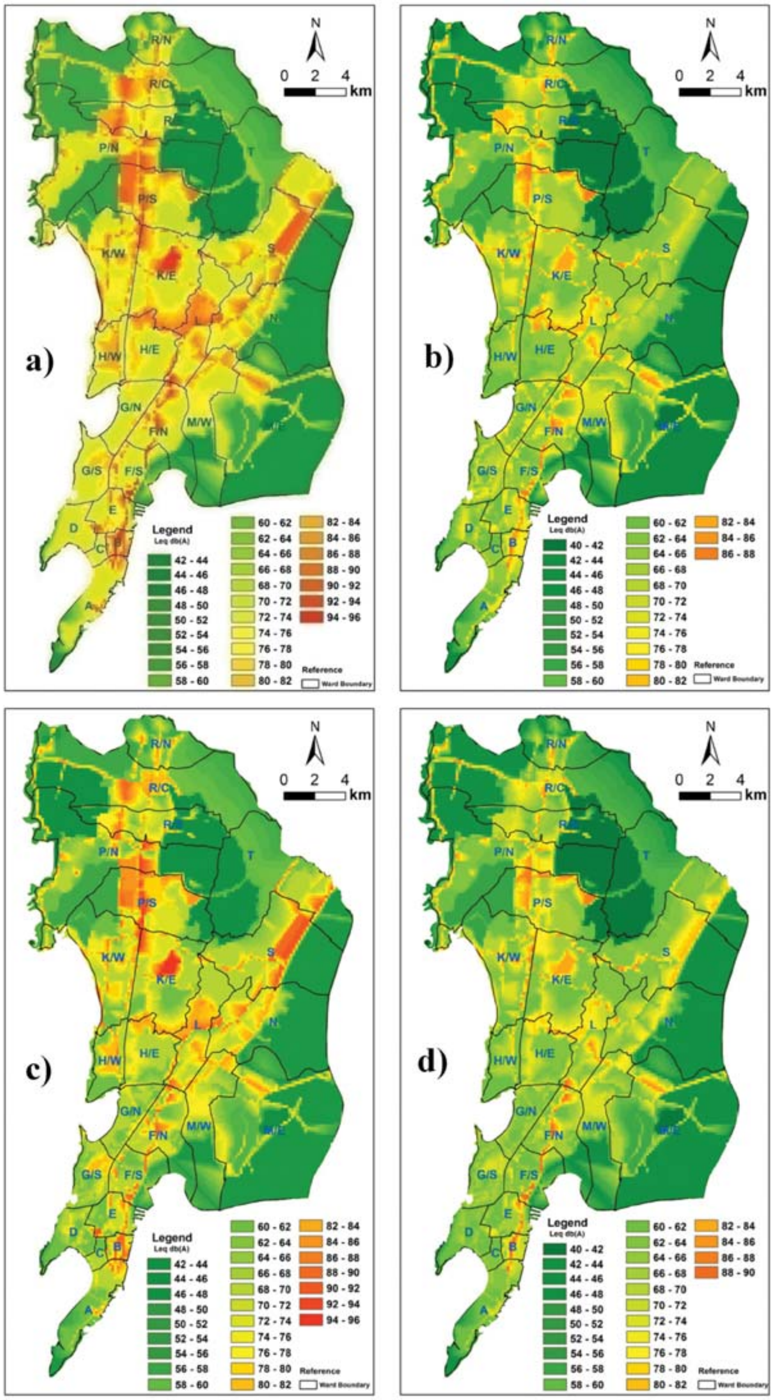

Fig. 3. Strategic noise map, (a) working day - day time (b)working day - night time (c) non-working day - day time (d) non-working day - night time

Table 3. Noise level and area coverage of the city.

Noise Level RangeLeq dB (A)	Area Cover (%)			
	Working Day		Non-working Day	
	Day	Night	Day	Night
<50	14.2	23.2	18.3	23.0
50-60	21.0	15.1	17.2	15.3
60-70	6.5	39.2	29.7	41.3
70-80	41.7	17.6	23.6	16.1
>80	16.6	4.9	11.2	4.3

nights are noisier than the day time. This may be attributed to the impact of more night activities as social entertainments, noisy bike riding and others vehicular pressure during night times of the non-working day. For a critical analysis of noise exposure, average noise levels have been measured for 24 wards of Mumbai (Fig. 4). It is observed from ward wise analysis of average noise level that the ward B is noisest for both working (84.2 dB(A)) and non-working (80 dB(A)) day time noise level in ward T is lowest for both working (50 dB(A)) and non-working (50 dB(A)) day time. For the wards, namely T, P/N, P/S, R/S, R/C, R/N noise level is shown in green shades which represents low noise level that may be derived by the thick vegetation cover (Sanjay Gandhi National Park, Mangrove of Malad creek and Manori creek) occurs in this area and open spaces. Similarly, ward S, N, M/E, M/W are accompanied by dense vegetation (Mangrove area of Thane creek) which can attribute to low noise level[34] in this area. In this study, it is found that ward A, B, C, D, E, F/N, F/S, G/N, G/S, H/E, H/W, K/E, K/W, L and part of the ward of P/N, P/S, R/C, R/S facing immense challenge in terms of exceeding noise level as these wards are surrounded by enormous built-up area which narrates drastic traffic congestion, honking, slow traffic. This study also asserts that honking is a severe threat to the rising noise levels in the city. During the analysis work of monitored data, it is found that silence zones are exceeding the permissible limit and similar situations are arising for other landuse categories like a residential area, commercial area and industrial area.

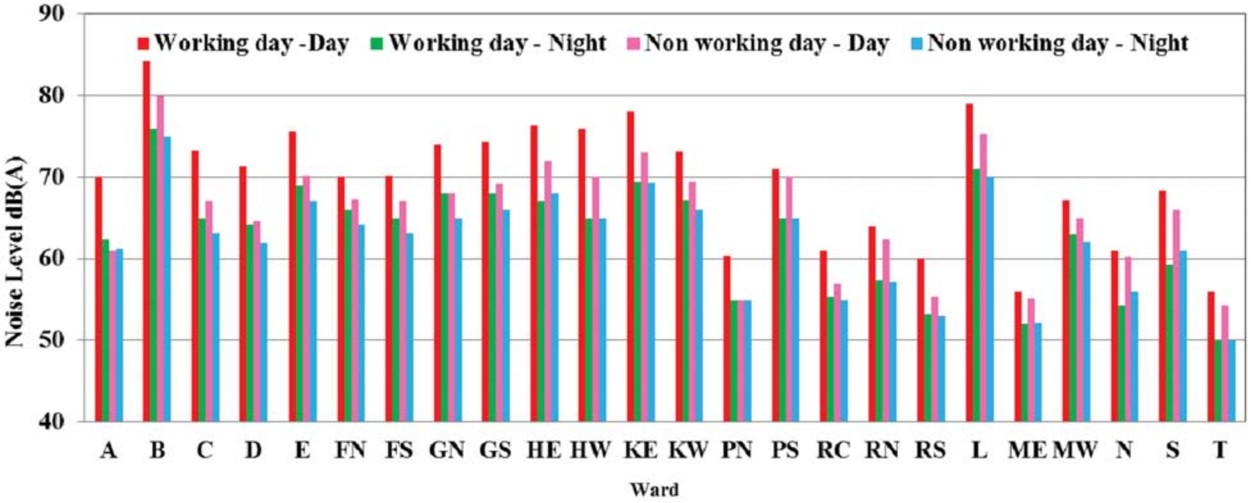

Fig. 4. Ward wise noise level of Mumbai

5. CONCLUSION AND RECOMMENDATIONS

An innovative attempt has been made to prepare spatial and strategic noise maps of Mumbai city based on ambient noise monitoring at various noise generating sources and receptors like land use specified by CPCB as industrial, commercial, residential and silence zone during working and non-working days. Noise levels are above the prescribed standards for all the specified categories except some location of the industrial area. Based on the strategic noise maps, it is observed that 50-60% of the city area is under the noise exposure of 60-80dB(A) during day and night time which shows significant noise pollution and would have an impact on human health. During noise monitoring, honking incidences were observed frequently in Mumbai was observed as major frequent activities in Mumbai which contributes additional noise apart from the traffic noise.

In order to control the noise level in the city, various measures are suggested considering noise generating sources, transmission path and receptors

- Awareness campaign on the impacts of noise pollution
- Judicious use of horn and the upper limit of noise range for horn should be capped to 100 dB (A) instead of the current practices of 112 dB (A)
- Banning of noise-producing sources like the loudspeaker, band music, crackers during the procession after 10 pm.
- The innovative design of acoustic barrier, vertical garden, dense vegetative belt
- Driver's behaviour and traffic sense are important to control noise pollution. A pledge for unnecessary honking while issuing valid license from the traffic department.
- Emphasis and more use of public transport instead of private vehicles.
- Formulation of city noise pollution control committee (CNPCC) for noise abatement considering the involvement of municipal Corporation, traffic police, educational and research institute, Non-Government Organisation and public participation.

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Assessment of noise barrier at Metro station construction site in Mumbai, India - A case study

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ABSTRACT

Mumbai, with a population of 12.4 Million, is financial capital of India and is constantly upgrading in terms of infrastructure to efficiently serve the needs of its inhabitants. Construction activities are one of the major source of noise pollution in this city. Mumbai Metro is a mega project which has been implemented to facilitate smooth and sustainable commute of citizens. But such long-term developmental activities gravely affect the environment if proper planning and care is neglected during project phase. In congested city like Mumbai, the impacts of noise pollution becomes more intense. Present study deals with assessment of a metro station construction site in Mumbai with respect to noise pollution. The site was fitted with noise barriers for a small portion of its perimeter. Ambient noise monitoring was conducted to assess the noise environment in and around the construction site as well as assessment of noise barriers on GIS (Geographic Information System) platform. GIS is very promising tool in representation of environmental noise and facilitated the assessment of the noise barrier efficiency in reducing noise levels in surrounding areas. The noise abatement measures undertaken at the construction site were assessed using GIS and hence, it can be applied as a tool to comprehend effectiveness of noise pollution management in an area.

1. INTRODUCTION

The ever increasing population in metropolitan cities render the existing infrastructure facilities totally inadequate, especially in developing countries, and also leads to high pollution levels. Construction activities are major contributor to air and noise pollution in urban areas. Major construction activities cannot be environment friendly and grossly exacerbates the already existing pollution problems leading to serious health implications to city dwellers[6,12].

At a construction site, noise is generated from various sources, for *e.g.*, excavating machineries like excavators, materials handling equipments like dump trucks, stationary equipments like pumps, power generators and air compressors and impact equipments such as pile drivers, rock drills etc. The average maximum noise levels of these equipments measured at 50 feet fall in the range of 73 to 110 dBA. Noise from blasting is also major source which goes upto 126 dBA[16]. This noise affects not only the construction workers but also surrounding residencies and environmental ecosystem. In a reflective environment such as residential buildings, the impacts of construction noise is usually experienced[4]. Construction noise has been found as a major cause of hearing loss in construction workers[11,13] and community annoyance[3,8]. As per the directions given by Govt. of India[2] in Air (Prevention and Control of Pollution) Act, 1981, regarding control of noise pollution, project implementation agencies should carry out construction activities within prescribed levels and also use the noise pollution mitigation plan during construction phase.

In cities, vehicular traffic is also the major source of escalating noise levels[20,21,22]. The rapidly growing transportation sector in a rapidly urbanising country like India, leads to congested roads producing air and noise pollution[14,15]. Large scale infrastructure projects are undertaken including the construction of Metro system to ease the vehicular load on roads and to provide better transportation facilities to city dwellers, consequently reducing the pollution[6]. The noise pollution levels during day and night in Mumbai city have been recorded exceeding the national norms in all the area categories[5]. To ease the problems of growing population, new age technologies need to be constantly implemented for improved and developed infrastructure. As a result, local trains with air-conditioned coaches, metro and monorails etc. are being introduced in the current railway network in major cities like Mumbai and also upcoming smart cities in India[5].

The construction activities for the Mumbai Metro project resulted in noise pollution in the vicinity. Presence of physical wall at the construction site plays a crucial role to attenuate noise level from source to receptor. In the present study, noise monitoring at construction site of one of the Metro station was conducted to assess the impact of construction activity on the ambient noise levels and the role of the noise-absorbing barrier in the reduction of the noise level. The construction contractor partially cordoned off the north side of the site with noise barriers of height 20 feet. Using noise level data, an attempt was made to utilize GIS, an adequate and efficient technique, to represent the noise level reduction due to noise barriers in the vicinity of the construction site. GIS-based maps of noise contours along with the noise barrier can be the perfect depiction of significance of acoustic wall at the construction site.

2. CASE STUDIES

2.1 Study area and noise monitoring locations

The study area is the construction site of a metro station in Mumbai. Spatially distributed seven locations were selected as noise monitoring stations within the study area to ensure proper representation of noise levels, as represented in Fig. 1. The locations comprised of noise source, receptors and boundary of work zone. They are strategically identified according to noise sources (excavators, bulldozers, construction activity), receptors (residential areas) and along the boundary of the work zone in the vicinity of the construction site as detailed in Table 1.

To create a realistic symbolical representation of the study area, 3D mapping technique is used. Unlike 2D maps, 3D designs, models and maps appropriately depict the physical dimension of an area. In this study, the Sketchup, friendly 3D making software was used to prepare the 3D anaglyph map (Fig. 2) to represent position of noise source and noise barriers along the boundry of construction site.

3. NOISE LEVEL MEASUREMENT

The methodology for measuring the noise level is divided mainly in two parts and is discussed below.

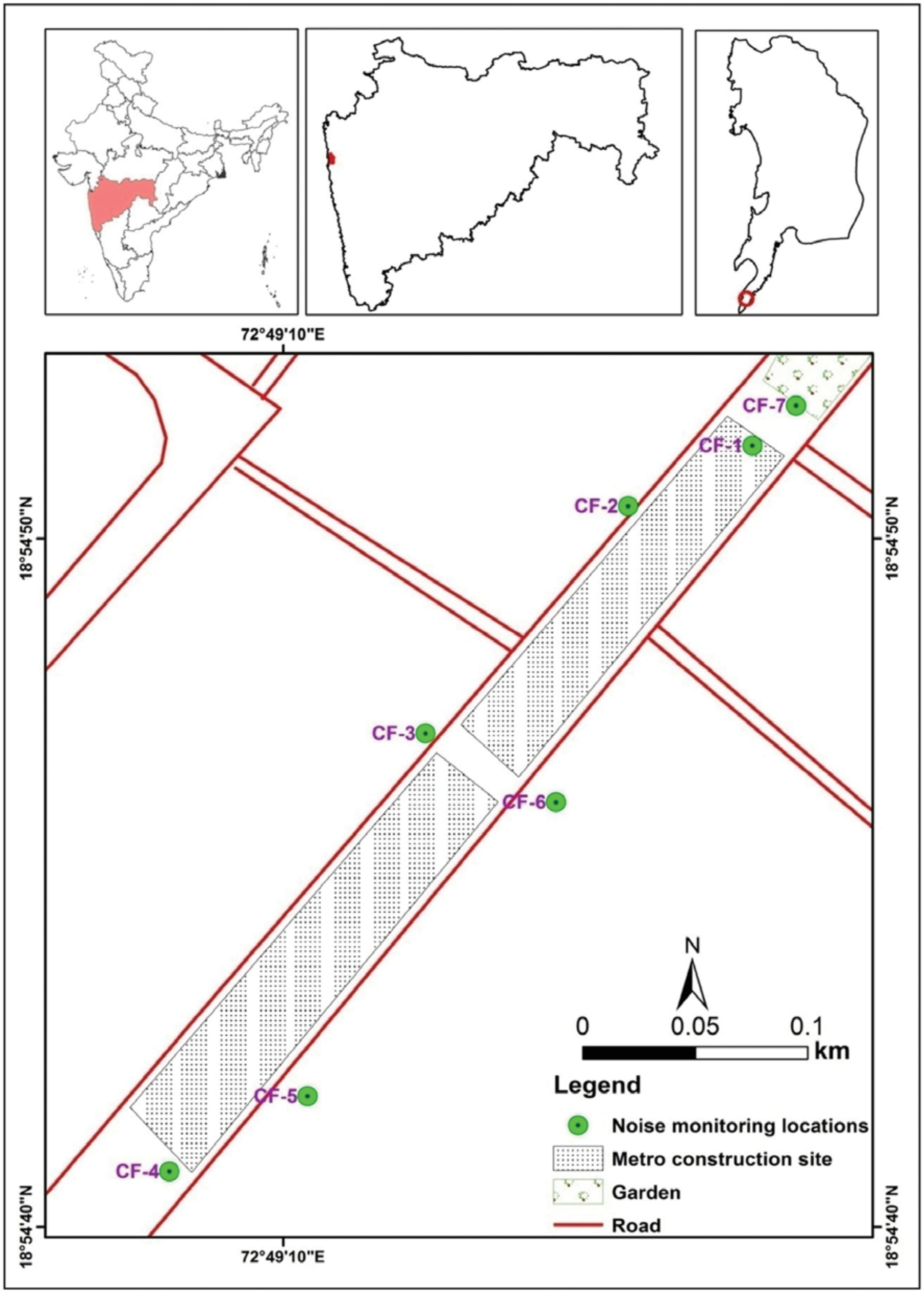

Fig. 1. Noise monitoring stations at Metro station construction site

Table 1. Noise monitoring locations at metro station construction site.

Sr. No.	Site Code	Area Category	Type	Distance from Noise Source (m)
1.	CF1	Construction site	Noise Source	3
2.	CF2	Residential	Receptor	57
3.	CF3	Boundary of work zone	Receptor	187
4.	CF4	Boundary of work zone	Receptor	405
5.	CF5	Residential	Receptor	344
6.	CF6	Residential	Receptor	177
7.	CF7	Boundary of work zone	Receptor	27

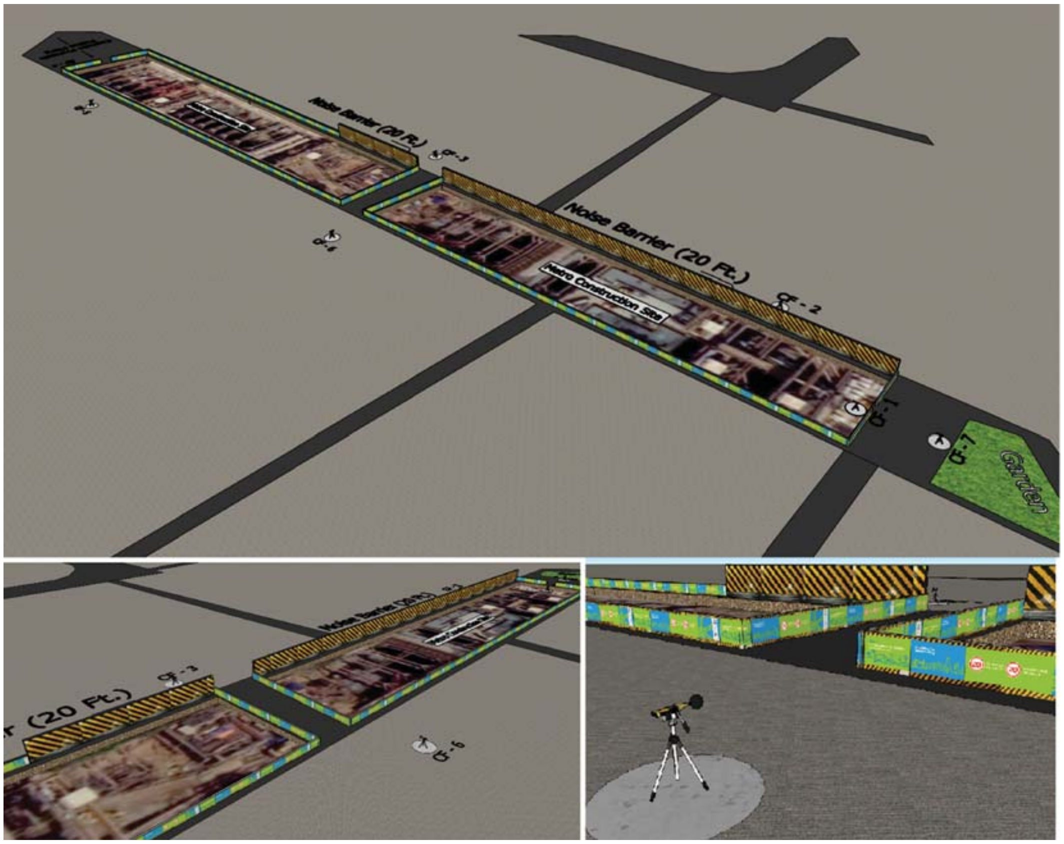

Fig. 2. 3D Anaglyph representation of study area

3.1 Data collection

In order to assess the ambient noise levels during construction phase, noise monitoring was carried out in selected locations for 24 hours for eight days (working and non-working days) during day time (06:00 hrs. to 22:00 hrs.) and night time (22:00 hrs. to 06:00 hrs.) as specified by CPCB (2000) in Noise Pollution (Control & Regulation) Rules, 2000. Calibrated sound level meters were used for noise measurements as per CPCB protocol for ambient noise moitoring 1 with 'fast' response mode due to the quickly changing nature of noise levels. Ambient noise is commonly measured in decibel at 'A' weighting scale as it replicates the response of human ear to noise and the unit is denoted as dBA. Data is logged at an interval of 1 second. The instrument was mounted on tripod stand at the height of 1.5 meters from the ground and wind-ball was used to minimize the effect of wind. The microphone on the sound level meter was positioned at least 3 meters away from the hard surface or walls to minimize the effect of reflections.

3.2 Data analysis

Analysis of equivalent continuous sound level (Leq): The sound level meter records the sound pressure level (SPL) in decibels (dB). From these readings, Leq or equivalent continuous sound level is calculated using Eq. 1 which represents the SPL of a steady sound that over a period of time has the same energy as fluctuating sound[17,18,19].

$$L_{eq,T} = 10\ \log\left(\frac{1}{n}\sum_{i=1}^{n}10^{\left(\frac{L_i}{10}\right)}\right) \tag{1}$$

Where, Li = noise level in dB
n = number of observations at equally spaced time interval
T = Time

3.3 Noise Mapping

Noise maps were prepared based on the digital information of the locations of noise measurement sites with respective noise level (Leq) in GIS environment. This helped in the preparation of spatial noise maps of the study area through geospatial modelling based on the limited sample points[23]. With ArcGIS ver.10.5 software, strategic noise maps were generated using Triangulated Irregular Networking (TIN) model with the help of the spatial analysis tool of ArcMap software where latitude, longitude and Leq values were used as input in place of X, Y and Z field, respectively. Noise contour maps were generated using geospatial technique (natural neighbor algorithm) in ArcGIS software with a grid resolution of 10 m and contour interval of 2 dBA.

4. RESULTS AND DISCUSSION

4.1 Ambient noise levels

Before the commencement of the Metro station construction project, the ambient noise levels at the proposed construction site were 69.9 dBA and 50.5 dBA during day and night, respectively[9] and have remained in this range due to moderate anthropogenic activities. During the construction at the site, noise monitoring was carried out at seven locations. The construction work used to be carried out during day time only i.e. from 6:00 am to 10:00 pm while at night no noise generating activity was observed during monitoring period. During noise monitoring, major construction activity was being carried out at CF1; hence, it is considered as the source site. Other six sites were considered as receptor sites. Excavation and rock breaking work was also going on in other parts of the site, mainly near CF4. It was found that the noise levels at all locations at and around the metro construction site were exceeding the pre-project phase ambient noise levels as well as the noise level standards w.r.t. residential as well as commercial area category. The prescribed noise standards for residential area category is 55 dBA for day time and 45 dBA for night time and for commercial area, it is 65 dBA for day time and 55 dBA for night time[10].

From Figure 3, it is observed that during seven days of monitoring period highest noise levels (Leq = 91.9 dBA) during day time was observed at CF6 on Day 2 and lowest noise levels (Leq= 68.5 dBA) during day time was observed at CF3 on Day 6 & 7. Absence of noise barriers at work zone boundary and road intersection for vehicles near CF6 has contributed to high noise levels at this site. On the contrary, lowest noise levels were observed at CF3 as it was located at the centre of work zone boundary and hence, was receiving less noise due to construction activities carried out at the either end of the work zone (*i.e.* CF1 and CF4). Also, CF3 was protected by 20 feet high noise barrier.

Similarly, during night time, highest noise level (Leq= 83.4 dBA) was observed at CF5 on Day 6 while the lowest noise level (Leq= 60.3 dBA) was observed near CF3 on Day 5.

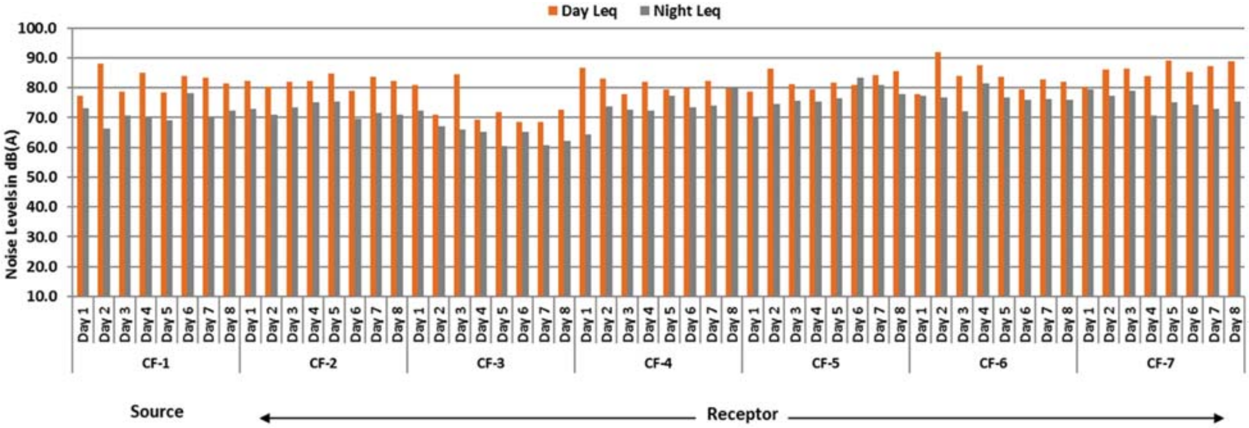

Fig. 3. Ambient noise levels during day and night time at Metro station construction site

Construction activities majorly included digging of rocky bed, blasting, excavation and heavy vehicular movements. Breaking of rocks or digging activity recorded high noise levels ranging from (Leq = 80.7 to 82.3 dBA) at the noise meter level (1.5m above ground). These activities were performed approx. 20-25 m below ground level. Therefore, its impact was not reflected to actual extent at ground level. Rock blasting was observed on few days with high noise levels (Leq= 80.2 dBA). Apart from these, traffic noise especially honking was recorded at an alarming noise level (Leq=82.1 dBA) near CF7, CF5 and CF4 due to traffic congestion owing to construction activities. Even though the sampling site CF1 was the source of the construction noise, noise levels at the receptors were observed to be higher than that at the source due to cumulative impact of traffic noise.

Figure 4 represents the average ambient noise levels of the monitoring sites for the entire duration of the monitoring period of 8 days. It is observed that, the highest noise levels (Leq = 86.6 dBA) were observed at CF7 site while the lowest noise levels (Leq = 66.7 dBA) were observed outside CF3 site. During day time, high noise levels above 82 dBA were observed at all the site locations due to construction activities

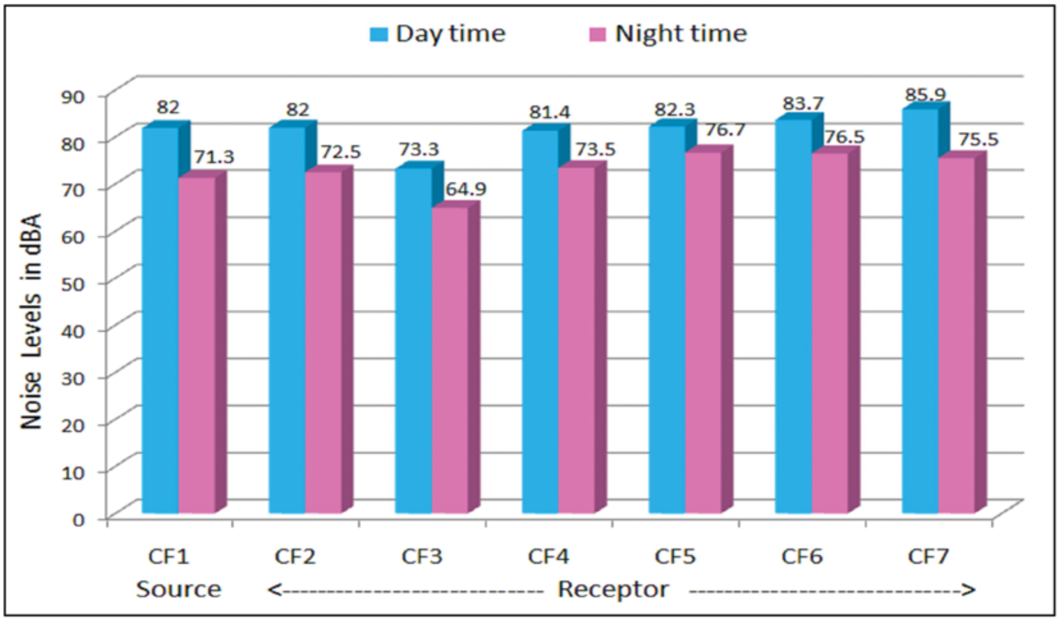

Fig. 4. Average ambient noise levels during eight days at Metro Station construction site

and traffic noise except CF3 (Leq = 77.6 dBA). During night time, high noise levels were observed near CF5 (Leq = 78.4 dBA) and CF6 (Leq = 77.2 dBA) due to traffic noise while low noise level was observed outside CF3 (Leq = 66.7 dBA).

4.2 Noise mapping: Representation of noise levels and their attenuation

Strategic and spatial noise maps were generated to see the variations of the noise level in day and night and determine the attenuation of noise level from source to receptor. The spatial noise maps of day and night (Fig. 5a and 5b) depict the noise level at a particular site which is crucial to identify the noise hotspot. The spatial noise maps were developed on GIS environ and every noise monitoring locations were symbolized as a circle and mapped using graduated symbol tool where range and different colour shades of the circles varied with the intensity of the noise level.

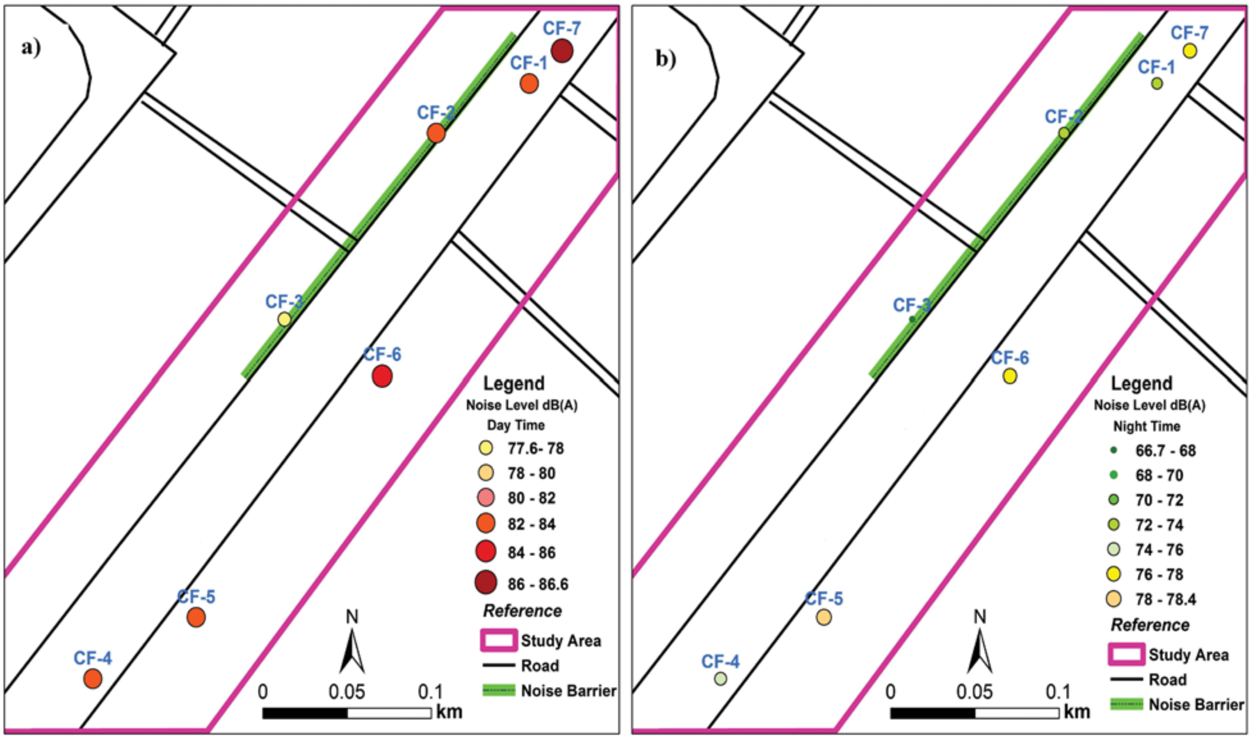

Fig. 5. Spatial representation of noise levels during
(a) Day time and (b) Night time at Metro station construction site

On the other hand, strategic noise maps (Fig. 6a and 6b) are an accurate demonstration of noise pollution of the entire study area. To generate a strategic noise map, which precisely portrays the existing condition, it is essential to use the noise monitoring data. The strategic noise maps are prepared using Leq values with the help of triangulated network modelling (TIN) under the geostatistical tools of ArcGIS software[7]. To create noise maps, the continous noise surface TIN model with natural neighbour algorithm worked as a crucial method where latitude, longitude and Leq values were used as input in place of X, Y and Z field, respectively.

In this study, an attempt has also been made to represent noise contours, which are superimposed (Fig. 7a and 7b) on the metro construction site based on the seven noise monitoring points with associated roads near the metro construction site. These lines represent the variation of sound pressure level (SPL) from source to receptor. The noise contours are superimposed on Google Earth for better visualization and understating. The average day and night contours are represented in Fig. 7a and Fig. 7b, respectively.

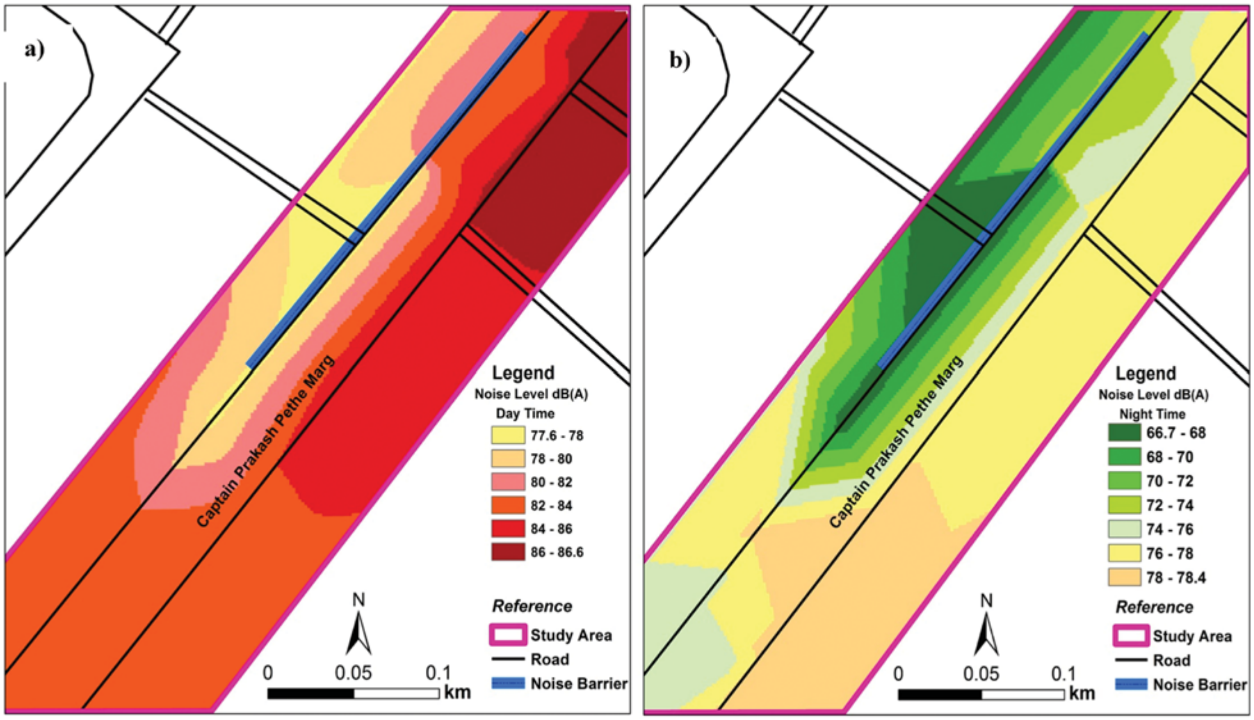

Fig. 6. Strategic noise maps of Metro station construction site for (a) Day time and (b) Night time

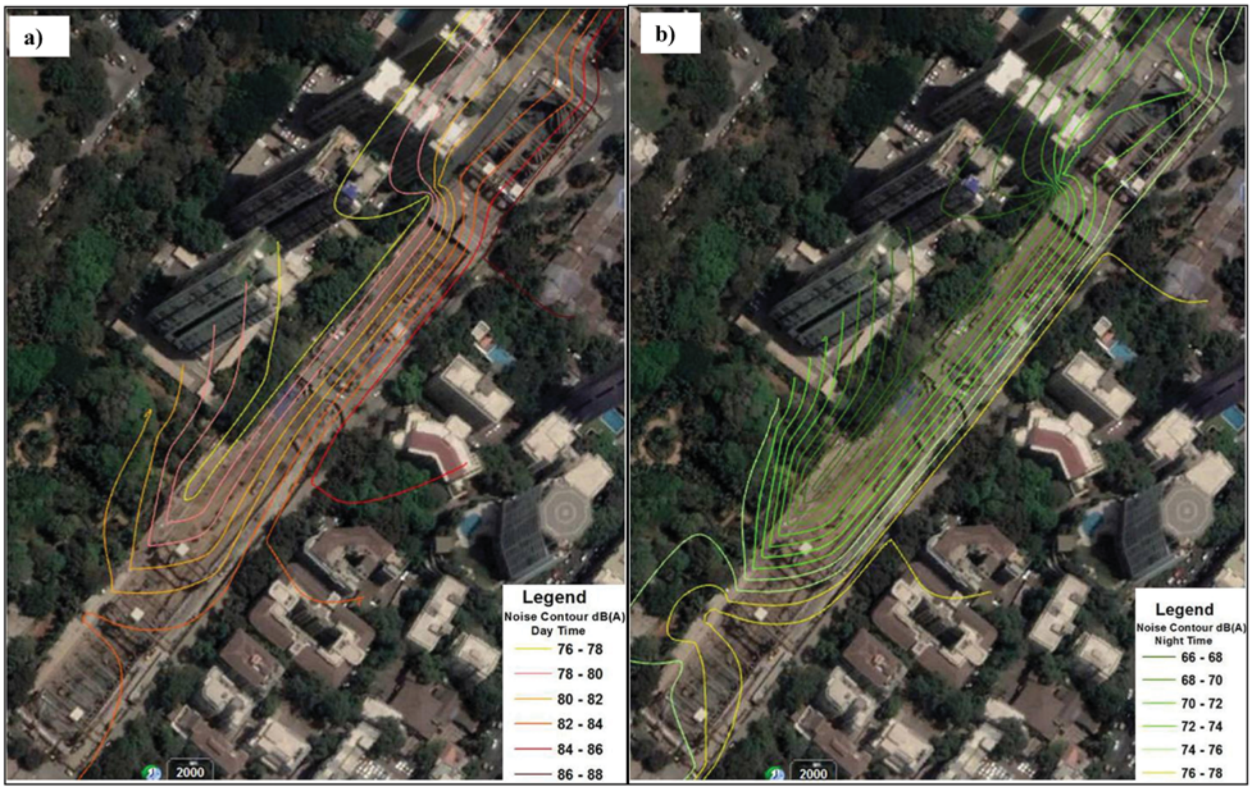

Fig. 7. Representation of noise contours on google earth image during (a) Day time and (b) Night time at Metro station construction site

High noise levels during day time (Fig. 7a) such as 86 dBA is indicated by the red line towards CF5 and CF6 whereas yellow line towards CF3 and CF2 indicate low noise levels of 76 dBA. During night time, high noise levels such as 76 dBA is indicated by the yellow line towards CF5, CF6 and CF4 whereas dark green line towards CF3 and CF2 indicate low noise levels of 66 dBA (Fig. 7b).

Based on spatial and strategic noise maps as well as contour maps (Fig. 5, 6 & 7), it is depicted that the noise level is high in the construction zone, but its intensity is reducing towards CF2 and CF3 side because of the presence of noise barrier and minimal traffic activities. On the contrary, noise levels are high towards south side of the study area, CF5, CF6 etc. due to traffic movement and absence of noise barriers. Drastic reduction in noise levels due to the noise barriers can be realized through the noise maps.

5. CONCLUSIONS

Construction noise in the present study was found to adversely affect peoples' quality of life. It makes people feel irritated and stressed which interrupts their ability to sleep leading to higher blood pressure, anxiety and acrimonous feelings toward the agencies responsible for producing the noise. From the noise monitoring carried out at metro construction site, it was observed that there was cumulative impact of construction and traffic noise at all the sampling locations. The noise levels recorded were extremely higher than the pre-project ambient noise levels and prescribed national norms. Ambient noise level for overall sampling locations of metro construction sites for day time ranged from 68.5 to 91.9 dBA and during night time, noise levels were in the range of 60.3 to 83.4 dBA.

The construction activities were being carried out majorly during the day time. Noise barrier with sufficient height was erected along small portion of the site perimeter on the northen side. Due to the absence of noise barriers at other locations, even though the construction was carried out away from the residential buildings, high noise levels were observed near the residences. Using noise level data, maps are produced on GIS platform that assess and represent the exposure to noise pollution. GIS tools proved very efficient in representation of noise barrier efficiency by accurately depicting the portion of study area exposed to high noise levels. This serves as a tool in better visualisation and understanding the noise abatement measures undertaken at a construction site.

In view of the above observations, the following measures should be taken to control the noise due to construction activities at metro construction sites:

- Noise barriers (acoustic sheds or partitions) of sufficient height should be erected on all sides of the construction site to control and cut down the impact of noise arising out of various activities in the surrounding areas.
- Noise abatement measures should be fitted across the construction site and machineries engaged in above-ground construction works such as acoustic enclosures for piling machines, DG sets etc.
- Strategic planning of worksites to reduce potential noise impacts on surrounding residential areas
- Planning construction activities to be undertaken at appropriate times of the day to control noise due to construction activities. For eg. High noise generating machines to be operated during day time only.
- Maintenance of vehicles and machines used for construction activities should be done regularly to avoid the unnecessary increase in noise levels.
- Simple modifications in old equipments, such as adding new mufflers or sound-absorbing materials, to be done to make them quieter.

6. CONFLICT OF INTEREST

On behalf of all authors, the corresponding author declares that there is no conflict of interest.

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Acoustically characterizing 'experience of transcendence' in Aachener Dom, Aachen-Germany

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ABSTRACT

Experience of 'Transcendence' is acoustically characterized in Aachener Dom, Aachen using participants' feedback at 23rd International Congress on Acoustics' organ concert by Prof. Michael Hoppe in Aachener Dom on September 10, 2019. 'Transcendence' experiences of 'awe' (AT_{AWE}), 'inspiration' (AT_{INSP}), and 'tranquility' (AT_{TRANQ}) were derived from perceived Acoustical Qualities of Loudness (SAQ_{LOUD}), Clarity (SAQ_{CLAR}), Reverberance (SAQ_{REV}), Intimacy (SAQ_{INT}), Directionality (SAQ_{DIR}), Envelopment (SAQ_{ENV}), Balance (SAQ_{BAL}), Silence from Background Noise (SAQ_{SNOIS}), Silence from Echoes (SAQ_{SECHO}) and Overall Acoustical Comfort (SAQ_{OVER}). In this study, subjective acoustical qualities showed significant relationship with AT_{INSP} (R^2=0.84; p=0.05) and AT_{TRANQ} (R^2=0.77; p=0.01) respectively. AT_{INSP} was found significantly predictable from SAQ_{CLAR} (p=0.02), SAQ_{DIR} (p=0.005), SAQ_{INT} (p=0.04), SAQ_{SNOIS} (p=0.06) and SAQ_{OVER} (p=0.03). AT_{AWE} showed significant positive linear regression with SAQ_{OVER} (p=0.04). AT_{TRANQ} was found significantly predictable from SAQ_{CLAR} (p=0.02), SAQ_{DIR} (p=0.06) and SAQ_{OVER} (p=0.01). Differences in perception of Subjective Acoustical Qualities were insignificant at p=0.05. Experience of 'transcendence' as 'awe' was perceived better than as 'inspiration' or 'tranquility' at p=0.06. The results indicate significant relationships between Acoustical Transcendence Impressions and Subjective Acoustical Qualities which if further explored and connected to sound decay and psychoacoustical parameters can form a unique description of Aachener Dom's intangible acoustical heritage.

1. INTRODUCTION

A worship space has capacity to induce a meta-physical experience of 'transcendence'[1] in a devotee. This study describes and characterizes this experience as acoustically induced perception of 'awe', 'inspiration' and 'tranquility'.

This pilot study was spontaneously arranged during ICA 2019 on the day of the organ concert at *Aachener Dom*, Aachen, shown in Figure 1.

Aachener Dom (Aachen's Cathedral) is one of the four most important pilgrimage churches of the world, in par with those of Jerusalem, Rome and Santiago de Compostela. This Church of Charlemagne dedicated to the Virgin Mary holds the mortal remains of Charlemagne (+814) and has been coronation church of the german-roman kings (936-1531). Aachener Dom, a UNESCO world Cultural heritage asset (1978) has evolved over twelve hundred years of history[2].

Fig. 1. (A) Delegates in Aachener Dom for live concert; (B) Exterior view of Aachener Dom

Eleven delegates from nine different countries participated in this acoustical test during a live organ concert for delegates of ICA 2019 at *Aachener Dom* by Prof. Michael Hoppe, the main organist of the cathedral. The objective was to assess the acoustical impact of organ music rendition on participants' perception of 'transcendence' in Aachener Dom. This study builds on earlier research done in the acoustical characterization of worship ambience in churches[3-13].

2. METHODOLOGY

2.1 Determining 'Acoustical Transcendence Impressions'

Prof. Hoppe, organist presented the following musical renditions on the pipe organ of the cathedral:

- ***Camille Saint Saëns :*** Prélude et Fugue in E major, op.99 no.3
- ***Johann Sebastian Bach :*** Concerto in D after Antonio Vivaldi
- ***Gabriel Pierné :*** Prelude and Cantilene from op.29
- ***Marcel Dupré :*** Variations sur un Noël-Variations on a French Folksong
- ***Louis Vierne :*** Scherzo and Finale, fromSymphony op.20 no.2

The participants' and the organist' locations during the live concert are shown in Figure 2.

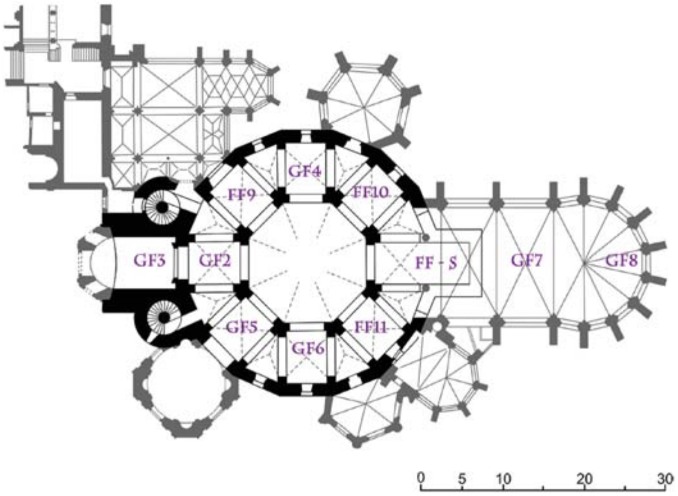

Fig. 2. (A) Delegates in Aachener Dom for live concert; (B) Exterior view of Aachener Dom

The listeners were instructed to score on ten desirable subjective acoustical qualities of the worship space using a structured questionnaire.

Each of these qualities provided a six point (0 to 5) differential scale on the evaluation sheet where ('0' implies '0% presence') ('1' implies 'very weak - 20% presence'); ('2' implies 'weak /mediocre - 40% presence'); ('3' implies 'fairly strong - 60% presence'); ('4' implies 'sufficiently strong - 80% presence'); ('5' implies 'optimally strong - 100% presence')

The following Subjective Acoustical Qualities were evaluated:

1. Subjective Acoustical Quality of Loudness (SAQ_{LOUD}) (The overall loudness or strength of the sound);
2. Subjective Acoustical Quality of Clarity (SAQ_{CLAR}) (The degree to which the musical notes are distinctly separated in time and clearly heard);
3. Subjective Acoustical Quality of Reverberance (SAQ_{REV}) (the persistence of sound);
4. Subjective Acoustical Quality of Directionality (SAQ_{DIR}) (the auditory impression that the sound comes from the axis of the sound source due to the arrival of substantial amount of direct sound);
5. Subjective Acoustical Quality of Intimacy (SAQ_{INT}) (the auditory impression of the apparent closeness of the source);
6. Subjective Acoustical Quality of Envelopment (SAQ_{ENV}) (the sense of being immersed in the sound or surrounded by it which happens when there is substantial amount of reverberant sound);
7. Subjective Acoustical Quality of Balance (SAQ_{BAL}) (the relative levels of bass and treble);
8. Subjective Acoustical Quality of Silence from Background Noise (SAQ_{SNOIS}) (where Background Noise is the sound heard other than from the source in the performance area);
9. Subjective Acoustical Quality of Silence from Echoes (SAQ_{SECHO}) (where Echoes are long delayed reflections that are clearly audible);
10. The Subjective Overall Acoustical Comfort (SAQ_{OVER}) (the overall acoustical comfort of the room);

Acoustical Transcendence Impressions of Awe (AT_{AWE}), Inspiration (AT_{INSP}) and Tranquility (AT_{TRANQ}) were derived from scores of Subjective Acoustical Qualities' perception and metaphysical impact[14], using Equation (1)

$$nATI = \frac{\sum (Y_{SAQ} X_{SAQ})_{MEAS}}{\sum (Y_{SAQ} X_{SAQ})_{REF}} \tag{1}$$

where,

nATI (as AT_{AWE}, AT_{INSP} and AT_{TRANQ}) is a normalized value of perception and impact of subjective acoustical qualities as an 'Experience of Transcendence' ($-1 \leq nAWI \leq +1$);

X_{SAQ} is the value of perception of the subjective acoustical qualities ($0 \leq X_{SAQ} \leq +5$);

Y_{SAQ} measures perceived metaphysical impact of acoustical qualities ($-1 \leq Y_{SAQ} \leq +1$);

$\sum (Y_{SAQ} X_{SAQ})_{MEAS}$ is a calculated value from X_{SAQ} and Y_{SAQ}

$\sum (Y_{SAQ} X_{SAQ})_{REF}$ is the optimal reference = 50

This calculation also accomodates listeners' perception of being not sure of the expected impact of subjective acoustical qualities as an 'Experience of Transcendence' in a given space.

2.2 Finding Significant Acoustical Relationships with 'Transcendence' experience

Significant regressions (at 95% level of significance) of Acoustical Transcendence Impressions (AT_{AWE}, AT_{INSP} and AT_{TRANQ}) with Subjective Acoustical Qualities were identified as character defining elements of an Acoustical Experience of 'Transcendence' in that space.

3. RESULTS AND DISCUSSION

3.1 Listeners' Acoustical Perception of the space

Although Clarity and Silence from Echoes showed to have been perceived better than the other acoustical qualities, differences between Subjective acoustical qualities were found to be only 80% significant (p=0.20) as shown in Table 1.

Table 1. ANOVA Tests on variance of different Subjective Acoustical Qualities

Data	**Mean**	**p-value**
SAQ_{LOUD}	3.91	0.20
SAQ_{CLAR}	4.00	
SAQ_{REV}	3.82	
SAQ_{DIR}	3.36	
SAQ_{INT}	3.18	
SAQ_{ENV}	3.27	
SAQ_{BAL}	2.64	
SAQ_{SNOIS}	3.73	
SAQ_{SECHO}	4.00	

3.2 Differences between derived Acoustical 'Transcendence' Impressions

Derived value of 'Acoustically Transcendent Inspiration' (AT_{INSP}) was found significantly better than its counterparts (AT_{AWE} and AT_{TRANQ}) at p=0.06 as shown in Table 2.

Table 2. ANOVA Tests on variance of different Acoustical 'Transcendence' Impressions

Data	**Mean**	**p-value**
AT_{AWE}	0.61	0.06
AT_{INSP}	0.68	
AT_{TRANQ}	0.59	

3.3 Significant Regressions between Measured and Derived Acoustical Parameters

'Acoustically Transcendent Inspiration' (AT_{INSP}) showed significant multiregressions with subjective acoustical qualities of Clarity, Directionality, Intimacy, Silence from Noise and Overall Acoustical Comfort (R^2=0.84; p=0.05) as shown in Equation (2) and 'Acoustically Transcendent Tranquility' (AT_{TRANQ}) showed significant relationship with subjective acoustical qualities of Clarity, Directionality and Overall Acoustical Comfort (R^2=0.77; p=0.01) respectively, as shown in Equations (3).

$$AT_{INSP} = 0.29 + 0.03\ SAQ_{CLAR} + 0.02\ SAQ_{DIR} + 0.01\ SAQ_{INT} + 0.01\ SAQ_{SNOIS} + 0.03\ SAQ_{OVER} \quad (2)$$

$$AT_{TRANQ} = 0.24 + 0.06\ SAQ_{OVER} + 0.03\ SAQ_{CLAR} + 0.01\ SAQ_{DIR} \quad (3)$$

AT_{INSP} was found significantly predictable from SAQ_{CLAR} (p=0.02), SAQ_{DIR} (p=0.005), SAQ_{INT} (p=0.04), SAQ_{SNOIS} (p=0.06) and SAQ_{OVER} (p=0.03) as shown in Equations (4 - 8).

$$AT_{INSP} = 0.45 + 0.06\ SAQ_{CLAR} \quad (4)$$

$$AT_{INSP} = 0.49 + 0.06\ SAQ_{DIR} \quad (5)$$

$$AT_{INSP} = 0.55 + 0.04\ SAQ_{INT} \quad (6)$$

$$AT_{INSP} = 0.50 + 0.05\ SAQ_{SNOIS} \quad (7)$$

$$AT_{INSP} = 0.40 + 0.08\ SAQ_{OVER} \quad (8)$$

'Acoustically Transcendent Awe' (AT_{AWE}) showed significant positive linear regression with Overall Acoustical Comfort (SAQ_{OVER}) (p=0.04) as shown in Equation (9).

$$AT_{AWE} = 0.40 + 0.06\ SAQ_{OVER} \tag{9}$$

'Acoustically Transcendent Tranquility' (AT_{TRANQ}) was found significantly predictable from Subjective Acoustical Qualities of Clarity (SAQ_{CLAR}) (p=0.02), Directionality (SAQ_{DIR}) (p=0.06) and Overall Acoustical Comfort (SAQ_{OVER}) (p=0.01) as shown in Equations (10 - 12).

$$AT_{TRANQ} = 0.38 + 0.05\ SAQ_{CLAR} \tag{10}$$

$$AT_{TRANQ} = 0.47 + 0.04\ SAQ_{DIR} \tag{11}$$

$$AT_{TRANQ} = 0.31 + 0.08\ SAQ_{OVER} \tag{12}$$

3.4 Variance of measured and derived Acoustical parameters in different listening zones

The variance of Subjective Acoustical Qualities and derived Acoustical Transcendence Impressions of Awe, Inspiration and Tranquility across listeners occupying ground floor locations with those on the upper gallery was found to be insignificant at $p \leq 0.05$.

4. CONCLUSION

This pilot study is an exploratory tool to investigate acoustical perception of 'Transcendence' in a worship apace. The results of this study permit the following conclusions to be drawn:

i. Although the listeners' perception of 'clarity' and 'silence from echoes' in Aachener Dom was found better than that of 'Loudness' or 'Directionality' or 'Intimacy' or 'Revereberance' or 'Envelopment' or 'Balance' or 'Silence from Background Noise' or 'Overall Acoustical Comfort', the difference is of only 80% significance. A larger group of participants could impact the level of significance and even the result as to which perceived quality is found better than the others.

ii. Perceived acoustical experience of 'transcendence' in the form of induced 'inspiration' in Aachener Dom is significantly better than that of induced 'awe' and 'tranquility'. Would that change with larger participation? Whatever the result, it is interesting to note that some variant of 'transcendence' is better perceived than others, in a given worship space.

iii. Perceived acoustical experience of 'inspiration' has significantly predictable relationship with subjective acoustical qualities of Clarity, Directionality, Intimacy, Silence from Noise and Overall Acoustical Comfort.

iv. Perceived acoustical experience of 'tranquility' has significant predictable relationship with subjective acoustical qualities of Clarity, Directionality and Overall Acoustical Comfort .

v. Perceived acoustical experience of 'awe' has significant predictable relationship with perceived Overall Acoustical Comfort.

vi. It is beneficial to note that the experience of 'Transcendence' in Aachener Dom, in all three variants (awe, inspiration and tranquility) is significantly predictable from perception of 'overall acoustical comfort' of the space.

vii. There are no significant differences between perceptions of listeners seated in the nave on ground floor with those listening to the renditions from the upper floor gallery.

viii. Listeners' perception of subjective acoustical qualities of a space as inducing 'transcendence' in the form of 'Awe', 'Inspiration' and ' Tranquility' captures the capacity of the worship space of Aachener Dom, Aachen to induce a unique Acoustical Experience of 'Transcendence', which if further explored and connected to sound decay responses and psycho acoustical parameters can form a unique description of Aachener Dom's intangible worship space acoustical heritage.

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Soundscaping 'Revitalising Spaces': extrapolating ISO/TS 12913-2:2018 methods to connect auditory, non-auditory, affective and metaphysical perceptions

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ABSTRACT

Human beings are self-transcending beings and long for 'revitalising' experiences. Soundscaping 'spaces which revitalize human-beings' (refered to as 'Revitalising Spaces') require connecting physical (auditory and non-auditory) sensations with affective and metaphysical perceptions of participants. This study extrapolates ISO/TS 12913-2:2018 soundscaping methods in an appropriate 'Questionaire' that accomodates a dimension of 'metaphysical (transcendence) experience' in a qualitative description of a soundscape. It includes perceptions of 'Heightened Awareness & Exhilaration', 'Contemplative Tranquility leading to Stillness', 'Harmonious connection to the Cosmos' and 'Inspiration & Deeper Understanding' as descriptors of metaphysical experience of a listener. Analysis of auditory, non-auditory, affective and metaphysical perception data gathered in this questionnaire can unearth significant connections between physical and metaphysical components of a soundscape, which will 'characterize' and 'identify' certain spaces of our neighborhood as 'revitalising spaces' - spaces that can satisfy our innate need for 'Transcendence' and therefore need to be preserved as cosmic intangible heritage.

1. INTRODUCTION

Human beings are self-transcending beings and are defined by their longing for 'transcendence' or 'revitalising experiences' either in nature or in spaces and activities designed for the same[1]. The experience of 'excitement' at a party or experience of 'concentration' in an examination hall or experience of 'serenity' on a hilltop or experience of 'Awe' in the wilderness[2] or experience of 'contemplation' in a cave or experience of 'tranquility' in a garden or experience of 'sacredness' in a worship space[3] are a few multi-faceted experiences that human beings aspire in 'Revitalising Spaces'. Experience of 'transcendence' which is beyond and deeper than affective experiences is essential for an environment to compose a 'Revitalizing Space'. Therefore, 'Revitalising Spaces' are pleasant, eventful, calm, vibrant and more. This 'transcendence' dimension of a 'Revitalising Space' is described and characterized here as extra-sensory perceptions of 'heightened awareness & Exhilaration', 'Contemplative tranquility leading to stillness', 'Harmonious connection to the cosmos' and 'Inspiration and deeper understanding'.

2. SOUNDSCAPING

'Sound' lies at the 'core' of every human experience, therefore it is important to know how each space (natural and built) should 'sound like' to generate holistic human experience[4].

'Noise' is a lifestyle choice of 'superficial' over 'substantial'; of 'discomfort' over 'comfort'; of 'war' over 'peace'. While Environmental Noise Management tries to eliminate noise, which is annoying, unhealthy and undesirable, 'Soundscaping' is an effort to identify, preserve and design acoustic environments that are comfortable, appropriate and desirable[5,6]. Thus, Soundscaping is an effort to promote health and well-being of human beings and the natural environment[7,8]. The research to identify and design 'positive' outdoor and indoor soundscapes has gained momentum[9,10].

The study of Soundscape is primarily based on human perception. The perceiving human being is the focus of attention. The listener needs to be trained in order to develop the sonological competence that is required to pay attention to the specific salient sounds of an acoustic environment. At the same time, the perception of auditory events is colored by the listener's socio-cultural background and psycho-phsiological condition. In order to decide on the 'quality' of the soundscape from a perceptual point of view, the descriptors of perception need to be comprehensive, appropriate and accurate. A number of efforts have generated such descriptors which inter-relate perceived soundscapes, restoration, quality of life, semiotics and urban planning[11,12]. The acoustical and psycho-acoustical indicators derived from physical measurements help to validate the descriptors of one's 'preferred perception' of an acoustic environment in a given space or 'context' as a relevant 'Soundscape' of that space[13,14,15].

3. SOUNDSCAPING 'REVITALISING SPACES' : SCOPE AND METHODOLOGY

This study extrapolates the soundscaping methods (Method A and Method B) outlined in ISO / TS 12913-2:2018 to characterize and connect the sensorial, affective and metaphysical experience of a listener in spaces with conducive revitalising environments.

Method A and Method B outlined in ISO / TS 12913-2:2018 are insufficient to characterize a revitalising space for the following reasons:

- These methods are framed for urban soundwalks and need upgradation for compatible valence assessment in 'rural' natural revitalising spaces
- Soundwalks to a revitalising space are more intense and require meditative sensorial and extra-sensorial perception than just a cursive walk with five-ten minutes silent halt at different locations.
- A revitalising space requires in depth assessment as 'incidental or natural' space as well as a space which is 'intentionally activated with revitalising stimuli like live music or singing' which is not accomodated in these methods.
- The scale type used for a revitalising space needs to have a uniform positive connotation. It cannot simultaneously hold contradictory responses of 'absence' (1) and 'annoyance' (5) with confused acceptance (2-4) as in Method A. Also, indication of 'never' with (1) and 'too much' with (5) is incongruent as both 'never' and 'too much' of a desirable attribute can be annoying and cannot be accomodated on a scale that is meant to show variance of a good attribute from its minimal to optimal state.
- Descriptors for a revitalising space need to be uniformly positive and not mixed up: 'How (un) pleasant...?', 'How appropriate...?'
- 'Acoustic quality' need to be described by more attributes than just 'loudness' as in Method A.
- The sound sources need to be assessed by the acoustical attributes than by 'just being heard' as in Method A.
- Perceived affective qualities can be summarizingly scored upon only as 'pleasant / unpleasant' and 'eventful / uneventful' as the other states of being calm / excited / chaotic / boring can be deduced.
- Subjective preferences of participants need to be more elaborately characterized than being very generic and reduced to only perception of appropriateness (as in Method A and Method B).

A suitable 'context' to be investigated as a 'revitalising space' is chosen. This revitalising context could be a sacred grove or a hilltop or a worship space or a cave or a sea-shore or a lake-side or a river bank etc. The listeners are chosen from varied gender, professions, musical leanings and age groups to bring in heterogenity in responses to the acoustic and non-acoustic environment of a given 'context'.

The 'incidental' natural 'acoustic environment' of the 'context' is supplemented with renditions of a 'revitalising tune' in human vocals or on musical instruments, which is termed as 'intentional' acoustic environment in a given 'context' of a 'revitalising space'. In this study, the chosen revitalising tune is 'Oh Lord my God, when I in awesome wonder', a popular hymn by Stuart K. Hine, praising God's creation alluding Psalm 93:1. The Konkani language version of the same hymn 'Tum Kitlo Xrextt' by Rabin D'Pietro is also used for comparison. Binaural recordings of the 'incidental' and 'intentional' acoustic environment during the time of 'listening' by the participants, are done in accordance with ISO / TS 12913-2, simulating the way human beings perceive the acoustic environment.

The binaural microphone head dummy is set at an average height of a human person (160 cm) axially oriented towards the sound sources and made to stand amidst the participating listeners. These recordings allow auralisation and assessmnet of psycho-acoustic indicators.

A small group of participants (as recommended by the techincal specifications) who voluntarily accept the invitation to participate in this soundscaping exercise, are instructed about nomenclature and methodology of soundscaping 'revitalising spaces'. Listeners are trained to perceive and record their sensorial, affective and metaphysical perceptions. A 'Questionaire' is filled by the listeners as guided in each 'context'. The weather condition at the moment of soundscaping is noted as windy / rainy / cold / clear / hot / calm etc,. This questionaire enables a guided interview with the participants and allows a comprehensive analysis of the listeners auditory and non-auditory perception of the 'acoustic' and 'non-acoustic' environment. Analysis of the 'affective' and 'metaphysical' experience of participants enables characterization of a given context as 'a revitalising space'. The statistical analysis is done using Microsoft Excel 2007 and Origin 6.1.

4. QUESTIONNAIRE TO SOUNDSCAPE 'REVITALISING SPACES': ADAPTING SECTIONS C.3.1/2 OF ISO/TS 12913-2:2018)

The questionaire used in this study in soundscaping 'revitalising spaces' is an extrapolated adaptation of Method A and Method B of ISO 12913-2:2018[14][16] and perspectives of Grounded Theory[17,18] so as to appropriately assess the participants' perceived sound source taxonomy; their psycho-physiological condition; their socio-cultural background; and their sensory, affective & 'metaphysical experience' in an 'incidental' natural acoustic environment and in an 'intentional' activated acoustic environment of a 'revitalising space'. This section details the different parts of the Questionaire.

4.1 Determining 'Acoustical Transcendence Impressions'

The questionaire lists questions such as:

- How good is my *'mood'* or 'mental health'?
- How good is my *'stamina'*?
- How good or fit are my sensory organs (ears, eyes, nose, *etc.*)?

The listeners response can vary from *'very little'* (20%) to *'little'* (40%) to *'moderate'* (50%) to *'fair'* (60%) to *'optimal'* (80%). The perceived impact of the psycho-physiological condition on the auditory and non-auditory sensation is noted by the listener as either *'negative'* or *'positive'* or *'unsure'*.

4.2 Assessment of perceived 'Sound Source Taxonomy'

The listed sound sources (as in Method A of ISO / TS 12913-2:2018) include: Natural Sounds (water, wind, thunder, Animals, birds, insects, trees etc.); Sounds from Human Beings (footsteps, voices etc); Traffic Noise (motorized, non-motorized); Other Noise (Machinery, Electronics etc). These sounds are also characterized as either 'Background Sounds' (continuous or frequent sounds) or 'Foreground sounds' (sounds that emerge and go). The sounds are listed in order, starting with the most noticeable.

4.3 Assessment of Perceived Auditory Sensations and their Affective and Metaphysical Impact

The chosen perceived auditory sensations are 'Loudness', 'Clarity', 'Tonality'' and 'Intimacy' of the sounds in the acoustic environment of the 'context'.

'Loudness' is listed as either 'not audible' (0%), 'too soft' (20%), 'soft' (40%), 'moderate' (50%), 'fair' (60%), 'optimal' (80%) or 'painful' (100%).

'Clarity' is listed as either 'not clear' (0%), 'very little' (20%), 'little' (40%), 'moderate' (50%), 'fair' (60%), 'optimal' (80%) or 'rough' (100%).

'Tonality' is listed as either 'no balance' (0%), 'very little'(20%), 'little' (40%), 'moderate' (50%), 'fair' (60%), 'optimal' (80%) and 'no variance' (100%).

'Intimacy' is listed as either 'can't relate' (0%), 'very little'(20%), 'little' (40%), 'moderate' (50%), 'fair' (60%), 'optimal' (80%) or 'intrudes' (100%).

The affective impact of each of the chosen auditory sensation is assessed by the perception of the latter as either 'pleasant' (+1) or 'unpleasant' (-1) or 'unsure' (0) and as either 'eventfulful' (+1), or 'uneventful' (-1) or 'unsure' (0).

The metaphysical impact of each of the chosen auditory sensation is assessed by the impact of the perception of the latter on the listener's metaphysical experience of 'heightened awareness', 'stillness', 'harmony' and 'inspiration' as 'negative' (-1) or 'positive' (+1) or 'unsure' (0).

4.4 Assessment of Perceived Non-Auditory Sensations and their Auditory, Affective and Metaphysical Impact

Human Experience is integral of the auditory and non-auditory sensations. The 'pleasantness' and the 'eventfulness' of non-auditory 'visual', 'tactile (thermal)' and 'olfactory' sensations respectively, is assessed as either 'very little'(20%), 'little' (40%), 'moderate' (50%), 'fair' (60%) or 'optimal' (80%). The impact of each of the chosen non-auditory sensation on one's auditory sensation is assessed as either 'positive' (+1) or 'negative' (-1) or 'unsure' (0)

The metaphysical impact of each of the chosen non-auditory sensation is assessed by the impact of the perception of the latter on the listener's metaphysical experience of 'heightened awareness', 'stillness', 'harmony' and 'inspiration' as 'negative' (-1) or 'positive' (+1) or 'unsure' (0).

4.5 Listener's Background and its impact

Personal traits chosen as descriptors of a listener's background are:

- Listeners' perception of 'appropriateness' of sounds in the tested context.
- Listeners' 'Familiarity with the 'context' either through 'prior experience' or through 'prior knowledge'.
- Listeners' perception of 'Surprise' or 'Novelty' during this visit
- Listeners' 'Personal Preference' for a given 'context''
- Listeners' 'Personal commitment to preserve spaces such as the given 'context'.

The perception of 'appropriateness' or 'familiarity' or 'preference' or 'novelty' or 'commitment to heritage' as descriptors of a listener's background is assessed as either 'very little'(20%), 'little' (40%), 'moderate' (50%), 'fair' (60%) or 'optimal' (80%). The impact of each of the above chosen descriptors of a listener's background on one's auditory and non-auditory sensation is assessed as either 'positive' (+1) or 'negative' (-1) or 'unsure' (0).

4.6 Summary Descriptors

Summary descriptors for the tested 'context' include: attractiveness of the space' and 'revitalising aura of the space' both of which are rated by listeners as from 'very little' (20%) to 'little' (40%) to 'moderate' (50%) to 'fair' (60%) to 'optimal' (80%).

As summary descriptors of the 'incidental' and 'intentional' 'acoustic environment', the listeners list 'sounds' that had positive and negative impact on them. They list 'sounds' that they would label as 'Sound marks' (sounds that contribute to the identity of the space).

4.7 Listener's Proposals

The last part of the questionaire leaves space for each listener to pen down their relevant and appropriate suggestions to conserve the tested 'context' as a 'revitalising space'.

5. DERIVATION OF AUDITORY AND NON-AUDITORY 'AFFECTIVE' AND 'METAPHYSICAL (TRANSCENDENCE)' IMPRESSIONS

In order to define the 'Meaning and Quality' of 'Affective' and 'Metaphysical (Transcendental)' experiences in 'Revitalising Spaces', a method is hereby presented to adequately quantify the affective and metaphysical quality of a 'Revitalising Soundscape'.

The scored subjective sensorial (auditory and non-auditory) perceptions and their respective impacts on affective and metaphysical experiences are normalized as 'affective and metaphysical impressions'.

The 'Affective Quality' is judged by 'Pleasantness and Eventfulness' of the perceived environment in 'Context'. The 'Meaning and Quality' of the induced Perception of 'Transcendence' in a 'Revitalising Space' is described by four Metaphysical impressions:

- Heightened Awareness and a sense of Exhiliration - expressed as 'Transcendent Awareness' (T_{AWARE}),
- Sense of Contemplative Tranquility leading to stillness - expressed as 'Transcendent Stillness' (T_{STILL}),
- Harmonious Connection to the Cosmos - expressed as 'Transcendent Harmony' (T_{HARM}),
- Inspiration and Deeper Understanding expressed as ' Transcendent Inspiration' (T_{INSP})

The listeners' feedback listener to the guided questionnaires (as to how the sensorial perceptions are related to the affective and metaphysical impressions and as to how the non-auditory affective impressions are impacting the auditory sensation) provides data that enables derivation of Acoustic Affective and Metaphysical (Transcendence) impressions', Non-Acoustical Affective Auditory Impressions and Non-Acoustical Affective Metaphysical (Transcendence) Impressions. This differentiation results into:-

- Four Acoustic Transcendence Impressions:
  - o Acoustic Transcendent Awareness (AT_{AWARE})
  - o Acoustic Transcendent Stillness (AT_{STILL})
  - o Acoustic Transcendent Harmony (AT_{HARM})
  - o Acoustic Transcendent Inspiration (AT_{INSP})
- Two Acoustic Affective impressions:
  - o Acoustic Pleasantness (A_{PLEAS})
  - o Acoustic Eventfulness (A_{EVENT})
- Three Non-Acoustic Affective Auditory impressions
  - o Visual Affective Auditory Impression (VA_{AUD})
  - o Tactile Affective Auditory Impression (TA_{AUD})
  - o Olfactory Affective Auditory Impression (OA_{AUD})
- Three Non-Acoustic Affective Transcendence Impressions of 'Heightened Awareness (nAT_{AWARE})
  - o Visual Transcendent Awareness (VT_{AWARE})
  - o Tactile Transcendent Awareness (TT_{AWARE})
  - o Olfactory Transcendent Awareness (OT_{AWARE})

- Three Non-Acoustic Affective Transcendence Impressions of 'Stillness' (nAT_{STILL})
    - Visual Transcendent Stillness (VT_{STILL})
    - Tactile Transcendent Stillness (TT_{STILL})
    - Olfactory Transcendent Stillness (OT_{STILL})
- Three Non-Acoustic Affective Transcendence Impressions of 'Harmony' (nAT_{HARM})
    - Visual Transcendent Harmony (VT_{HARM})
    - Tactile Transcendent Harmony (TT_{HARM})
    - Olfactory Transcendent Harmony (OT_{HARM})
- Three Non-Acoustic Affective Transcendence Impressions of 'Inspiration' (nAT_{INSP})
    - Visual Transcendent Inspiration (VT_{INSP})
    - Tactile Transcendent Inspiration (TT_{INSP})
    - Olfactory Transcendent Inspiration (OT_{INSP})

Acoustic Affective Impressions and Acoustic Transcendence Impressions are constituted using (1)

$$X_{AI} = \frac{\sum (Y_{SAQ} X_{SAQ})_{MEAS}}{\sum (Y_{SAQ} X_{SAQ})_{REF}} \tag{1}$$

where,

- X_{AI} as (A_{PLEAS}, A_{EVENT}) & (A_{TAWARE}, A_{TSTILL}, A_{THARM}, A_{TINSP}) respectively, is derived Acoustic 'affective' or 'Transcendence Impression' of a 'Revitalising Soundscape' ($-1 \leq nXI \leq +1$) - which quantifies the quality of Acoustic Affective or Metaphysical (Transcendence) Experience in a 'Revitalising Space'.
- Polarity (±1) is significant as it indicates positive or negative impact on listeners' 'acoustic affective experience' or ' acoustic metaphysical (transcendence) experience' in a given space.
- X_{SAQ} is the value of the subjective acoustical qualities ($1 \leq X_{SAQ} \leq +5$);
- Y_{SAQ} measures perceived impact of subjective acoustical qualities of the sound sources on A_{PLEAS}, A_{EVENT}, AT_{AWARE}, AT_{STILL}, AT_{HARM} and AT_{INSP} on a three point differential bipolar scale as either 'impacting' (+1) or 'not impacting' (-1) (whereas a score=0 implies that the listener is 'not sure' of the impact).
- $\sum (Y_{SAQ} X_{SAQ})_{MEAS}$ is a calculated value from X_{SAQ} and Y_{SAQ}
- $\sum (Y_{SAQ} X_{SAQ})_{REF} = 20$ is optimal reference value

Cumulative Non-Acoustic Affective Auditory Impressions and Cumulative Non-Acoustic Affective Transcendence Impressions are constituted using (2)

$$X_{nAI} = \frac{\sum [Y_{nAI} \ (X_{nAP} + X_{nAE})]_{MEAS}}{\sum [Y_{nAI} \ (X_{nAP} + X_{nAE})]_{REF}} \tag{2}$$

where,

- X_{nAI} as (nAA_{AUD} - cumulative of VA_{AUD}, TA_{AUD}, OA_{AUD}), (nAT_{AWARE} - cumulative of VT_{AWARE}, TT_{AWARE}, OT_{AWARE}), (nAT_{STILL} - cumulative of VT_{STILL}, TT_{STILL}, OT_{STILL}), (nAT_{HARM} - cumulative of VT_{HARM}, TT_{HARM}, OT_{HARM}), (nAT_{INSP} - cumulative of VT_{INSP}, TT_{INSP}, OT_{INSP}) respectively, is derived Non-Acoustic 'affective' Auditory Impression (nAA_{AUD}) (which quantifies the affective impact of non-auditory - visual, tactile and olfactory - perceptions on auditory sensation) or Non-Acoustic 'affective' 'Transcendence Impression' of a 'Revitalising Soundscape' (nAT_I) (which quantifies the quality of non-Acoustic Affective Metaphysical (Transcendence) Experience in a 'Revitalising Space'. ($-1 \leq X_{nAI} \leq +1$)

- Polarity (±1) is significant as it indicates positive or negative impact on listeners' 'non-acoustic affective experience' or ' non-acoustic metaphysical (transcendence) experience' in a given space.
- X_{nAP} is the value of Pleasantness for non-acoustical impressions (visual, tactile and olfactory) ($1 \leq X_{nAP} \leq +5$);
- X_{nAE} is the value of Eventfulness for non-acoustical impressions (visual, tactile and olfactory) ($1 \leq X_{nAE} \leq +5$);
- Y_{nAI} measures perceived impact of affective non-auditory perceptions on auditory sensations and nAT_{AWARE}, nAT_{STILL}, nAT_{HARM} and nAT_{INSP} on a three point differential bipolar scale as either 'impacting' (+1) or 'not impacting' (-1) (whereas a score=0 implies that the listener is 'not sure' of the impact).
- $\sum[Y_{nAI}\ (X_{nAP} + X_{nAE})]_{MEAS}$ is a calculated value from X_{nAP} and X_{nAE}
- $\sum[Y_{nAI}\ (X_{nAP} + X_{nAE})]_{REF} = 30$ is optimal reference value

6. PERFORMERS' CRITERION IN AN 'INTENTIONAL' REVITALISING ACOUSTIC ENVIRONMENT'

Performers' criterion is assessed through an evaluation sheet filled through an interview with the performers (singers & musicians). The questions posed to them are:

- Could you hear your own rendition loud and clear?
- How good was the 'tonal' quality of your rendition?
- How 'intimate' did your rendition sound to you?
- How good was the impact of 'scenery', 'smell' and 'feel' of the space on your performance?
- Did you enjoy performing in this space?
- Did you feel pleasant while performing?
- Did you feel eventful while performing?
- Did you experience 'transcendence' in the form of 'heightened awareness' stillness', 'harmony' or 'inspiration' in this space?
- How would you rate this space as a 'Revitalising Space?

All Questions are scored on a five point (1 to 5) differential scale.

7. MEASURING INSTANTANEOUS, STATISTICAL AND PERCENTILE SOUND LEVELS

The sensory perceptions as shaping the soundscape of a revitalising space has to be qualified by noise ambience of a given space. In order to measure environmental noise levels with ease, a scientifically researched software App such as Android based 'Noise Capture App' version 1.2.15 Jul3,2020r.32ec098 (developed for measuring environmental noise using a smartphone)[19] can be calibrated on a smartphone to:

- Measure instantaneous sound levels and Equivalent Noise Level (Leq) in dB(A) over entire measurement duration.
- Measure a 'noise level spectrum' for each third octave band between 100Hz and 16KHz.
- Measure statistical sound levels in dB(A): minimum, mean, maximum.
- Analyse percentile noise levels in dB(A) over entire measurement duration: *Background Noise Level* (LA90)-A-weighted noise level that is exceeded for 90% of the measurement period; *Median Sound Level* (LA50)-A-weighted noise level that is exceeded for 50% of the measurement period; *Noise Annoyance Level* (LA10)-A-weighted noise level that is exceeded for 10% of the measurement period;
- Analyse Repartition of the Noise Exposure (RNE) representing the distribution of percentile sound levels over time of entire sound exposure.

Visual representations of acoustic environments as provided by 'Noise Capture' broadens the understanding of a soundscape's composition, character and capacity to revitalise or annoy.

8. RESULTS : SIGNIFICANT VARIANCES AND REGRESSIONS

Amongst many relevant investigations through analysis of the scored data of the listeners, following significant variances and regresions could be yielding important results:

- Variances between 'Incidental Sources' (Natural, Human, Machines) and 'Intentional Sources' (Performances - vocal and instrumental)
- Variances between 'Natural Sources' (Birds, Animals, Wind *etc.*) and 'Intentional Sources' (Performances - vocal and instrumental)
- Variances between different Genres of 'Intentional Sources' (Performances - vocal and instrumental)
- Regressions between 'Acoustic Affective Impressions' and 'Subjective Acoustical Qualities of the 'Acoustic Environment'
- Regressions between 'Acoustic Transcendence Impressions' and 'Subjective Acoustical Qualities of the 'Acoustic Environment'
- Regressions between 'Non-Acoustic Affective Auditory Impressions' and 'Non-Acoustic Affective Transcendence Impressions' of the 'Acoustic Environment'
- Regressions between 'Acoustic Affective Impressions' and 'Non-Acoustic Affective Auditory Impressions' of the 'Acoustic Environment'.
- Regressions between 'Acoustic Affective Impressions' and 'Non-Acoustic Affective Transcendence Impressions' of the 'Acoustic Environment'.
- Regressions between 'Acoustic Transcendence Impressions' and 'Non-Acoustic Affective Auditory Impressions' of the 'Acoustic Environment'.
- Regressions between 'Acoustic Transcendence Impressions' and 'Non-Acoustic Affective Transcendence Impressions' of the 'Acoustic Environment'.

9. CONCLUSIONS

- This study presents a detailed process of characterizing a soundscape of a 'Revitalizing Space' through significant relationships between sensory perception, 'affective impressions', 'metaphysical (transcendence) impressions and noise levels.
- The questionaire presented here (adapting/extrapolating ISO/TS 12913-2:2018 soundscaping methods) appropriately assesses the trained participants' perceived sound source taxonomy; their psycho-physiological condition; their socio-cultural background; and their sensory, affective & 'metaphysical experience' in an 'incidental' natural acoustic environment and in an 'intentional' activated acoustic environment of a 'Revitalising Space'. This questionaire can also enable a researcher in a guided interview with the participants.
- Accompanying Binaural acoustical measurments in accordance with ISO/TS 12913-2:2018, simulating the way human beings perceive the acoustic environment provide valuable recordings for auralisation and to deduce psycho-acoustic indicators.
- Smartphone based easy measurement of instantaneous (L_{eq}), statistical (LA90, LA50, LA10) and percentile (RNE) sound levels (dB) of the acoustic environment, enables visual representations of acoustic environments and broadens the understanding of a soundscape's composition, character and capacity to revitalise or annoy.
- Assessment of Performers criterion and the impact of diffrent genres of rendition on the listeners helps to judge as in what mode (incidental or intentional) the given space (context) revitalises the performers better.
- 'Soundscapes' constructed from the collected comprehensive data inclusive of the participants'

'affective' and 'metaphysical experience' will allow 'Revitalising spaces' of the neighborhood to be identified, characterized and conserved for posterity as cosmic intangible heritage.

- The ability to quantitatively describe the 'Quality' of diverse 'Revitalising Soundscapes' of natural environment will enable design of adequate 'Architecture of Happiness' and 'Revitalising built Environment.

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Marine propeller noise control by optimized geometrical modification

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ABSTRACT

The present work aims at numerical study of propeller noise control by using geometry modification. Based on certain optimized geometrical parameters of a 6 bladed marine propeller such as pitch, thickness, skew and camber, a new propeller is modeled. Unsteady non-cavitating noise of this Propeller at specified rotating speed and flow speed is predicted. Finite volume code is used to carry out numerical simulations. Large eddy simulation (LES) formulation is adopted in CFD analysis and Ffowcs William's- Hawkings (FW-H) formulation is used in acoustical analysis. Through this study, it is shown that propeller noise can be reduced drastically by adopting geometrical modifications without compromising on hydrodynamic performance.

1. INTRODUCTION

It is well known that underwater radiated noise of marine vehicle is to be minimized to reduce its vulnerability to attack by adversary. Propeller is a major contributor to this noise. Propeller noise depends upon propeller geometry, propeller wake inflow and propeller isolation. This Propeller noise is generated due to the pressure difference in rear and aft end of the propeller blade. The parameters of the propeller which changes the noise levels are the number of blades, the Pitch angle, the blade area, the diameter of blade, Skew Angle, Trailing edge geometrical modifications and Propeller blade finishing fineness. In this study, a six bladed propeller is modeled by using different optimized parameters such as Pitch, Skew, Thickness and Camber. Non-cavitating noise generated by the propeller is predicted using FW-H equation and eddy viscosity model of Large Eddy Simulation (LES) in computational fluid dynamics software. Impact of geometrical modifications on Torque and Thrust is also studied. This paper presents the approach followed for this study and results obtained.

2. LITERATURE REVIEW

Many researchers worked on Propeller noise over the years. Some of the relevant literature for marine propeller noise is briefly discussed here.

V. Rama Krishna et al. (1) aimed to identify a propeller which is producing less noise. This pa-per deals with the prediction of the unsteady non-cavitating marine propeller noise of 5, 6 and 7 blades with

+10° pitch, +5° pitch, existing pitch and -5° pitch, -10° pitch at rotational speed 840 rpm and vehicle speeds of 7.62 m/sec, using eddy viscosity model of large eddy simulation (LES) available in computational fluid dynamics fluent software and using Ffowcs Williams-Hawkings (FW-H) formulation. From this numerical study on these propellers, it is found that the propeller of 6 blades with +5° pitch generates least noise. Finalized the propeller which is producing low noise as well as which generates required Thrust and Torque by changing the di-ameter of propeller. Finally obtained the noise reduction of 9.4 dB with the new redesigned Pro-peller when compared with the baseline propeller for the same thrust and torque.

V. Rama Krishna et al. (2) aimed at controlling the noise generated by the propeller by chang-ing skew angle of the propeller. The aim is to identify the skew angle of a propeller at which propeller noise is least. Unsteady non-cavitating noise of marine propeller of 6 blades with +5° skew, +10° skew, +15° skew and +20° skew and existing propeller at rotating speed of 780 rpm and vehicle speed of 7.08 m/sec was predicted. The methodology adopted in CFD analysis is ed-dy viscosity model of Large Eddy Simulation (LES) and Ffowcs Williams-Hawkings (FW-H) formulation was used for acoustic analysis. From this numerical study on these propellers, it is found that for the propeller under study, +15° skew angle generates least noise.

V. Rama Krishna et al. (3) aimed at controlling the propeller noise by changing its thickness. In this work, noise was investigated by varying blade thickness of 5 and 6 bladed marine propellers. Numerical simulation of a chosen propeller was resorted to for prediction of unsteady non cavitating propeller noise. The approach involved solid modeling of the propeller followed by CFD modeling including water domain around the propeller. Pressure fluctuations predicted through CFD analysis were used for acoustic analysis employing FWH method and eddy viscosity model of Large Eddy Simulation. Pressure based, unsteady implicit formulation of second order was chosen as solver. Noise spectrum was predicted over the frequency range of 0-10 kHz. Noise was predicted for blade thickness increments of 0.1mm to 0.5mm at specified operating conditions of propeller speed. From the results it is observed that increase in blade thickness leads to reduced noise and among the studied configurations, 6 bladed propellers with 0.5mm blade thickness increment generates lowest noise. While designing marine propeller for low noise, it is also important to ensure that it satisfies hydrodynamic performance requirements. Hence, in this study hydrodynamic performance parameters such as thrust and torque were checked for the low noise propeller configuration and it was found to be better than base line propeller.

V. Rama Krishna et al. (4) aimed at the controlling the noise generated by the propeller by changing Camber of the propeller. The study involves various camber values of blades with rotating speed of 780 rpm and at 7.08 m/s vehicle speed. The methodology adopted in CFD analysis is eddy viscosity model of large eddy simulation (LES) and in acoustical analysis is Ffowcs Williams-Hawkings (FW-H) formulation.From this numerical study on these propellers, optimized camber is arrived at for generating least propeller noise.

Mohammad et al. (5) studied various methods of noise reduction for marine propeller. There are various methods of reducing propeller noise like modification of inlet flow, changing the propeller geometry and the confinement of the propeller. These reduction techniques divided into various groups depends up on the type of noise (cavitation and non-cavitation noise), technology and cost, and the frequency of the identified noise. They studied the effects of trailing edge noise from the propeller.

Maaloum et al. (6) presented theoretical study using a hydrodynamic approach on the tonal noise of propeller blades. Acoustic analysis was carried out using the Ffowcs Williams and Hawkings (FW-H) equation. The vortex surface method and an aero-acoustic approach was used for prediction of unsteady hydrodynamic forces applied on the propeller blades.

Chang-Sup Lee et al. (7) Suggested a design method for increasing performance of the marine propellers including the WCT propeller. It is observed to maximize the performance of the pro-peller by adjusting expanded areas of the propeller blade. Results show that efficiency can be increased up to over 2% through the suggested design method.

3. BRIEF DESCRIPTION OF PROPELLER

The dimensions of the reference propeller configuration studied are mentioned in Table 1.

Table 1. Dimensions of Reference propeller model.

Diameter (m)	0.389 m
Expanded Area ratio, EAR=A_E/A_0	0.58
Number of Blades	6
Hub ratio	0.245
Series	NACA 66

Propeller blade is made of Forged Aluminium Al-24345 alloy and its material Specifications are depicted in Table 2.

Table 2. Material Specifications.

Density (kg/m^3)	2689.8
Young's Modulus (GPa)	68.3
Poisson's Ratio	0.34
Proof Stress (MPa)	385

Fig. 1 shows the Reference Propeller under analysis.

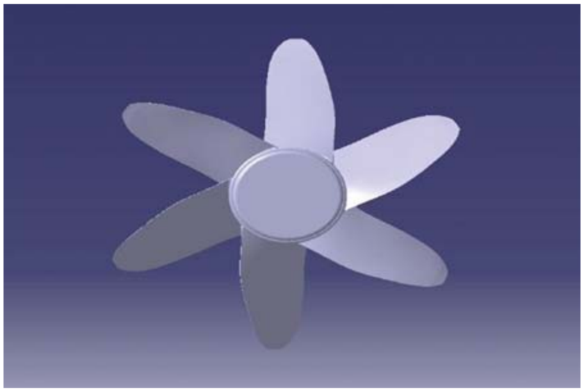

Fig. 1. Reference Propeller

4. NUMERICAL MODEL OF PROPELLER

The propeller was modelled using CATIA V5 R20. The propeller is generated by dimensions of each section of the blade at various radii *i.e.* geometrical characteristics of propeller at different sections. In this paper, various optimized parameters from our previous studies as described below are taken and using these parameters an optimized propeller is modeled in CATIA software as shown in Fig. 2. The following optimized parameters are taken for the modelling compared to reference propeller.

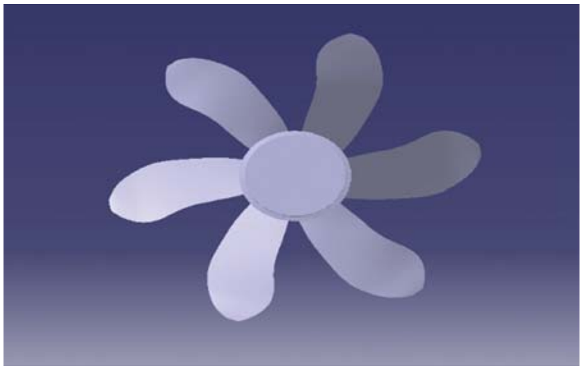

Fig. 2. Optimized Propeller

- Camber increased to +0.2 mm
- Thickness increased to +0.5 mm
- Skew increased to +15°
- Pitch increased to +5°

The type of mesh used for this analysis is as follows:

Type of Element : Tetrahedral, Mesh type: Fine, Mesh Size: 11 mm.

Number of nodes : 35373, Number of elements: 183857

Optimum mesh size of 11 mm is arrived through iterative study by using various mesh sizes.

The meshed model of this 6 bladed marine optimized propeller is shown in Fig. 3.

Fig. 3. Meshed model of optimized propeller

5. CFD ANALYSIS

The optimized propeller which was modeled using CATIA V5 is uploaded into ANSYS software for CFD analysis. The numerical simulation is carried out using FLUENT module. LES turbulence model is taken in this CFD analysis to solve the model. Necessary inputs are given to the module to get the solution.

Rotating Surfaces relatively are defined as moving wall and are dependent on the fluid around them. Velocity inlet of the wall is taken as 7.08 m/sec. Fluid zone in the inner volume is defined as moving mesh at 780 rpm in x-direction. Large eddy simulation (LES) methodology is adopted for the CFD analysis on the optimized propeller.

Total pressure distribution of optimized propeller is shown in Fig. 4.

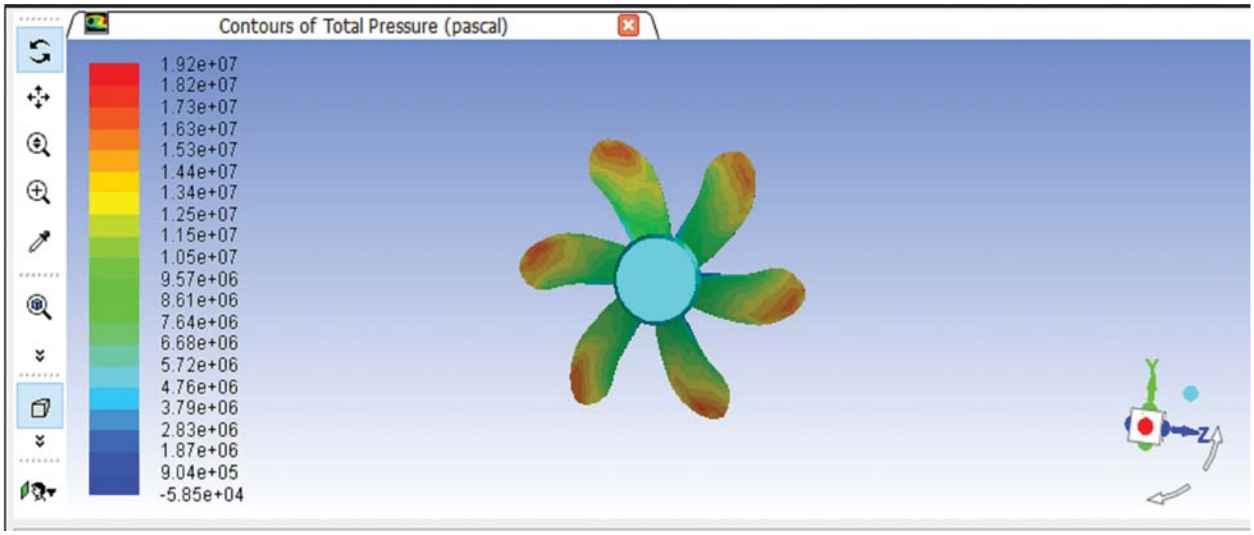

Fig. 4. Total pressure distribution of optimized propeller

6. ACOUSTIC ANALYSIS

The output from CFD results is processed into Acoustic module for Acoustic analysis. Ffowcs Williams-Hawkings (FW-H) formulation is adopted for Acoustic analysis.Noise spectrum was predicted over the frequency range of 0-2 kHz. The optimized lowest overall sound pressure level obtained after the analysis is 104.843dB which is depicted in the graph shown in Fig. 5.

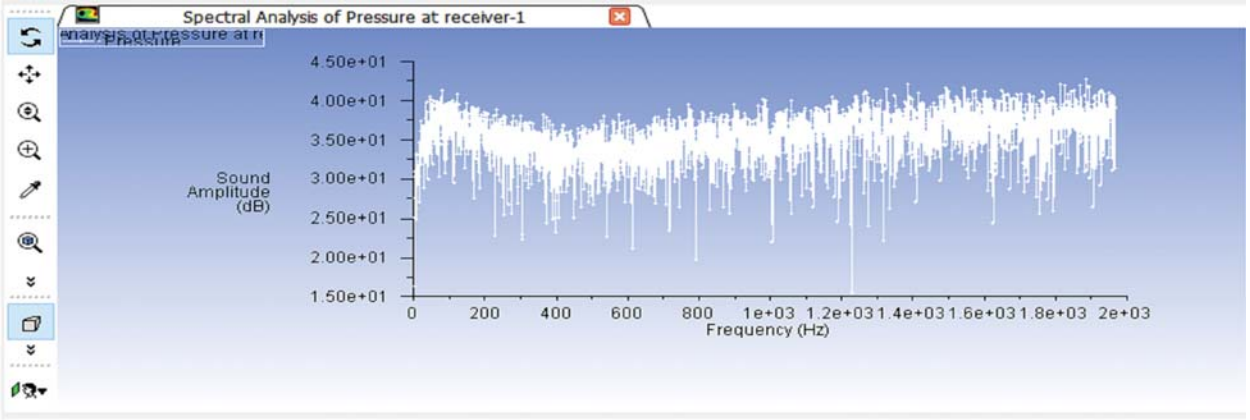

Fig. 5. SPL vs frequency graph of optimized propeller

A comparative table of overall sound pressure levels of propeller with out and with different geometrical modifications is given in Table 3.

Table 3. Comparison of noise levels with different geometrical modifications.

S.no	Propeller Geometry	Overall Noise levels (dB//1 µ Pa)
1	Reference propeller	130 dB
2	With +5° Pitch increment	127 dB
3	With +0.2 mm Camber increment	124 dB
4	With 15° Skew increment	119 dB
5	With 0.5mm Thickness increment	116 dB
6	With Combined geometry changes	105 dB

It can be seen clearly that by a combination of optimum geometric parameters, noise levels could be drastically reduced from 130 dB to 105 dB / / 1 µ Pa

7. CALCULATION OF THRUST AND TORQUE COEFFICIENTS

Thrust and Torque values of Reference and Optimised Propellers which were obtained from the CFD analysis is shown in Table 4.

Table 4. Thrust and Torque of Reference Propeller.

Parameter	Reference Propeller	Optimized propeller
Thrust , T in N	1385.73	1638
Torque, Q in N-m	51.89	114

Operating conditions are:

Density of sea water (ρ) = 1029 kg / m3

Diameter of propeller (D) = 0.389 m

The Thrust and Torque coefficient were calculated from the following equations.

Thrust coefficient, $K_T = \frac{T}{\rho n^2 D^4}$

Torque coefficient, $K_Q = \frac{Q}{\rho n^2 D^5}$

Thrust coefficient and Torque coefficient for reference propeller:

Thrust coefficient (K_T) = 1385.73 / (1029*169*0.389^4) = 0.348

Torque coefficient (K_Q) = 51.89 / (1029*169*0.389^5) = 0.0335

Thrust coefficient and Torque coefficient for Optimized propeller:

Thrust coefficient, K_T = 1638 / (1029*169*0.389^4) = 0.411

Torque coefficient, K_Q = 114 / (1029*169*0.389^5) = 0.073

Comparison of Thrust coefficient and Torque coefficient of Optimized propeller to reference propeller is shown in Table 5.

Table 5. Comparison of thrust and torque coefficients of reference propeller with optimized propeller.

Parameter	Reference Propeller	Optimized Propeller
Thrust coefficient	0.348	0.411
Torque coefficient	0.0335	0.073

From the above table, it can be seen Thrust and Torque coefficients are increased for Optimized propeller compared to reference propeller. Thus, this optimized propeller is found to generate low noise and more Thrust and Torque than reference propeller.

8. CONCLUSIONS

Underwater non-Cavitating noise produced by marine propeller with geometrical modifications has been studied in this paper. Through this study, it has been shown that by optimized geometrical modifications, noise level of propeller can be drastically reduced without compromising Thrust and Torque requirements. This finding has great significance for marine vehicles to achieve better acoustic stealth.

9. ACKNOWLEDGEMENT

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A review article on the natural fibrous based sound absorbing acoustic materials

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ABSTRACT

Noise pollution is the serious environment pollution that affects human health. Noise is basically a displeasing or undesired or unwanted sound which make us uncomfortable as it interferes our sleep, speech etc. and leads to Noise pollution. Therefore, this is a main concerned to the researchers to prevent this noise propagation. One of the Solution of this problem is to use different kind of materials which absorb the sound have been widely used in practical life. The basic fundamentals and principals of the sound and its propagation, sound absorbing materials and their characteristics and the factors which influences the sound absorption has been discussed in this paper. This paper provides an insight to the importance of the sound absorbing materials and factors which we should take care before developing any sound absorption material for the purpose of practical life uses.

1. INTRODUCTION

Acoustics is the branch of science in which we deal with the sound. "Sound is a disturbance which propagated through a medium particle causes an alternation in pressure and this disturbance is generated because of the medium particles movement which can be sensed by a person or can be detected by an instrument. Sound propagates in form of a longitudinal wave in which particle motion is along the direction of the sound propagation direction and it required a medium such as in liquids, plasma, and gaseous medium to travel[1]. When sound wave travels through a medium it causes vibration to the medium particles of certain frequency and as wave passes through the medium two regions formed at one region crowd of particles occurs between molecules in the air called compression region and each other particles pushes one another and enter into the second region of low pressure called rarefaction. In the compression process each molecule travels straight with a certain velocity through the medium, which is the velocity of the sound wave[2]. Therefore, particles move in the wave propagation direction hence sound wave are longitudinal waves. Speed of sound wave depends on medium properties like bulk modulus, density which in turn depend on temperature. So depending upon the medium through which sound wave passing, sound travels with different speeds in different mediums, depending upon the pressure gradient[3]. Human hear can respond to the minute pressure variations in the air if they are in audio able frequency range from 20 Hz to 20 KHz. Normally, the human's threshold of hearing is about 20 μPa pressure which is much lower than normal atmospheric pressure level. So, emitted sound travels in the form of longitudinal pressure wave which calculated in the terms of frequency in Hertz which has a relationship with wavelength as shown in equation (1).

$$? = C \lambda \tag{1}$$

where, ? = frequency, c = velocity of light and λ = wavelength of sound waves.

Sound absorption process and sound absorption coefficient (SAC): - When the sound wave interacts with an acoustic barrier, leads to three things: -

Absorption - Certain part of sound is absorbed and get dissipated in the form of heat.

Transmission - Some part of wave just crossed the barrier and appears on the other side of barrier.

Reflection - Some part of sound gets back to the same side after being collided by the barrier.

The amount which is being reflected, transmitted or absorbed is dependent upon the properties of the material.

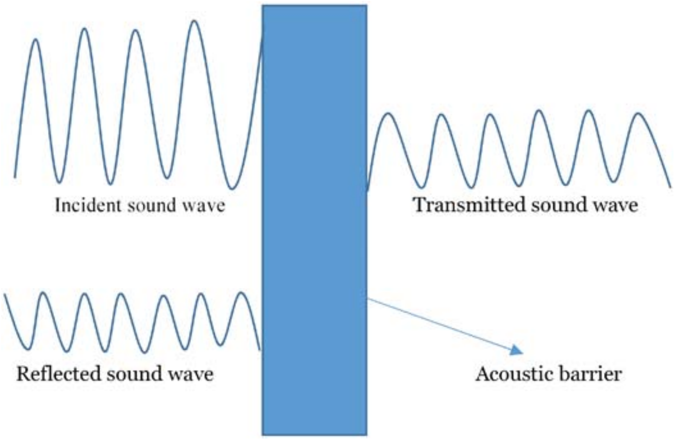

Fig. 1. Interaction of sound wave with acoustic barrier.

SAC is the ratio between the amount of the absorbed sound energy and the amount of the incident sound energy. It measures the amount of sound being absorbed by a material The higher the absorption coefficient, higher the absorption which indicates that very less amount of sound energy is reflected back. Sound absorption coefficient is frequency dependent quantity. When an energy is incident on the material three types of waves are generated which are shown in figure as incident wave, reflected wave and transmitted wave. So, the SAC is defined as:

$$\alpha = I_a / I_i \tag{2}$$

where, α = sound absorption coefficient, I_a = absorbed sound intensity in W/m^2 and I_i = incident sound intensity in W/m^2

2. MEASUREMENT AND METHODS

There are several methods for measuring SAC and NRC among them two are commonly evolved first is impedance tube method and second is reverberation chamber method.

2.1 Reverberation chamber method

The impedance tube method only measures the SAC and NRC of normal incidence field or direct field while reverberation chamber designed to measure the absorption coefficient for diffused field or random incidence sound field. Reverberation chamber basically a large room with very hard and reflective exposed walls which helps in creating diffusing field.


(a) (b)

Fig. 2. (a) Reverberation chamber without sample and
(b) Reverberation chamber with Sample installed at National Physical Lab, Delhi

Reverberation chamber is useful for testing relatively large samples like acoustic panels, furniture's *etc.*[4]. Reverberation chamber designed at national physical laboratory, New Delhi has:

Table 1. Specification of reverberation chamber at NPL, New Delhi.

Specifications of Reverberation Chamber	
Dimensions:	6 m × 6.5 m × 7 m
Volume :	271 m^3 (Receiving Room), 257 m^3 (source room)
Cut-off frequency :	80 Hz
Reverberation Time :	5 secs (Receiving Room) 7 sec (Source Room)

The test of the sample follows the two steps in first step we measure the reverberation time (which is the time taken to decay sound by 60dB in closed space when sound source ceases)[2] in chamber without the sample and in second step we measure the same with sample. Then their difference gives the absorption coefficient of the material. Several measurements taken for each test condition and average result determined.

Sound in a closed room or in reverberation chamber reflected back from its surfaces and walls; these reflections in combined form called reverberation. So the reverberation time depends upon the material characteristic and the size of room. The sound source played for some time then it stopped and after 5dB attenuation we start to measure reverberation time till sound power level decreases by 60Db[2]. As the decay time can alter with the frequency so this measured with each octave band. Therefore, reverberation time calculated for each band and SAC is calculated of room without the sample. After characterizing the empty chamber, we now characterize the room with sample installed in it and reverberation time of the chamber calculated with sample in the same way as before. So, we calculate the SAC and NRC of the material by using formula:

$$SAC = \frac{55.3V}{S(331 + 0.6t)} \tag{3}$$

Here, T_w is the reverberation time without sample(s) and T_s is the reverberation time with sample(s) placed in the reverberation chamber while *S, V* and *t* are sample area (m^2), volume of the reverberation chamber (m^3) and temperature (°C) of the chamber respectively. This formula is originally derived empirically by Sabine[5].

For noise control purposes NRC is normally used which is the average of SAC at different frequencies. NRC provide how good is the surface of material for sound absorption. Noise Reduction Coefficient using formula:

$$NRC = \frac{\alpha_{250} + \alpha_{500} + \alpha_{1000} + \alpha_{2000}}{4} \tag{4}$$

Where, α_{250}, α_{500}, α_{1000} and α_{2000} are the average values of the SAC at 250 Hz, 500Hz, 1000 Hz and 2000 Hz frequency respectively.

2.2 Impedance tube method

The impedance tube system contains of a sound source which emit sound of desired frequency at one end while Sample which is to be characterize is inserted in the tube at the other end. In this method sound is incident normally to the sample. Two microphone also placed in this system just before the sample. This system is useful for small samples measurements. The experimental setup is meet with the standards of ISO-10534-2, ASTM E1050-12 and transmission loss ASTM E2611-09. Sound source is loudspeaker which emit sound wave of particular frequency, then microphones measures the sound pressure at different locations. A software is also attached with this system which then calculate the acoustic properties of the inserted material based on frequency response functions measured at different locations. Therefore, by calculations and measurements this system helps us to obtain SAC of the material[6].

Fig. 3. Impedance tube system at National Physical Lab, New Delhi.

3. SOUND ABSORBING MATERIALS

Materials which have the ability of absorbing the incident energy as much as possible and reflect as minimum as possible energy called sound absorbing material. The main function of sound absorptive materials is that they convert impinging acoustic energy into the form of heat energy. The absorptive characteristics of acoustical materials is largely dependent onto the pore/void size, interconnections between pores/voids, materials composition and thickness etc. Sound is absorbed because as we know sound is the pressure wave which travels as the medium particles moves and friction occurs between the air particles and the material in this process sound energy loss occurs in the form of heat, if the velocity of the air particles is large than there is more friction and the sound absorption also increased. Sound absorption coefficient is important factor that determine acoustical performance of acoustical material.

There has been different kind of materials which have been developed and are utilizing in practical life for the sound absorption purposes. Fibrous materials have been used at large scale due to their porous structure which are produced cheaply and there is subcategory in fibrous materials which include synthetic fibre, natural fibre, inorganic materials and metallic materials[7]. They offer various advantage like low processing cost, sustainable, biodegradable, recyclable and no adverse impact on nature.

Porous sound absorbing materials - These type of materials contains large number of uniformly distributed pores inside the material which are interconnected with each other. For example, fibrous materials, foams and different composites with internal pores are porous sound absorbing materials. Porous sound absorbing materials have good SAC at high frequency region but lower SAC at lower frequency region[8]. This type of materials uses has been widely growing because of their high SAC and other various advantages like they are produced cheaply and their application field is growing continuously. The principal of sound attenuation in these materials is due to the friction occurring between the sound wave and the fibre assemblies of the material. The SAC value of fibrous materials is mainly depending upon the materials composition like porosity, thickness, pore size, and other microstructural parameters *etc.*

3.1 Inorganic and metallic fibres

These materials have several advantages like they provide high resistance to the corrosion, high temperature resistance coefficient and they are long lasting. These type of materials received attention for sound absorption because they offer some special features like as large specific surface area, high mechanical strength and excellent permeability. For example, Inorganic materials like glass wool, mineral wool has been extensible used in noise reduction. Metallic fibrous materials like stainless steel fibre, nickel fibre and aluminium fibre are used for noise reduction because of their above described special properties. Various studies have been done on this type of materials like rock wool, glass fibre, carbon fibre. This type of materials replacing the traditional natural and synthetic materials for example aluminium fibre has been used in subways, tunnels and highways etc. glass fibre has excellent mechanical properties at low weight with compared to other type of materials therefore glass fibre among the inorganic materials has been widely used for industrial purposes such as in building construction. Studies observed that with increasing thickness sound absorption increases in glass fibre at lower frequency region. The average SAC of over 0.8 can be achieved in the frequency range of 100 - 6400 Hz with 30 mm thickness.

3.2 Synthetic fibrous materials

Synthetic fibres has the structural diversity and tailored cross-sections such as circle, triangle and hollow which provides the improvement in the acoustic absorption properties compared to the natural fibrous materials. Apart from this, Synthetic fibre has excellent mechanical properties such as good strength and flexibility. Synthetic fibrous usually developed in the form of sheets and felts. Mineral wool and glass wool are the example of synthetic materials. The acoustic absorption properties are better of these materials because of their thinner diameter and antifungal property but they have adverse impact on environment. Blending of natural material with fibrous materials is also an emerging application for better sound absorption. for example, Thilagavathi et al. reported that needle-punched polypropylene nonwovens were produced by blending with banana, bamboo and jute fibres respectively and the results indicated that bamboo/polypropylene nonwoven had the highest NRC[9]. Veerakumar and Selvakumar observed that kapok/polypropylene nonwoven fabric has excellent SAC over wide frequency range[10]. Kapok/polypropylene fibre assemblies of 30:70 with high bulk density and low porosity exhibited the highest SAC when air gap created behind the material. Recently attention has been growing towards the fibre reinforced composites. Porous absorbing concrete slab has been used for preventing noise by the trains.

3.3 Natural fibrous materials

A great attention has been shifted towards the utilization of the natural fibrous because of their specific advantages that they are biodegradable, renewable which made them eco-friendly but they have some shortcomings as well like lower anti fungus, durability, moisture, lower interfacial adhesion and fire resistant qualities. Researchers are trying to improve these shortcomings of natural fibrous materials. Bamboo fibre, tea-leaf fibre, date palm fibre, coir fibre, kenaf, hemp and cane fibre were investigated for the sound absorption[11]. The light dense, large lumen and thin wall structures will increase the friction between sound wave and fiber surface. In a study it was observed that sound absorption properties of the kapok fiber are excellent due to large semen structure and it has hollow structures in which sound wave interacts and acoustic energy converted into the heat energy. Further blending of different fibrous material together used for improving NRC and thermal insulation. So, the structural optimization and modification in the material improves the acoustical behaviour of the material[12].

3.4 Nano fibrous materials

These materials are very lightweight and good SAC at lower frequency range[13] but the production cost of these type of materials is too much expensive than other materials which is the main limitation of these type of materials. Nano fibrous materials has large surface area and effective airflow resistivity so absorb efficient amount of energy. It has been proven in a previous research study that the interaction between sound waves and the larger specific surface of nanofibers, air friction inside the Nano pores and vibrations of the Nano layers contributes for the noise absorption. There is a possibility of nanofiber movement in the structure and it can influence the sound absorption. Therefore, Nano fibrous layer has different sound absorption properties in comparison with other conventional fibrous materials due to their unique micro structures. So the SAC can be improved by increasing surface area of Nano fiber layer. Further, as they are light in weight so largely utilizing in industries. Composites absorbing material consist of nanofiber layers and foam structure improves the SAC.

So the above we discussed different type of sound absorbing materials which have been utilizing in different fields for controlling noise. Each type of materials has its some special features *i.e.* advantages and disadvantages so a material is chosen carefully for particular application in practical life. Composition of the material plays major role on sound absorption like porous soft materials like foam, fibre glass, cloth absorption more amount of sound because porous materials have large surface to propagate sound wave and porous materials particles or fibres can vibrate so energy can dissipate into heat while dense materials like glass, concrete etc. reflect more incident energy rather absorb.

Recent trend of research : Sound absorptive materials are utilizing in preventing noise control on a large scale. A lot of research had been done on sound absorption materials like glass wool, mineral wool which are widely used in practical life but they have adverse effects on environment like large emission of CO_2 and also not biodegradable therefore recent trend on martials for sound absorption purposes shifting towards the materials which are environmental frank, sustainable, recyclable, biodegradable these qualities meet with natural fiber materials like vegetable fiber material kneaf, hemp, bamboo, jute and waste products like sheep wool, wheat straw and rice husk *etc.*[14]. they also have light weighted, low processing cost and have positive impact on nature as they are biodegradable, recyclable and less CO_2 emitter but big disadvantage is they are less fire resistant and poor moisture resistant as compared with traditional synthetic materials for example glass wool. Further acoustical properties can be improved by combined different type of materials referred as composite materials. A research study on wood fiber and polyester fiber composite material had shown that higher SAC at higher frequency range. The SAC more than 0.8 in the frequency range of 2892-6500 Hz, and the highest SAC was observed 0.97 at 4660 Hz[15]. Another research on kapok nonwoven fabrics and effect on adding this material with hollow polyester suggest that higher the content of kapok higher the absorption, When the content of kapok fiber is 90%, the SAC reaches to 0.83 at 2500 Hz which indicate that higher the hollow structure of kapok higher the absorption of sound wave[16]. This is the behaviour of porous materials where sound absorption increases with frequency *i.e.* higher absorption at higher frequencies. In a different research work on wastage sugarcane fiber has been done, showed that average absorption coefficient 0.65 between the frequency 1.2-4.5 kHz which is comparable to the traditional synthetic absorber[17].

4. FACTORS WHICH INFLUENCED THE NOISE ABSORPTION

There are various factors which affects the sound absorption properties of the acoustic materials and these factors play a crucial role while selecting and developing sound absorption material to getting better performance from them. The factors which influenced materials absorption coefficient are materials thickness, materials density, porosity etc. are discussed briefly here.

4.1 Thickness of material

Thickness of material greatly influence the absorption coefficient of the material it has direct relationship at lower frequency (100Hz to 2000Hz) but thickness is almost independent at the higher values of frequencies (above 2000Hz) because at higher frequency wavelength becomes small[18]. So increased thickness improves absorption coefficient till 2000 KHz frequency. Higher wavelength or low frequency required a thicker material for better contact and making better absorption. So here a crucial fact to point that the thickness is the order of one tenth of the wavelength for obtaining effective absorption at lower frequency but at higher frequencies no relevant effect of thickness of the material on sound absorption. Physics behind this can be understood as when the frequency is low means wavelength is high and sound wave with higher wavelength can be absorbed if the material is thicker. A pine board sample made from vetiver grass has been tested in reverberation chamber for sound absorption coefficient and the results are matching the theoretical statements. SAC results of pine board sample at two different thickness has been given in below fig. 4.

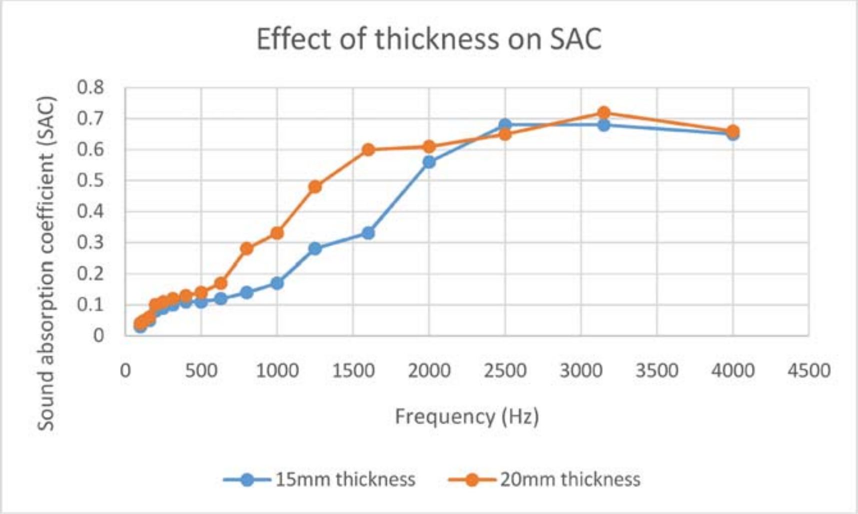

Fig. 4. Pine board sample installed in a reverberation chamber at rigid surface backing at CSIR-National Physical Laboratory, New Delhi.

4.2 Density of the material

Density of material also influenced the absorption of the material. Higher density means higher mass per unit area or more fibre per unit area which increase absorption at middle and higher frequencies because surface friction increases[19]. Density of the material affects the acoustic impendence and this acoustic impedance determine the reflection coefficient of the material. Based on the various studies; it was found that less dense, more open structured materials absorb sound of lower frequencies below 500Hz and the denser structured material absorbs frequencies above than 2000 Hz. A vetiver grass based pine

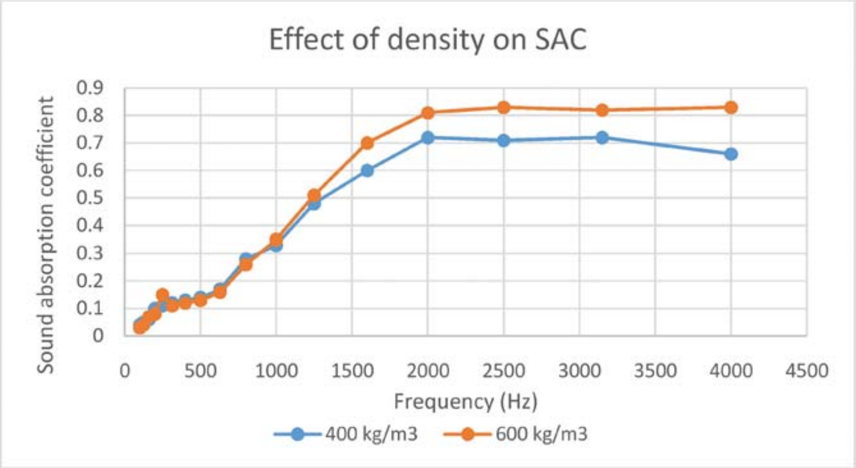

Fig. 5. Pine board sample installed in a reverberation chamber at rigid surface backing at CSIR-National Physical Laboratory, New Delhi.

board sample has been tested in reverberation chamber for sound absorption coefficient and the results are matching the theoretical statements. SAC results of pine board sample at two different densities has been given in below fig. 5.

4.3 Porosity

In porous materials the pore type, pore size and number of pores are considered while studying about sound absorption. In porous material structures, dissipation of sound energy occurs due to internal friction and viscous effect. For dissipation of the sound energy, sound wave must be entering into the porous material and material should have enough porous on the surface of material so that sound enters and get dissipated[18].

4.4 Fibre size

Fibre size or diameter is inversely dependent on sound absorption coefficient *i.e.* with increasing fibre diameter the absorption coefficient decreases[18]. Smaller fibre diameter would increase low sound frequency absorption by providing more surface area and tortuous path to the sound wave which increases airflow resistivity. Various studies show that fine denier fibres perform better acoustically than course denier fibres.

4.5 Airflow resistivity

When sound wave tries to move through the tortuous passages its amplitude decreases by friction provided by the air particles as the fibre interlocking inside material causes friction which causes sound energy into heat. airflow resistance is the resistance faced by air particle while going through a material, it is the ratio between the pressure inside a material and the airflow linear velocity, while steady airflow conditions maintained[20]. The SAC can be enhanced by increasing resistivity of fibrous material up to certain value after that it starts to decreases. For porous materials the airflow resistance is inversely proportional to the square of the pore size. The airflow resistivity of common sound absorbing materials lies in the range of 2×10^3 to 2×10^5 Pa. s/m^2. So, better sound absorption at higher airflow resistance but when airflow resistance is much higher than the sound absorption has less values because then it became difficult for a wave to propagate through the medium.

4.6 Tortuosity

It is the measurement of the elongation of the sound wave motion or how the pore inside the material deviates from the normal in comparison to the thickness of the material. It describes how the internal structure of the material influences acoustical properties of the material. In a study, it has been observed that tortuosity affects the peak position of quarter wavelength peak while height and width of the peaks affected by the porosity and air flow resistivity[20].

4.7 Influence of air gap

It has been observed that air gap between the sample and the backing of the plunger of the impedance increases the SAC increases at medium and higher frequencies although showing minima at lower frequencies[21]. Moreover, it had been observed that for different air gaps the maxima peak also shifts (higher the air gap, peak shifted towards lower frequency side). Therefore, there is optimum values of the air gap where maximum SAC occurred and beyond certain air gap no influence on SAC.

4.8 Influence of film

Films are attached on the fibrous or porous sound absorbing materials to protect them from detrimental environment and to avoid of the falling of fibres from the material fibrous and porous sound absorbing material. These films are normally highly reflective and influence sound absorption properties of the material. For example, films namely polyvinyl chloride, PVC is widely used.

4.9 Humidity

Speed of sound is directly proportional to the humidity in the air, so more the humidity more the speed and more the speed more the absorption of sound waves.

So apart from these main factors other factors such as Placement / Position of Sound Absorptive, Surface Impedance, Compression etc. also affects the acoustical properties of sound absorption materials[18].

5. CONCLUSIONS

This review, mainly summarized the mechanism of sound absorption process, different type of sound absorbing materials in which special focus on fibrous materials which are useful for noise reduction application. Fibrous materials have some special properties like they are light weight and can be formed easily and cheaply. Further, various factors which influenced the sound absorption properties of materials has been discussed as these factors play vital role on SAC. The applications of sound absorbing materials also have been reviewed, traditional inorganic glass wool, carbon fibre has been widely utilized for noise reduction. To predict sound absorption properties and obtaining better sound absorbing materials is still interesting topic in the field of research in acoustics. Recently, the investigation on the acoustic materials has been shifted more towards natural fibrous materials from traditional synthetic fibrous materials because of advantages like they are light weight, biodegradable, eco-friendly, abundantly available and less hazardous to human health as they are less toxic.

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