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THE EFFECTS OF NOISE FROM INTERNAL DRAINAGE SYSTEMS ON DAILY HUMAN ACTIVITY AND SLEEP PATTERNS

* Rabee Rustum[1] and Anaebo Chike Emmanuel[2]

[1,2] Department of Civil Engineering, Heriot-Watt University, Dubai Campus, United Arab Emirates

*Corresponding Author, Received: 24 Oct. 2022, Revised: 31 March 2023, Accepted: 23 April 2023

ABSTRACT: Human fascination with tall buildings is one that has trickled down through history. From the ancient Roman pyramids down to the modern-day Burj Khalifa, standing at 828m high. The number of multi-story buildings continues to increase around the world, and as a result, the quality of life for those people living in these buildings requires ongoing evaluation. Many residents of multi-story buildings complain about noise disturbances from internal drainage systems, mostly from toilets flushing in the upper levels. This paper seeks to establish whether or not the noise from internal drainage systems in multi-story buildings affects daily human activity and sleep patterns with the aid of a sound level meter and a questionnaire. A survey was undertaken on a 6-story building, and a sound level meter was used to measure noise levels on different floors in the building. The result obtained from each floor were 42, 39, 41.6, 40.9 and 42.2 dBs, respectively, which is negligible and showed that the building height does not influence the noise, while the survey which was carried out on occupants aged between 15 and 35 proved that noise from the drainage system does not affect human activity and sleep pattern. Principally because the noise does not last longer than a few seconds, with a typical duration of 15 seconds or less, the result from this test can be studied further for a wider application, such as noise reduction in classrooms, libraries and hospital wards, to mention a few.

Keywords: Multi-Storey building, Acoustics Emissions, Drainage, Sleep Patterns

1. INTRODUCTION

Multi-story buildings have seen a significant rise in number in recent years. Starting from around the middle of the 20th Century, the growth rate in their numbers has been considerable, particularly in cities in Asia and Europe. In developed cities across the globe, multi-story buildings are often the main feature of urbanization [1]. Multi-story buildings also bring economic implications as they often increase the cost of buying land. In addition, they can also add aesthetic value and can influence the lifestyle of people living in and around these developments)[2].

However, modern structures must offer their residents comfort, of which curbing sound emissions is one significant aspect [3]. Unfortunately, sound emissions can be found in buildings where proper provisions have not been made to tackle such problems. Sound emissions in multi-story buildings can come from, for example, floor impact noise, neighbors, and electronic and elevator equipment. In addition, it is not uncommon that emissions in new buildings arise from the plumbing systems. And while noise from sanitary facilities is not peculiar to multi-story buildings, it is essential to tackle this problem as multi-story buildings are home to a large number of residents. Over time, occupants living with plumbing noise problems realize that such noises can be irritating during the day and can interfere with sleep at night [4].

In the construction industry, there is a range of materials that possess high sound insulation properties; in particular, studies show that multiple-walled pipes can significantly reduce sound emissions[5]. Another method of reducing noise in pipes involves using sound insulation materials. Although these different materials can be tested and the material properties compared [6], there is no evidence that noise emissions have been completely eliminated in most buildings. The present study deals with the noise in the drainage system and buildings, measure the integrated average sound pressure level, and questionnaire survey results.

2. RESEARCH SIGNIFICANCE

The research reported herein has reported the acoustic emissions generated from internal drainage systems in multi-floor occupancy buildings. In addition, a questionnaire has been circulated to understand the effects, if any, of noise from drainage on sleep behavior and premature awakening and to gather subjective responses from residents. This study is an experimental one, looking at a 6-story building and focusing on the effect of sound transmission on occupants. Acoustic measurements were made to gain an understanding of the extent of transmission that might affect occupants' well-being. Thus, the work has been done so as to help propose a systematic approach to reducing sound emissions during the design and installation stages. Hence the goal is to ascertain the level of sound emissions from multi-story building sanitary facilities and how best to properly mitigate any adverse effects by identifying suitable sound-insulation material. Information on methods and materials are presented along with detail on data collection techniques, followed by the main results and recommendations for future research.

3. REVIEW OF THE LITERATURE

From the beginning of civilization, tall structures have fascinated humankind. This dates back to 2600 BC when the Egyptian pyramids were constructed and are still regarded as one of the seven wonders of the ancient world [7]. Currently, the tallest building in the world is the Burj Khalifa, located in Dubai in the United Arab Emirates, standing at 828m tall [8]. However, multi-story buildings require modern technology to aid their function, part of which is the provision of sanitary facilities for the removal of wastewater. Noise has a significant impact on the well-being of people and their health. Hence insulation of noise in buildings can help expel basic airborne and impact noise associated with buildings [23]. The research aims at finding adequate material required to insulate sound in the mechanical system. Normally addition of materials on either side of walls or floor to double frame can significantly improve the insulation of sound [22]. A speaker in one room talking at 60 dB may be heard in the other room at 20 dBs, which is barely audible, but when the speaker increases his voice to 75 dBs, the sound in the other room could be 35 dBs which is audible, by double framing the wall the sound can be significantly reduced. This principle can be replicated in the plumbing system in the building, where an additional coating of material on the pipe can further insulate sound in the plumbing system and better the living condition of the building occupants.

3.1 Sound Emission from Drainage

Sound is generated in pipes due to solid, gaseous, and liquid waste transport. Sound waves can travel through elastic mediums and liquid and various solid materials [9,10]. The majority of audible frequencies range between 20 and 20,000 Hz. Humans hear sound best between 1,000 and 5,000 Hz [11].

Audible ranges are divided into 10 octave bands, representing specific frequency spectrums. These range from 16,000 Hz to 31.5 Hz and sometimes are separated into third-octave bands for accuracy. If 500 Hz is taken as a medium frequency, its low and high frequencies will range between 300 Hz and 750 Hz, respectively. Hence, the knowledge of the third-octave bands aids the overall calculation of sound level[12].

Burk et al. (2011)[13] stated that an A-weighting is applied to sound measurements that consider the relative sound perceived by the human ear, recognizing the ear's sensitivity to low audio frequencies, particularly below 1,000 Hz, with B-, C- and Z-weightings used to measure very low, medium and very high frequencies. Ray (2010) [14] also noted that a minor change in the decibel reading leads to a significant change in the sound produced, which has an impact on what the person hears. The NIH (2014) [15] pointed out that the duration of exposure to certain sounds is a significant factor in the amount of pleasure or discomfort experienced by the listener. Thus, humans should limit their exposure time to certain sounds beyond 85 dB, and for every 3 dB beyond 85 dB, the exposure time should be cut by half to avoid permanent hearing damage.

The average sound level in dwellings is typically around 25 dB, with 60 dB being the norm for offices, depending on the activity and overall quality. This results in noise rating (NR) curves for background noise evaluation, as reported by Ref. [16].

3.2 Causes of Noise in the Drainage System

Causes of noise in drainage systems include water hammers, impact noises on bends and tees, flow noises, and falling solid matter noise. When the water closet, WC, is flushed, noise emissions are typically transmitted via connected structures. While a degree of noise within the room housing the sanitary facility is usually deemed acceptable, consequent sound in surrounding apartments is undesirable, and measures should be taken to prevent this[11]. In addition, water hammers can lead to the unwanted movement of improperly attached pipes, causing vibrations, noise and, in some cases, the loosening of joints and fittings [17]. Flow impact on bends and tees designed can also lead to noise; horizontal movement of sewage leads to flow noise, as vertical movement leads to falling noise[18].

3.3 Transmission of Noise in the Building

Sound is transmitted through a building by air and solid-borne pathways. Structure-borne transmission involves sound emissions through solid materials and is regarded as the main noise path. Noise can also convert from one form to another, e.g. from structure-borne to airborne and vice versa. According to BS 8233: 2014[19], two stages of plumbing noise should be considered during the design and construction stages. Porous materials tend to absorb the sound of middle to high frequencies based on their thickness. Typical materials are:

- Hard finish: Plaster on a solid backing,
- Porous absorber: 50 mm mineral fibre 50 kg/m^3,
- Panel absorber: 9 mm ply, 50 mm cavity containing 25 mm mineral fibre,
- Perforated panel: 14% perforations, 25 mm cavity containing mineral fibre,
- Perforated gypsum tiles/board, 16% perforations, suspended with 200 mm plenum.

4. METHODOLOGY

The two major pieces of equipment required for this analysis are the Nor140 sound analyzer and the calibrator. The Nor140 sound analyzer is a precision handheld device used to record sound and monitor building acoustics in real time. The calibrator is inserted within the microphone cartridge of the sound level meter.

4.1 Acoustic Emission Measurements

Measurements were collected from a 6-storey student residence with modern engineering design and technology. Each floor has the same layout from top to bottom, with each room having a toilet with a bathtub, WC and a washbasin. Care was taken to ensure that the faucets in the bathtub and washbasins were turned off and there was no ongoing plumbing activity in the building before the test was carried out.

The Nor140 sound analyzing device was placed on the ground floor, and the water closet was flushed on the 5th, 4th, 3rd, 2nd and 1st floors in turn, and the results were recorded on the ground floor. This was repeated for each floor. The sound pressure level measurements were made using 1/3 octave bands because this produces more precise results. These were then converted to octave bands so as to make comparisons with the required standards. Equation 1 aids in calculating the sound pressure level for different octaves [20].

$$L\boldsymbol{p} = 10 \log \left(\mathbf{10}^{\frac{L_1}{10}} + \mathbf{10}^{\frac{L_2}{10}} + \mathbf{10}^{\frac{L_3}{10}} + .. + \mathbf{10}^{\frac{L_n}{10}} \right) \quad (1)$$

4.2 Questionnaire

A series of questions were drafted for the purpose of understanding the effect of noise emissions from the drainage system on the sleep pattern and daily activities of the residents of the multi-storey building. The questionnaire was developed and delivered online, and deployed a scaling system to assist respondents (aged 15-35 years). The questionnaire was designed in accordance with ISO (2003)[21] recommendations and uses a direct question method. The procedure used to choose the words for the questionnaire scale was done in a way that is consistent with its position on a numerical scale of 1 to 5 for most of the questions. The questionnaire was used to answer the following questions:

1. Have you lived or currently lived in a multi-story building?
2. Are you satisfied or dissatisfied with the noise from your water closet as a result of flushing?
3. Are you satisfied or dissatisfied with the noise from your building drainage system?
4. Does the noise from your water closet as a result of flushing affect your daily activities?
5. How heavy or high do you sleep?
6. Does the noise from the flushing of the water closet from the upper floors affect your sleep?
7. Does the noise from the flushing of the water closet from your adjacent neighbour affect your sleep?

5. RESULTS AND DISCUSSION

5.1 Acoustic Results

Using Equation 1, all the measurements were calculated in octave bands and plotted, as shown in Figure 1. The frequencies analyzed were for audible frequencies only, ranging from 16 Hz to 8 kHz, and compared with the NR curve. NR curves for dwellings are 25 and 30. The NR curve is used to ascertain where the SPL level exceeds standards by

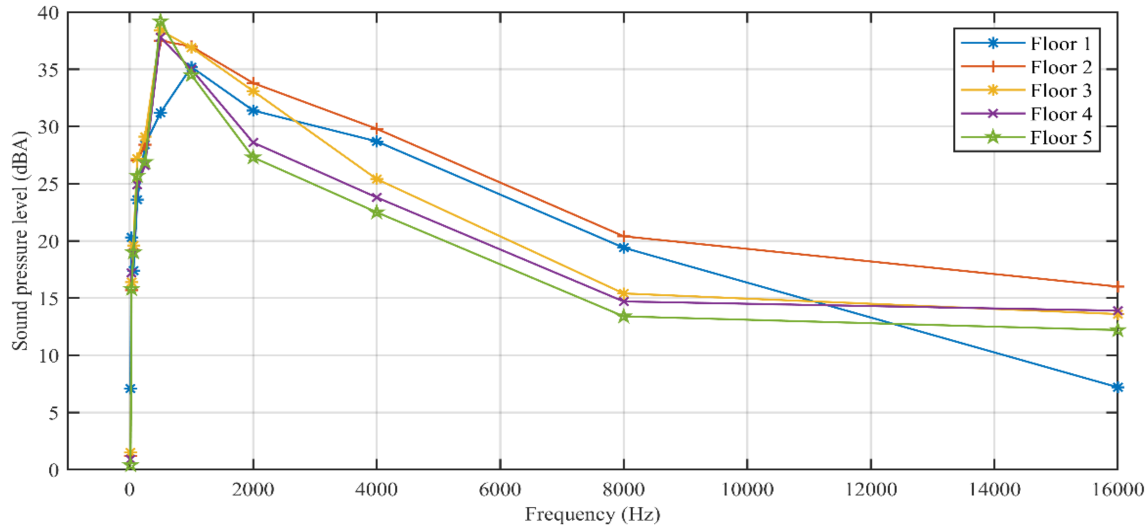

Fig. 1 Integrated average sound pressure level dBA

comparing the sound pressure level lines measured with the NR curve, representing typical sound pressure level values with respect to octave bands.

Table 1 illustrates the results obtained from a series of noise tests run with the aid of a sound level meter on different levels of the multi-story building.

Table 1 The sound level from flushing at different levels in a building

Location of measurement	LAeq, dBA
Background noise	26.0
Ground floor measurement from flush at 1st	42.0
Ground floor measurement from flush at 2nd	39.0
Ground floor measurement from flush at 3rd	41.6
Ground floor measurement from flush at 4th	40.9
Ground floor measurement from flush at 5th	42.2

The results show that the sound level from the five floors tested is similar, which means that when the toilet is flushed, irrespective of the level it is flushed from, the sound is transmitted through the pipes equally down the building. This means that the height of the building does not influence sound transmission through the internal drainage system of a multi-story building. The results in Table 1 show the average value of the results presented graphically in Figure 3.

Figure 2 shows the same measurements as in Table 2, but with octave bands, the result of the tests represented graphically for integrated average sound pressure levels. The results illustrated in Figure 2 show the corresponding values for the tests carried out. The green curve depicts the NR curve of 30. From the Figure, the sound measurements at frequencies just above 250 Hz to 4.0 KHz clearly fall above the acceptable values for dwellings. As a result, there is a need to further analyze the noise levels to ascertain the noise level that needs to be reduced in A-weighting frequency.

From the graph below, it can be seen that the noise from each floor is similar throughout; from the moment the toilet is flushed from any level, it follows the same pattern, with little difference, which may be caused by the speed of the sound takes from the source to arrive at the point of collection with the sound level meter. The noise peaked at a frequency of 500 Hz and 39.2 dBA, which is well within the limit of 45 dBA for toilet flushing noise within a residential building.

Table 2 Loudest SPL octave band measurement analysis

Frequency	31.5 Hz	63 Hz	125 Hz	250 Hz	500 Hz	1.0 kHz	2.0 kHz	4.0 kHz
Drainage measurement SPL, dB	57.7	45.8	43.7	37.7	42.4	37	32.6	28.8
NR 30 curve	75.8	59.2	48.1	39.9	34	30	26.9	24.7
Reduction needed	-18.1	-13.4	-4.4	-2.2	8.4	7	5.7	4.1
A-weighting correction factor	-39.4	-26.2	-16.1	-8.6	-3.2	0	1.2	1
Reduction needed in A-weighting	-	-	-	-	5.2	7	6.9	5.1

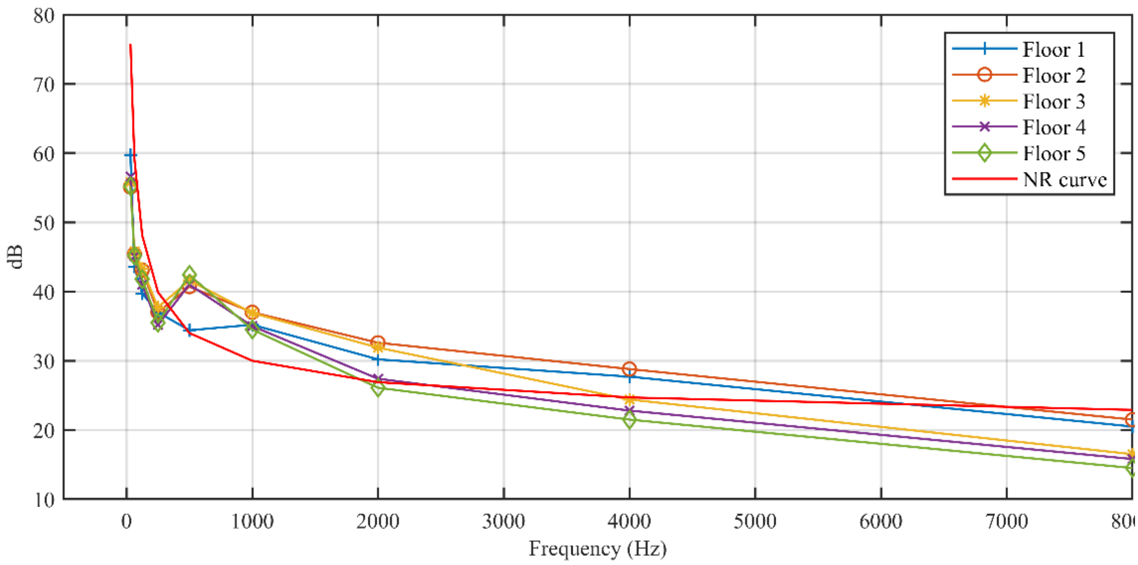

Fig. 2 Drainage measurement results

Table 2 shows that only noise of frequencies ranging from 500 Hz to 4 kHz needs reduction with all sound pressure levels not exceeding 10 dB; this indicates that the acoustic emissions are not so high but can result in discomfort for residents. As such, it is pertinent that more insulation should be added to reduce the noise emissions in the drainage system.

5.2 Questionnaire Results

Results are presented in percentages illustrating the survey responses from 90 participants to understand their perception of noise from the flushing of WCs in the multi-story building under consideration. Key findings are presented below, and graphical results are available in Figures 3 to 9.

The tolerance level of respondents to noise from the flushing of the water closet: This aspect reflects how satisfied or dissatisfied respondents are about the noise emission from their water closet when flushed. The range spa was 'very dissatisfied' to 'very satisfied'. 33.3% of respondents were neither satisfied nor dissatisfied, followed by 31.1% who said they were satisfied, 26.6% who were dissatisfied, 5.5% very dissatisfied, and 3.3% very satisfied. This shows that most respondents are either indifferent about the noise from the flushing of the water closet or satisfied with it.

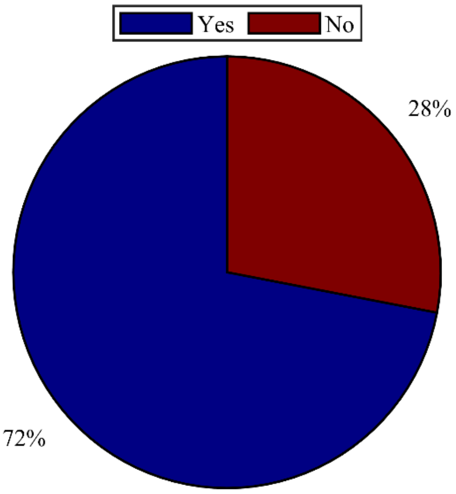

Fig. 3 Have you lived or currently live in a high-rise building?

Respondents' satisfaction with noise insulation: This question aims to understand the overall satisfaction level of respondents with noise insulation in their building of residence. Out of the 90 respondents that participated in the survey, 35.5% were satisfied with the insulation level of their building, 27.7% were dissatisfied, 26.6% were neither satisfied nor dissatisfied, 6.6% were very satisfied, and just 3.3% were very dissatisfied. This shows that most of the respondents were either satisfied or indifferent.

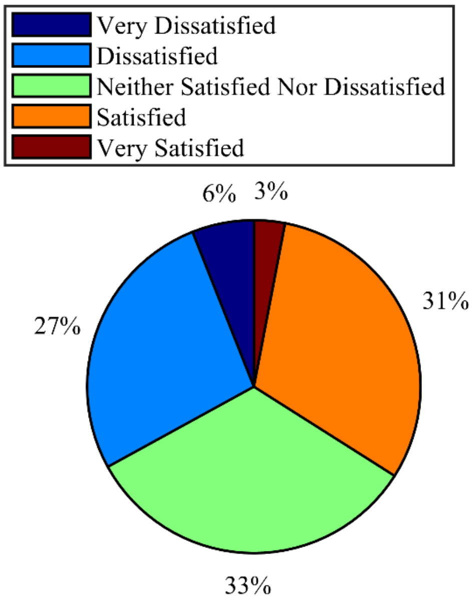

Fig. 4 Are you satisfied or dissatisfied with the noise from your water closet as a result of flushing?

Impact of water closet flushing noise on daily human activity. This question was drafted to understand if toilet flushing affects daily human activities such as reading, working, or watching a movie. 51.1% disagreed that noise from the flushing of the water closet affected their daily activity, 21.1% neither agreed nor disagreed, 14.4% agreed, 8.8% strongly disagreed, and 4.4% strongly agreed. This shows that most respondents are not affected by noise from toilet flushing, and others are indifferent, leaving just the small number who believe it bothers them. Those may be individuals who are more intolerant of noise of any kind.

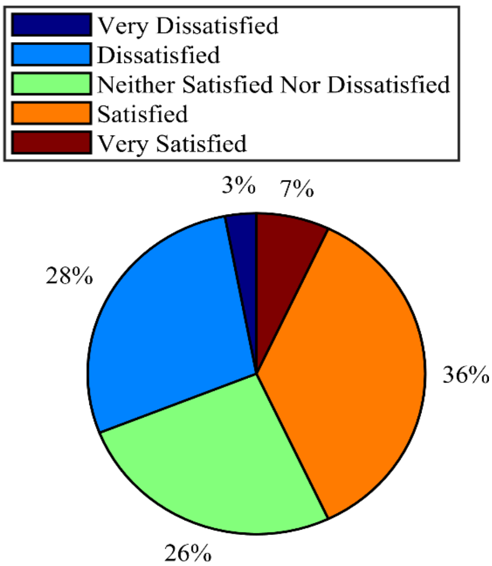

Fig. 5 Overall, are you satisfied or dissatisfied with the noise installation of your building drainage system?

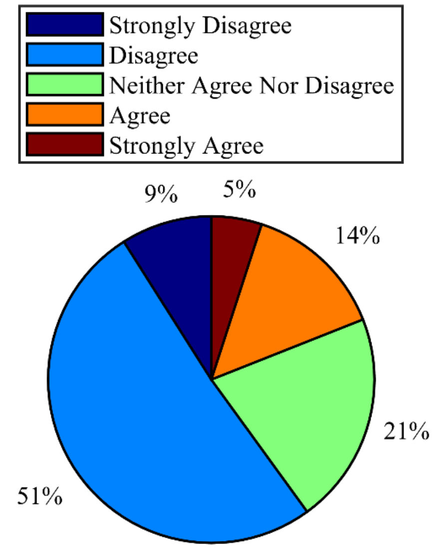

Fig. 6 The noise from my water closet as a result of flushing affects my daily activity.

Impact of water closet flushing noise from upper floors on sleep: Ninety respondents gave their verdict on the impact of flushing water closets from upper floors on their sleep pattern. 46.6% of respondents noted that noise from the flushing of water closets from upper floors does not affect their sleep pattern, 21.1% agree, 17.7% neither agree nor disagree, 13.3% strongly disagree, and just 1.1% strongly agree. This shows that the majority of respondents are of the opinion that water closet flushing from upper floors has no impact on their sleep patterns. Those who felt their sleep was disturbed may be light sleepers whose sleep patterns can easily be interrupted by the mildest of sounds.

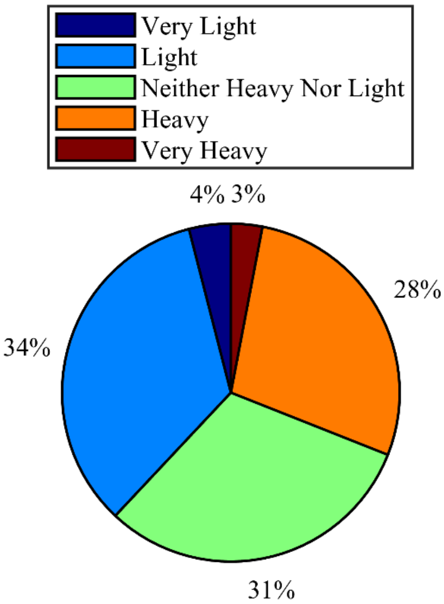

Fig. 7 How heavy or light do you sleep?

Impact of water closet flushing noise from a next-door neighbor on sleep: This survey showed that noise generated from the flushing of the water closets from the adjacent neighbors on the same floor has no impact on sleep patterns. Of the 90 respondents, 44.4% disagreed, 22.2% strongly disagreed, 16.6% agreed, 14.4% neither disagreed nor agreed, and only 2.2% strongly agreed. This is an indication that sleep is not affected by noise from the flushing of the toilet from a neighbor's residence on the same floor.

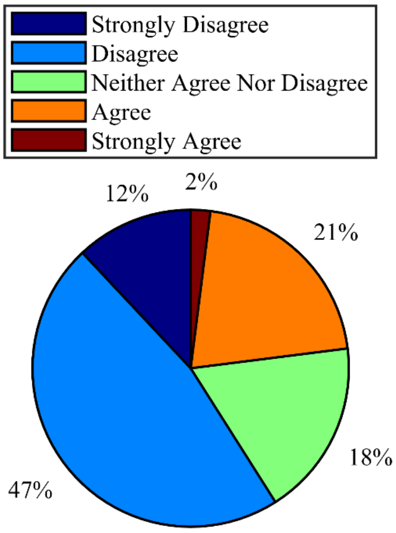

Fig. 8 Noise from the flushing of the water closet from the upper floors affects my sleep.

From the analysis carried out, it is observed that while most respondents claim that the noise from flushing water closets does not disrupt their daily activity and sleep pattern, others believe it does. This finding is confirmed by the acoustic emissions levels presented herein. The analyses also show that there is a need for further insulation. Hence, the pipes should be insulated further to reduce noise emissions.

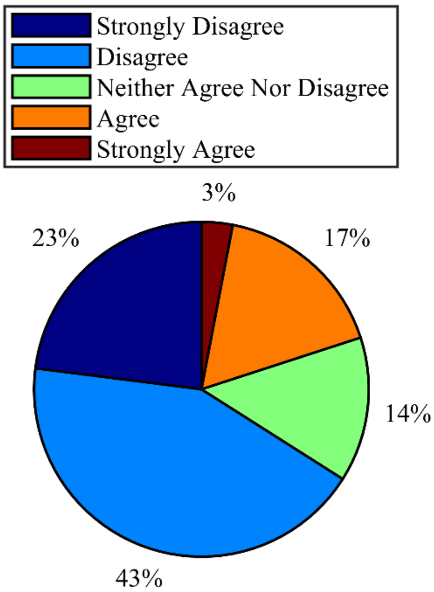

Fig. 9 Noise from the flushing of the water closet from my next-door neighbor affects my sleep.

6. CONCLUSION AND RECOMMENDATION

To further reduce the noise level within a multi-story building, it is pertinent to run further tests to confirm the best materials to protect residents from unwanted noise. In addition, it is pertinent to analyze the acoustic emissions generated from the hydraulic jumps that occur at junctions between vertical and horizontal stacks and determine optimum places to create bends and velocity breaks, hence decreasing the acoustic emissions. The result from this test can be studied further for a wider application, such as noise reduction in classrooms, libraries and hospital wards, to mention a few.

7. ACKNOWLEDGEMENTS

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