Optimizing Worker Safety: Modelling Age, Exposure Duration and Noise Effects on Hearing Threshold in Quarry Workers

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ABSTRACT

Quarries play a vital role in the construction industry. However, studies indicate that the age of quarry workers and their years of exposure to quarry activities contribute to hearing issues. Data on the effects of noise and related factors on hearing damage among Nigerian quarry workers are limited. This study aimed to investigate the effect of age, exposure duration, and noise levels in quarries on workers' hearing thresholds. In 2022, 204 quarry workers aged 18 to 65 were randomly selected from four quarries in the southwestern Nigeria. A follow-up study in 2023 included 185 workers. Questionnaires captured their age and exposure years, while digital sound level meter was used to measure noise levels. Hearing thresholds were tested at eight frequencies (250 Hz to 8 kHz) using an audiogram. Eight regression models were developed using response surface methodology to predict the effects of age, exposure, and noise on hearing thresholds. Noise levels at the quarries ranged from 87.3 to 116.98 dB(A), exceeding the permissible 85 dB(A) limit. The models predicted R^2 values between 0.71 and 0.82. Safe hearing thresholds were predicted for the workers aged ≤ 52 years and with ≤ 32 years of exposure. The models showed strong predictability, making them useful for planning recruitment and operational policies in the quarry industry. It was concluded that age, exposure duration, and noise levels significantly affect quarry workers' hearing thresholds.

KEYWORDS

Occupational health
Ages of workers
Years of exposure
Industrial noise exposure
Safe hearing threshold

1. INTRODUCTION

Sound is generally understood as a pressure wave in the atmosphere. The Human sense of hearing can detect both of its characteristics: pressure intensity and pressure frequency. Pressure intensity is sensed as loudness, whereas pressure frequency is sensed as pitch. For human hearing perception low-frequency noise refers to sounds at 250 Hertz (Hz) and below. High frequency noise is 2000 Hz and above. Mid-frequency noise falls between 250 and 2000 Hz (Negm et al., 2024). The formal recording of an individual's hearing forms the basis of the audiogram. Auditory sensitivity is usually assessed by means of pure tone audiometry, which measures the lowest detectable sound levels at different frequencies. This measurement may reflect the loss of sensitivity to weak sounds (Lobarinas et al., 2013), an individual's threshold hearing to pure tones at different frequencies (250-8000 Hz) is performed. Due to the increasing level of industrialisation, industrial noise is a growing problem. It is very important to be able to quantify and control this noise and as a consequence, a safety precaution is needed in order to reduce the effect.

The most notable effect of occupational noise is the tendency of a worker being exposed to excessive noise to have permanent loss of hearing due to the high hearing threshold, which can occur on a daily basis over many years in the workplace. Such hearing impairment generally regarded as noise induced hearing loss (NIHL) always occurs gradually and if not noticed, may cause permanent damage. As age affects hearing sensitivity, hearing threshold shift at high frequency is first affected and the loss is irreversible (Gyamfi et al., 2016). In audiometry, such loss is described as a permanent threshold shift. Audiometric testing involves means of obtaining the minimum threshold at which a person can detect sound at a particular frequency; as a result of age or damage, the intensity at which a stimulus can be detected increases. It is in this sense that hearing loss can be described as a threshold shift. The hearing threshold shift initially affects frequencies of 6, 4, or 3 kHz. As the loss progresses, it can extend to frequencies of 8, 2, 1 kHz, 500 Hz and eventually 250 Hz.

Previous study shows that workers in rockmines, quarries, sawmills, textile factories and printing processes that work with machineries that produce noise much higher in magnitude than the endurance level and therefore expose workers to potential hearing threshold shift (Ismail et al., 2013). In the same vein, quarry workers in Nigeria are exposed to high levels of noise due to the machine used in their daily operation. Although, the situation could be improved if appropriate PPE is embraced, but it was observed that some of the quarry workers in Nigeria failed to embrace the protective measures due to some self-claimed conveniences (Ojolo & Ismail, 2011). Increasing construction works and industrialisation might aggravate this situation in Nigeria, therefore there is need to investigate the impact of this occupational noise on quarry workers in Nigeria. The most serious pathological effects of noise on workers are the development of excessive hearing threshold leading to hearing loss or complete deafness. Continuous exposure to noise above 90 dB(A) may lead to the permanent hearing loss which the victims may be unaware of (Asfahl, 2004). Hearing loss is being categorized according to the various grade of impairment with corresponding audiometric values and performance. World Health Organisation (1991) reported that 25 dB or less – No impairment, 26 – 40 dB – slight impairment, 41 -60 dB – moderate impairment, 61 – 80 dB – severe impairment, and 81 dB or greater – profound impairment including deafness. (England & Lassen, 2014) analysed noise effects on memory performance in different age groups in order to see whether there are interactions of age with noise in their effects of memory. As the literature shows that hearing problem is associated with age and years of exposure, it can be deduced that there will be a certain point or range of age, years of exposure and noise level at which the damage can occur to workers'

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physiological system. However, some works are being done specifically on the effect of age independently on hearing threshold; the effect of years of exposure to noise independently on hearing threshold; and the effects of noise level perceived by the workers independently on hearing threshold. The effect of each of the three factors was varied using different experimental methods.

Kerketta et al. (2016) considered age, years of exposure and workstation, using SPSS 16.0 package and Generalized Linear Model ANOVA with the result that workers will develop NIHL after 25 years of starting work at noisy work zone in the open cast chromite mines but noise level and frequency were not considered. Also, the specific age bracket for the workers that can justify the 25 years of exposure was not highlighted without any predictive model for the hearing threshold. Akanbi & Oriolowo (2016) worked on age and years of exposure using statistical analysis of one factor at a time and reported that the age of the workers was the major contributory factor but no interacting effects were explored. Akanbi et al. (2021) explored into age, years of exposure and noise level considering main factors effects and factors interaction effects using SPSS design but focused on 3, 4, 6 and 8 kHz frequency. The noise level has the highest contribution while age has the least prediction ability on hearing threshold. Age or years at which factors interaction influencing the hearing threshold not specified.

Therefore, since every worker has variations in age, years of exposure and noise levels, there may be different physiological differences among them. It will be of high benefit for the worker to engage at the appropriate workstation which cannot contradict their health and wellbeing status during work and after work. More so, an employer will ensure of having adequate manpower with little or no absenteeism. Hence, the objective of this work is to develop models predicting workers' safe hearing threshold with regard to the synergistic effect of age, years of exposure and noise level. The workers' race, ethnicity and lifestyle like smoking, alcohol consumption not considered in this study. Only continuous noise from the machinery in the quarry was considered.

2. MATERIALS AND METHODS

2.1. Subject Selection

Two hundred and seventy-one quarry workers in the selected four sites, 204 were randomly sampled in the months of June – July, 2022, representing 75.30% of the population of the quarry workers and which is adequate, since minimum of 30% is the recommended percentage for a population below 10,000 (Neuman, 2007). A follow-up research arrangement was conducted between the months of September and October, 2023 with one hundred and eighty-five (185) subjects out of the original 204 who participated in the study in the year 2022. This arrangement was carried out in order to verify whether there is change or not in the hearing threshold of the same workers that participated in the experiment in two consecutive years of this study. Workers from different sections of each quarry were selected. No preselecting process was undertaken and all subjects had the purpose and the experimental procedure explained to them. The permission of the quarry management was obtained before the study commenced. Notice was sent to the subjects (quarry workers) before the experiment began; followed by questionnaire distribution among the subjects. The workers in this study had completely rested for 48 hours (Yawson et al, 2024) or more after their day shift to prevent transient hearing loss. This study considered the operators that are exposed directly to the following noise emitted equipment: Primary Crushers, Secondary Crushers, Dumpers, Payloader, Wagon drilling machine, Lathe, Drilling Machine and Excavator. Their operations were used in categorizing the workers into ten groups: Primary Crusher, Secondary Crusher, Compressor, Dumper, Wagon Drilling, Pay loader, Lathe, Drilling Machine, Excavator operators and administrative staffs.

2.2. Assessing Noise Levels

This study considered the operators that are exposed directly to the following noise emitted equipment: Primary Crushers, Secondary Crushers, Dumpers, Payloader, Wagon drilling machine, Lathe, Drilling Machine and Excavator. Their operations were used in categorizing the workers into ten groups: Primary Crusher, Secondary Crusher, Compressor, Dumper, Wagon Drilling, Pay loader, Lathe, Drilling Machine and Excavator operators and administrative staffs. With the location of noise sources, the noise levels exposure over eight hours at an hour interval which workers are exposed to were assessed with Digital Sound Level Meter (TESTO 815, Test Equipment Depot, United State of America) with sound calibrator (TESTO 0554.0452, Test Equipment Depot, United State of America), in conformity to the American National Standard Institute, ANSI, and Standard SI. 4 – 2006 (IAPA, 2008). The fast response setting of the digital Sound Level Meter was used in this work since it measures how noise fluctuates over time rather than noise exposure (OHS, 2014). The correct use of the microphone was ensured in obtaining accurate measurements by pointing it directly at the sound source; measurements were taken at 1.5m above the ground and 3m from the noise source with microphone mounted on a conventional tripod of substantial construction. Reflecting and obstacles objects were avoided. Measurements were made when the average wind speed measured with Cup Anemometer (GS026, Texas, United State of America) was less than 5m/s; A microphone windshield was used for all outdoor measurements. Air temperature was between 18.1°C and 32.5°C. There were no background noise level differences greater than 10 dB(A).

2.3. Measurement of Pure Tone Audiogram / Hearing Status (Audiometric Test)

This test was conducted in an audiogram sound proofing testing booth (TRIVENI TAM -10 5100B) (Howard, et al., 2017), on each subject at the hospital in Ibadan by an audiologist. Audiometric air conduction tests were performed by presetting a pure tone at frequencies of 250, 500, 1000, 2000, 3000, 4000, 6000 and 8000 Hz stepwisely, since this range of frequency captures the human speech frequencies and are the notable communication range; and the aim of using these frequencies were not for medical management (healthy hearing.com, 2020) at 5dB(A) interval to the ear of the participant through an earphone. The hearing threshold (dB) was recorded at the frequency at the particular lowest tone that participants responded to. Normal hearing was considered normal if the threshold level was less than or equal to 25 dB(A) at a frequency (Ghimire et al., 2019, healthy hearing.com, 2020). The stimulus intensity was increased beyond 25 dB(A) at any frequency until a response was obtained. Intervals of 5 seconds in duration were maintained between the tones. The preset tone duration was 1 – 3 seconds. The total time used to perform the audiometric test on a subject was 3 – 5 minutes.

2.4. Introduction to the ANFIS Modelling

Adaptive Neuro Fuzzy Inference System (ANFIS) used the ability of Fuzzy Logic (FL) to reason with Neural Network (NN) to learn (Ilse et al., 2020). The fuzzy inference system (FIS) makes use of each fuzzy rule to describes a local behaviour of the system (Amirian, 2019). ANFIS is the network structure that make use of FIS and employs hybrid-learning. The basic structure of FIS is a model that maps input (Age, Years of exposure and Noise level) characteristics to input membership functions, and the output membership function to a single-value output (Hearing Threshold) or a decision associated with the output (Hearing Threshold) (Aslan et al., 2019). Using a given input/output dataset, the toolbox function "anfis" in MATLAB constructs a fuzzy inference system (FIS) whose membership function (MF) parameters are tuned (adjusted) using either a backpropagation algorithm alone or in combination with a least-squares type of method (Karaboga & Kaya, 2018).

The ANFIS model interface (GUI) is being partitioned into four parts and this accounts for the steps involved in using this model. These parts are: Load data points, generate FIS, train FIS and test FIS (Kisi et al., 2018). The methodology involved in the ANFIS training is Grid Partitioning 'genfis1' which helps to produce all possible rules to interpret the problem for better accuracy (Talpur et al., 2017). Different input MF types were used for data training and model analysis. The data partitioning involved set of odd data point for training, and even number dataset as checking data as:

```
Training_data = Data(1:2:end,:)
Checking_data = Data(2:2:end,:)
```

The data collected from all quarries consisting of 185 data points from second year data (Since the same 185 subjects out of 204 in the year 2022, were also captured in the year 2023; test of variance equality have shown that both variances of hearing threshold values of workers for the two dataset 2022 and 2023 are equal) with 4 variables (age, years of exposure, noise level and hearing threshold) were subjected to the predictive ability of exhaustive search in ANFIS training using MATLAB statistical software to determine the most significant parameters and then made predictions. The input variables are age, years of exposure and noise Level while the output variable is hearing threshold level at different frequency levels (i.e., 250 Hz, 500 Hz, 1 kHz, 2 kHz, 3 kHz, 4 kHz, 6 kHz and 8 kHz).

2.5. Exhaustive Search

Exhaustive search is a tool that can solve problems, by providing an adequate solution appropriately (Kisi et al., 2018). The syntax structure of exhaustive search is:

Algorithm 1: Process of calling exhaustive search with the given parameters and returning the outputs

```
[input_index, elapsed_time] =
exhsrch(in_n, trn_data, chk_data, input_name, mf_n,    epoch_n)
        Where,
        input_index : index of the inputs selected by exhsrch,
        elapsed_time: time in input selection,
in_n: number of inputs to be selected from the input candidates (restricted to be 1…4)
    trn_data: original training data
    chk_data: original checking data
    input_name: input name for all input candidates
    mf_n: number of membership function for each input
epoch_n: number of training epochs for ANFIS (default to 1)
```

2.6. Response Surface Method (RSM)

Response surface methodology was used to develop mathematical models and to conduct statistical analysis of the parameters' interactions (age, years of exposure and noise level) on response surface (hearing threshold), using Matlab Statistical Software.

2.7. Model Estimation

Design Expert software 6.0.8 was used to perform data analysis and develop a predictive model based on ANOVA, obtaining a regression model, plotting of three-dimensional surface response and response optimization at various frequencies. Each response was analysed separately.

The model performance predicted by ANFIS was evaluated using correlation coefficient (R) as in Equation (1) from (Ismail & Syazwan, 2023); and Root Mean Square Error (RMSE) as in Equation (2) from Abdulkadir et al., (2018).

$$R = \frac{\sum(obs-obs')(pre-pre')}{\sqrt{\sum(obs-obs')^2\sum(pre-pre')^2}} \quad (1)$$

$$RMSE = \sqrt{\frac{1}{N}\sum(obs-pre)^2} \quad (2)$$

where, obs = observed values; pre = predicted values; obs' = average value of observed values; pre' = average value of predicted values. Source: (Amutha & Porchelvan, 2011).

2.8. Designs of Experiments (DOE)

This work follows three (3) important phases which could be used to make a meaningful study as reported by Shihabudheen & Pillai (2018). They include the experimental or planning phase, the design phase and the analysis phase. A Historical Data Design (HDD) model was used to analyse and optimize the experimental data. Design-Expert version 6.0.8 was used for the modelling of the identified variables. Analysis of variance (ANOVA) was used for the analysis of the data obtained from this experiment for frequencies ranging from 250 Hz to 8000 Hz. The interaction between age, years of exposure and noise level, and the response of different regression models developed for hearing threshold was investigated. The quality of the fitted polynomial model was expressed by the coefficient of determination R^2, and its statistical significance was checked by the Fisher's F-test using the in-built statistical program in Design-Expert version 6.0.8. Model terms were evaluated by the p-value (probability) with a 95% confidence level.

2.9. Selections of Regression Model Inputs

In this study, the exhaustive search method was applied to select the best combination of predictors (age, years of exposure and noise level) for each of the responses (hearing threshold). Exhaustive search revealed the best combination of age; years of exposure and noise level. In order to avoid overfitting, the minimum training RMSE and minimum checking RMSE were established, then the minimum difference between the training and checking RMSE was explored. (Math works, 2017). RMSE as in Equation (2) was also utilized for the task.

2.10. Regression Modelling

The obtained data was fitted to a second order polynomial regression model presented in Equation (3). This task was separately performed for each of the response variables (hearing threshold), using the selected predictors (age, years of exposure and noise level) as inputs.

$$Y = \beta_0 + \sum_{i=1}^{k} \beta_i X_i \sum_{i<1}^{k} \beta_{ij} X_i X_j + \sum_{i=1}^{k} \beta_{ii} X_i^2 + \in \quad (3)$$

For each response, the statistical significance of the regression model terms was evaluated by ANOVA. Also, the models' predictive performances were checked by lack-of-fit test, R^2, Adj R^2, Pred R^2, Adeq Precision and F-test as reported by Oladapo & Akanbi (2015). The significance of the F-value was adjudged at 95% level of confidence using Design Expert version 6.0.8 software. The numerical and graphical clarifications were also performed by the same software for the clarity of the interaction relationship of age and years of exposure to the noise level. The regression models were then used to predict the response (hearing threshold) based on the values of the predictors (age, years of exposure and noise level). The degree of correlation between the predicted hearing threshold and actual values was examined to ensure the accuracy of the model.

3. RESULTS AND DISCUSSION

3.1. Test of Variance Equality for the Year 2018 and 2019 Experiment Dataset

The F values of variances equality at frequency of 250 Hz, 500 Hz, 1 kHz, 2 kHz, 3 kHz, 4 kHz, 6 kHz and 8 kHz were not significant at the respective p-values as each of them was greater than alpha values of 0.05. Both variances of hearing threshold values of workers for two datasets are roughly equal, the variance ratio is approximately 1 (R Core Team, 2017; Shear et al., 2018; Nordstokke & Colp, 2018). Conclusively, the datasets on hearing threshold in the year 2022 and 2023 came from the same population of quarry workers. Thus, either dataset obtained in the year 2022 or 2023 experiment can be used for computation work. This work makes use of 2023 dataset.

3.2. Noise Measurement at Various Facilities under Study.

The four studied quarries consisted of different production units having more or less of the same types of machinery. The noise measurement was in the range of 87.3 dB(A) to 116.98 dB(A) in the production section, which implies that the noise levels produced exceeded the limiting threshold level of 85 dB(A) (NIOSH, 2023), except in administrative block where the noise level was less than the threshold of 85 dB(A). It was observed that each of all four quarries produced an excessive amount of noise injurious to the hearing capabilities of workers.

3.3. Presentation and Analysis of the Models

Equations (4) to (11) are the obtained models from the analysis.

$$HT_{250\ Hz} = 44.14 + 0.6AG - 0.2NL - 0.01AG^2 \quad (4)$$

$$HT_{500\ Hz} = 337.4 - 2.6AG - 0.01AG*NL - 0.03AG^2 - 0.01NL^2 \quad (5)$$

$$HT_{1\ kHz} = 48.12 - 1.6AG + 0.6YE + 0.02AG^2 \quad (6)$$

$$HT_{2\ kHz} = 196.76 - 3.03AG + 1.5YE + 0.03AG^2 - 0.01NL^2 \quad (7)$$

$$HT_{3\ kHz} = 60.9 - 1.16AG + 0.02AG^2 - 0.04YE^2 \quad (8)$$

$$HT_{4\ kHz} = 104.3 - 0.35AG - 0.08AG*YE \quad (9)$$

$$HT_{6\ kHz} = 35.08 - 0.16AG \quad (10)$$

$$HT_{8\ kHz} = 87.26 - 1.53AG \quad (11)$$

The proposed 8 models can be used to estimate the hearing threshold for the quarry workers for the fitness in their workstation from the statistical prove as in Table 1.

The control experimental groups which were selected randomly from the working places of 15 -17 dB(A) considered to be relatively quiet indicated how the models resulting from the Design of Experiments are able to explain the hearing thresholds of the subjects in different environments. In the control experimental groups are subjects (workers) that were not exposed to noise. In the real experimental groups are subjects (workers) that were exposed to noise.

Thus, the significant F-value and R^2 as shown in Table 2 for the two groups suggest that, for each model, age, years of exposure to noise and noise level are potent factors to account for the changes in the hearing threshold of workers that are exposed to noise and the workers that are not exposed to noise in the quarries.

In the real experiment, the quarry workers on field in this group exhibited higher hearing threshold level than the workers in the control group working in the relatively quiet environment. This reason also indicates the impact of occupational noise on the hearing threshold of workers working in the noisy environment.

3.4. Robustness of the Models

Two types of validation exercises performed were internal (self) validation (that is the adequacy of the models was verified), and external validation. The software (Expert design, Version 6.0.8) itself compared the measured hearing threshold of all the categories of the quarry workers with the predicted values. The measured values were in agreement with the predicted values. This is the ‘self-validation’ mechanism of the software. This demonstrated that the response models were adequate. Apart from the ‘self-validation’ mechanism inbuilt into the software, external validation of the models was performed. This was done by measuring the responses (hearing threshold) and the input variables (age, years of exposure and noise level) from different quarry workers that did not participate in activities that led to the development of the predictive models.

Table 1: Statistics for Hearing Threshold 250Hz-8kHz.

	250 Hz	500 Hz	1 kHz	2 kHz	3 kHz	4 kHz	6 kHz	8 kHz
Most Significant Factor	Not Feasible*	Age	Age	Age	Age	Age	Age	Age
Lack of Fit	Not Feasible*	0.7630	0.8452	0.7794	0.7834	0.8095	0.1785	0.7861
Std. Dev	1.20	2.18	3.23	3.74	4.00	6.19	5.13	5.03
Mean H.T.	25.20	28.36	31.72	35.73	38.81	47.77	36.70	40.27
C.V.%	4.77	4.21	4.74	3.25	2.75	2.56	3.18	4.52
R^2	0.8302	0.7831	0.7415	0.7746	0.8193	0.8454	0.7705	0.7897
Adj.R^2	0.8215	0.7720	0.7282	0.7630	0.8100	0.8374	0.7587	0.7789
Pred.R^2	0.8074	0.7604	0.7109	0.7462	0.7951	0.8206	0.7291	0.7667
Adeq Precision	50.4099	44.493	35.892	42.7045	44.8068	50.3536	38.8199	40.2909

Table 2: Summary of ANOVA for Models and Statistics for Hearing Threshold of Real and Control Experiments.

Frequency	Real Experiment			Control Experiment			
	Mean Hearing Threshold (dB)	F-value	R^2	Mean Hearing Threshold (dB)	F-value	R^2	F-value significance
250 H_Z	25.20	95.09	0.8302	22.82	99.79	0.9656	< 0.0001 significant
500 H_Z	28.36	70.21	0.7831	24.90	81.48	0.9582	< 0.0001 significant
1 kH_Z	31.72	55.79	0.7415	27.00	30.96	0.8970	< 0.0001 significant
2 kH_Z	35.73	66.83	0.7746	29.22	30.61	0.8959	< 0.0001 significant
3 kH_Z	38.81	88.17	0.8193	31.34	26.08	0.9726	< 0.0001 significant
4 kH_Z	47.77	106.30	0.8454	34.56	69.16	0.9511	< 0.0001 significant
6 kH_Z	36.70	65.29	0.7705	27.85	36.93	0.9122	< 0.0001 significant
8 kH_Z	40.27	73.01	0.7897	30.87	33.41	0.9038	< 0.0001 significant

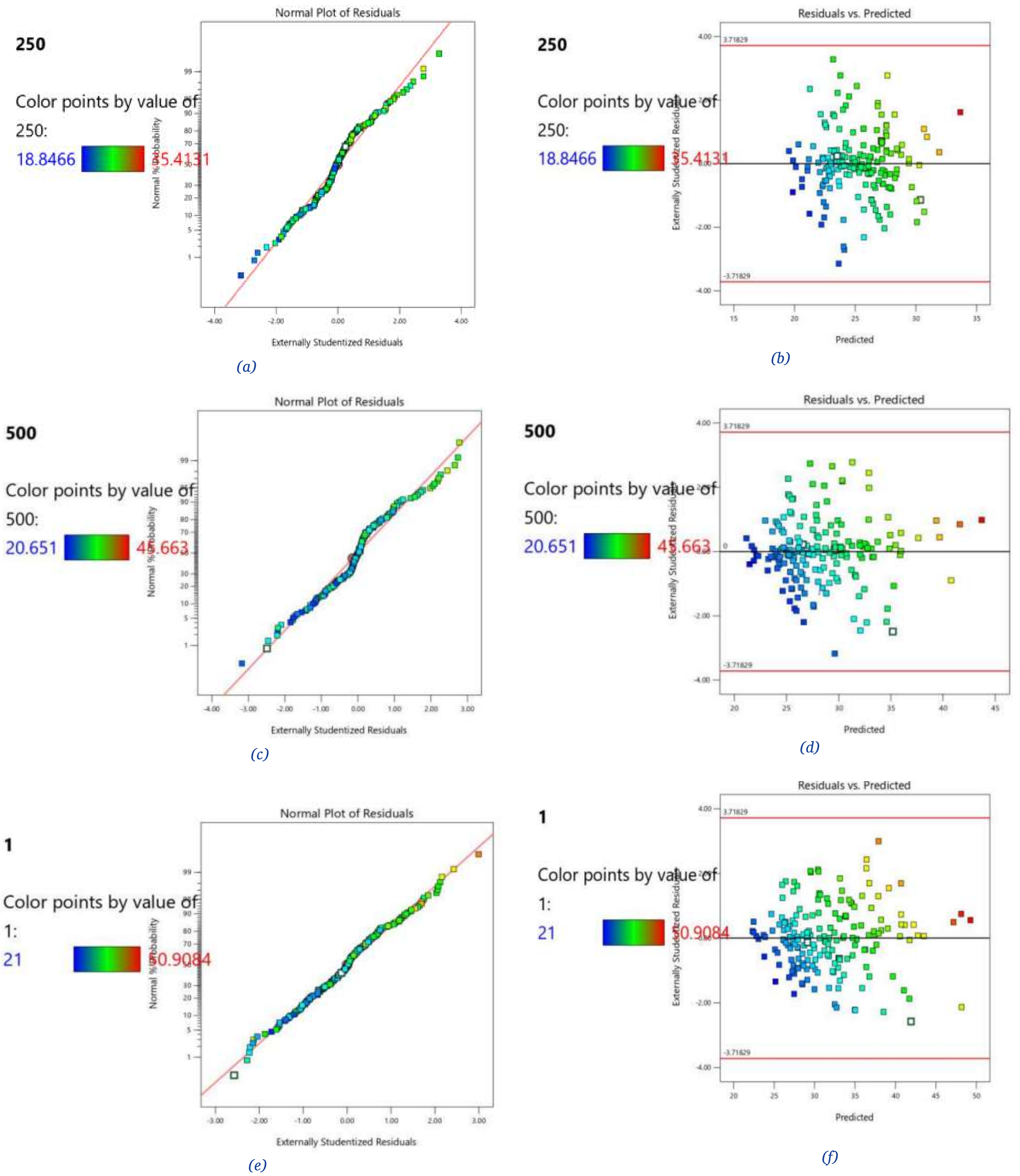


Figure 1: Normal probability of residuals and predicted output for the frequency 250 Hz, 500 Hz and 1 kHz (a) Normal plot of residuals at 250 Hz (b) Residual vs. predicted plot at 250 Hz (c) Normal plot of residuals at 500 Hz (d) Residual vs. predicted plot at 500 Hz (e) Normal plot of residuals at 1 kHz (f) Residual vs. predicted plot at 1 kHz

The independent variables (age, years of exposure and noise level) were fed into the models using Microsoft Excel 2010 professional software. The predicted values were in agreement with the measured values as in Figures 1 to 3. This demonstrated that the response models were effective.

3.5. Selection of values of age, years of exposure and noise level for the safe hearing threshold

Objective: Finding the values of age, years of exposure and noise level that suit 25-30 dB hearing threshold. MATLAB Interface of Design Expert 6.0.8 was used to carry out the selection process for the variables combinations for each frequency.

It was discovered that age is the major determinant in predicting hearing threshold of healthy quarry workers. The optimal safe value for age, years of exposure and noise level is 38 years, 32 years and 111.7 dB respectively as indicated in Table 3 as well as in final iteration of optimization results in Figures 4 and 5.

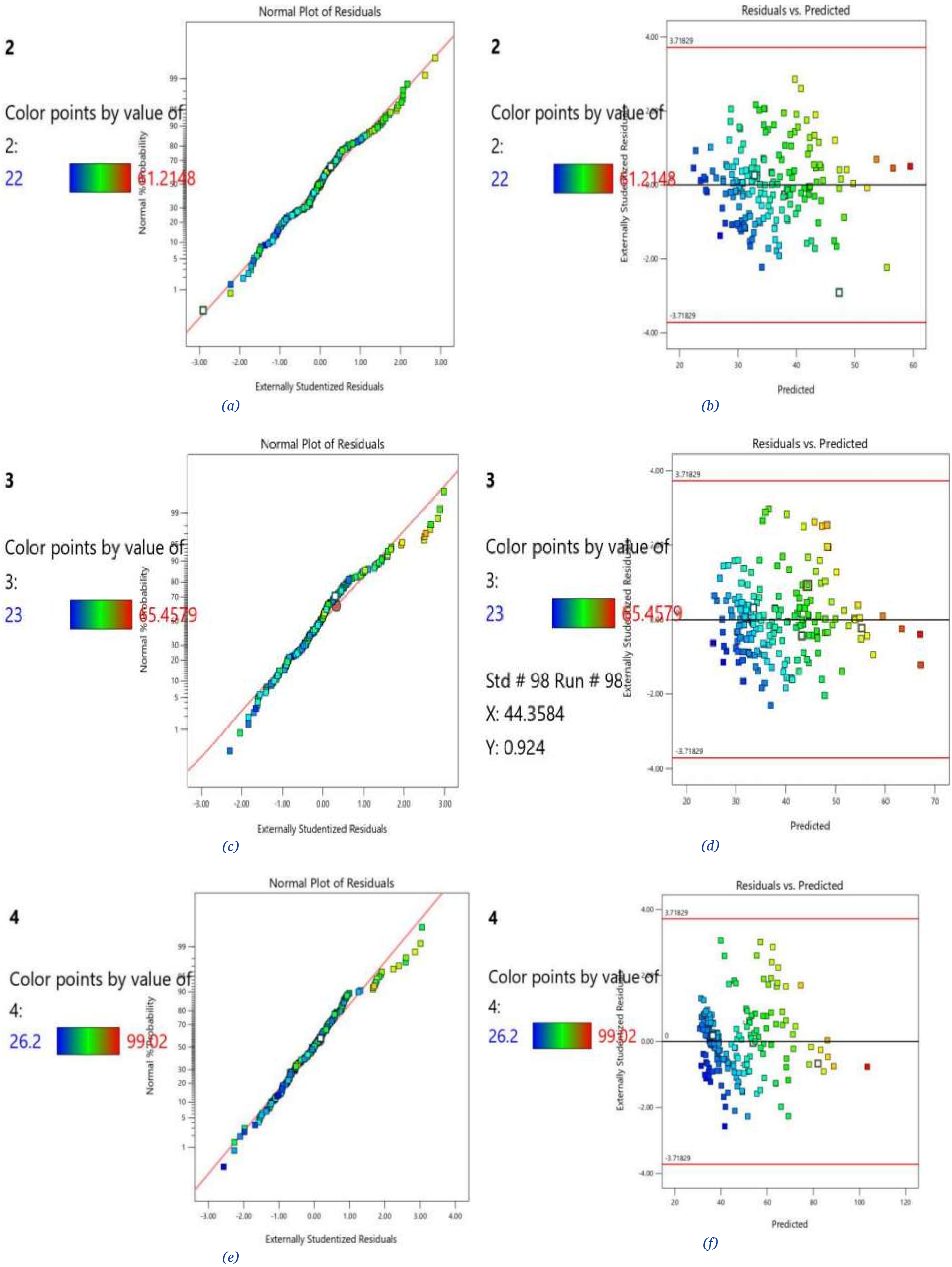


Figure 2: Normal probability of residuals and predicted output for the frequency 2, 3 and 4 kHz (a) Normal plot of residuals at 2 kHz (b) Residual vs. predicted plot at 2 kHz (c) Normal plot of residuals at 3 kHz(d) Residual vs. predicted plot at 3 kHz (e) Normal plot of residuals at 4 kHz(f) Residual vs. predicted plot at 4 kHz

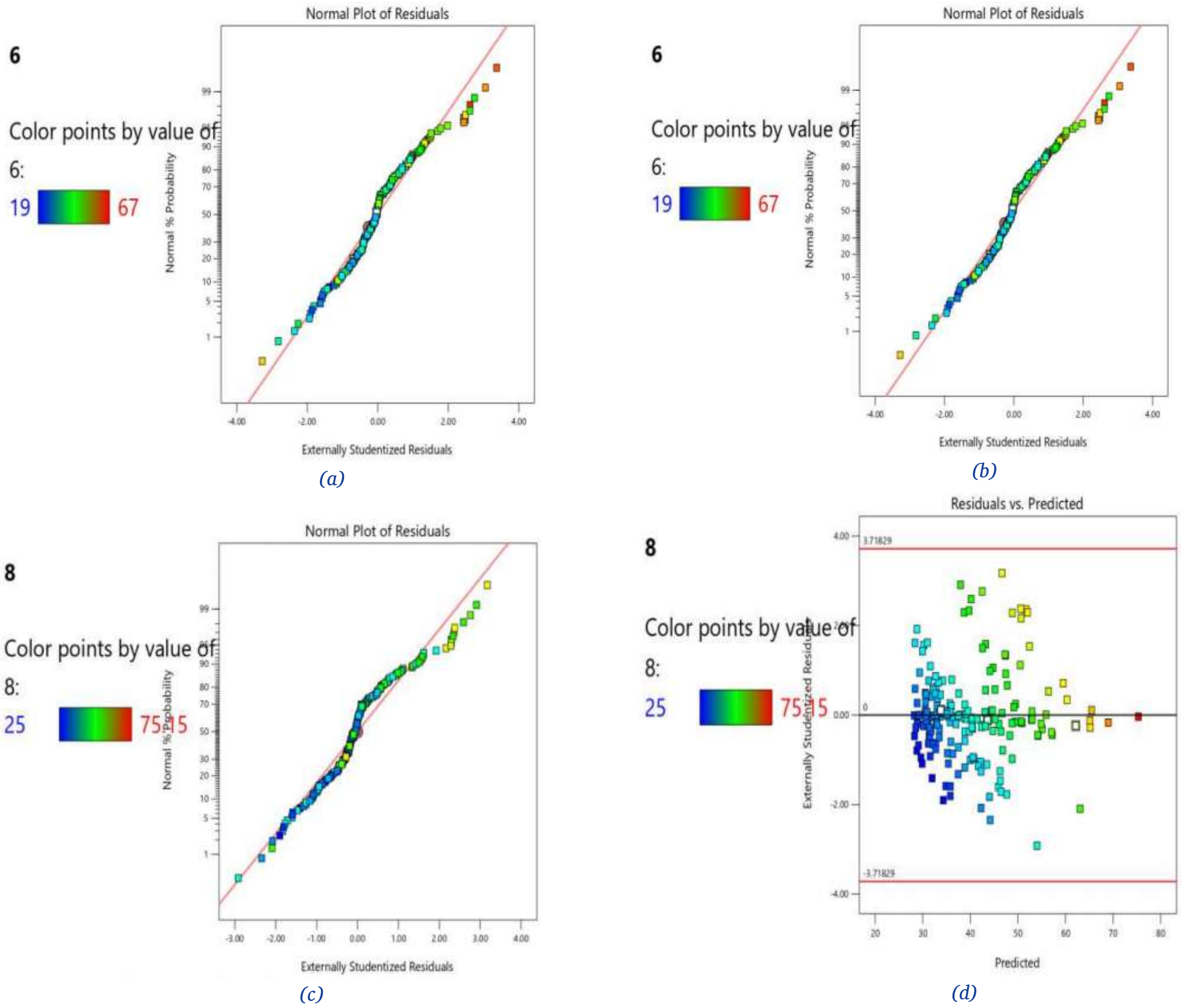


Figure 3: Normal probability of residuals and predicted output for the frequency 6 and 8 kHz: (a) Normal plot of residuals at 6 kHz (b) Residual vs. predicted plot at 6 kHz (c) Normal plot of residuals at 8 kHz (d) Residual vs. predicted plot at 8 kHz

In this work, the point of entry to the quarry work is 18 years. By the time the quarry worker of age 38 years had 32 years of exposure; the worker must have started the job at the age of (38-18) years, which was 20 years then. In this vein, by the time the worker of 20 years of age have 32 years of noise exposure in the quarry, he must have attained (20 + 32) years of age. Therefore, the optimal age and years of exposure for the quarry worker in service should be 52 years or less with 32 years or less respectively.

Table 3: Summary of the values of age, years of exposure and noise level which can synergistically results to the safe hearing threshold values of 25-30 dB for the quarry workers.

Frequency (Hz)	Age (Years)	Exposure (Years)	Noise level (dB)
250 Hz	57	36.5	93.2
500 Hz	49	33	96.7
1 kHz	43	13	108.4
2 kHz	42	3	94.8
3 kHz	52	2	108.9
4 kHz	60	3	99.7
6 kHz	55	1.05	106.4
8 kHz	38*	32*	111.7*

*Safe values

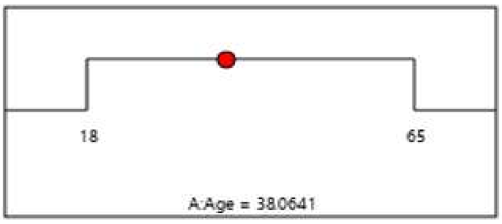
The workers at the production section in the quarry are expected to maintain a safe hearing threshold until the age of 52 years or younger. Such workers assigned to the production section should be regularly rotated to less noisy areas to reduce the exposure time. Therefore, if a quarry worker must maintain a safe hearing threshold within the range of 25-30 dB, the age of the workers should be 52 years or less, with 32 years or less working exposure in the quarry. In order to enhance this condition, hearing protective device should not be left out. Thus, the expression as shown in Equation (12) can be used to explain the relationship between the present age of the worker in the quarry and the optimal year of exposure to the noise.

$$(X - 18) + Y \leq 52 \quad (12)$$

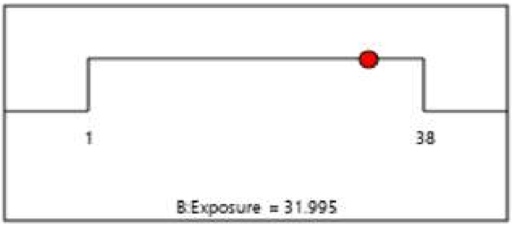
Where X represents the present age of the workers and Y represents the optimal years of exposure to the noise.

3.6. Discussion of Results

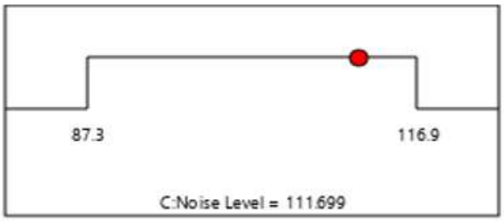
The present study investigated the physiological response of quarry workers working in noisy environments. The average noise measurement values in the four quarries of study, 44.45 dB(A) in the administrative section, and average value of 100.17 dB(A) in the production section (see Appendix C) which is more than the Permissible Exposure Limit. The mean hearing threshold among all workers in the quarry was 45.6 dB(A), 75% had a hearing threshold level higher than 25 dB(A).



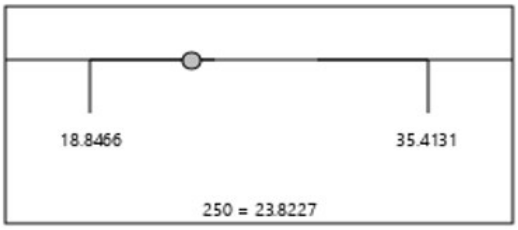
(a)



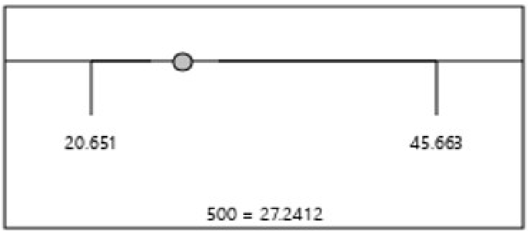
(b)



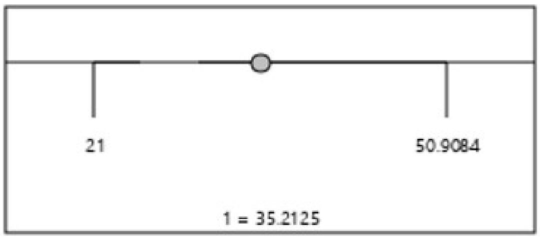
(c)



(d)



(e)

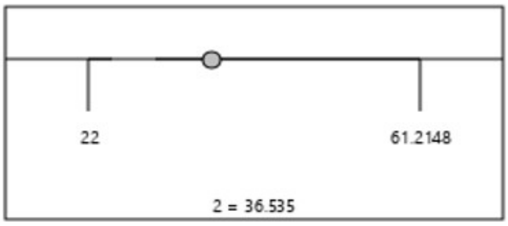


(f)

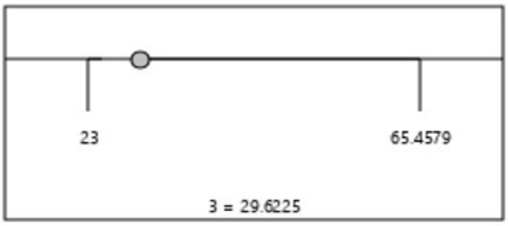
Figure 4: Final iteration ramp of optimization results for the hearing threshold: (a) Safe age is 38.0641 years (b) Safe exposure is 31.995 years (c) Safe noise level is 111.699 dB(d) At 250 Hz, hearing threshold is 23.8227 dB(e) At 500 Hz, hearing threshold is 27.2412 dB (f) At 1 kHz, hearing threshold is 35.2125 dB

3.6.1. Predictive Models

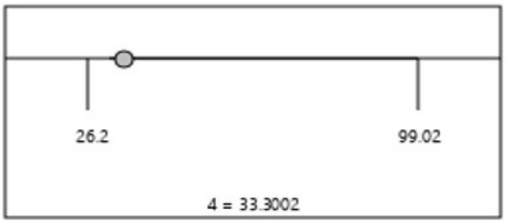
The developed 8 predictive models (equation 4 to 11) at various frequencies showed that age of workers can predict the hearing threshold across frequencies 250 Hz – 8 kHz, while years of exposure can predict the hearing threshold at 1 kHz, 2 kHz and 4 kHz only; and Noise level can predict the hearing threshold at the frequency 250 Hz and 500 Hz only, established models are reliable for the prediction of a hearing threshold. The entire diagnostic test proved the model as reliable as in Table 1 and Figure 1.



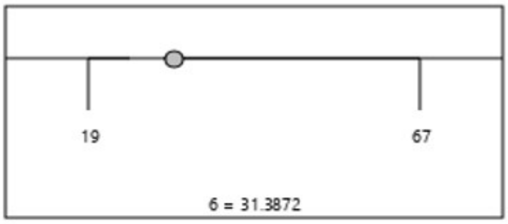
(a)



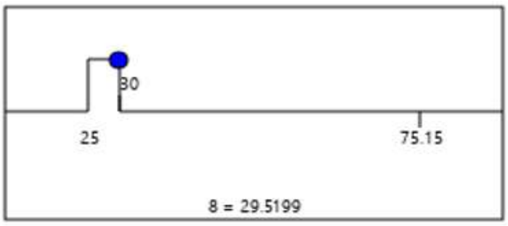
(b)



(c)



(d)



(e)

Figure 5: Final iteration ramp of optimization results for the hearing threshold: (a) At 2 kHz, hearing threshold is 36.535 dB at 3 kHz, hearing threshold is 29.6225 dB (c) At 4 kHz, hearing threshold is 33.3002 dB(d) At 6 kHz, hearing threshold is 31.3872 dB (e) At 8 kHz, hearing threshold is 29.5199 dB

3.6.2. Safe Values of Hearing Threshold

A worker of 52 years of age having not more than 32 years of exposure to noise level of 112dB or less at the quarry workstation 8 hours daily will exhibit safe hearing threshold of 25 – 30 dB. Any worker of age 52 years or less with 32 years or less of years of exposure will be considered as a fit worker for the production section of the quarry job.

4. CONCLUSIONS

Two hundred and four subjects from four different quarries volunteered to participate in this research work in the year 2022, while in the year 2023, one hundred and eighty-five subjects were available among the two hundred and four subjects that participated initially in this research in order to ensure whether there is a variation in the workers' hearing threshold in the two consecutive years of the experiment. The audiometry test was performed on each subject after taking all the necessary precautions. Measurement of the noise levels of the machine used in quarry operations was also taken at 1.5 m above the ground and 3 m from the noise source.

It can be concluded that machines used in quarry operations produce 87.3 - 116.9 dBA noise levels which is greater than the acceptable threshold sound level; except in the administrative section where the noise level is 44.45 dBA which is less than the acceptable threshold of 85 dBA. The differences between the noise levels in the administrative block and quarry sections are due to the greater exposure of the workers in the quarry section to high noise levels and hence higher hearing threshold than the administrative workers. It was observed that none of the quarry workers embraced the usage of any hearing protective device (HPD). This study has established statistically that all respondents at all four different quarries were subjected to about the same working conditions and environmental noise levels.

This research work presented 8 models for the prediction of the hearing threshold of the quarry workers between frequencies 250 Hz to 8 kHz. The models showed good predictive ability. The models satisfactorily enabled the determination of the hearing threshold of the quarry workers easily. Thus, having known the parameters of the 3 main factors effects aforementioned, the hearing threshold of a worker at various frequencies can be determined. This study established the safe settings of the three variables (age of workers, years of exposure and noise level) that can synergistically accommodate relatively a safe hearing threshold that a quarry worker is expected to possess at various frequencies. Age is the major predictor of the hearing threshold of quarry workers at frequencies between 250 Hz and 8 kHz. Thus having known the age of the workers, years of exposure to noise and the noise level of the workstation, the quarry workers' employer can use these findings useful when recruiting workers to ensure a safe working environment for the worker's hearing status.

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CONFLICTS OF INTEREST

The authors declare no conflict of interest regarding the publication of this article.

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APPENDICES

APPENDIX A: Questionnaire On Hearing Threshold for The Quarry Workers

Research Questionnaire

Subject Number _______
The following questions request you to provide information about yourself. Your responses to these questions will be kept confidential. Your honest response is needed as possible throughout. The information provided is only for research purpose.

1) Age:
2) Gender (Circle one): Male Female
3) Years of experience
4) Job position:
5) Do you operate machine? yes ( ) No ( )
6) If yes type of machine
7) Have you ever sustained any injury which resulted to the hearing problem? Yes / No
a) If "Yes," please describe the injury and estimate the approximate injury period.
8) Please circle any of the following specific illnesses or conditions, either if you presently have, or if you had the illness/condition in the past.
(a) Tuberculosis
(b) Ulcer
(c) Diabetes
(d) Hearing problems
(e) Sight problems
(f) Hypertension
(g) Specify Others.

APPENDIX B: Results of F Test of Variance Equality of Hearing Threshold of Baseline Year and a Subsequent Year at Different Frequencies

Frequency	F value	p-value	Hearing Threshold Variance 1 (Year 2022)	Hearing Threshold Variance 2 (Year 2023)	Variance Ratio	Confidence Interval	
250 Hz	0.78235	0.08791	14.56627	18.61857	0.782352	0.5889462	1.0372038
500 Hz	0.77075	0.07027	24.28018	31.50188	0.7707535	0.580215	1.021827
1 kHz	0.97523	0.86	41.51171	42.56598	0.9752321	0.734144	1.2929148
2 kHz	1.1535	0.3237	65.98964	57.20787	1.153506	0.8683471	1.5292619
3 kHz	1.1377	0.3728	95.86349	84.26381	1.137659	0.8564176	1.5082526
4 kHz	1.234	0.1463	233.5254	189.2402	1.234016	0.928954	1.635998
6 kHz	0.89301	0.4307	141.7866	158.7743	0.8930076	0.6722465	1.1839056
8 kHz	0.94078	0.6701	134.6766	143.1541	0.940781	0.7082098	1.2472412

F test of variance equality is an inferential statistical indicator to show whether there is significant difference in variances between two datasets. The test is a means of showing whether two datasets come from the same population even though a measurement from the population differs in time, such as in years, because it is expected that a measurement (a measurement of a variable) on a normal distribution should have approximately the same variance irrespective of the time the measurement is taken as long the experiment conditions are still valid. In the case of hearing threshold measurements for the base year (the first year) and second year, there are significant differences in hearing threshold values at experimental frequencies; because the measurements came from the hearing threshold of the same population of quarry workers, their variances should be approximately equal. F value is the variance ratio value.

The F values of variance equality at frequency 250 Hz, 500 Hz, 1 kHz, 2 kHz, 3 kHz, 4 kHz, 6 kHz and 8 kHz are not significant at the respective p-values as each of them is greater than alpha values of 0.05, thus suggest the acceptance of null hypothesis that the true variance ratio of hearing threshold at each frequency is equal to 1. The variance ratio is only equal to 1, when both variances of hearing threshold values of workers for two datasets are roughly equal. Each variance ratio is approximately 1. Conclusively, the datasets on hearing threshold came from the same population of quarry workers.

The confidence interval of 95% is a statistic that shows confidence in the estimate obtained. 95% confidence interval is the probability that out of 100 samples drawn from the population of quarry workers, there is confidence that 95% of those samples will contain the population's true variance ratio within the stated interval. Apparently, the variance ratio interval for each of hearing threshold is compact, as the upper and lower limits are closer to 1 than not.

APPENDIX C:

Table C.1: Average noise levels (dBA) measured at workstations in the four quarries in 2022

Type of Machine	Q1	Q2	Q3	Q4
Primary Crusher	115	112.3	114.3	114.5
Secondary Crusher	116.9	112.3	114.9	112.2
Compressor	113.5	108.3	113	101.7
Dumper	96	94.5	92.8	96.5
Wagon Driller	94.4	91.1	92.3	98.1
Pay Loader	93.1	91.5	92.8	93.3
Drilling Machine	93.0	97.2	97.0	90.2
Lathe	88.3	87.3	88.0	88.2
Excavator	97.3	93.2	97.0	95.4
Administrative	39	28.4	53.3	59.7
Mean	100.83	98.63	100.23	98.90
Standard Deviation	11.0	9.7	10.7	9.1

Table C.2: Average Noise Levels (dBA) Measured at Workstations in the Four Quarries in 2023

Type of Machine	Q1	Q2	Q3	Q4
Primary Crusher	116	113	115	115.5
Secondary Crusher	116.9	114	114	112
Compressor	114	109	113	103
Dumper	98	95	93	97
Wagon Driller	95	91	93	98.0
Pay Loader	94.1	92	93.8	93
Drilling Machine	94.5	98	97.5	91
Lathe	88	87.5	87.3	88
Excavator	98	94	98.0	96
Administrative	39	28.8	50	60
Mean	101.61	99.28	100.51	99.28
Standard Deviation	10.9	10.1	10.6	9.3