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RESEARCH ARTICLE

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Noise and frequency propagation in natural stone processing plants

Zekeriya Duran[a,*], Bülent Erdem[b], Tuğba Doğan[c], Mehmet Genç[d]

[a]*Sivas Cumhuriyet University, Sivas Vocational School of Technical Sciences, Sivas, 58140, Türkiye, ORCID: 0000-0002-9327-8567*
[b]*Sivas Cumhuriyet University, Geophysics Engineering Department, Sivas, 58140, Türkiye, ORCID: 0000-0002-1226-9248*
[c]*Sivas Cumhuriyet University, Industrial Engineering Department, Sivas, 58140, Türkiye, ORCID: 0000-0002-2628-4238*
[d]*Malatya Turgut Ozal University, Hekimhan Mehmet Emin Sungur Vocational School, Malatya, 44400, Türkiye, ORCID: 0000-0002-9950-0720*

Abstract

In this study, 510 noise measurements recorded in eight natural stone processing plants operating in Sivas City, Turkey were evaluated and the noise levels and dominant frequency bands of 11 different processing machines used in these plants were determined. The daily equivalent noise level of all natural stone processing plants was around or above the exposure limit value (87 dBA) specified in relevant regulations. Considering the machines and plant environment, the frequency ranges for the highest noise levels were mostly between 630 Hz - 5000 Hz, centering around 3150 Hz. Variations in the noise level of the processing machines in separate plants where similar processes were carried out was primarily related to the plant size and machine layout, the number of machines operating simultaneously and the type of natural stone processed. While the difference between the noise levels of gangsaws, bridge cutting, ST cutting, head/side cutting, trimming, cement filling, slab polishing, narrow polishing, chamfering and splitting machines were statistically significant, aging machines generated similar noise levels.

Keywords: ⅓ octave band frequency, Hypothesis testing, L_{Aeq}, $L_{EX,8h}$, Noise and frequency mapping, Natural stone processing machinery

1. Introduction

Natural stone mining depends on intense manpower. There are many large and small natural stone quarries and processing plants in Turkey. Noise-induced hearing loss is an irreversible but preventable occupational disease. Employees in natural stone processing facilities are more exposed to the harmful effects of noise than other mining

* Corresponding author. Tel.: (346)4875520
E-mail address: zduran@cumhuriyet.edu.tr

activities. Noise is a type of energy that can be transmitted through the air as pressure waves. Human ear can perceive these pressure waves that it feels as sound or noise. A normal and healthy young person can hear sounds in the frequency range of 20 Hz - 20000 Hz, but the human ear cannot respond equally to all frequencies [1]. Therefore, simply measuring the physical density of a sound pressure level is not sufficient to evaluate the potentially harmful effect of noise. High frequency noise has been reported to be more harmful than low frequency noise [2, 3]. Noise exposure may cause several negative health effects on people, including stress, cardiovascular diseases, hypertension, respiratory and neurological problems, and sleep disturbance. It is stated that high frequency sounds have effects such as high blood pressure, fatigue, hearing loss, headache, tinnitus, dizziness and nausea, depending on personal sensitivity and aging [4-6]. It is also reported that prolonged exposure to occupational and/or environmental noise may contribute to an increased risk of cardiovascular disease [7-10]. Hearing tests performed in natural stone processing facilities have revealed that the employees suffered from moderate to severe hearing loss [11-13]. It is necessary to identify the frequency distribution of the noise in terms of engineering controls [14]. Noise control through frequency analysis has been described as a vital tool widely used for the selection of hearing protectors and for environmental or communal noise assessment [15]. Controlling high frequency noise is both easier and cheaper than low frequency noise [16, 17]. The amount of sound transmitted from the outside of the buildings to the inside is greater in low frequency sound than in high frequencies. Therefore, thicker sound-absorbing materials are required compared to high-frequency sounds, as low-frequency sounds can pass through obstacles more easily [18]. Thus, it can be inferred that measures to be taken against noise propagation may be easier since the dominant frequencies are in the high frequency range in natural stone processing plants.

There are various approaches to define the frequency ranges that the human ear can hear as low, medium and high frequency ranges. The low frequency limit can be set at 200 Hz [19-23] or 250 Hz. According to an approach, sounds between 250 Hz - 2000 Hz fall into the medium frequency range and sounds with a higher frequency from 2000 Hz fall into the high frequency range [24, 25]. Bilgili et al [26] proposed the following scheme to identify the frequency of the sound considering the A and C-weighted sound levels: generally low frequency when (dBC – dBA ≥ 2), broadband equal sound level frequency when (dBC - dBA = 0) and generally high frequency when (dBC – dBA < 2). The World Health Organization (WHO) recommends C-weighted measurement along with A-weighted measurement in the examination of low and high frequency noise [26, 27]. In a study examining the effect of sound frequency on hearing loss, 48 % of 152 personnel with an average age of 32 had hearing loss due to noise, and it was revealed that the frequency of hearing loss started in the 6000 Hz region, especially in the left ear. In another study, it was stated that 40.4 % of the employees in this sector had a hearing loss and the maximum equivalent noise level was in the region of 4000 Hz [28]. The blocks supplied from quarries are handled in the slab and tile lines in the processing facilities, and are brought to the product sizes and specifications desired by the market. A series of equipment including gangsaws, bridge cutting, block cutting, head/side cutting, trimming, chamfering, polishing, cement filling and aging machines are generally used throughout the whole processing stages. It should be noted that the noise level to which the personnel working in natural stone processing facilities are exposed is above the limits specified in international standards [29-35]. It was reported that noise generated in stone processing facilities poses a risk to human health [32, 33, 36]. Researchers suggest that natural stone processing facilities be established away from residential areas [29, 31]. Employees should use personal ear protection equipment when working with high-noise emitting machinery like marble cutting machines, marble saws and polishing equipment [30, 31, 37]. Huang et al [35] reported that the noise levels that employees in natural stone processing plants are exposed to mostly correspond to the high frequency range (2000 Hz - 4000 Hz). The noise emitted in the cutting process varies according to the type of natural stone being processed. Şengün et al [38] recorded higher noise levels with andesite and basalt type rocks. Table 1 enumerates the detrimental impacts of noise on human health. Workers at natural stone processing plants are more exposed to second and third degree noise, which can have a major physiological impact, given the detrimental effects of noise on human health.

Table 1. Effects of noise on humans [26, 39, 40].

Level of Noise	Exposure range (dB)	Health Effects
1st level noises	30–65	Discomfort, uneasiness, anger, fury, sleep disorder, and attention deficit.
2nd level noises	65–90	Physiological reactions; increase in blood pressure, acceleration in heart rate and respiration, decrease in pressure in the cerebral fluid, sudden reflexes.
3rd level noises	90–120	Physiological reactions, headaches.
4th level noises	120–140	Permanent damage to the inner ear, deterioration of balance.
5th level noises	>140	Serious brain damage, burst eardrum.

2. Material and methods

In this study a total of 510 noise recordings were taken from eight natural stone processing facilities located in Sivas city, Turkey and its vicinity. Processing plants, which were coded between A and H to avoid a positive or negative bias, operated some or all of the following 11 machines: gangsaws, bridge cutting, ST block cutting, head/side cutting, trimming, cement filling, slab polishing, narrow polishing, aging, chamfering and splitting. At the time of measurement, the following natural stones were processed in the plants; limestone at plants A, C, F, G and H, yellow travertine at plants B and E and classic travertine at plant D. Noise exposure measurements were carried out in accordance with TS EN ISO 9612 [41] "Acoustics - Determination of occupational noise exposure - Engineering method", calibration for IEC 60942 : 2003 [42] and TS 2607 ISO [43] "Acoustics - Determination of occupational noise exposure and estimation of noise-induced hearing impairment" (Fig. 1). The task-based measuring method was used in this work for measurement purposes, and it was also used to eliminate uncertainties. As a result, for each assignment, measurements were taken three times for a minimum of five minutes. The microphone was positioned between 0.1 and 0.4 meters from the external auditory canal entry, in the middle plane of the employee's head, level with the eyes, and on the side of the ear that was most exposed. The individual taking the measurement positioned himself behind and next to the employee, maintaining this position throughout [44]. In both standards, the root-mean-square (RMS) of the frequency-weighted sound pressure values is defined for a nominal 8-hour working day ($L_{EX,8h}$) for assessing the noise exposure of workers during a working day. The frequency-noise relationship was also studied. A high-precision noise level meter equipped with an ⅓ octave band filter and suitable for all noise measurements specified in the annexes of the "Environmental Noise Assessment and Management Regulation" of the Ministry of Environment and Urbanization was used in field measurements. Noise measurements were carried out with A, C and Z (linear) frequency weightings over three profiles. The noise meter was calibrated before and after each measurement round as per the relevant directives. Frequency analyses were made of the noise levels recorded in the natural stone processing plants and the frequency and noise propagation maps were drawn taking into account the plant layout. The Surfer (Golden Software) application was used to create noise propagation maps [45].

Fig. 1. Noise measurements at a marble plant.

3. Results and discussion

A noise-vibration analysis package [46] was utilized for extracting the ⅓ octave frequency-noise relation of the recordings. Fig. 2 illustrates the frequency-noise relationship of the aging machines in natural stone processing facilities B and E using the A measurement scale in the event that the topic is discussed through an example. While workers in these factories who operate aging machines are subjected to similar dominant frequencies of noise, workers in other natural stone processing facilities may be exposed to different prominent frequency ranges. Because natural stone processing plants have a lot of machinery and industrial settings, the frequencies with the highest noise levels fall primarily between 630 Hz and 5000 Hz, with a concentration in the 3150 Hz frequency range. There is no natural stone processing plant with dominant low frequency ranges (Table 2).

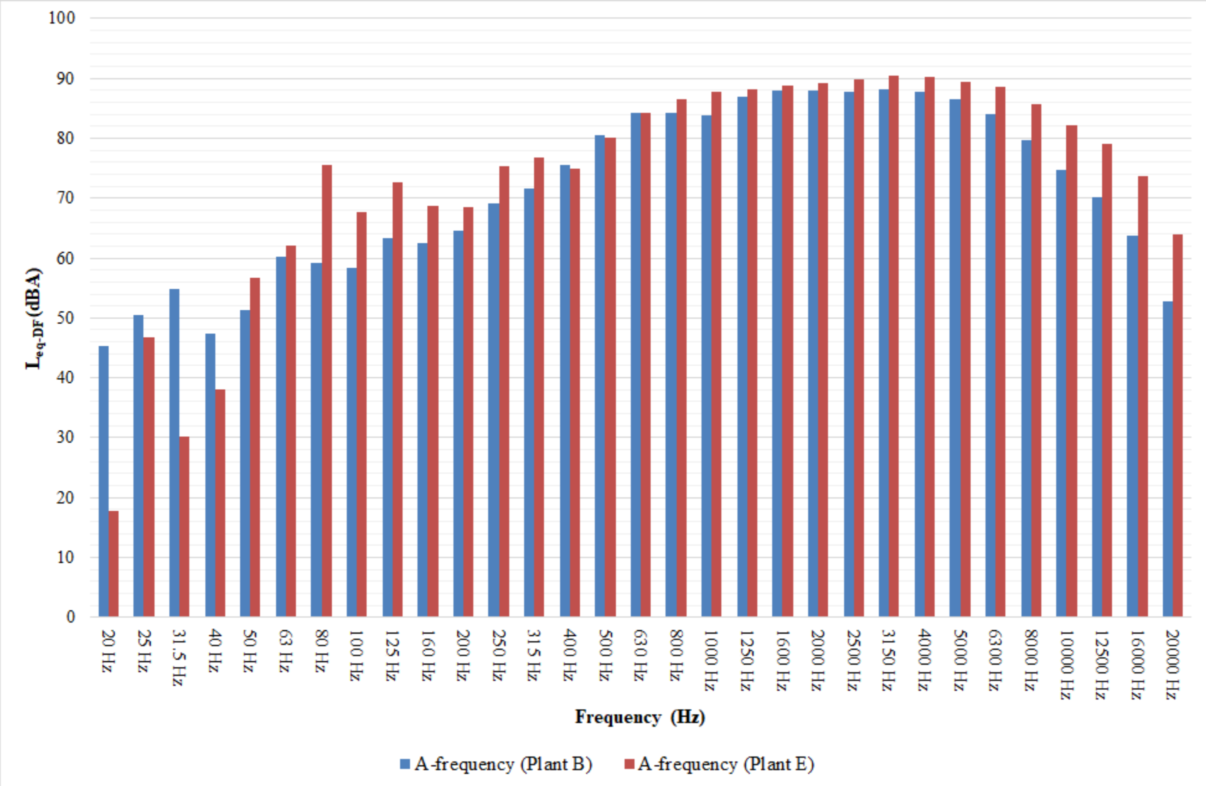

Fig..2. Frequency-noise relationship of aging machine groups.

A, C and Z-weighted equivalent continuous sound levels (L_{eq}) and daily personal noise exposure of workers along with dominant frequencies (DF) for processing machines at all plants are presented in Table 2. The following conclusions have been reached by evaluating the noise data. Among the six plants using gangsaws, there were no significant differences between the $L_{EX,8h}$ levels of the gangsaws in natural stone processing plants A, B, D and H. There were no high-noise machines in the vicinity of the gangsaws and the $L_{EX,8h}$ fluctuated around 89 dBA. The highest and lowest $L_{EX,8h}$ were from plants C and E with 94.4 dBA and 84.1 dBA, respectively. The main reason for the high noise level in plant C was that the gangsaw had been placed in a separate compartment with ST block cutting and head/side cutting machines nearby with high noise intensity (Fig. 3). On the other hand, the noise intensity in plant E was low compared to others due to the small number of machines spread across the large facility. Considering the A-frequency weighting, the highest noise level in the gangsaws corresponded to the medium frequency range in plants A and C (Fig. 4), and to the high frequency range in others. The results obtained were consistent with the literature. Çınar and Şensöğüt [32] reported the noise level of gangsaw machines as 87.51 dBA in two marble factories operating in Konya city, Türkiye.

Table 2. Noise levels and corresponding dominant frequencies (DF) at plants.

Machine [Code]	Plant	A - weighted				C - weighted				Z - weighted			
		L_{eq-DF} dBA	L_{eq} dBA	$L_{EX,8h}$ dBA	DF (Hz)	L_{eq-DF} dBC	L_{eq} dBC	$L_{EX,8h}$ dBC	DF (Hz)	L_{eq-DF} dBZ	L_{eq} dBZ	$L_{EX,8h}$ dBZ	DF (Hz)
Gangsaw [1]	A	80.8	90.1	89.8	630	82.6	91.5	91.2	400	82.6	92.4	92.1	400
	B	80.9	89.5	89.2	4000	82.5	90.9	90.6	400	84.1	92.1	91.8	400
	C	86.1	94.7	94.4	630	88.8	94.7	94.4	500	88.8	96.0	95.7	500
	D	82.3	89.3	89.0	4000	80.5	89.3	89.0	4000	81.3	89.5	89.2	4000
	E	76.5	84.4	84.1	4000	78.2	84.4	84.1	2500	79.0	86.7	86.4	5000
	H	80.2	90.0	89.7	4000	83.6	91.5	91.2	315	83.6	92.3	92.0	315
Bridge cutting [2]	A	88.1	94.5	94.2	3150	86.7	95.0	94.7	3150	87.2	94.9	94.6	3150
	B	87.3	95.3	95.0	2000	88.3	95.4	95.1	1600	88.6	95.8	95.5	1600
	C	79.6	87.8	87.5	800	80.4	87.8	87.5	800	80.4	89.0	88.7	800
	D	92.9	96.0	95.7	4000	91.0	96.7	96.4	2500	91.9	100.2	99.9	4000
	H	75.7	84.9	84.6	2500	75.1	85.6	85.3	2500	75.2	86.3	86.0	2500
ST block cutting [3]	A	90.0	96.6	96.3	3150	87.5	96.8	96.5	3150	87.9	97.5	97.2	3150
	B	90.9	98.4	98.1	3150	95.9	102.6	102.3	100	96.3	103.0	102.7	100
	C	90.9	99.1	98.8	1600	89.6	98.7	98.4	1000	89.9	98.8	98.5	1000
	D	94.7	96.8	96.5	1000	94.7	97.4	97.1	1000	94.7	97.4	97.1	1000
	E	85.3	92.9	92.6	3150	85.0	94.4	94.1	3150	85.5	94.4	94.1	3150
	F	93.7	100.1	99.8	3150	92.0	98.9	98.6	3150	92.5	99.7	99.4	3150
	G	92.3	98.8	98.5	3150	90.3	97.8	97.5	3150	90.8	98.3	98.0	3150
Head/side cutting [4]	A	88.2	94.3	94.0	3150	91.2	93.7	93.4	3150	91.6	95.1	94.8	3150
	B	92.7	99.2	98.9	3150	94.8	99.8	99.5	3150	95.2	100.6	100.3	3150
	C	89.1	97.4	97.1	3150	87.5	96.7	96.4	1250	88.0	97.2	96.9	2150
	D	92.5	99.9	99.6	4000	90.7	99.9	99.6	4000	91.5	99.9	99.6	4000
	F	82.5	91.8	91.5	3150	82.3	92.8	92.5	100	82.6	93.6	93.3	100
	G	88.7	95.3	95.0	4000	86.9	94.6	94.3	4000	87.7	95.2	94.9	4000
	H	83.2	90.4	90.1	4000	81.0	92.1	91.8	160	81.0	92.6	92.3	1660
Trimming [5]	A	86.2	93.7	93.4	1000	86.2	93.7	93.4	1000	86.2	94.0	93.7	1000
	B	87.7	95.7	95.4	3150	92.0	96.5	96.2	25	95.0	98.7	98.4	25
	C	81.4	90.5	90.2	3150	83.0	92.5	92.2	3150	83.0	91.0	90.7	3150
	E	94.4	100.2	99.9	5000	92.6	100.2	99.9	5000	93.9	100.4	100.1	5000
	G	87.4	94.8	94.5	4000	85.7	94.2	93.9	4000	86.4	94.7	94.4	4000
Cement filling [6]	A	78.5	86.7	86.4	3150	82.6	90.3	90.0	25	87.0	91.8	91.5	25
	B	63.6	68.0	67.7	500	66.8	68.0	67.7	500	66.8	79.0	78.7	500
	H	77.2	84.4	84.1	800	72.7	86.4	86.1	800	72.7	86.9	86.6	800
Slab polishing [7]	A	78.0	86.7	86.4	3150	79.5	89.7	89.4	250	83.9	90.0	89.7	250
	C	80.4	89.7	89.4	800	85.8	90.3	90.0	800	85.8	91.4	91.1	800
Narrow polishing [8]	A	80.6	89.1	88.8	3150	83.2	92.5	92.2	250	83.8	93.3	93.0	250
	B	85.9	93.3	93.0	3150	86.9	94.1	93.8	1000	87.0	94.7	94.4	1000
	C	79.5	86.5	86.2	800	80.3	87.8	87.5	800	80.3	87.5	87.2	800
	D	89.4	97.3	97.0	2500	87.8	97.3	97.0	2500	88.1	97.4	97.1	2500
	F	79.6	87.2	86.9	1250	80.3	89.2	88.9	800	80.3	89.3	89.0	800
	G	85.6	93.0	92.7	3150	84.6	93.2	92.9	3150	84.9	93.7	93.4	3150
Aging [9]	B	90.4	99.3	99.0	3150	96.4	101.7	101.4	80	96.9	102.4	102.1	80
	E	88.1	97.2	96.9	3150	91.3	101.8	101.5	31.5	95.8	102.0	101.7	20
In-plant [10]	A	81.3	88.1	87.8	3150	80.6	90.5	90.2	100	82.8	91.0	90.7	100
	C	79.6	86.3	86.0	1000	79.9	87.4	87.1	1000	79.9	87.6	87.3	1000
	D	83.0	92.9	92.6	2500	83.1	92.8	92.5	2500	83.3	93.6	93.3	2500
	E	74.3	88.5	88.2	4000	72.9	89.6	89.3	1000	74.3	89.7	89.4	1000
	H	76.9	86.7	86.4	3150	75.6	88.8	88.5	400	75.6	89.7	89.4	400

Chamfering [11]	A	83.0	90.0	89.7	3150	81.3	91.3	91.0	3150	82.8	91.8	91.5	3150
	C	78.7	86.8	86.5	1600	79.5	86.8	86.5	800	79.5	88.0	87.7	800
Splitting [12]	B	94.7	101.6	101.3	3150	93.0	101.6	101.3	3150	93.5	101.5	101.2	3150
	C	85.6	93.8	93.5	3150	79.7	95.6	95.3	3150	79.9	93.8	93.5	3150

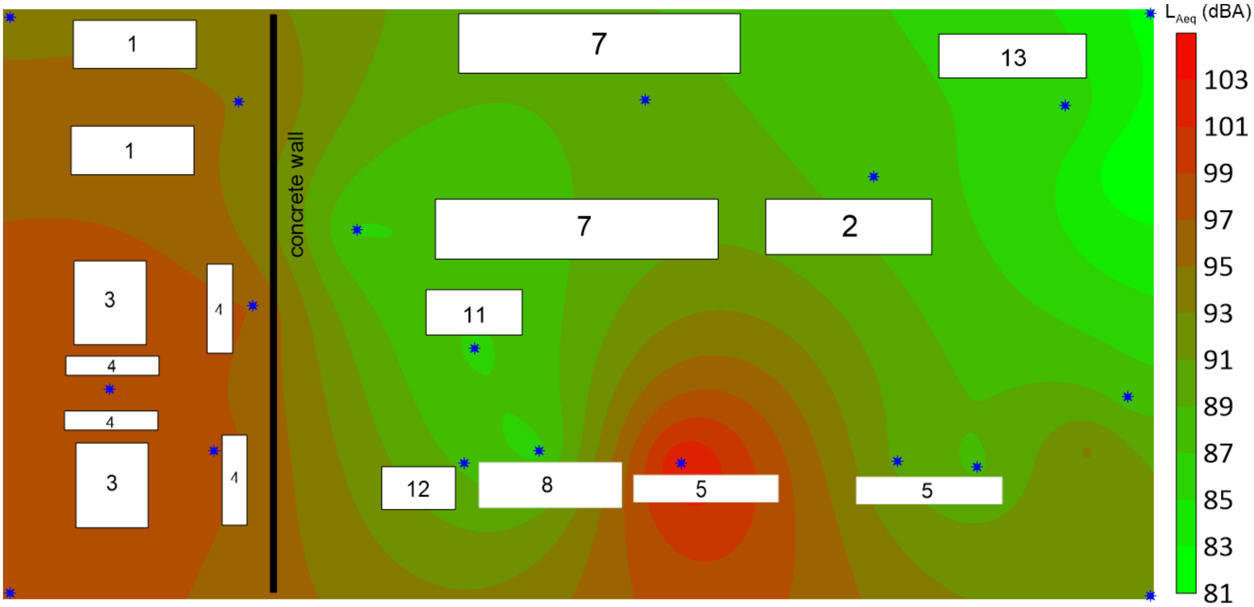

Fig. 3. A-weighted L_{Aeq} map of Plant C (storage area [13], measuring point [✱]).

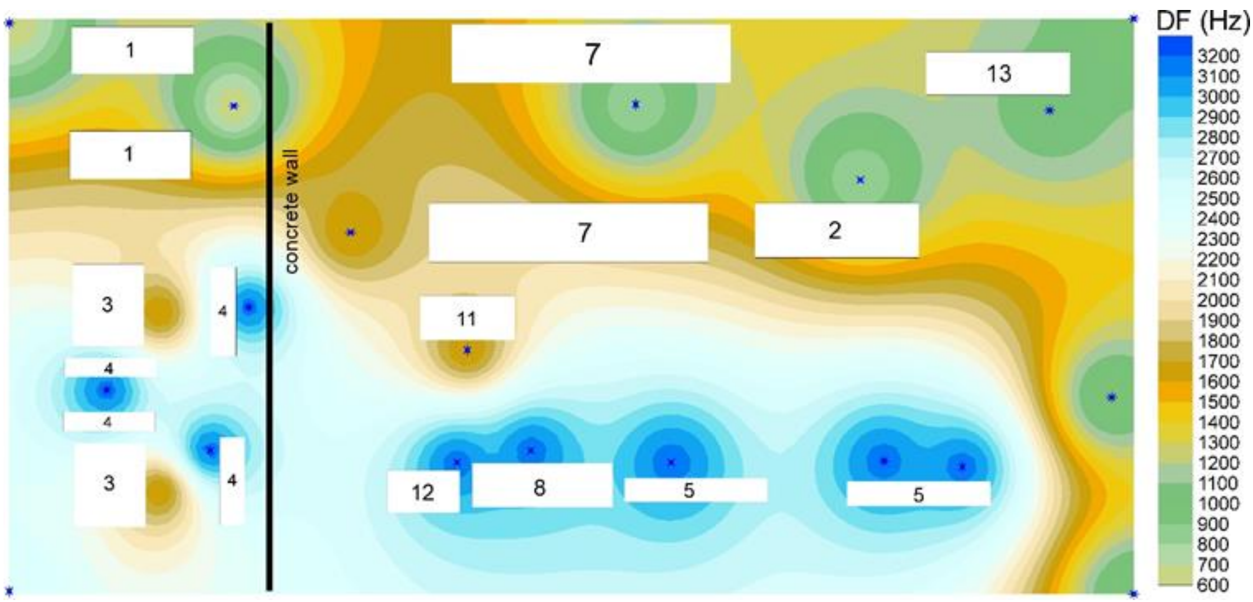

Fig.4. A-weighted frequency map of Plant C (a).

Five bridge cutting machines were monitored within the scope of the study. The lowest daily equivalent noise level of 84.6 dBA was from plant H, where a small number of processing machines had been spread over a relatively large factory area (Fig. 5). Similar to gangsaws, the bridge cutting machines in plants A, B and D were placed in such a way that there were no other high-noise processing machines nearby. The average $L_{EX,8h}$ of the bridge cutting machines in these three plants was 95 dBA. The highest noise levels in bridge cutting machines fell into the medium frequency range in natural stone processing plants B and C, and to the high frequency range in other plants. Fig. 6 illustrates the A-frequency weighted dominant frequency distribution across plant H.

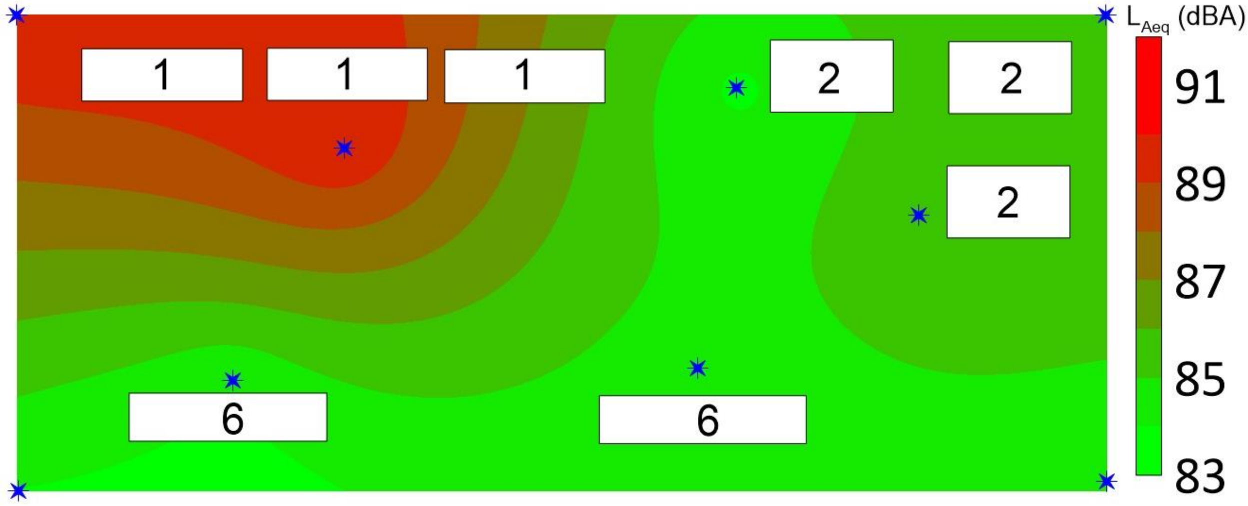

Fig. 5. A-weighted L_{Aeq} map of Plant H.

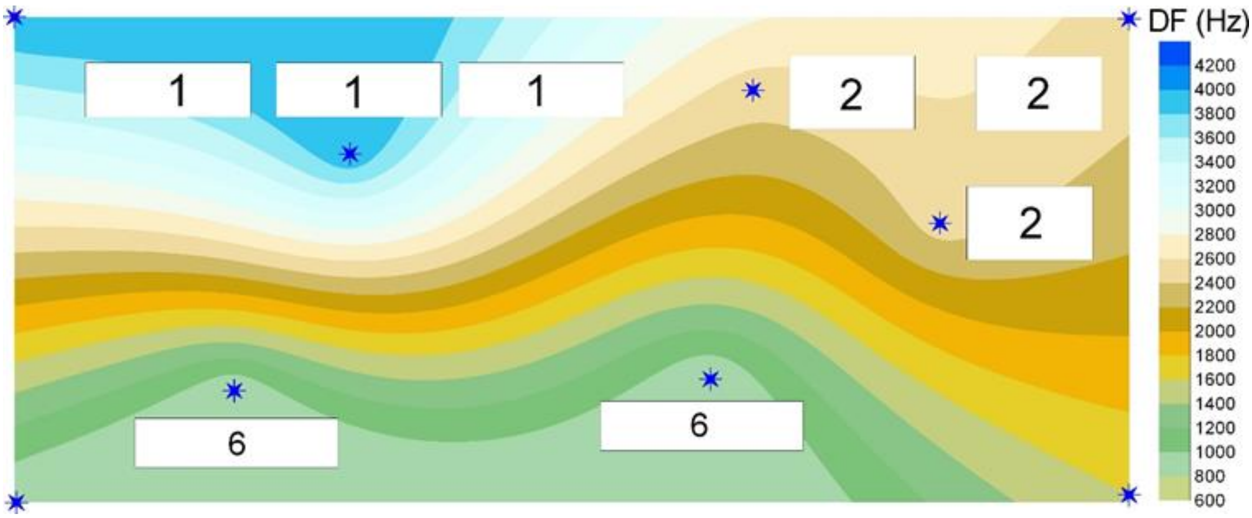

Fig. 6. A-weighted frequency map of Plant H.

One of the most widely monitored equipment in the study was the ST block cutting machine with seven units. The $L_{EX,8h}$ of ST block cutting machines ranged between 96.3 dBA and 99.8 dBA averaging at 98 dBA in all plants except plant E. Adjacent to the ST machines in these plants, there were head cutting machines that produced high levels of noise. These findings are consistent with the noise level of the ST machine of 96 dBA at a marble factory in South Aceh, Indonesia by Lindawati et al [34]. However, the $L_{EX,8h}$ in plant E, where the processing machines had been scattered over wide open spaces, has decreased to 92 dBA (Fig. 7). Considering the A-frequency weighting, the highest noise levels in the ST machines were in the medium frequency range in plants C and D, and in the high frequency range in other processing plants. The dominant frequency distribution of the processing machines in plant E is presented in Fig. 8.

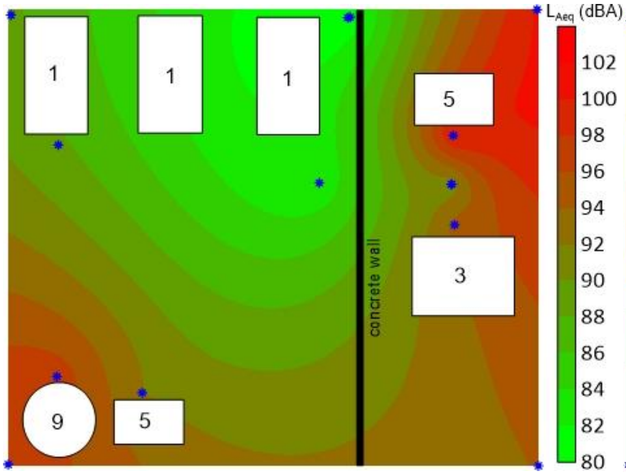

Fig. 7. A-weighted L_{Aeq} map of Plant E.

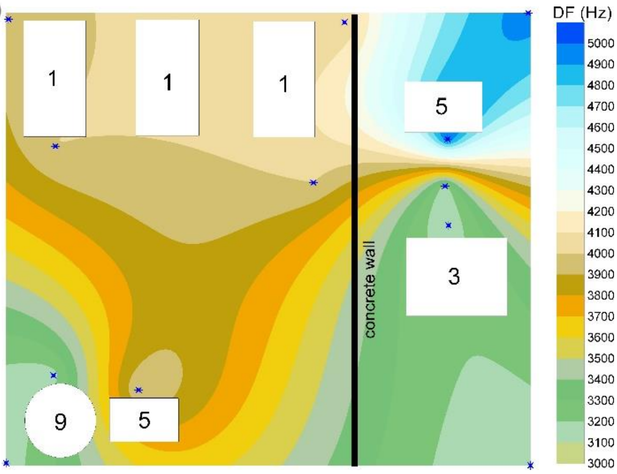

Fig. 8. A-weighted frequency map of Plant E.

Another machine with the highest noise measurement rounds is the head/side cutting machine with 7 units. Again, as the head/side cutting machines operating in plants B, C and D were placed in isolated locations together with the ST machines, their noise levels were higher than those in other natural stone processing plants. Daily equivalent noise levels of the machines varied between the lowest 90.1 dBA (plant H) and the highest 99.6 dBA (plant D). The highest noise level of the machines in all plants fell into the high frequency region.

Among the five plants with trimming machines, the equivalent daily noise levels of plants B and E were found higher than the others as they were located adjacent to the aging machines. The $L_{EX,8h}$ values of the trimming machines varied between 90.2 dBA and 99.9 dBA with an average of 94.7 dBA, which is consistent with the study of Çınar and Şensöğüt [32] in which the average daily equivalent noise level of the trimming machine was 96.7 dBA. Except for the natural stone processing plant A, where the highest noise level is in the medium frequency region, the highest noise level is in the high frequency region in all other processing plants. As a typical example, the noise and dominant frequency maps of plant G are given in Fig.9.– Fig.10.

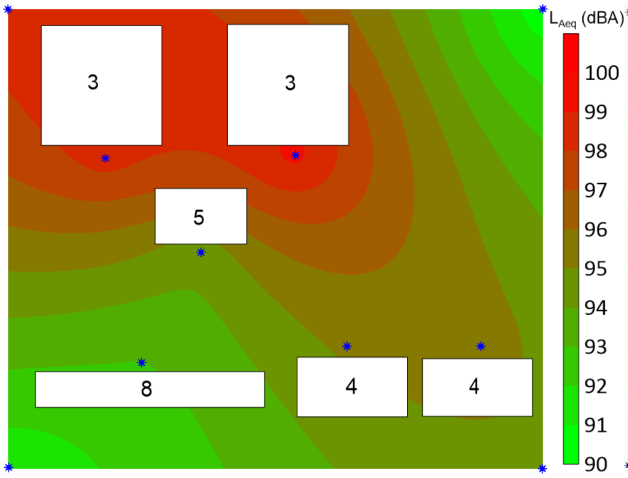

Fig. 9. A-weighted L_{Aeq} map of Plant G.

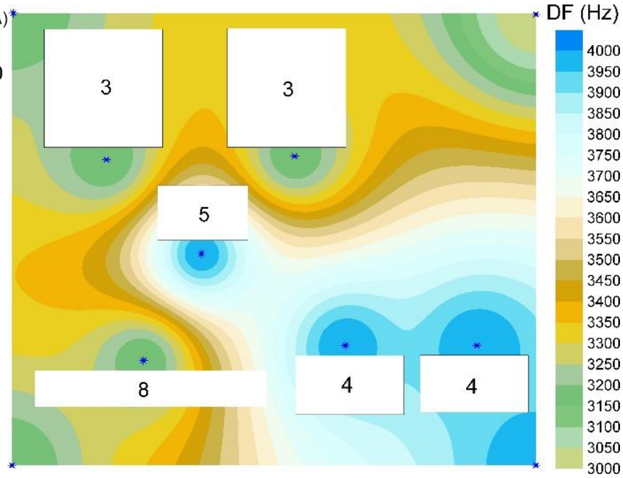

Fig. 10. A-weighted frequency map of Plant G.

The noise levels of the narrow polishing machines in the six plants changed from 86.2 dBA at plant C with no high-noise emitting machine alongside narrow polishing line to 97.0 dBA at plant D with ST, head cutting and bridge cutting machines located near the narrow polishing line. Excluding plant D, where high-noise processing machines were located together, the noise levels in other natural stone processing plants were fairly balanced and averaged at 90.7 dBA. With reference to previous studies, Çınar and Şensöğüt [32] measured the noise level of the polishing machine as 89.55 dBA in two marble factories. As for the dominant frequency distribution, the highest noise levels were in the medium frequency range in plants C and F, and in the high frequency range in other natural stone processing plants.

Three cement filling machines were sampled in the study. The $L_{EX,8h}$ in plants A and H was found to be quite close to each other due to the fact that filling machines were in a location with other natural stone processing machines of the same type. As for the cement filling machine at plant B, which operated in a separate compartment, the $L_{EX,8h}$ was as low as 67.7 dBA. For the cement filling machines, the maximum noise levels fell into the medium frequency range in plants B and H, and to the high frequency range in plant A.

The daily equivalent noise levels in the slab polishing machines that operated in wide and open places in plants A (Fig. 11) and C were similar. The maximum noise level was in the high frequency range in plant A (Fig. 12) while it was in the medium frequency range in plant C.

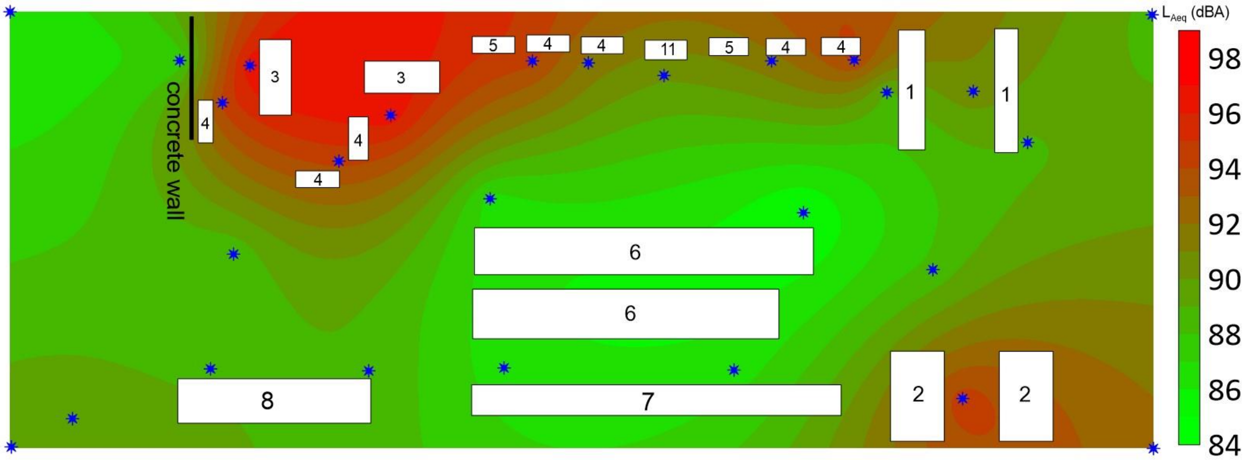

Fig. 11. A-weighted L_{Aeq} map of Plant A.

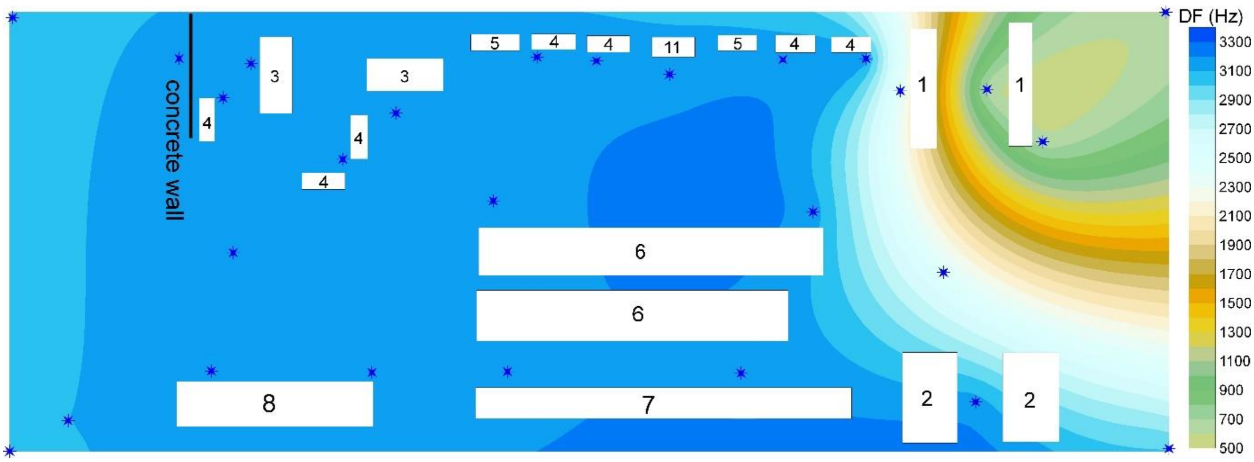

Fig. 12. A-weighted frequency map of Plant A.

The equivalent daily noise levels of the two chamfering machines operating in plants C and A were 86.5 dBA and 89.7 dBA, respectively. The tighter layout of plant A was reflected in the higher noise level. The highest noise level in plant A was in the high frequency range while it was in the medium frequency range in plant C.

In the study, splitting machines used in plants B and C were also sampled. $L_{EX,8h}$ levels were calculated as 101.3 dBA at plant B and 93.5 dBA at plant C. The high noise level at plant B has been attributed to the splitting machine being in an obstructed environment with high-noise emitting head cutting and ST machines. Referring to previous studies, Çınar and Şensöğüt [32] reported the noise level of two splitting machines in marble plants in Konya, Turkey as 94.44 dBA. Noise generated by both machines were in high frequency range. Comparable $L_{EX,8h}$ levels were achieved of the aging machines used in plants B (Fig. 13) and E. This condition was attributed to the fact that the aging machines were surrounded by other high-noise emitting machines. The highest noise level of the machines in two plants were located in the high frequency region (Fig. 14).

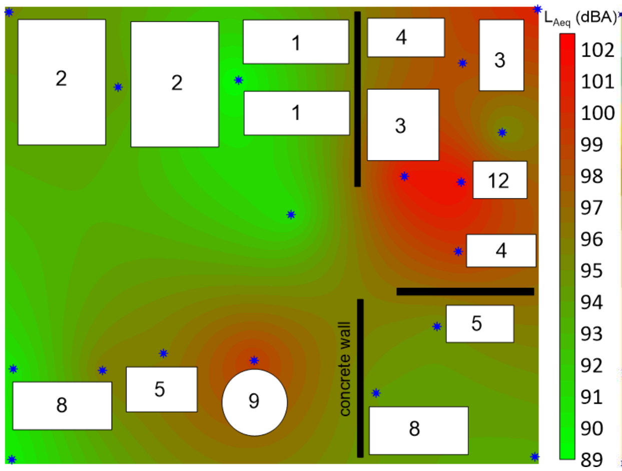

Fig. 13 A-weighted L_{Aeq} map of Plant B.

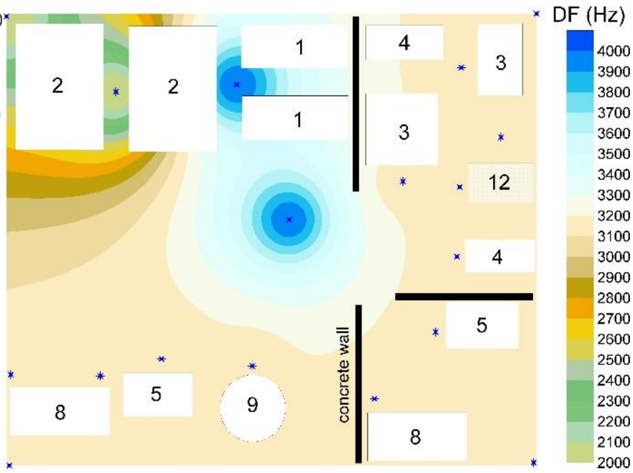

Fig. 14. A-weighted frequency map of Plant B.

Representative ambient noise levels varied between 86.0 dBA and 92.6 dBA, with an average of 88.2 dBA for the processing plants. Nevertheless, differences in the layout planning of natural stone processing machines and the use of equipment with varying noise levels were also reflected as significant variations in the sound level ranges (lowest to highest) in the plants, as follows: 7 dBA at plant H, 10 dBA at plant G, 11 dBA at plant D, 13 dBA at plants A and F, 17 dBA at plant B, 21 dBA at plant E and 22 dBA at plant C.

Considering the A frequency weighting, the dominant frequency range of natural stone processing plants was as follows: 630 Hz - 3150 Hz at plant A, 500 Hz - 4000 Hz at plant B, 630 Hz - 3150 Hz at plant C, 1000 Hz - 4000 Hz at plant D, 3150 Hz - 5000 Hz at plant E, 1250 Hz - 3150 Hz at plant F, 3150 Hz - 4000 Hz at plant G and 800 Hz - 4000 Hz at plant H. Thus, plants E and G were characterized by high frequency noise, while other natural stone processing plants were characterized by medium and high frequency noise.

Again, taking into account the A frequency weighting, the dominant frequency range of natural stone processing machinery among plants is as follows; gangsaws: 630 Hz - 4000 Hz, bridge cutting machines: 800 Hz - 4000 Hz, ST block cutting machines: 1000 Hz - 3150 Hz, head/side cutting machines: 3150 Hz - 4000 Hz, trimming machines: 1000 Hz - 5000 Hz, cement filling machines: 500 Hz - 3150 Hz, slab and narrow polishing machines: 800 Hz - 3150 Hz, aging and splitting machines: 3150 Hz and chamfering machines: 1600 Hz - 3150 Hz. From these findings, which are in line with Engin et al [37], it is evident that regardless of operational and occupational parameters, aging and splitting machines consistently produced the same high-frequency noise, while different types of polishing machines also produced noise in the same frequency range. Head/side cutting machines operated in a narrow band of the high frequency range, while other processing machines were spread over the medium-to-high frequency ranges.

Effects of the natural stone processing machine types, the layout of the machines within plants and the types of natural stones on the noise generated were investigated through hypothesis tests on a statistical analysis package [47]. The level of significance was set at 5 %. The compliance of the data with normal distribution was determined by applying the Kolmogorov-Smirnov test and the one-way variance analysis was utilized in hypothesis tests. The mean and standard deviation of the $L_{Ex,8h}$ representing some 510 measurements was 92.80 dBA ± 5.21 dBA.

The variation of and the differences between noise levels of natural stone processing plants were analyzed using all the data recorded in each facility. Plants B, D, F and G generated averaged noise levels in excess of 95 dBA, while plant H appeared as the quietest one with an average daily equivalent noise level of 86.95 dBA. The results of one-way variance analysis presented in Table 3 reveal that there are statistically significant differences between daily equivalent noise exposures ($pL_{EX,8h} < 0.001$). Accordingly, while the difference between the $L_{EX,8h}$ levels at plants H (group a), A, C and E (group b) and B, D, F and G (group c) was not statistically significant within a specific group, it was significant on an intergroup basis.

Table 3. Hypothesis testing on plant-based daily equivalent noise exposure.

Test	A	B	C	D	E	F	G	H	p
Duncan	92.38 ± 3.42^{b}	95.42 ± 6.02^{c}	92.10 ± 5.25^{b}	95.35 ± 4.52^{c}	90.98 ± 6.19^{b}	95.68 ± 6.19^{c}	95.51 ± 2.38^{c}	86.95 ± 5.22^{a}	<0.001

a-c: Means sharing a letter in their superscript are not significantly different at the .05 level.

Table 4 summarizes the results of hypothesis tests showing that the difference between the daily equivalent noise levels of all machine categories in the different plants was statistically significant ($p < 0.001$). Considering the gangsaws, three groups with low (plant E), medium (plants A, B, D, H) and high (plant C) noise levels emerged, with a statistically significant difference between the $L_{EX,8h}$ levels. Bridge cutting machines were divided into three groups with low (plants C and H), medium (plants A and B) and high (plant D) noise levels through hypothesis tests. Though plants within each group did not differ in terms of $L_{EX,8h}$ levels, groups showed statistically significant differences ($p < 0.001$). ST block cutting machines were also divided into groups as low (plant E), lower-medium (plants A, D, G), upper-medium (plants C, F, G) and high (plant B), where intergroup differences were statistically significant. Hypothesis tests revealed a statistically significant difference in $L_{EX,8h}$ levels between head/side cutting machine groups of low (plants A, F, G and H), medium (plants A, B, C and G) and high (plants C and D) at the 0.05 level. Considering plants A and G equivalent, there was a statistically significant difference between $L_{EX,8h}$ levels of trimming machines. Similarly, statistically significant differences were found between the $L_{EX,8h}$ levels of all cement filling machines. Hypothesis tests categorized the narrow polishing machines into groups of low (plant C), medium (plants A, B, F, G) and high (plant D) $L_{EX,8h}$ levels. While there was no statistically significant difference between the $L_{EX,8h}$ levels of the narrow polishing machines within each group, there was a significant difference between the groups at the 0.05 level. Hypothesis tests were used to investigate whether there was a statistically significant difference between the $L_{EX,8h}$ levels across working environments. Plants C, E and H; A, E and H; D and H were classified in low, medium and high-noise groups, respectively. That plant H is included in all groups has shown that the $L_{EX,8h}$ levels in the working environment of this plant can be considered equivalent to other facilities. Nevertheless, the difference between the $L_{EX,8h}$ levels of the groups was found to be statistically significant at the 0.05 level.

Table 4. Hypothesis testing on machine-based daily equivalent noise exposure.

Machine	Test	A	B	C	D	E	F	G	H	p
Gangsaw	Tukey	91.05 ± 1.65^{b}	90.54 ± 3.18^{b}	94.83 ± 0.75^{c}	89.07 ± 0.12^{b}	84.90 ± 4.15^{a}	-	-	91.00 ± 1.05^{b}	<0.001
Bridge cutting	Tukey	94.51 ± 1.88^{b}	95.03 ± 1.06^{b}	87.90 ± 0.69^{a}	99.85 ± 3.93^{c}	-	-	-	85.31 ± 1.59^{a}	<0.001
ST cutting	Duncan	96.75 ± 0.99^{b}	101.03 ± 3.07^{d}	98.58 ± 0.96^{c}	96.70 ± 0.35^{b}	92.38 ± 1.97^{a}	99.23 ± 1.48^{c}	97.98 ± 0.79^{bc}	-	<0.001
Head/side cutting	Duncan	94.29 ± 3.16^{ab}	99.57 ± 2.03^{b}	96.84 ± 3.24^{bc}	99.60 ± 0.00^{c}	-	92.43 ± 0.90^{a}	94.73 ± 1.40^{ab}	91.40 ± 1.15^{a}	<0.001
Trimming	Duncan	93.50 ± 0.17^{b}	96.73 ± 1.72^{c}	90.29 ± 2.48^{a}	-	99.97 ± 0.12^{d}	-	94.27 ± 0.69^{b}	-	<0.001
Cement filling	Tukey	89.28 ± 2.88^{c}	71.37 ± 6.35^{a}	-	-	-	-	-	85.66 ± 1.37^{b}	<0.001
Narrow polishing	Duncan	90.61 ± 2.16^{b}	93.66 ± 2.90^{b}	86.73 ± 0.92^{a}	97.03 ± 0.06^{c}	-	88.27 ± 1.19^{b}	93.01 ± 1.79^{b}	-	<0.001
In-plant	Duncan	89.52 ± 1.46^{b}	-	86.45 ± 1.89^{a}	92.84 ± 3.46^{c}	88.59 ± 4.74^{ab}	-	-	88.10 ± 1.54^{abc}	<0.001

a-d: Means sharing a letter in their superscript in a row are not significantly different at the .05 level.

The effect of the natural stone type on the noise level has also been investigated. Table 5 illustrates that rocks processed at five plants and categorized under the limestone group had lower $L_{EX,8h}$ levels, while the group consisting of yellow and classical travertines caused higher noise emission. The difference between the $L_{EX,8h}$ levels of the groups was statistically significant.

Table 5. Hypothesis testing on natural stone type-based daily equivalent noise exposure.

Test	Yellow travertine	Limestone	Classic Travertine	p
Tamhane	94.46 ± 6.03^b	92.00 ± 4.61^a	97.01 ± 4.90^b	<0.001

a-b: Means sharing a letter in their superscript are not significantly different at the .05 level.

Independent sample t-tests were applied to decide whether there was a statistically significant difference between the $L_{EX,8h}$ levels of slab polishing, chamfering, splitting and aging machines. There is statistically no significant difference between the aging machines in plants B and E (p = 0.280), at the 0.05 level (Table 6). On the contrary, there is a statistically significant difference between the slab polishing machines in plants A and C (p = 0.016), chamfering machines in plants A and C (p < 0.001) and splitting machines in plants B and C (p < 0.001).

Table 6. Independent sample t-tests on machine-based daily equivalent noise exposure levels.

Machines	Plant	N	Mean ± SD	Test statistic	p[1]
Slab polishing	A	9	88.21 ± 1.71	-2.682	0.016
	C	9	90.30 ± 1.60		
Chamfering	A	9	90.68 ± 0.89	6.643	< 0.001
	C	3	86.90 ± 0.69		
Splitting	B	3	101.27 ± 0.06	6.210	< 0.001
	C	9	93.27 ± 3.86		
Aging	B	9	100.82 ± 1.49	1.386	0.280
	E	3	98.50 ± 2.77		

[1] Independent sample t-test

4. Conclusions and Recommendations

The results obtained in this study, which covered a total of 510 noise exposure measurements recorded from processing machinery used in eight natural stone processing plants in Sivas, Turkey and its surroundings, are given below.

ST block cutting, trimming, splitting, aging, bridge cutting, narrow polishing and head/side cutting machines have produced high levels of noise. Gangsaws, chamfering, slab polishing and cement filling machines emitted relatively lower levels of noise. However, differences were detected between the noise levels of a certain type of processing machinery in different natural stone processing plants. This discrepancy was attributed to the change in the types of natural stones processed, plant layout and the number of processing machines operating simultaneously during the measurements.

In all other production plants except plant E, the noise level in gangsaw machines exceeded 85 dBA, the highest exposure action value, according to the *Regulation on the Protection of Employees from Noise-Related Risks*. Every plant except H had noise levels in bridge cutting machines that above 85 dBA, the highest exposure action value. The noise level in ST block cutting, head/side cutting, trimming, slab polishing, narrow polishing, aging, chamfering, and splitting machines measured in all natural stone production facilities exceeds the maximum exposure action value. Regarding the cement filling machines, the noise level at Plant B was lower than the lowest exposure action value set in the applicable regulation, owing primarily to the fact that the filling machine in this facility was located in a different compartment. In contrast, the noise level in plant A exceeds the maximum exposure action value.

When the noise exposed by the workers in natural stone processing plants is evaluated with the A-frequency weighting, the highest noise levels varied between 630 Hz - 5000 Hz and concentrated at 3150 Hz. Thus, the dominant frequencies fluctuated between medium and high frequency ranges. It should be noted that no machines in any natural stone processing plants have produced noise in the low frequency region.

Considering the C-frequency weighting, the noise generated in the plants was distributed over all frequency ranges. Also, in C and Z-frequency weightings, the frequency regions with the highest noise level were close.

Examining $L_{EX,8h}$ values revealed that a difference of less than 2 dB was found between $L_{EX,8h}$ values based on A and C-frequency weightings (dBC – dBA $\leq$ 2), and less than 1 dB between C and Z-frequency weightings (dBZ - dBC $\leq$ 1). Therefore, it would be beneficial to conduct high frequency sound measurements with A and C-frequency weightings. But, it may not be necessary to measure noise based on Z-frequency weighting.

The noise levels that employees in natural stone processing plants are exposed to were mostly in the 3rd degree noise class, which may cause physiological reactions and headaches on the employees.

Employees in natural stone processing industries are exposed to noise levels that much exceed the maximum exposure action value specified in the *Regulation on the Protection of Employees from Noise-Related Risks*. Employees should be informed at regular intervals on the steps that will be taken to prevent noise-induced hearing loss from progressing to an occupational disease. Permanent hearing loss cannot be treated, although temporary hearing loss can. Facilities that process natural stone should periodically assess the noise levels and implement the appropriate safety measures. The battle against noise needs to be initiated at the source, carried out between the source and the recipient, and then concluded at the receiver. Training on the proper and regular use of personal protective equipment should continue, checks should be performed, and workers should be trained on how to perform the checks. Furthermore, the frequency of noise at the source must be considered while selecting personal protection equipment and materials to reduce noise at the source. Wearing ear protection with muffs is advised because the noise that employees in natural stone processing factories are typically exposed to is in the high frequency range. Depending on their age and level of sensitivity, workers in these facilities who do not wear ear protection could have side effects such headaches, tinnitus, fatigue, dizziness, and nausea in addition to elevated blood pressure and headaches. When developing the layout of machines in newly built natural stone processing facilities, it is more appropriate in terms of worker health to plan the facility while taking into account the noise and dominant frequency values of the machines as well as the production line.

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Author Contributions

Zekeriya Duran and Bülent Erdem envisioned and planned the research project. Zekeriya Duran, Tuğba Doğan and Mehmet Genç carried out the material preparation and data gathering tasks. Zekeriya Duran and Tuğba Doğan conducted the statistical analyses. Zekeriya Duran, Bülent Erdem, Tuğba Doğan and Mehmet Genç all contributed to the preparation of the article format. All authors commented on the final form of the manuscript.

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