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Investigation and development of sound absorption of plasters prepared with pumice aggregate and natural hydraulic lime binder

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ABSTRACT

Historical structure properties and indoor requirements should be taken into consideration in plaster layer mixture type selection during the historical building restoration. In the research, it has been aimed to increase the sound absorption coefficient in plaster layers with the direction of accurate restoration application decisions. In the plaster content, natural hydraulic lime binder which is frequently used in historical building restoration was researched and the pumice aggregate type instead of river sand aggregate was investigated to show the effect of lightweight aggregate type. The experimental analyses which are sound absorption, compressive strength, flexural strength, capillarity of water absorption and open porosity, were performed to compare different plaster layer types. The effects of aggregate combination volumetric ratio, polypropylene fiber ratio, flax fiber ratio, and crumb rubber additive ratio were analyzed. It was understood that sound absorption coefficients can be enhanced by means of the mortar mixture content changes and the use of lightweight aggregate type. Especially, the use of pumice aggregate instead of river sand aggregate in the mortar mıxture can significantly increase the sound absorption coeffıcıent in the range of 1400–2700 Hz. Also, the use of pumice aggregate instead of river sand aggregate has increased compressive strength and flexural strength remarkably in this research. It was especially observed that the use of additives which are listed as polypropylene fiber, flax fiber and crumb rubber in the mortar mixture, can be a very effective method to increase sound absorption performance not only in high frequencies but also low frequencies. As a result, the sound absorption research based on different mortar mixture types in plaster layers were systematically conducted to increase sound absorption coefficients in accordance with the historical building requirements.

1. Introduction

Historical buildings should be protected and the original form of historical buildings should not be changed during the restoration process. Restoration process in the historical building must be carried out without altering the characteristic design choices from the time when they were first designed. Especially, vault, dome or the other forms should be conserved in the interior of the room and retain their characteristics from the time when they were first used [1].

Large room volumes are commonly observed in historical buildings. The separation of rooms of large volumes contrary to its original structure should be prevented and suspended ceiling systems, which is incompatible of the original room form, should not be preferred in the historical buildings. The conservation of original room forms, which have large volumes, is in line with the philosophy of basic conservation. In summary, large room volumes in historic buildings should not be reduced. However, it is important to take into account the acoustic problems which may arise from having a high room volume. Historical buildings with large room volumes are frequently beset by problems acoustics in terms of background noise, echo and unwanted reverberation [2]. In such historical spaces, reverberation time should be kept within the desired range to ensure speech intelligibility. In fact, in such historical rooms, the increasing of the sound absorption coefficient of the plaster surfaces plays a crucial role if the objective is the decrease the reverberation time to the desired level. To be able to reduce reverberation time in historical large rooms, the sound absorption coefficient of plaster surfaces should be increased without reducing the original room volume [3].

On the restoration of the historical buildings, the other important parameter is the material selection in the plaster layer. Material selection must be appropriate with building materials and must not give damage to the historical building structure. Article 9 of the Venice charter issued in 1964 indicates that "*The process*

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of restoration is a highly specialized operation. Its aim is to preserve and reveal the aesthetic and historic value of the monument and is based on respect for original material and authentic documents" [4]. In this research, it is aimed to increase the sound absorption coefficient in the plaster layer to be compatible with the historical structure. It is suggested to increase the sound absorption coefficients by means of changing the mortar mixture type in the plaster layer without giving damage to the original structure.

In the researches of authors Güleç & Tulun [5], Uğurlu & Böke [6], Özkaya & Böke [7], Sağın & Böke [8] and Akçay et al. [9], it was observed that mortar samples were obtained from the historical buildings before restoration, samples were analyzed in detail and restoration mortar mixture types were researched according to sample analyses in Turkey. However, the researches which restoration mortar mixture types are determined in line with plaster sample analyses with taking into account to increase sound absorption coefficients in the plaster layer, are not observed sufficiently. In order to increase sound absorption and satisfy the acoustical requirements, it was suggested to change of plaster mixture content type without giving damage to the historical building structure. Mortar mixtures based on natural hydraulic lime binder, which are commonly used in restoration works, were researched.

In this context, plaster mortars used in historical buildings were investigated in the first stage of the research and sound absorption analyses were explained in detail. In the first stage of the research, the effect of plaster thickness without changing the mortar mixture content was examined and it was stated that the increase of thickness may increase the sound absorption coefficient [1]. In the second stage of the research, mortar mixtures prepared with river sand aggregate were investigated, the effect of sound absorption coefficient based on mortar mixture content was analyzed and new mortar mixture types were offered to increase sound absorption coefficients in the plaster layer prepared with river sand aggregate and natural hydraulic lime binder [2]. The effects of binder/aggregate volumetric ratio in the mixture, the effects of the aggregate particle size range in the mixture, and the effects of the additive material ratio in the mixture were researched. In the second stage of the research, it was defined that when the binder ratio in the mixture increases, it may affect the sound absorption coefficient negatively. Also, it was stated that the use of superfine aggregate (between 0 and 2 mm) in the plaster layer can have an adverse effect on the sound absorption coefficient. Moreover, the additives which are listed as polypropylene fiber, flax fiber and crumb rubber was researched to use in the plaster layer and it was noted that additives can increase sound absorption at low frequencies. However, it was observed that the use of polypropylene fiber, flax fiber and crumb rubber additive in the plaster layer can decrease the sound absorption at high frequencies and the peak point in which the maximum absorption occurs [2]. The mentioned studies were given in the literature and were not be re-evaluated in this paper in detail. In this paper, pumice aggregate was investigated in detail as lightweight aggregate type in the mortar mixture prepared with natural hydraulic lime binder and new mixture types were suggested to increase sound absorption coefficients in the plaster layer prepared with pumice aggregate and natural hydraulic lime binder. Besides, the use of additives which are polypropylene fiber, flax fiber and crumb rubber was researched in the plaster layers prepared with pumice aggregate. In this stage of research, it was demonstrated that the use of additives with pumice aggregate in the plaster can increase sound absorption not only at low frequencies but also at high frequencies. Moreover, it was stated that the use of additives with pumice aggregate in the plaster layer can improve the peak point in which the maximum absorption occurs. Also, it was understood that the use of additives with pumice aggregate in the plaster layer can enhance sound absorption coefficients in wide frequencies range. In Sections 4 and 5, sound absorption results related to the research were explained in detail.

With related to the subject in the literature, there are numerous researches about using local materials in the mortar mixture. The use of local materials in the plaster layers was researched in the literature. Randazzo et al. [10] researched clay plasters typically used in Europe and performed clay plasters sound absorption tests. Their results revealed that the addition of natural fibers can increase sound absorption at high frequencies. Degrave-Lemeurs et al. [11] mentioned that clayed earth can be found easily on a local scale. Researchers examined the sound absorption properties of hemp-clay mixtures. In the study, it was demonstrated that decreasing hemp-clay mixtures density can improve sound absorption in general. Bouzit et al. [12] researched characterization of natural gypsum materials and their composites for building applications. Moroccan natural gypsum materials were investigated in the research, the gypsum samples come from Agadir (AG) and Safi (SG) ores in southwestern Morocco were analyzed and researchers stated that the samples produced by agadir and safi ores have high sound absorption performance than conventional plasters. In this research, the pumice aggregate type obtained from Turkey was investigated.

The relation between the sample thickness and sound absorption was examined in literature studies. It was observed that the sample thickness has a great importance on sound absorption coefficients. Shen et al. [13], Kim & Lee [14], Bartolini et al. [15], Moretti et al. [16], Buratti et al. [17], Lim et al. [18] and Putra et al. [19] researched different sample thicknesses in the same material and authors showed that increasing the sample thickness leads to an increase in low frequency sound absorption. Hence, in this research, fixed plaster thickness was used to compare different mixture types. It was observed that the restoration work conducted in Turkey are frequently used plaster thickness of 3 cm. Also, 3 cm plaster layer application coded as V.1660/E04 [20] which is related to plastering on curved surfaces, exists in 2019 application details for historical structure prepared by The Directorate General of Foundations of the Republic of Turkey. In this paper, the sound absorption coefficients of 3 cm thick plaster layers were examined.

In the literature, two basic methods for the measurement of the sound absorption coefficient exist. In the first method, the sound absorption coefficient measurement is performed in accordance with the EN ISO 354 standard [21] and the sound-absorption coefficient is tested in a reverberation chamber. EN ISO 354 standard explains how the sound absorption coefficient of the diffusive sound can be measured, and the sound absorption coefficient used in the reverberation time can be determined with this method. The other sound absorption coefficient measurement method, which is carried out in accordance with the EN ISO 10534-2 standard [22], provides to obtain normal incidence sound absorption coefficient. Everest & Pohlmann [23] stated that the random-incidence coefficients are always higher than normal-incidence coefficients. In the ASTM C384-04 standard [24], it was noted that estimates of the random incidence or statistical absorption coefficients for materials can be obtained from normal incidence impedance data. Also, the study conducted by London [25] which searched to estimate diffusive incidence sound absorption coefficient (random incidence) from normal incidence sound absorption coefficient was referred in the ASTM C384-04 standard. In the research performed by London [25], it was observed that diffusive incidence sound absorption coefficient (random incidence) is higher than the normal incidence in general. As a result, in the literature researches, it was observed that normal-incidence coefficients are generally lower than random-incidence coefficients.

In general, EN ISO 354 standard provides more accurate results than EN ISO 10534-2 standard in diffusive incidence sound absorption coefficient. EN ISO 10534-2 standard method is more practical and much faster when there is a need for a large number of sound absorption coefficient measurements, and has been used in the majority of researches involving sound absorption coefficient measurements in the literature [1]. Degrave-Lemeurs et al. [11] mentioned that in the measurement of sound absorption in a reverberation room, tests are expensive and time-consuming due to the large amount of material needed. Bouzit et al. [12] indicated that a precise measurement of the acoustic properties is normally performed in reverberating rooms, under sound diffuse field conditions, but it is very expensive and time-consuming, due to the amount of material needed for fabricating large samples. In this research, the sound absorption coefficient measurements were performed in accordance with the EN ISO 10534-2 standard and impedance tube measurements results give general information about sound absorption for 17 different experiments.

The main aim of this study is the enhancing plaster layer sound absorption coefficients compatible with historical building structure. In this research, mixture content changes were researched in order to increase sound absorption in the plaster layer. The effects of aggregate combination volumetric ratio, polypropylene fiber ratio, flax fiber ratio, and crumb rubber additive ratio were investigated in the mortar mixtures. Mixture content change strategies were explained detail in the sample preparation section.

2. Methodology

The sound absorption coefficients were measured with an impedance tube in accordance with the EN ISO 10534-2 standard [22]. In this research, measurements of the sound absorption coefficient were carried out by the Turkish Standards Institute in accordance using the TS EN ISO 10534-2 standard. In the Turkish Standards Institute Acoustics Department, sound absorption coefficients were obtained using a SCS 9020B-branded impedance tube (Fig. 1a). Measurement results of the sound absorption coefficient were calculated using the SCS VIBRO-ACOUSTIC program and the SpectraPLUS-DT program integrated into SCS 9020B-branded impedance tube. Samples with two different diameter values were produced in order to be able to measure the sound absorption coefficient of frequencies in the range of 63–6300 Hz. When the sound absorption coefficient of frequencies in the range of 63–1500 Hz was calculated from samples of 100 mm diameter, the sound absorption coefficient of frequencies in the range of 1500–6300 Hz was calculated from samples of 28 mm diameter.

In this research, all of the samples subjected to sound absorption tests were produced in thicknesses of 30 mm and the samples were used to compare different mixture type in sound absorption tests. Before sound absorption test, all of the plaster layer samples were left in the open air for 180 days. In the literature, it can be seen that different samples are measured for each material in order to obtain a more accurate result during the measurement of sound absorption coefficient. Three different samples were tested for each material in certain frequency ranges in the research of Buratti et al. [26], Moretti et al. [16], Arenas et al. [27], Belekrum et al. [28], Chen et al. [29] and Bozkurt & Demirkale [1,2]. In this study, the average of the three different plaster layer samples produced with the same mixture type was taken into consideration in the sound absorption coefficient calculation. The curve of the sound absorption coefficient was obtained taking into account the average measurement result from the three samples of 100 mm diameter with the same type mixture and three samples of 28 mm diameter with the same type mixture. In the sound absorption test, a total of six samples at 30 mm thickness (3 samples of 100 mm diameter, and 3 samples of 28 mm diameter) were measured for each mixture type. 102 different samples (three samples with large diameters and three samples with small diameters of each thickness) were measured for the 17 different type sound absorption coefficient tests.

In order to compare the sound absorption coefficient values of the different mixture types, the single number grading methods which are independent of frequencies were examined. The NRC (Noise Reduction Coefficient) value which has seen wide use for sound absorption coefficient evaluations in the literature, was measured using the single number grading method specified in

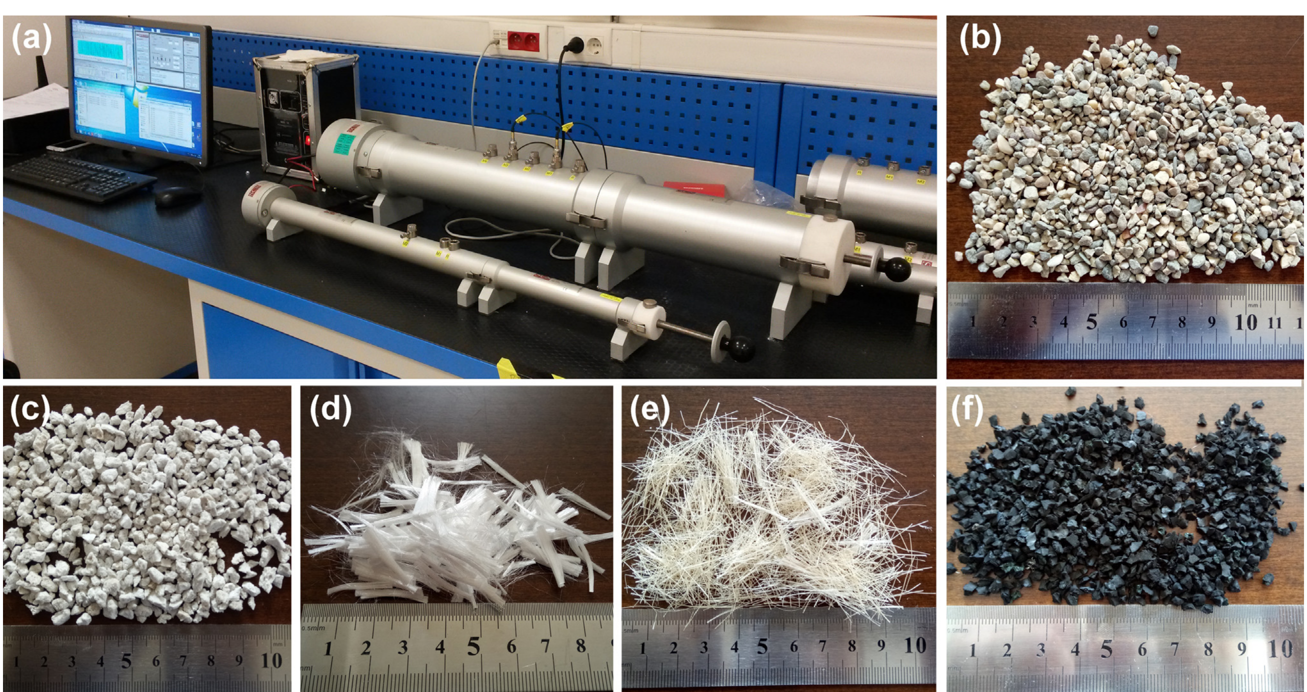

Fig. 1. The impedance tube and mixture materials, a) Impedance tube, b) River sand aggregate (between 2 and 4 mm), c) Pumice aggregate (between 2 and 4 mm), d) Polypropylene Fiber (20 mm length), e) Flax Fiber (20 mm length), f) Crumb rubber (between 4 and 2 mm) [3].

the ASTM C423-17 [30] and ASTM C634-13 [31] standards. The sound absorption coefficients of the plaster layers were analyzed with their NRC values (Eq. (1)) and the measurement results were compared in terms of their NRC values.

$$NRC = \frac{\alpha_{250} + \alpha_{500} + \alpha_{1000} + \alpha_{2000}}{4} \quad (1)$$

where

α_{250} = Sound absorption coefficient of 250 Hz	α_{1000} = Sound absorption coefficient of 1000 Hz
α_{500} = Sound absorption coefficient of 500 Hz	α_{2000} = Sound absorption coefficient of 2000 Hz

The weighted sound absorption coefficient (α_w) [32] and SAA (Sound Absorption Average) [30] may be used a single number rating of sound absorption in the literature. SAA is a single number rating which is obtained from the average of the sound absorption coefficients of a material for the twelve one-third octave bands from 200 through 2500 Hz, inclusive, measured (SAA = (α_{200} + α_{250} + α_{315} + α_{400} + α_{500} + α_{630} + α_{800} + α_{1000} + α_{1250} + α_{1600} + α_{2000} + α_{2500})/12). The weighted sound absorption coefficient (α_w) is a single number frequency independent value which equals the value of the reference curve at 500 Hz after shifting it as specified in EN ISO 11654 standard [32]. EN ISO 11654 standard indicates that whenever a practical sound absorption coefficient α_{pi} exceeds the value of the shifted reference curve by 0,25 or more, one or more shape indicators shall be added, in parentheses, to the α_w value. In this research, in order to show shape indicators, the notation H according to EN ISO 11654 standard was used when the excess absorption occurs at 2000 Hz or 4000 Hz. The weighted sound absorption coefficient (α_w) is generally used for diffusive incidence sound absorption coefficient (the measurement of sound absorption in a reverberation room). Moreover, the impedance tube measurement results may be used to obtain the weighted sound absorption coefficient (α_w) according to normal incidence in the literature [27] and the weighted sound absorption coefficient (α_w) according to normal incidence gives general information to compare different materials.

In the scope of this research, in addition to the sound absorption coefficient experiments, some complementary experiments were carried out. More specifically, in order to investigate the effect of mixing ratio changes on the measurement results, further experimental analyses which are listed as compressive strength, flexural strength, open porosity, capillary water absorption tests, were conducted other than the sound-absorption coefficient measurements. In this respect, other parameters except sound absorption coefficient were examined. Compressive strength, flexural strength, open porosity, capillary water absorption tests were performed for the seventeen different mixture types (before experimental analyses, the produced samples were kept in the open air for 180 days). For flexural and compressive strength tests, the samples were prepared in the size of 40 × 40 × 160 mm and subjected to compressive and flexural strength tests in accordance with the BS EN 1015-11 [33]. Moreover, open porosity tests in accordance with the BS EN 1936:2006 standard [34] and the capillary water absorption tests in accordance with the BS EN 1015-18:2002 standard [35] were performed for each mixture type.

3. Sample preparation

The restoration mortars generally used in Turkey were defined in the prepared report [36]. The report includes descriptions of the restoration constructions of the Directorate General of Foundations of the Republic of Turkey and defines the pricing and content of restoration constructions. The mixtures included in the report were investigated and the mixture content presented in Table 1 was examined.

This study investigates the mixture content which is shown in Table 1 and intends to increase the sound absorption coefficient. The mortar mixtures were changed and the effects of the changes on the sound absorption coefficient were researched under the following headings:

- The effects of changes in the aggregate combination type on the sound absorption coefficient
- The effects of the polypropylene fiber additive on the sound absorption coefficient
- The effects of the flax fiber additive on the sound absorption coefficient
- The effects of the crumb rubber additive on the sound absorption coefficient

Previous studies explaining the relationship between the binder volumetric ratio and sound absorption were researched in a literature review, and it was observed that increasing the binder volumetric ratio leads to a decrease in sound absorption in general terms. This situation can be seen especially in the researches of authors Horoshenkov et al. [37], Gle et al. [38] and Belekrum et al. [28]. Also in the previous phase of this research, mortar mixtures prepared with river sand aggregate and natural hydraulic lime binder were examined to analyze sound absorption and it was indicated that increasing the binder ratio in mixtures can have an adverse effect on the sound absorption coefficient [2]. Hence, the binder ratio in the mixtures was reduced in the pumice aggregate analyses and prepared mortar mixtures binder/aggregate volumetric ratio was determined to be 1:3 (This ratio is lower than Table 1).

A literature search of aggregate particle size range demonstrated (in mixtures based on binders) that the use of aggregate in very small sizes (fine sand) can decrease the sound absorption coefficient. This was observed in detail in the experimental studies performed by Neithalath [39], Zhao et al. [40], Palomar et al. [41] and Arenas et al. [27]. Moreover, in the previous phase of this research, mortar mixtures prepared with river sand aggregate and natural hydraulic lime binder were investigated to analyze sound absorption and it was shown that superfine aggregate (between 0 and 2 mm) could have an adverse effect on the sound absorption coefficient, and that using an aggregate of 2–4 mm without 0–2 mm aggregate can be useful in increasing the sound absorption coefficient [2]. Hence, mortar mixtures were prepared with using only 2–4 mm aggregate particle size in the pumice aggregate analyses (only 2–4 mm aggregate particle size was used in the mortar mixtures and Table 1 content was changed to increase sound absorption).

Shen et al. [13], Zhao et al. [40] and Palomar et al. [41] investigated different aggregate combinations in the mixture. Also, authors showed that changing aggregate combination can lead to an increase in sound absorption. In this research, the effect of aggregate combination on sound absorption was examined in the plaster layer by means of changing river sand (Fig. 1b) and pumice aggregate (Fig. 1c) ratio in the mortar mixtures.

Table 1
The mortar mixtures selected from the prepared report [36].

500 kg Natural Hydraulic Lime 3.5 (NHL 3.5) (Binder/Aggregate volume ratio ≈ 1/1.56)
0.600 m^3 sand (Between 2 and 4 mm)
0.400 m^3 sand (Between 0 and 2 mm)
360 L of water

The polypropylene fiber additive is the one of the alternative materials which is used in the restoration works carried out in Turkey [2]. Hence, the effects of polypropylene fiber additive on sound absorption coefficient were examined. Neithalath [39] used polypropylene fiber additive in different proportions to a maximum of 1.5% in the research on porous concrete and it was showed that polypropylene fiber additive may improve the sound absorption coefficient. It was indicated that a polypropylene fiber additive may increase sound absorption coefficients at certain frequency values in the researches of Zhao et al. [40] and Palomar et al. [41]. Also, in the previous phase of this research, mortar mixtures prepared with river sand aggregate and natural hydraulic lime binder were examined to determine the effect of polypropylene fiber additive on sound absorption (in different proportions to a maximum of 2%) and it was determined that the use of polypropylene fiber additives in the mixtures increases the sound absorption coefficient at low frequencies up to 750 Hz [2]. In this research which is related with pumice aggregate analyses, five different mortar mixture samples were prepared including a maximum of 2% polypropylene fiber (Fig. 1d), and the effects of the different ratios of polypropylene fiber additive on the sound absorption coefficient were investigated.

It was observed that the flax fiber (Fig. 1e) additive may be used in the restoration mortar mixtures in Turkey [20]. Moreover, in the previous phase of this research, mortar mixtures prepared with river sand aggregate and natural hydraulic lime binder were analyzed to define the effect of flax fiber additive on sound absorption (in different proportions to a maximum of 0,6%) and it was explained that adding flax fiber additives to the mixtures can be a good way to improve the sound absorption coefficient, and flax fiber additives have especially positive effects on the sound absorption coefficient at low frequencies up to 900 Hz [2]. In this research which is related with pumice aggregate analyses, to investigate the effects of the addition of flax fiber on the sound absorption coefficient, five different mixture contents were produced with ratios in a range of 0–0.6%. In this direction, the effects of the different ratios of flax fiber on the sound absorption coefficient were examined.

In the literature review, it was seen that the use of crumb rubber may be beneficial to improve sound absorption coefficient. In the researches of authors Stankevičius et al. [42], Sukontasukkul [43], Mohammed et al. [44], Pastor et al. [45], Holmes & Browne [46], Medina et al. [47], Gandoman & Kokabi [48] and Corredor-Bedoya et al. [49], this situation can be observed. In the previous phase of this research, (*the mortar mixtures prepared with river sand aggregate and natural hydraulic lime binder*), it was noted that the use of crumb rubber additives in certain proportions in place of aggregate can be a positive effect on sound absorption coefficient at low frequencies [2]. The use of crumb rubber (Fig. 1f) as a substitute for aggregate was investigated.

In the literature, it is shown that painting concrete and brick surfaces can affect the sound absorption coefficient value negatively. On the lists in which the authors Metha et al. [50], Barron [51] and Long [52] presented sound absorption coefficient values based on different frequencies, it was shown that painting concrete and brick surfaces decreases the sound absorption coefficient value. Also, in the book prepared by Everest & Pohlmann [23], it was demonstrated that painting concrete surfaces reduces the sound absorption coefficient value. Moreover, on the list on which sound absorption coefficient values are presented according to frequencies given in the book written by Cox and D'Antonio [53], it is noted that the painting of plaster surface can decrease the sound absorption coefficient. In brief, a search of previous studies reveals that the painting of mortar based surface coatings decreases the sound absorption coefficient value. In this research, the application of paint is not recommended in order to increase sound absorption performance and samples were subjected to sound absorption coefficient measurements without paint. In Fig. 2, in order to demonstrate surface properties on the upper scale, the surface photos of produced samples were shown. It is predicted that the suggested mixture types can be used without painting in the room surfaces and the use of plaster surfaces without painting is visually appropriate. It is clear that the mixtures produced through these studies can be used both in restorations and modern buildings constructions.

3.1. The mixtures based on aggregate combination volumetric ratio in the mixture of aggregate

The effect of using pumice aggregate as a light aggregate instead of river sand aggregate in the mortar mixture was investigated in order to increase sound absorption in the plaster layer. In the scope of the study, pumice aggregate ranges of 4–2 mm and river sand aggregate ranges of 4–2 mm were examined. A research was performed to better understand which aggregate combination type is optimal for the increase of the sound absorption coefficient. In this research, it was observed that an approximate density value of the pumice aggregate (between 2 and 4 mm) is 510 kg/m^3, while an approximate density value of the river sand aggregate (between 2 and 4 mm) is 1480 kg/m^3. The two different aggregate type were mixed at different ratios, and mixtures were prepared without changing the total aggregate volume. Mixtures were produced so as to have pumice aggregate ratios proportionate to the total aggregate of 0%, 25%, 50%, 75% and 100%. The mixtures were codified based on the increasing pumice aggregate amounts as R1, C1, C2, C3 and P1, respectively. The results of the measurement of the R1 coded sample are given in the previously published article and in this publication, it is also given R1 coded sample measurement results in order to compare the pumice aggregate mixtures (in the previously published article, R1 coded mixture was defined as K2 [2]). The water content of the mortar mixtures was determined in accordance with the BS EN 1015-2 [54] and BS EN 1015-3 [55] standards. The mixture content and mortar flow values are shown in Table 2.

3.2. The mixtures based on polypropylene fiber ratio

The effects of different percentages of polypropylene fiber additive on the sound absorption coefficient were investigated. Five different mixture types were prepared including different polypropylene fiber ratios. The ratios of the polypropylene fiber added to the mixtures were defined as 0%, 0.5%, 1.0%, 1.5% and 2.0% of the aggregate volume, and the resulting mixtures were coded, based on increasing polypropylene fiber quantities, as P1, P2, P3, P4 and P5 respectively. An approximate density value of the polypropylene fiber (910 kg/m^3) was obtained from the literature [39], and the mixtures were produced. The mixture contents are given in Table 3.

3.3. The mixtures based on flax fiber ratio

The effect of the addition of flax fiber additives in different percentages on the sound absorption coefficient was investigated. Five different mixture types were produced containing different ratios of flax fiber and the mixtures were compared with each other. The ratios of flax fiber ratios added to the mixtures were defined as 0%, 0.15%, 0.30%, 0.45% and 0.60% of the aggregate volume, and mixtures were coded in terms of the increasing flax fiber content as P1, P6, P7, P8, and P9, respectively. The approximate density value of flax fiber (1500 kg/m^3) was obtained from the literature [56–58] and mixtures were produced. The mixture content and mortar flow values are presented in Table 4.

Fig. 2. The pictures of the samples, a) R1 mixture type, b) C2 mixture type, c) P1 mixture type, d) P4 mixture type, e) P8 mixture type, f) P13 mixture type [3].

Table 2
The mixture ratios of R1, C1, C2, C3 and P1 [3].

	R1 [2]	C1	C2	C3	P1
River Sand Aggregate (Between 2 and 4 mm)	1 vol	0.75 vol	0.50 vol	0.25 vol	0 vol
Pumice Aggregate (Between 2 and 4 mm)	0 vol	0.25 vol	0.50 vol	0.75 vol	1 vol
Natural Hydraulic Lime 3.5 (NHL 3.5)	0.333 vol	0.333 vol	0.333 vol	0.333 vol	0.333 vol
Water	0.271 vol	0.292 vol	0.312 vol	0.333 vol	0.354 vol
Fresh Mortar Flow Value (mm) (In Accordance With BS EN 1015-2)	175 ± 3	170 ± 3	170 ± 3	170 ± 3	160 ± 3

Table 3
The mixture ratios of P1, P2, P3, P4 and P5 [3].

	P1	P2	P3	P4	P5
Aggregate (Pumice) (Between 2 and 4 mm)	1 vol	1 vol	1 vol	1 vol	1 vol
Natural Hydraulic Lime 3.5 (NHL 3.5)	0.333 vol	0.333 vol	0.333 vol	0.333 vol	0.333 vol
Water	0.354 vol	0.379 vol	0.416 vol	0.437 vol	0.448 vol
Polypropylene Fiber Ratio – %	0%	0.5% (4.55 gr/lt)	1.0% (9.1 gr/lt)	1.5% (13.65 gr/lt)	2.0% (18.2 gr/lt)

3.4. The mixtures based on crumb rubber volumetric ratio in the mixture of aggregate

The effect of adding crumb rubber at different percentages in the place of pumice aggregate was investigated. Five different mixture types were prepared to contain different crumb rubber ratio (crumb rubber added instead of pumice aggregate to mixtures but in the same volumes) at this stage and then different mixtures compared with each other. The crumb rubber was added to the mixtures instead of the pumice aggregate at ratios of 0%, 7.5%,

Table 4
The mixture ratios of P1, P6, P7, P8 and P9 [3].

	P1	P6	P7	P8	P9
Aggregate (Pumice) (Between 2 and 4 mm)	1 vol	1 vol	1 vol	1 vol	1 vol
Natural Hydraulic Lime 3.5 (NHL 3.5)	0.333 vol	0.333 vol	0.333 vol	0.333 vol	0.333 vol
Water	0.354 vol	0.365 vol	0.375 vol	0.385 vol	0.396 vol
Flax Fiber Ratio – %	0%	0.15% (2.25 gr/lt)	0.30% (4.55 gr/lt)	0.45% (6.75 gr/lt)	0.60% (9.1 gr/lt)
Fresh Mortar Flow Value (mm)(In Accordance With BS EN 1015-2)	160 ± 3	160 ± 3	155 ± 3	155 ± 3	155 ± 3

15%, 22.5% and 30% respectively, and the mixtures were coded according to the increasing crumb rubber ratios as P1, P10, P11, P12 and P13, respectively. All the crumb rubber additives that were added to mixtures in place of the pumice aggregate were determined as having a particle size of 2–4 mm. Attention was paid to ensuring that both the used pumice aggregate particle sizes and the added crumb rubber particle sizes were in the same range. The mixture contents and mortar flow values are shown in Table 5.

4. Results of the experiments

In this chapter, the measurement results were given according to mixture types. The results of aggregate combination volumetric ratio in the mixture of aggregate, the results of polypropylene fiber ratio in the mixture, the results of flax fiber ratio in the mixture and the results of crumb rubber additive volumetric ratio in the mixture of aggregate were detailed.

4.1. The aggregate combination volumetric ratio in the mixture of aggregate

Sound absorption coefficient measurement results based on the aggregate combination ratio were given in Table 6. In these analyses, the highest NRC value was obtained in P1 mixture type which does not consist of river sand aggregate in the mortar mixture. The α_w value of the mixtures is equal but at 4000 or 2000 Hz, all mixtures except the C1 show a high absorption character according to EN ISO 11654. Mechanical, open porosity and water absorption tests were shown in Table 7. The maximum compressive strength and flexural strength were obtained in P1. The highest SAA and

Table 5
The mixture ratios of P1, P10, P11, P12 and P13 [3].

	P1	P10	P11	P12	P13
Aggregate (Pumice) (Between 2 and 4 mm)	1 vol	0.925 vol	0.850 vol	0.775 vol	0.700 vol
Crumb Rubber (Between 2 and 4 mm)	0 vol	0.075 vol	0.150 vol	0.225 vol	0.300 vol
Natural Hydraulic Lime 3.5 (NHL 3.5)	0.333 vol	0.333 vol	0.333 vol	0.333 vol	0.333 vol
Water	0.354 vol	0.354 vol	0.354 vol	0.354 vol	0.354 vol
Fresh Mortar Flow Value (mm)(In Accordance With BS EN 1015-2)	160 ± 3	160 ± 3	160 ± 3	165 ± 3	165 ± 3

Table 6
1/3 octave band sound absorption coefficient measurement results and NRC, SAA and α_w value (for normal incidence) – R1, C1, C2, C3 and P1 [3].

Frequency (Hz)	R1 [2] Pumice aggregate volumetric ratio in the mixture of aggregate = 0%	C1 Pumice aggregate volumetric ratio in the mixture of aggregate = 25%	C2 Pumice aggregate volumetric ratio in the mixture of aggregate = 50%	C3 Pumice aggregate volumetric ratio in the mixture of aggregate = 75%	P1 Pumice aggregate volumetric ratio in the mixture of aggregate = 100%
100	0.01	0.01	0.01	0.01	0.01
125	0.01	0.01	0.01	0.01	0.01
160	0.02	0.01	0.01	0.02	0.01
200	0.02	0.01	0.01	0.01	0.01
250	0.02	0.01	0.01	0.01	0.01
315	0.03	0.02	0.02	0.02	0.02
400	0.06	0.06	0.05	0.06	0.05
500	0.05	0.04	0.03	0.04	0.03
630	0.05	0.03	0.02	0.03	0.02
800	0.12	0.07	0.06	0.07	0.06
1000	0.22	0.17	0.15	0.14	0.11
1250	0.32	0.30	0.41	0.28	0.27
1600	0.32	0.40	0.53	0.65	0.48
2000	0.29	0.33	0.32	0.40	0.48
2500	0.23	0.22	0.23	0.25	0.27
3150	0.26	0.16	0.19	0.19	0.20
4000	0.35	0.21	0.37	0.26	0.31
5000	0.61	0.50	0.50	0.44	0.54
NRC	**0.145**	**0.138**	**0.128**	**0.148**	**0.158**
SAA	0.144	0.138	0.153	0.163	0.151
α_w (ISO 11654) for normal incidence	0.15 (H)	0.15	0.15 (H)	0.15 (H)	0.15 (H)

Table 7
Measurement results based on aggregate combination volumetric ratio in the mixture of aggregate [3].

	R1 [2]	C1	C2	C3	P1
Compressive strength (N/mm^2)	2.24	2.47	2.55	2.58	2.84
Flexural strength (N/mm^2)	0.99	1.06	1.08	1.26	1.75
Open porosity (%)	21.14	24.81	27.09	29.84	32.45
Coefficient of water absorption of the sample of mortar due to capillary action , ($kg/m^2min^{0,5}$)	1.16	1.70	1.84	2.06	2.01

capillary water absorption level belong to C3. P1 has the maximum open porosity level.

4.2. The polypropylene fiber ratio in the mixture

Sound absorption coefficient measurement results based on polypropylene fiber ratio in the mixture were shown in Table 8. It was observed that the NRC value of the mixture (coded as P2) which contains 0.5% polypropylene fiber additive ratio in the mortar mixture, was the highest and also, the maximum SAA value was acquired in P5. Although the α_w value of the mixtures is equal, P2, P4 and P5 demonstrate a high absorption character at 4000 and 2000 Hz according to EN ISO 11654. The results of the material measurement were shown in Table 9. In the results, the maximum compressive strength and flexural strength were obtained from P1. Furthermore, P4 has the highest open porosity ratio and the highest capillary water absorption level.

4.3. The flax fiber ratio in the mixture

Sound absorption coefficient measurement results based on flax fiber ratio in the mixture were given in Table 10. The NRC and SAA value of the mixture containing 0.60% flax fiber (coded as P9) were the highest according to the impedance tube measurement result. According to EN ISO 11654, the α_w value of the mixtures is 0.15 while P7, P8 and P9 show a high absorption character at 4000 and 2000 Hz. Compressive strength, flexural strength, open porosity and the capillary water absorption coefficient results were shown in Table 11. P1 has the highest compressive and flexural strength. It was observed that P9 has the highest open porosity and capillary water absorption coefficient level.

4.4. The crumb rubber volumetric ratio in the mixture of aggregate

Sound absorption coefficient measurement results based on crumb rubber volumetric ratio in the mixture of aggregate were given in Table 12. The NRC and SAA value of the mixture which contains 15% crumb rubber volumetric ratio in the mixture of aggregate, was found to be the highest (Table 12) according to the results of the impedance-tube measurement tests. Also, the α_w value of the mixtures which contain crumb rubber instead of pumice aggregate in the mixture of aggregate, have the highest value. Moreover, the α_w value of P10, P11, P12 and P13 mixtures is 0.20 and these mixtures show a high absorption character at

Table 8
1/3 octave band sound absorption coefficient measurement results and NRC, SAA and α_w value (for normal incidence) – P1, P2, P3, P4 and P5 [3].

Frequency (Hz)	P1 Polypropylene fiber ratio in the mixture = 0.0%	P2 Polypropylene fiber ratio in the mixture = 0.5%	P3 Polypropylene fiber ratio in the mixture = 1.0%	P4 Polypropylene fiber ratio in the mixture = 1.5%	P5 Polypropylene fiber ratio in the mixture = 2.0%
100	0.01	0.01	0.01	0.01	0.01
125	0.01	0.01	0.02	0.01	0.01
160	0.01	0.01	0.02	0.01	0.01
200	0.01	0.01	0.02	0.01	0.01
250	0.01	0.02	0.02	0.02	0.02
315	0.02	0.02	0.03	0.03	0.03
400	0.05	0.07	0.10	0.07	0.10
500	0.03	0.04	0.05	0.04	0.05
630	0.02	0.04	0.05	0.04	0.04
800	0.06	0.09	0.10	0.09	0.10
1000	0.11	0.19	0.23	0.18	0.22
1250	0.27	0.36	0.40	0.41	0.48
1600	0.48	0.70	0.33	0.73	0.67
2000	0.48	0.47	0.28	0.46	0.42
2500	0.27	0.29	0.22	0.31	0.28
3150	0.20	0.24	0.18	0.32	0.24
4000	0.31	0.41	0.25	0.65	0.35
5000	0.54	0.74	0.48	0.61	0.66
NRC	**0.158**	**0.180**	**0.145**	**0.175**	**0.178**
SAA	0.151	0.192	0.153	0.199	0.202
α_w (ISO 11654) for normal incidence	0.15 (H)	0.15 (HH)	0.15	0.15 (HH)	0.15 (HH)

Table 9
Measurement results based on polypropylene fiber ratio in the mixture [3].

	P1	P2	P3	P4	P5
Compressive strength (N/mm^2)	2.84	2.34	2.52	2.40	2.55
Flexural strength (N/mm^2)	1.75	1.43	1.27	1.27	1.31
Open porosity (%)	32.45	36.30	38.67	41.85	40.62
Coefficient of water absorption of the sample of mortar due to capillary action ($kg/m^2min^{0,5}$)	2.01	2.22	2.43	2.68	2.15

Table 10
1/3 octave band sound absorption coefficient measurement results and NRC, SAA and α_w value (for normal incidence) – P1, P6, P7, P8 and P9 [3].

Frequency (Hz)	P1 Flax fiber ratio in the mixture = 0.00%	P6 Flax fiber ratio in the mixture = 0.15%	P7 Flax fiber ratio in the mixture = 0.30%	P8 Flax fiber ratio in the mixture = 0.45%	P9 Flax fiber ratio in the mixture = 0.60%
100	0.01	0.01	0.01	0.02	0.01
125	0.01	0.01	0.01	0.02	0.02
160	0.01	0.02	0.01	0.02	0.02
200	0.01	0.01	0.01	0.02	0.02
250	0.01	0.02	0.02	0.02	0.02
315	0.02	0.03	0.03	0.03	0.04
400	0.05	0.08	0.11	0.08	0.09
500	0.03	0.04	0.04	0.05	0.06
630	0.02	0.03	0.03	0.05	0.06
800	0.06	0.07	0.08	0.11	0.13
1000	0.11	0.16	0.17	0.23	0.27
1250	0.27	0.37	0.41	0.44	0.43
1600	0.48	0.65	0.76	0.78	0.62
2000	0.48	0.38	0.41	0.41	0.52
2500	0.27	0.24	0.26	0.26	0.33
3150	0.20	0.20	0.21	0.23	0.29
4000	0.31	0.31	0.38	0.41	0.46
5000	0.54	0.43	0.61	0.67	0.88
NRC	**0.158**	**0.150**	**0.160**	**0.178**	**0.218**
SAA	0.151	0.173	0.194	0.207	0.216
α_w (ISO 11654) for normal incidence	0.15 (H)	0.15	0.15 (HH)	0.15 (HH)	0.15 (HH)

Table 11
Measurement results based on flax fiber ratio in the mixture [3].

	P1	P6	P7	P8	P9
Compressive strength (N/mm^2)	2.84	2.57	2.33	2.61	2.66
Flexural strength (N/mm^2)	1.75	1.66	1.50	1.48	1.45
Open porosity (%)	32.45	33.49	33.50	34.48	36.76
Coefficient of water absorption of the sample of mortar due to capillary action (kg/m^{2}min^{0,5})	2.01	1.81	2.13	2.14	2.69

Table 12
1/3 octave band sound absorption coefficient measurement results and NRC, SAA and α_w value (for normal incidence) – P1, P10, P11, P12 and P13 [3].

Frequency (Hz)	P1 Crumb rubber volumetric ratio in the mixture of aggregate = 0.0%	P10 Crumb rubber volumetric ratio in the mixture of aggregate = 7.5%	P11 Crumb rubber volumetric ratio in the mixture of aggregate = 15.0%	P12 Crumb rubber volumetric ratio in the mixture of aggregate = 22.5%	P13 Crumb rubber volumetric ratio in the mixture of aggregate = 30.0%
100	0.01	0.01	0.01	0.01	0.01
125	0.01	0.01	0.01	0.01	0.01
160	0.01	0.02	0.01	0.02	0.02
200	0.01	0.02	0.02	0.02	0.02
250	0.01	0.02	0.03	0.03	0.03
315	0.02	0.03	0.04	0.05	0.04
400	0.05	0.13	0.11	0.12	0.11
500	0.03	0.07	0.09	0.09	0.11
630	0.02	0.09	0.13	0.12	0.14
800	0.06	0.16	0.23	0.19	0.23
1000	0.11	0.29	0.39	0.31	0.35
1250	0.27	0.33	0.45	0.37	0.46
1600	0.48	0.24	0.47	0.28	0.36
2000	0.48	0.30	0.44	0.31	0.36
2500	0.27	0.29	0.35	0.26	0.32
3150	0.20	0.31	0.39	0.26	0.33
4000	0.31	0.50	0.55	0.37	0.52
5000	0.54	0.64	0.55	0.55	0.64
NRC	**0.158**	**0.170**	**0.238**	**0.185**	**0.213**
SAA	0.151	0.164	0.229	0.179	0.211
α_w (ISO 11654) for normal incidence	0.15 (H)	0.20 (H)	0.20 (H)	0.20 (H)	0.20 (H)

Table 13
Measurement results based on crumb rubber volumetric ratio in the mixture of aggregate [3].

	P1	P10	P11	P12	P13
Compressive strength (N/mm^2)	2.84	2.06	1.79	1.32	1.10
Flexural strength (N/mm^2)	1.75	1.48	1.27	1.01	0.97
Open porosity (%)	32.45	31.12	32.31	31.62	33.06
Coefficient of water absorption of the sample of mortar due to capillary action (kg/m^{2}min$^{0.5}$)	2.01	1.61	1.88	1.75	1.84

4000 or 2000 Hz according to EN ISO 11654. The results of material measurements were given in Table 13. In these results, P1 mixture type has the maximum compressive and flexural strength. In addition, P10 mixture type has the minimum capillary water absorption level and open porosity. The maximum open porosity was obtained in P13. P1 has the biggest capillary water absorption level.

5. Discussion

The discussion section was explained in two different subsections. In the first sub-section, the effects of mortar mixture ratio were examined. In the second subsection, the comparison of all sound absorption measurements was clarified.

In the first subsection, the parameters that depend on the mortar mixture ratios were investigated. According to changing mixture parameters, sound absorption, mechanical, open porosity and water absorption tests were examined. In this section, the changes in only one parameter have been taken into consideration for each analysis type. Sound absorption was investigated with two different parameters. The NRC value which is used in the single number grading method frequency-based analyses is the important parameter of sound absorption and was discussed with compressive strength, flexural strength, open porosity and water absorption tests in order to evaluate changing mixture properties. In reverberation time analysis, sound absorption value based on frequency is taken into consideration to obtain the required range in frequency based reverberation time. For that reason, the frequency-dependent sound absorption coefficient was detailed as the important parameter of sound absorption.

In the second subsection, a totally of 17 different sound absorption measurement results were compared with each other. Evaluation of all sound absorption measurements was performed. The mixtures which have maximum NRC value were explained, respectively. Also, the mixtures which have the highest sound absorption coefficient based on frequency were clarified.

5.1. The effects of mortar mixture ratio

In this subsection, the effects of aggregate combination volumetric ratio in the mixture of aggregate, the effects of polypropylene fiber ratio in the mixture, the effects of flax fiber ratio in the mixture and the effects of crumb rubber additive volumetric ratio in the mixture of aggregate were discussed.

5.1.1. The effects of aggregate combination volumetric ratio in the mixture of aggregate

In the mortar mixtures, the use of 4–2 mm particle size pumice aggregate instead of 4–2 mm particle size river sand aggregate were examined and a comparison of NRC values attained from the measurements is also shown on the graphic, from which a correlation between NRC and pumice volumetric ratio in the mixture of the aggregate was tried to be made. It was observed that the NRC value decreased at first adding of pumice aggregate and the minimum NRC value was obtained when the pumice volumetric ratio in the mixture of the aggregate was 0.5 (Fig. 3). Also, it was observed that the NRC value showed a continuous increase in the pumice aggregate volumetric ratio range of 0.5–1 and the highest NRC value was obtained with the maximum the pumice volumetric ratio in the mixture of the aggregate. It was determined that as the pumice aggregate volumetric ratio in the mixtures increases, flexural and compressive strengths also increase, to a significant level. Although pumice aggregate is lighter than river sand aggregate, it was determined that the use of pumice aggregate instead of river sand aggregate effects positively the compressive and flexural strengths. It was further determined that as the pumice aggregate volumetric ratio increases, open the porosity ratio also increases continuously. As the pumice aggregate volumetric ratio in the identified mixtures increases, capillary water absorption levels increase, in general.

On the graphic, it was seen that an increase of pumice aggregate in the mixture of aggregate can affect positively the peak points which the maximum sound absorption coefficient based on frequencies is observed (Fig. 4). On the other hand, with the addition of pumice aggregate, at low frequencies up to 1200 Hz, a decrease in the sound absorption coefficient was observed. In this context, it has been determined that sound absorption in the range of 400–1000 Hz is generally decreased when the pumice ratio in the mixture of aggregate increases. It was seen that the use of pumice aggregate instead of the use of river sand aggregate in the mixtures can be a more effective way for increasing sound absorption coefficient in the range of approximately 1400–2700 Hz. This research may provide suitable mixture alternatives for 1400–2700 Hz fre-

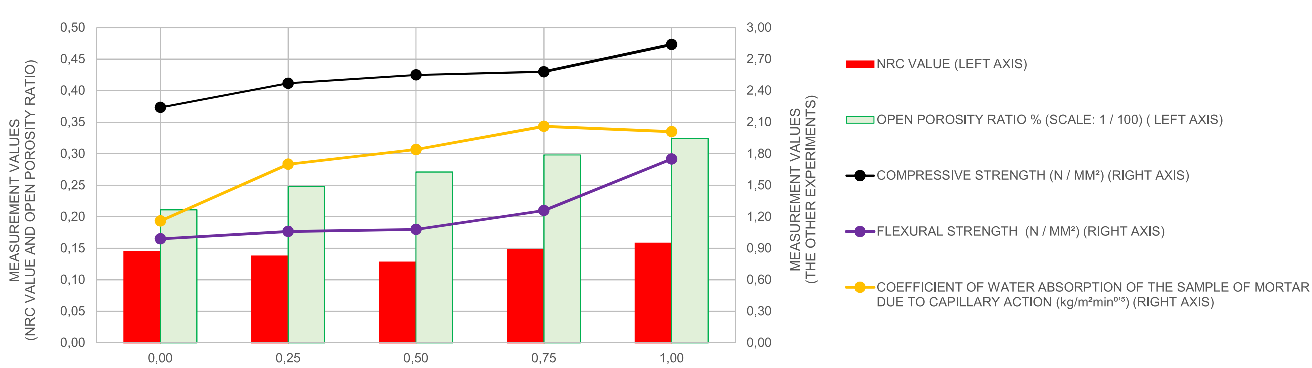

Fig. 3. The comparison of pumice aggregate volumetric ratios in the mixture of the aggregate [3].

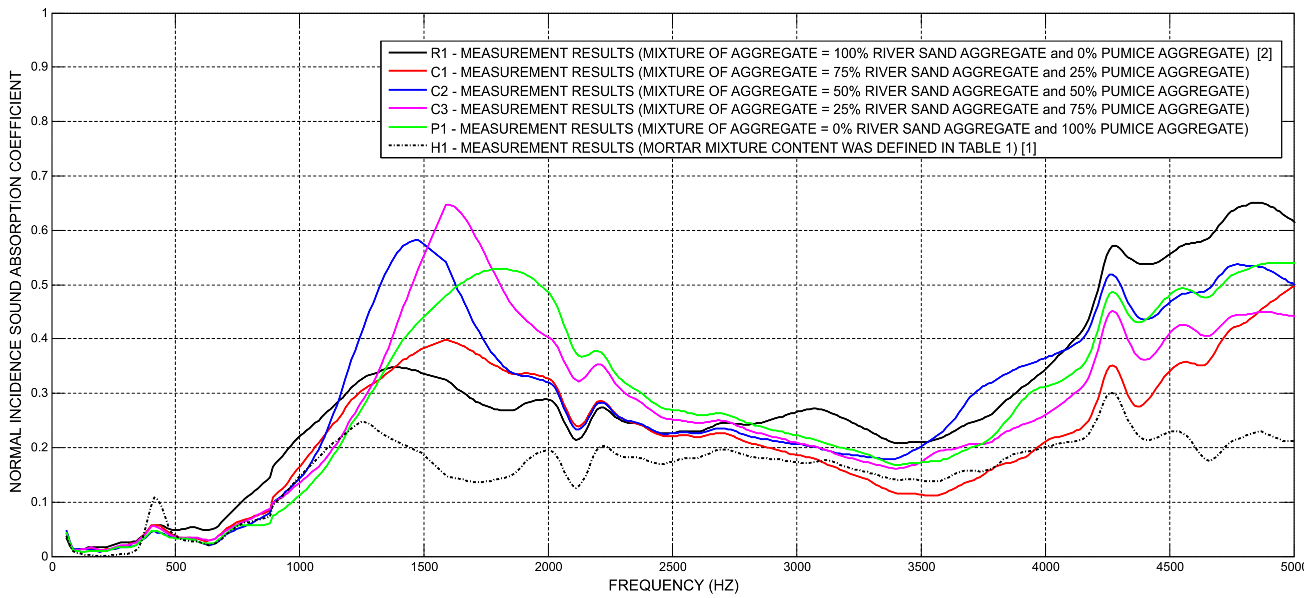

Fig. 4. The comparison of sound absorption coefficient curves – R1, C1, C2, C3, P1 and H1 [3].

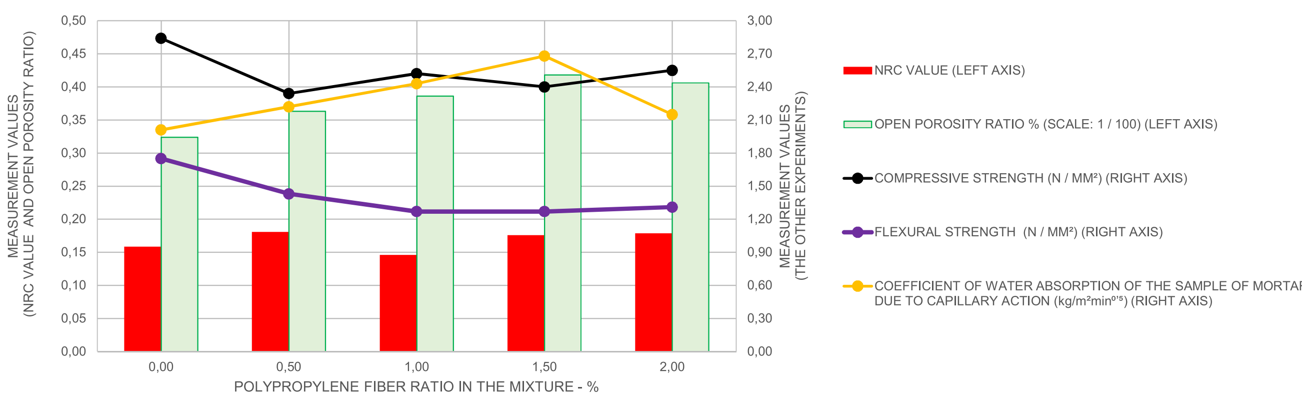

Fig. 5. The comparison of polypropylene fiber ratios in the mixture [3].

quency range improvements in the reverberation time calculations. It was seen that all of the mixtures prepared for increasing the sound absorption coefficient are generally better than the type of mixture defined in Table 1. The sound absorption coefficient curve of the 3 cm thick plaster layer which is produced from the mixture content in Table 1, was given in order to demonstrate the increase in sound absorption based on changing mixture types. The sound absorption analyses of the content of the mortar mixture which were given in Table 1, were detailed in the previously published manuscript and 3 cm thick plaster layer in this mixture type was coded as H1 [1].

5.1.2. The effects of polypropylene fiber ratio in the mixture

It was observed that the polypropylene fiber additive affects positively the NRC value in general and the maximum NRC value was obtained from the mixture which polypropylene fiber ratio in the mixture is 2.0% (Fig. 5). However, only the use of polypropylene fiber additive ratio of 1.0% in the mortar mixture was reduced the NRC value. It was determined that the polypropylene fiber additive has a negative effect on compressive strength in general. Also, the polypropylene fiber additive in mortar mixture which is prepared with pumice aggregate decreases flexural strength. It is estimated that this situation may only occur with a pumice aggregate size of 2–4 mm (without using 0–2 mm aggregate at all). It was observed that as the ratio of polypropylene fiber in the mixture increases, so does the open porosity. It was understood that adding polypropylene fiber additive in the range of 0–1.5% to the mixture increases the capillary water absorption level.

The ratio of polypropylene fiber has an effect on the sound absorption coefficient and it was determined that the polypropylene fiber additive in mortar mixtures increases the sound absorption coefficient generally in the range of 100–1400 Hz (Fig. 6). In this analysis, it was understood that it is a good method to use polypropylene fiber additive in mortar mixtures in order to increase the sound absorption coefficient at low frequencies. Also, it was observed that polypropylene fiber additive in mortar mixtures can increase the peak points which the maximum sound absorption coefficient based on frequencies is obtained. It was also determined that the use of 1.0% polypropylene fiber additive ratio in mortar mixtures decreases sound absorption in general compared to the other mortar mixtures which contain polypropylene fiber additive at different ratios. The maximum sound absorption coefficient in the range of 2500–4000 Hz frequency was obtained by means of the use of 1.5% polypropylene fiber

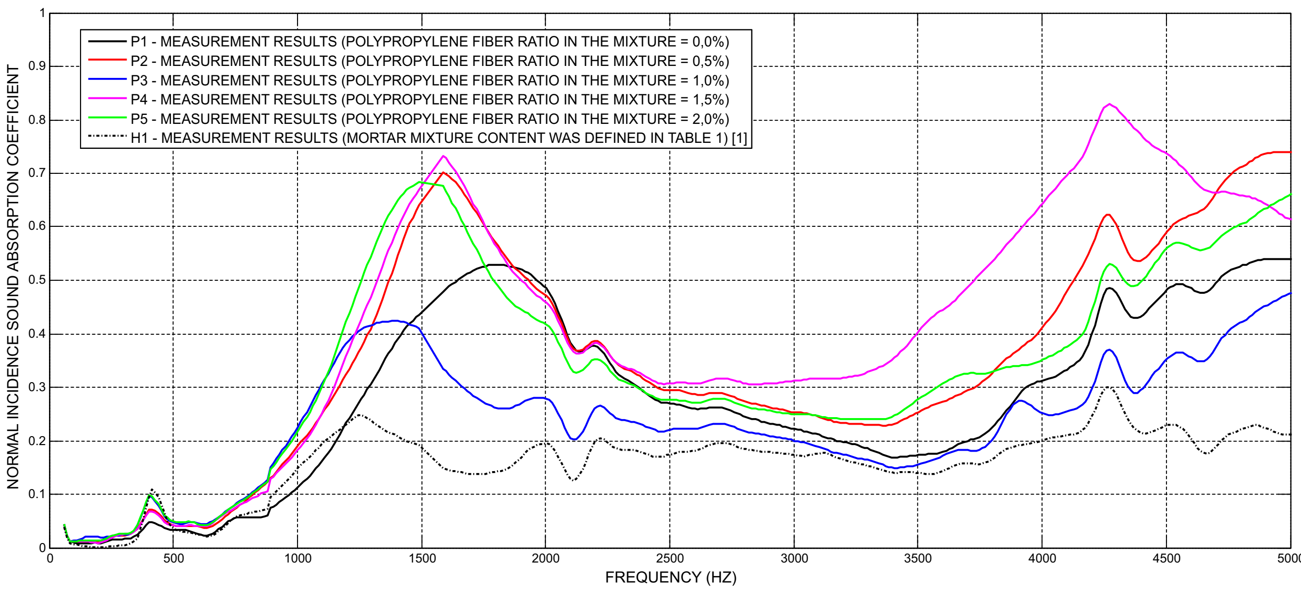

Fig. 6. The comparison of sound absorption coefficient curves – P1, P2, P3, P4, P5 and H1 [3].

additive ratio in the mortar mixtures. It was observed that all of the mixtures which were prepared with pumice aggregate and polypropylene fiber additive for increasing the sound absorption coefficient are generally better than the type of mixture defined in Table 1.

5.1.3. The effects of flax fiber ratio in the mixture

It was determined that the NRC value increases in general when the flax fiber ratio in the mortar mixture is increased (Fig. 7). In general terms, it was understood that flax fiber additive affects the compressive strength negatively. Similar to compressive strength, it was observed that the flexural strength decreases as the ratio of flax fiber increases. Flax fiber additives reduce the flexural strength of the mixture, which may be attributed to the use of aggregate in the 2–4 mm range only (without using 0–2 mm aggregate at all). It was also determined that capillary water absorption level and open porosity ratio in general increase as the ratio of flax fiber increases. In summary, it was observed that when flax fiber additive increases in the mixture, flexural and compressive strength decrease in general while NRC value, open porosity ratio and capillary water absorption level generally increase.

It was understood that the rate of flax fiber is very effective in the rate of sound absorption and especially the peak points which the maximum sound absorption coefficient based on frequencies is obtained, increases with the increase of flax ratio (Fig. 8). It was observed that the flax fiber additive in mortar mixtures increases the sound absorption coefficient generally in the range of 100–1700 Hz and it was determined that it is a good method to use flax fiber additive in mortar mixtures in order to improve sound absorption coefficient at low frequencies. The sound absorption coefficient of low frequencies can be increased significantly by means of using the flax fiber additive in the mortar mixture. It was also observed that flax fiber additive can improve the sound absorption coefficient at high frequencies. The use of 0.6% flax fiber ratio in mortar mixtures is generally more effective in terms of increasing sound absorption compared to the other mortar mixtures which contain flax fiber additive at different ratios. It is determined that all of the mixtures which were prepared with pumice aggregate and flax fiber additive for increasing the sound absorption coefficient have generally higher sound absorption than the type of mixture defined in Table 1. In addition, it can be understood that the rate of sound absorption in high frequencies generally increases with the increase of the flax fiber ratio. In general, the flax fiber additive has a very positive effect on the sound absorption coefficient and the flax fiber additive can improve the sound absorption coefficient in all frequency ranges.

To compare the flax fiber additive mixtures with the polypropylene fiber additive mixtures, fiber additives were added to mortar mixtures of 1 m^3 at equal weights, and the results were shown in Fig. 9. It was seen that the use of flax fiber rather than

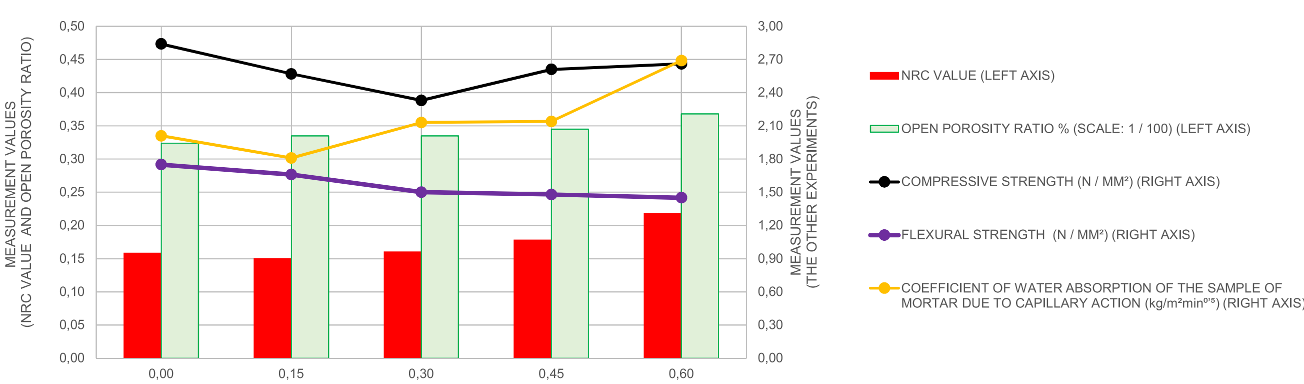

Fig. 7. The comparison of flax fiber ratios in the mixture [3].

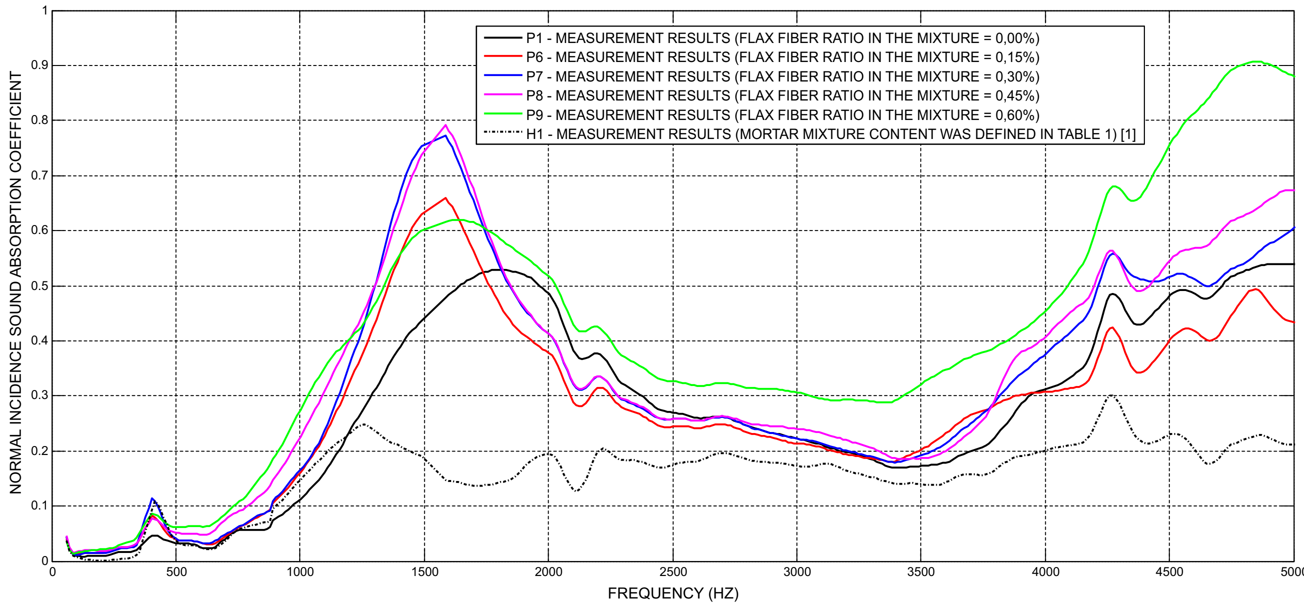

Fig. 8. The comparison of sound absorption coefficient curves – P1, P6, P7, P8, P9 and H1 [3].

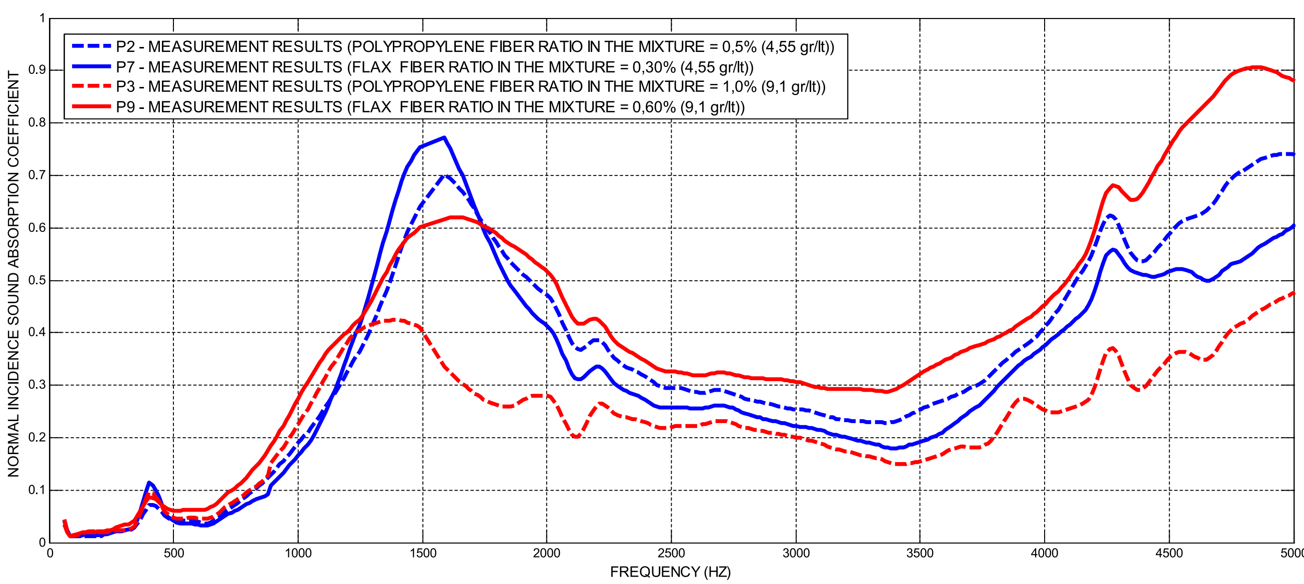

Fig. 9. The comparison of sound absorption coefficient curves in the mixtures according to the fiber types [3].

polypropylene fiber as an additive in mixtures produced with pumice aggregates may be a good approach to developing the sound absorption coefficient (Fig. 9).

5.1.4. The effects of crumb rubber volumetric ratio in the mixture of aggregate

In Fig. 10, an increase was observed in the NRC value when the crumb rubber ratio in the mixture is 7.5%. Then, the maximum NRC value was obtained from the mixture type which the crumb rubber content reached a ratio of 15%. The minimum NRC value was obtained from the mixture type which does not include crumb rubber additive. Hence, the use of crumb rubber additive instead of pumice aggregate in the mixture affects positively the NRC value in general. In compressive and flexural strength tests, it was seen that when the ratio of the crumb rubber in the aggregate increases, compressive and flexural strength reduce notably. With the change of the crumb rubber ratio in the mixture, it was seen that the slight fluctuation in the open porosity ratio level occurred. It was understood that the open porosity ratio can be increased and decreased with crumb rubber change but the amount of open porosity change is quite low. The capillary water absorption level decreased when the addition of the crumb rubber ratio is 7.5% in the mixture and the maximum capillary water absorption level was obtained from the mixture which does not include crumb rubber additive. Also, it was seen that the capillary water absorption level can increase and decrease with the change of crumb rubber ratio. As a result, when the crumb rubber additive increases in the mixture, it was noted that compressive and flexural strengths decrease regularly and considerably. However, it was seen that the NRC value can increase with the increase of the crumb rubber additive in the mixture content.

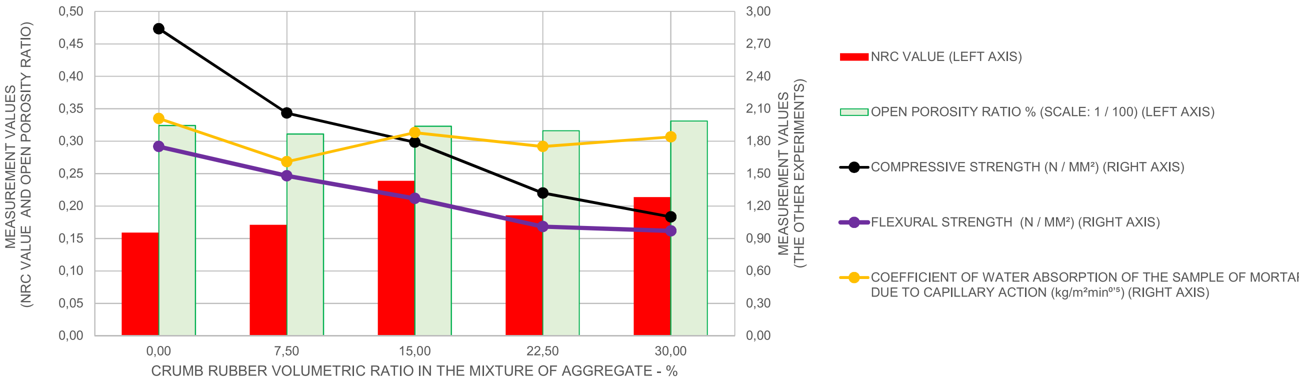

Fig. 10. The comparison of crumb rubber volumetric ratios in the mixture of aggregate [3].

It was observed that the use of crumb rubber additive in place of aggregate is effective on the sound absorption coefficient. It can be understood that the crumb rubber additive can increase the sound absorption coefficient at low frequencies until 1200 Hz (Fig. 11), while at frequencies in range of 1700–2200 Hz; the sound absorption coefficient of the mixture without crumb rubber is generally higher than other mixtures which contain crumb rubber additive. In this analysis, it was also understood that it is a good method to use crumb rubber additive in mortar mixtures in order to increase the sound absorption coefficient at low frequencies. It was determined that the crumb rubber additive in mortar mixture increases the sound absorption coefficient in the range of 2700–5000 Hz. It is observed that all of the mixtures which were prepared with pumice aggregate and crumb rubber additive for increasing the sound absorption coefficient have generally higher sound absorption than the type of mixture detailed in Table 1.

5.2. The comparison of all sound absorption measurements

In this subsection, 17 different plaster layer sound absorption results were compared with each other according to impedance tube measurement results. The NRC value which is used in the single number grading method and the frequency-dependent sound absorption coefficients were investigated for sound absorption coefficient evaluation.

In this research, the type of mixture detailed in Table 1 was changed and some modifications were performed to increase sound absorption of the mixture which is coded as H1. According to impedance tube measurement results, 17 different NRC results were given in Fig. 12. Maximum NRC was obtained in P11 coded plaster layer which includes 15% crumb rubber volumetric ratio in the mixture of aggregate. The second highest NRC was acquired in P9 coded plaster layer which contains 0.6% flax fiber ratio in the mixture. The third highest NRC value belongs to P13 coded plaster layer which includes 30% crumb rubber volumetric ratio in the mixture of aggregate. The maximum NRC value is 0.238 while the minimum NRC value is 0.095. The minimum NRC value was obtained in H1 coded plaster layer. As a result, by changing plaster mıxture content, NRC value was increased significantly ratio (Fig. 12). In general, the use of additives which are listed as polypropylene fiber, flax fiber and crumb rubber in the mortar mixture increases NRC value in this research which pumice aggregate type was used in the mixture (Table 8, Table 10, Table 12, Fig. 5, Fig. 7, Fig. 10 and Fig. 12). However, it was observed in the previous phase of the research that the use of additives (polypropylene fiber, flax fiber and crumb rubber) in the mortar mixture generally decreases NRC value when the river sand aggre-

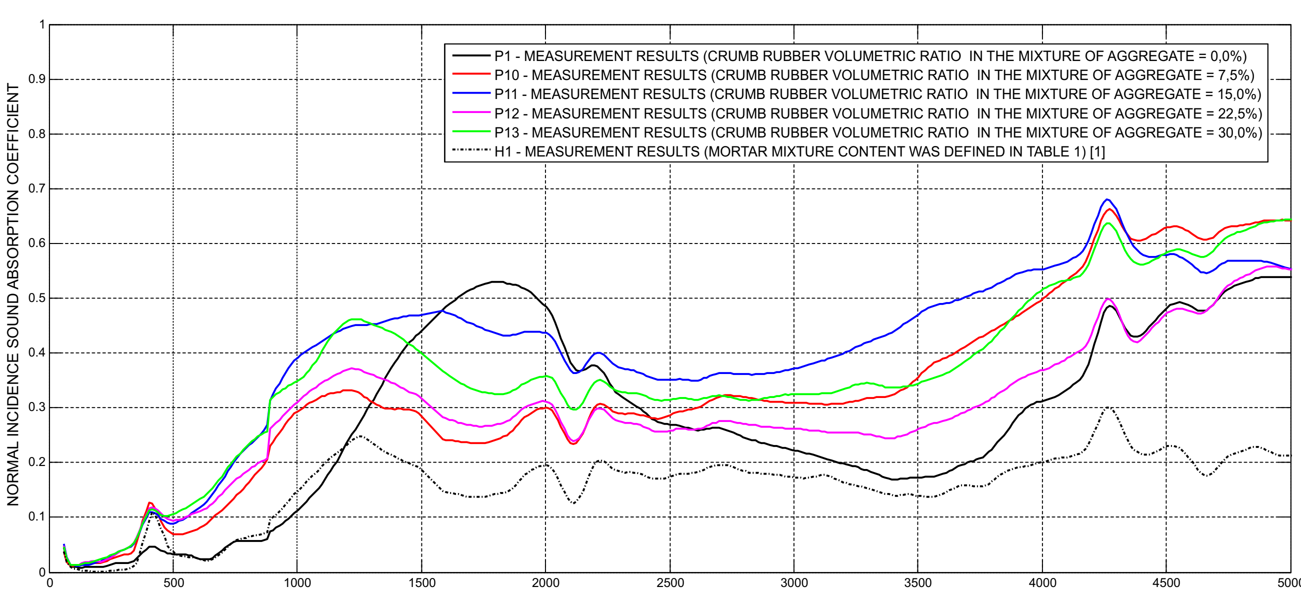

Fig. 11. The comparison of sound absorption coefficient curves – P1, P10, P11, P12, P13 and H1 [3].

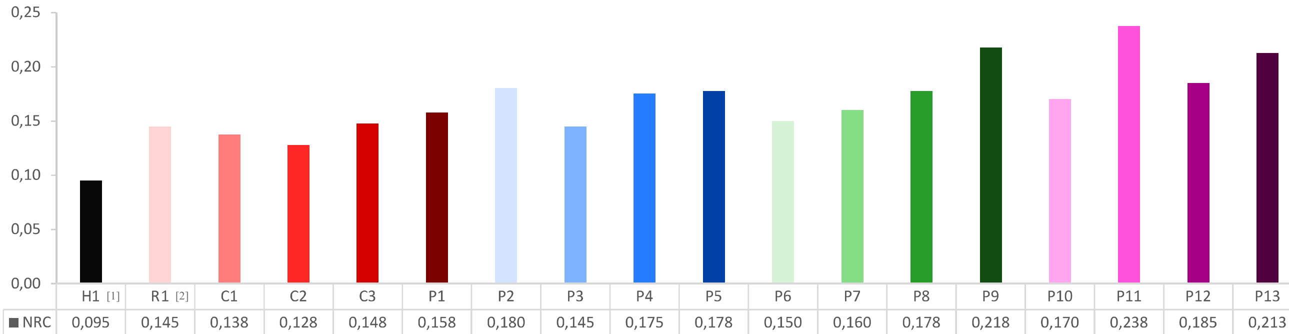

Fig. 12. 1/3 octave band sound absorption coefficient measurements NRC results (for normal incidence) [3].

gate type is used [2]. Moreover, it was seen that the use of maximum pumice aggregate ratio in the mixture (instead of river sand aggregate type) is a good way to increase NRC value in the aggregate combination volumetric ratio analysis (Table 6, Fig. 3 and Fig. 12). As a result, it was understood that the use of pumice aggregate type instead of river sand aggregate in the mixture can improve NRC value in the plaster layer and the use of lightweight aggregate type can be a good method to improve NRC value.

In this research, the mixtures which have maximum absorption characters based on frequencies were determined. 17 different plaster layer sound absorption curves were investigated and in the scope of the research, 6 different types of plaster layer which can demonstrate maximum sound absorption performance based on related frequency, were shown in Fig. 13. Also, the plaster layers which have the highest sound absorption coefficient in the related frequency range were shown in Table 14 and the related frequency ranges were defined approximately. Fig. 13 and Table 14 may be useful in selecting the maximum sound absorption coefficient according to the desired frequency range. For example, the maximum sound absorption in the range of 435–850 Hz was obtained in P13 and the maximum sound absorption in the range of 1750–2300 Hz was acquired in P9. Furthermore, the maximum sound absorption in the range of 2300–3750 Hz was obtained in P11 and the maximum sound absorption in the range of 3750–4480 Hz was acquired in P4. In high-frequency evaluations, the maximum sound absorption in the range of 4480–5000 Hz belongs to P9. In Table 14, all of the frequency ranges related to maximum sound absorption were given in detail. In brief, this pumice aggregate type research offers new mixture types in order to increase sound absorption based on frequency in the plaster layer.

In this study, it was pointed out that sound absorption coefficients can be increased by the use of pumice lightweight aggregate type rather than river sand aggregate type (Table 6 and Fig. 4). Furthermore, it was determined that the use of pumice aggregate instead of river sand aggregate in the mortar mixture can significantly enhance the sound absorption coefficient in the range of 1400–2700 Hz. In general, the use of additives which are listed as polypropylene fiber, flax fiber and crumb rubber in the mortar mixture can increase not only low-frequency sound absorption but also high-frequency sound absorption (Table 8, Table 10, Table 12, Fig. 6, Fig. 8 and Fig. 11). However, it was observed that in the previous phase of the research which was used river sand aggregate type in the mortar mixture, the use of additives (polypropylene fiber, flax fiber and crumb rubber) generally decreases sound absorption at high frequencies (maximum sound absorption in range of 3000–5000 Hz belongs to the mixture which was prepared without additive) [2]. Furthermore, it was observed

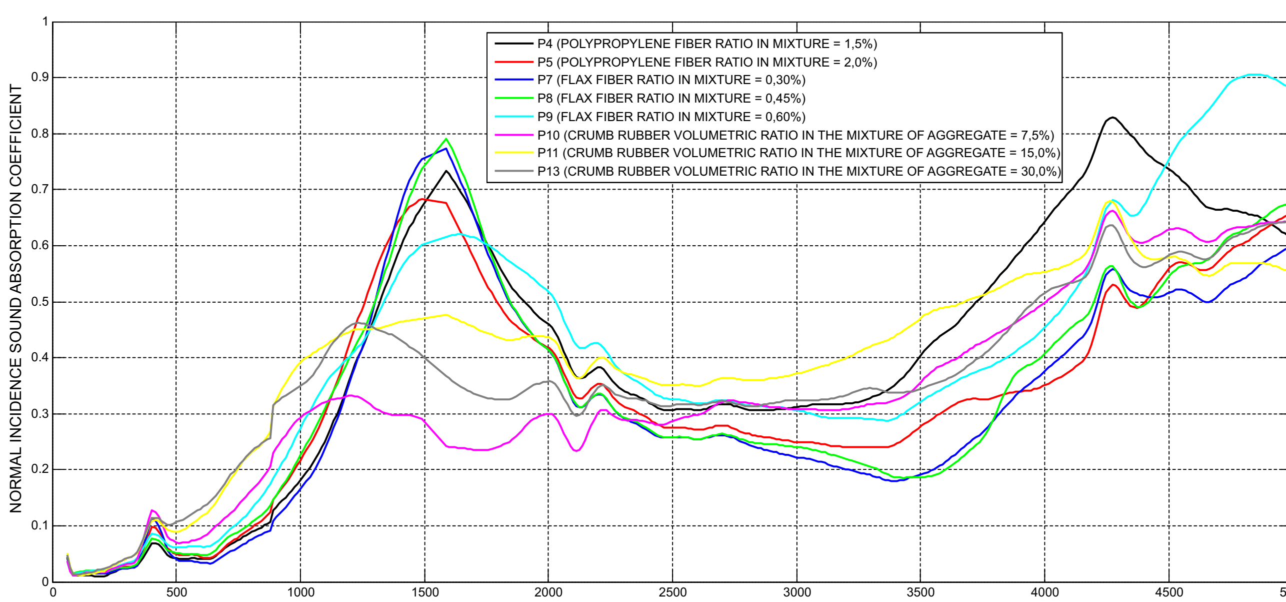

Fig. 13. The mixtures which have the highest sound absorption coefficient based on frequency [3].

Table 14
The plaster layers which have the highest sound absorption coefficient in the related frequency range [3].

Frequency range (Hz)	Code of Plaster Layer	General Properties of Plaster Layer
63–75 Hz	P11	Crumb rubber volumetric ratio in the mixture of aggregate = 15.0%
75–175 Hz	P8	Flax fiber ratio in the mixture = 0.45%
175–370 Hz	P13	Crumb rubber volumetric ratio in the mixture of aggregate = 30.0%
370–435 Hz	P10	Crumb rubber volumetric ratio in the mixture of aggregate = 7.5%
435–850 Hz	P13	Crumb rubber volumetric ratio in the mixture of aggregate = 30.0%
850–1150 Hz	P11	Crumb rubber volumetric ratio in the mixture of aggregate = 15.0%
1150–1225 Hz	P13	Crumb rubber volumetric ratio in the mixture of aggregate = 30.0%
1225–1375 Hz	P5	Polypropylene fiber ratio in the mixture = 2.0%
1375–1540 Hz	P7	Flax fiber ratio in the mixture = 0.30%
1540 Hz- 1750 Hz	P8	Flax fiber ratio in the mixture = 0.45%
1750–2300 Hz	P9	Flax fiber ratio in the mixture = 0.60%
2300–3750 Hz	P11	Crumb rubber volumetric ratio in the mixture of aggregate = 15.0%
3750–4480 Hz	P4	Polypropylene fiber ratio in the mixture = 1.5%
4480–5000 Hz	P9	Flax fiber ratio in the mixture = 0.60%

that when the polypropylene fiber, flax fiber and crumb rubber additives are used in the mortar mixtures, the use of pumice aggregate type instead of river sand aggregate type in the plaster layer generally increases sound absorption in the range of 1300–1800 Hz. During the analysis of additive effect in the plaster layer, it was seen that in the range of 1300–1800 Hz, the use of pumice aggregate instead of river sand aggregate in the plaster layer generally increases the peak points which the maximum absorption occurs. As a result, it was understood that the use of pumice aggregate type instead of river sand in mortar mixtures changes the sound absorption properties in the plaster layer.

6. Conclusions

It is very important to keep reverberation times within a room under control and reverberation times need to be reduced to the desired range in order to ensure speech intelligibility. In this context, it was aimed to increase the sound absorption coefficient of the plaster layer coating while the selection of the plaster layer type was intended to be appropriate with historical building materials. Hence, natural hydraulic lime binder type which is usually used in the restoration of historical buildings was investigated. The pumice aggregate was also examined (as the lightweight aggregate type). 3 cm thick plaster layers which have different mixture content, were prepared and the effects of the varying mixture contents on the sound absorption coefficient were evaluated. The effects of aggregate combination volumetric ratio, polypropylene fiber ratio, flax fiber ratio, and crumb rubber additive ratio on the sound absorption coefficient were investigated in the plaster layers. The samples produced from the P11-coded mixture (crumb rubber volumetric ratio in the mixture of aggregate = 15%), has the highest NRC value, and the samples produced from the P9-coded mixture containing 0.30% flax fiber has the second-highest NRC values among the investigated mixtures (Fig. 12).

The following issues were determined from the results of the test analyses;

- In analyses of aggregate combination volumetric ratio in the mixture of aggregate, it was determined that the use of pumice aggregate instead of river sand aggregate can increase the sound absorption coefficients and NRC value. Moreover, it was indicated that the use of pumice aggregate instead of river sand aggregate in the mortar mıxture can significantly increase the sound absorption coeffıcıent in the range of 1400–2700 Hz. Also, it was understood that the use of lightweight aggregate type in the mortar mixtures can be a good method to increase sound absorption coefficients. In mixtures prepared using only 2–4 mm aggregate, when the pumice aggregate volumetric ratio was increased, compressive and flexural strengths also increase to a significant level. As the pumice aggregate volumetric ratio increases, generally, the open porosity and capillary water absorption ratios increase as well.
- The use of polypropylene fiber additives in the mortar mixture can increase the sound absorption coefficient at low frequencies up to 1400 Hz. Also, the use of polypropylene fiber additives in the mortar mixture can increase NRC value and the sound absorption coefficient in the range of 2200–5000 Hz. It was pointed out that the use of polypropylene fiber can improve sound absorption capacity not only low frequencies but also high frequencies. It was observed that the polypropylene fiber additive can be an adverse effect on flexural strength in mortar mixtures prepared using only 2–4 mm aggregate and can be effect negatively to compressive strength. It was noted that when polypropylene fiber additive was increased in the mortar mixture, the open porosity and capillary water absorption level also increased in general.
- It was observed that the sound absorption coefficient at low frequencies up to 1700 Hz can be increased by means of using flax fiber additives in the mortar mixture and in general, adding flax fiber additives to the mixtures can be a good method to increase the sound absorption coefficient at high frequencies. The effects of both the polypropylene fiber additive and the flax fiber additive on the sound absorption coefficient were compared, and it was seen that the flax fiber is usually better than polypropylene fiber when they are added to mortar mixtures as equal weights within the same unit volume. It was understood that when flax fiber additive was increased in the mortar mixture, compressive and flexural strengths decreased generally and the open porosity ratio and NRC value level increased in general.
- It was determined that the use of crumb rubber additives in certain proportions in place of pumice aggregate can increase the sound absorption coefficient significantly at low frequencies until 1200 Hz. Also in the range of 2700–5000 Hz, it was observed that the use of crumb rubber additive instead of pumice aggregate can increase the sound absorption coefficient. It was understood that the use of crumb rubber additive instead of pumice aggregate can improve not only low-frequency sound absorption but also high-frequency sound absorption. Furthermore, the maximum α_w value was obtained from the mixtures which contain crumb rubber in the mixture of aggregate (Table 12). It was noted that the use of crumb rubber in place of aggregates decreases compression and flexural strength significantly and the use of crumb rubber additives can decrease the capillary water absorption level.

The different plaster layer types were prepared at varying ratios within the scope of this research and the mixtures which maximum absorption based on frequency was acquired were determined (Fig. 13 and Table 14). This study offers new plaster layers and may be useful in selecting the maximum sound absorption coefficient according to the desired frequency range.

In the reverberation time analyses, diffuse incidence sound absorption coefficients are used. According to normal incidence measurements, it was observed that some of the plaster layer NRC results are too close and differences between some of the plaster layer types are quite small. It has been estimated that the improvement of the sound absorption may be neglected in diffuse incidence when the differences between plaster layer normal incidence sound absorption results are too close. In order to obtain more reliable measurement results, it is necessary to measure the diffuse incidence sound absorption coefficient according to the ISO 354 standard. Laboratory measurements according to the ISO 354 standard are needed in order to give strength to the results from normal incidence. In this study, the sound absorption coefficient measurements were carried out in accordance with the EN ISO 10534-2 standard and impedance tube measurements results give general information about sound absorption for different plaster layers.

In the research, the lab analyses were performed generally using pumice type aggregates. It is planned to carry out experimental researches on the use of different lightweight aggregate types instead of pumice aggregate in the continuation of this study. The improvement of sound absorption by making changes to the mortar mixture content in a method that is compatible with the historical structure is a very broad research topic for future researches.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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