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RESEARCH ARTICLE

Sound Insulation Performance of Sustainable LC³ Mortars with Barite and Waste Rubber Aggregates

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ABSTRACT

This study investigates the potential of limestone calcined clay cement (LC³) as a sustainable binder for developing a single-layer composite material incorporating barite and rubber aggregates, hypothesized to achieve enhanced sound insulation performance compared to conventional multi-layered wall systems. Mortars were prepared using LC³ with 55% clinker, 30% metakaolin, 15% limestone, substituting 45% of cement clinker. Hybrid mixtures of barite and rubber aggregates (barite-to-rubber volume ratios of 2:1 and 1:2) were tested at aggregate-to-binder ratios of 2.0, 2.75, and 3.5 to evaluate their combined mass and damping effects on acoustic performance. Experiments were conducted to determine physical, mechanical, and acoustic properties of the developed composites. Airborne sound transmission loss (STL) and R_{avg} (single-number descriptor derived from STL data) were measured with an impedance tube. R_{sim} (single-number descriptor derived from STL data) measured with *INSUL* in 1/3 octave bands. Results revealed that the mortar with an aggregate-to-binder ratio of 2.75 and a 2:1 barite-to-rubber combination (2B1R) achieved the highest R_{avg} (30.18 dB) value at 90 mm thickness and R_{sim} (50 dB) at 120 mm thickness, exceeding those of mixtures with ratios of 2.0 and 3.5. *INSUL* software simulations extended the experimental findings and provided predictions about room-scale result values, unlike impedance tubes.

Keywords: Sound transmission loss, LC³ binder, Barite-rubber composite mortar, Acoustic performance, Impedance tube, *INSUL*

1. Introduction

The construction industry is under growing pressure to reduce its environmental footprint. Cement production accounts for nearly 8% of global anthropogenic CO₂ emissions, primarily due to the calcination of limestone and the high energy demands of clinker production. To address this issue, a new ecological cement—LC³ (Limestone Calcined Clay Cement) [1] has been developed by combining Portland cement, calcined clay, limestone and gypsum. LC³ production emits about 30% less CO₂ than OPC and conventional pozzolanic cements due to the lower calcination temperature of clay and the absence of limestone decarbonation [2, 3]. Moreover, LC³ is eco-

nomically advantageous, as its manufacture requires less energy and utilizes abundant, low-cost raw materials such as metakaolin, limestone, and gypsum, keeping production costs generally below those of OPC [2]. LC³ can be produced using locally available and low-grade raw materials such as dolomitic limestone and low-quality kaolinite clays, which are often considered waste in conventional cement production [3]. The typical composition of LC³-50 (where 50 refers to the percentage of clinker) consists of 50% clinker, 30% calcined clay (metakaolin), 15% limestone, and 5% gypsum [2]. Clays, rich in kaolinite exhibit high pozzolanic reactivity when calcined at 700–850 °C, forming metakaolin (MK)—an amorphous aluminosilicate (Al₂Si₂O₇). The calcination

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process requires significantly lower temperatures than clinker production, allowing LC³ to be produced with conventional equipment such as rotary kilns and ball mills already used in cement plants. During hydration, metakaolin reacts with calcium hydroxide released by Portland cement to form C–A–S–H phases, while its alumina content reacts with limestone to form carboaluminate phases. These reactions refine the pore structure, enhance mechanical strength, and contribute to durability at both early and later ages [4, 5]. The reactivity of calcined clay primarily depends on its kaolinite content. When the clay contains at least 40% kaolinite, LC³-50 mortars can achieve mechanical strengths comparable to those of ordinary Portland cement (OPC). Research has shown that early-age strength in LC³ mortars is higher than that of binary blended systems (such as metakaolin–Portland or limestone–Portland cement). This improvement is attributed to the rapid formation of alumina-bearing hydrates within the first seven days of curing [3]. Furthermore, the metakaolin–limestone interaction allows mechanical properties to be retained even at high clinker replacement levels (up to 45%) [4]. European standards permit clinker substitution up to 55%, provided that sufficient reactivity is ensured by the pozzolanic component [6]. The LC³ binder formulated by Dhandapani and Santhanam [7], incorporated 55% Portland cement, 30% metakaolin, and 15% limestone by mass. In the study by Avet et al. [5], LC³ mortars were cast using the same combination, confirming the suitability of this composition. Studies indicate that replacing 30% calcined clay and 15% limestone results in only a minor reduction in compressive strength compared to using 30% calcined clay alone [6]. Maintaining a 2:1 ratio of calcined clay to limestone enables clinker replacement up to 50%, significantly lowering CO₂ emissions. The function of gypsum powder in LC³ mortars is to accelerate the hydration of cement, especially at early ages. The hydration of C₃A in the presence of gypsum powder forms monosulfoaluminate in the early ages and, when the sulfate source is depleted in later ages, stabilizes other hydration products [8]. Despite an increase in porosity, LC³ mortars maintain mechanical strength comparable to OPC up to high clinker replacement levels [4]. Consequently, LC³ mortars maintain comparable mechanical performance while demonstrating improved environmental sustainability.

Acoustic comfort has become a critical aspect of building performance, as inadequate airborne sound insulation is associated with stress, reduced productivity, and health problems for occupants [9, 10]. In urban areas with high population density and external noise exposure, designing building partitions

with effective sound insulation is essential to ensure compliance with regulations and to improve indoor environmental quality [11]. Traditional approaches often rely on increasing the mass or thickness of partitions, yet these strategies may conflict with modern requirements for lightweight, resource-efficient, and sustainable construction materials [12, 13].

In the study by Yu et al. [14], it was observed that frequency has a significant effect on the sound insulation properties of foam sandwich panels. The sound reduction index (R) of foam sandwich panels increased as the frequency increased from 100 Hz to 4000 Hz. An increase of approximately 20 dB was observed at low frequencies and up to 50 dB at high frequencies. Experiments conducted with panels of different thicknesses and densities showed that the weighted sound reduction index (R_w) increased with increasing thickness and density. Júnior et al. [15] reported R_w values in the range of 29–39 dB for plaster-block partitions with thicknesses between 50 and 100 mm.

Recent studies have highlighted the effect of porosity and different types of aggregate gradation on acoustic behavior in lime–cement mortars [16], as well as the performance of recycled and lightweight aggregates in sound insulation applications [17, 18]. In porous concrete systems, Kim and Lee [19] demonstrated that aggregate gradation and porosity strongly influence absorption and resonance behavior, though their work focuses more on absorption models than on R_w per se. Shebl et al. [20] investigated the role of ultra-fine silica/sand (UFS) with a maximum particle size of 20 μm in improving the mechanical and acoustic properties of cement mortars. Adding up to 5% UFS to the cement mortar reduced sound absorption and the noise reduction coefficient (NRC). This is because UFS fills the voids in the mortar, reducing its porosity and forming a denser (more compact) structure, while also forming a stronger bond with the mortar. However, adding 7.5% and 10% UFS to the mortar increased its porosity and the noise reduction coefficient began to increase.

Ivanova et al. [21] prepared a new composite wall by using glass foam particles and Portland cement, zeolite and other materials, and studied the airborne sound insulation performance of the new composite wall. The developed panels could be used for sound-insulated non-porous interior partitions in residential and industrial buildings, expanding the range of building materials available.

By influencing key parameters such as density, pore structure, and stiffness, aggregate selection plays a decisive role in shaping the acoustic behavior of mortars. High-density aggregates such as barite (BaSO₄) have long been investigated for enhancing radiation

shielding and mass-related sound insulation [22]. Ahmad et al. [23] established that barite as a high-density aggregate enhances acoustic insulation via increased mass, reinforcing the mass law principle in dense concretes. In contrast, recycled rubber aggregates obtained from end-of-life tires are valued for their damping capability and porous structure, which improve sound absorption and noise attenuation at mid-to-high frequencies [24–26]. Smirnova et al. [27] found that incorporating crumb rubber into cementitious composites improves damping and sound absorption performance.

The separate acoustic effects of barite and rubber aggregates have been demonstrated in different studies in literature. According to the mass law of sound insulation, the greater the mass, the harder it is for the material to vibrate, which indicates that the material will have better sound insulation [28]. Barite improves sound insulation by increasing density, while rubber provides damping at medium–high frequencies due to its elastic and porous structure [27, 28]. Fediuk et al. [29] highlighted that hybrid and rubberized mixes frequently exhibit improved acoustic behavior in their review of innovative concretes.

Limestone calcined clay cement (LC^3) binder offers a reduced environmental footprint and mechanical performance comparable to Portland cement. Despite extensive studies on the mechanical and chemical behavior of LC^3 , its acoustic properties have only been reported in the study by Söyek Abay and Tanaçan [30]. Considering that pore morphology, which is a critical parameter influencing acoustic insulation, it was hypothesized that the finer pore structure of LC^3 mortars could positively contribute to sound transmission loss, making it a promising alternative for acoustic efficient, eco-friendly building materials. In the previous research, barite and waste rubber aggregates are used individually and in combination, at an aggregate-to-binder ratio of 2.75. However, methodological validation models remained limited, and the research was applied to only one type of LC^3 binder to aggregate ratio of 2.75 leaving a knowledge gap on the potential for mutual influence of high-density and damping materials in this binder system.

This study addresses this gap by investigating the airborne sound insulation performance of LC^3 mortars incorporating barite and rubber hybrid combinations with varying aggregate to binder ratios. The variations in binder proportion, combined use of barite for mass enhancement, and rubber for damping, can effectively improve the R_{avg} and R_{sim} value across frequency ranges most relevant to human hearing. Experimental impedance tube measurements were complemented with *INSUL* software [31] simulations.

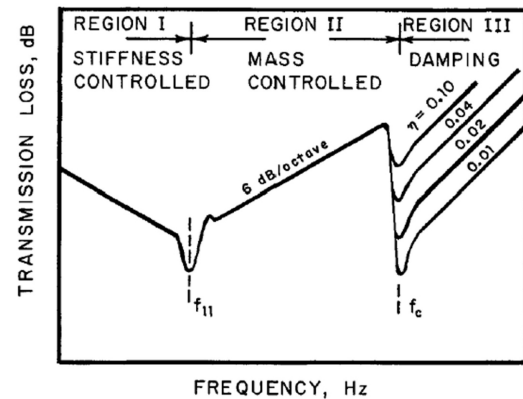


Fig. 1. Sound transmission loss of a panel (mass law graph) [33].

Since sound and material structure interaction is frequency dependent, different material properties govern sound insulation at different frequency ranges. In panel-type structural elements, sound transmission is dominated by bending waves, whose reduction depends on the bending stiffness (K), which is a function of the elastic modulus (E) and the thickness (d) of the element. Resonance occurs when the incident sound frequency coincides with the longitudinal wave frequency determined by the element geometry (Fig. 1). Below the lowest resonance frequency (f_r or f_{11}), sound attenuation is controlled by stiffness, and transmission loss decreases at approximately 6 dB per octave, while the influence of other material properties is negligible [32]. Between the natural frequency and the critical frequency (f_c), sound insulation is governed by the mass of the element, and the mass law applies. At the critical frequency, interaction between incident sound waves and bending waves causes a deviation from the linear increase in transmission loss. Above the critical frequency, the transmission loss curve enters the interference region, characterized by an initial sharp drop due to the coincidence of air wave velocity and bending wave velocity, followed by an increase of up to 10 dB per octave. In this high-frequency region, damping properties of the material become dominant [32]. This discussion has been expanded in the “Results and Discussion” section.

The central hypothesis of this study was that a single-layer composite, combining high mechanical performance with elevated porosity to enhance sound wave attenuation, could achieve an improved sound transmission loss (STL, R) and a single-number descriptor (R_{avg} and R_{sim}), offering a viable alternative to conventional multi-layered wall sections. In this study, impedance tube test results were interpreted based on the mass law principles (Fig. 1). Compressive strength, a reliable indicator of mortar

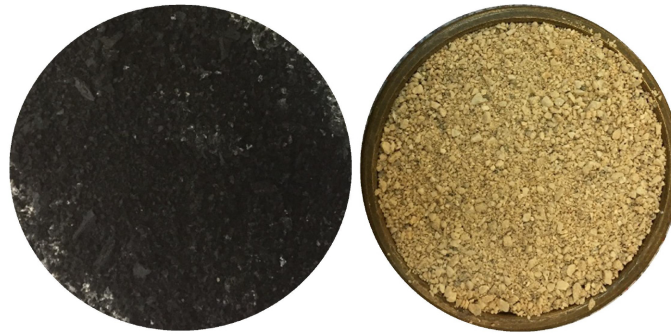


Fig. 2. (a) 0–8 mm waste rubber aggregates (left); (b) 0–8 mm barite aggregates (right).

quality [34], was selected for comparison, and the relationship between compressive strength and R_{avg} was examined across the entire set of test results. By experimental measurements and simulation-based modeling, the research seeks to establish a scientific relationship between LC³'s structural properties and its sound reduction performance, contributing to both material science and building acoustics disciplines.

2. Materials and methods

Materials and methods used in experimental study to develop acoustic insulation material are given in detail in the following sections.

2.1. Materials

The binder materials consisted of LC³ are Portland cement (classified as CEM-I 42.5 R, containing 95–100% clinker); Metakaolin (MK), and limestone (LS). Assuming the mass law of heavy material would increase STL, barite and based on the assumption that reduced rigidity would improve damping, waste rubber was used as aggregates. Waste tire rubber was utilized after thorough processing to remove steel and fabric components, ensuring material purity for the acoustic application. As part of the experimental program, 55% clinker, 30% metakaolin, and 15% limestone were added to the mixture to produce LC³ cement. Due to the presence of gypsum in the Portland cement content (3.96% SO₃), no additional gypsum was added. Semi-quantitative elemental analysis was conducted on Portland cement, metakaolin and limestone, using a Philips 71 PW-2404 model X-Ray Fluorescent Spectrometer (XRF). The data on the barite analysis was provided by the supplying company. All analytical results containing XRF analysis and cumulative particle size distributions of all dry components used in the study are presented in Söyek Abay and Tanaçan [30]. Accordingly maximum grain size of PC, MK and LS was 45

microns. Sieve analysis procedures were conducted in accordance with EN 196-6 [35] standards to ensure accurate particle size characterization. Finer aggregates are known to increase porosity due to their higher surface area, coarser aggregates were expected to reduce pore volume and enhance mortar density [36]. For this reason, a maximum aggregate size of 8 mm was used in this study (Fig. 2). XRF analysis confirmed that the Portland cement met the requirements specified in EN 197-1 [37]. CaO content of LS is approximately 53.66%. The metakaolin contained 56.10% SiO₂ and 40.23% Al₂O₃, with the Al₂O₃ ratio exceeding the ideal threshold of 39.50% as referenced by the Turkish General Directorate of Mineral Research and Exploration [38]. These compositional characteristics are particularly significant as they directly influence cement hydration processes. The specific gravities of the LC³ binder components were determined to be 3.15 for Portland cement, 2.29 for MK, and 2.64 for LS. For the aggregate components, the specific gravities measured were 2.56 for river sand, 4.21 for barite, and 1.16 for waste rubber. The pozzolanic reactivity of MK was evaluated according to TS 25 standards [39]. The 7-day pozzolanic reactivity test yielded flexural and compressive strength values of 4.00 MPa and 19.77 MPa, respectively. These results successfully met the minimum performance requirements specified in TS 25 [39], confirming the suitability of the MK for use in the LC³ binder system.

2.2. Experimental method

Firstly, LC³ based mortar was produced with aggregate-to-binder ratio of 2.75 according to ASTM C 595-20 [40]. Then the aggregate-to-binder ratio was increased to 3.5 and decreased to 2. Hybrid aggregates consisting of two parts barite to one part rubber (2B1R) and two parts waste rubber to one part barite (2R1B) were mixed with LC³ by volume. The water-to-binder ratio was determined by flow test per ASTM C 1437 [41], yielding a flow of 113 mm

Table 1. Experimental series, specimen codes, materials and mixture ratios.

Mixture Code	Binder LC ³ (g)			Aggregate (g)		Water/Binder Ratio
	PC	MK	LS	Barite	Rubber	
LC-2B1R8-2	137.5	75	37.5	539.75	74.35	0.55
LC-2B1R8-2.75	137.5	75	37.5	753.76	103.84	0.58
LC-2B1R8-3.5	137.5	75	37.5	944.55	130.12	0.70
LC-2R1B8-2	137.5	75	37.5	269.86	148.71	0.56
LC-2R1B8-2.75	137.5	75	37.5	376.88	207.69	0.60
LC-2R1B8-3.5	137.5	75	37.5	472.27	260.25	0.71

LC: LC³; %55 Portland cement CEM I 42.5 R (PC), %30 metakaolin (MK), %15 limestone (LS) Flow: 113 mm

**Fig. 3.** The samples produced and their sections: a) LC-2R1B8-2.75 (left) and LC-2B1R8-2.75 (right), b) LC-2B1R8-2.75, c) LC-2R1B8-2.75.

maintained across all mixtures. Six test series with materials, codes, and mixing ratios are detailed in Table 1. Mortars were cast in $40 \times 40 \times 160$ mm prismatic molds using the coding format X-XX-X: the first group indicates binder (LC³), the second indicates aggregate part-type and size (e.g. 2B1R8: 2B: 2 parts barite, 1R: 1 part rubber, 8 mm), and the third indicates aggregate-to-binder ratios (2.0, 2.75, 3.5) by weight.

Three specimens were prepared per test. Following the flexural strength test, the resulting halves (six in total) were used for compressive strength testing (Fig. 3). After 24 h demolding, specimens were cured for 27 days at $20 \pm 2^\circ\text{C}$ at $95 \pm 5\%$ humidity, then oven-dried at $100 \pm 5^\circ\text{C}$ to constant weight. Tests were conducted in accordance with relevant standards: bulk density was determined following EN 1015-10 [42], capillary water absorption according to EN 1925 [43], and water absorption under atmospheric pressure as specified in EN 13755 [44]. The ultrasonic pulse velocity and dynamic modulus of elasticity were measured in accordance with EN 14579 [45], while flexural and compressive strengths were evaluated following EN 196-1 [46].

Sound insulation performance of the mortar samples was evaluated in accordance with the EN ISO 10534-2 [47], using the transfer-function method.

Prior to testing, all microphones were calibrated at a reference sound pressure level of 94 dB and a frequency of 1 kHz to ensure measurement accuracy. The sound transmission loss (STL) measurements were performed using an impedance tube system (Fig. 4) (Brüel and Kjær 4206, Hottinger Brüel and Kjær Co., Ltd., Denmark). This method employs a tube setup equipped with four microphones and a digital frequency analysis system to determine the normal-incidence transmission loss of materials through the acoustic transfer matrix approach. For acoustic insulation measurements with the impedance tube, cylindrical specimen thicknesses of 60, 90, and 120 mm, enabled comparison with partition walls, were prepared with diameters of 100 mm and 28 mm to determine sound insulation characteristics within the frequency ranges of 63–1600 Hz (low frequency) and 1600–6300 Hz (high frequency), respectively. The sound transmission loss of three specimens prepared within the same mixture composition was measured, and the average of these three measurements was reported as the transmission loss result. Fig. 5 shows the mortars prepared for physical-mechanical and STL tests.

Sound transmission loss varies with frequency; therefore, sound insulation performance was evaluated using both frequency-dependent STL values; R_{avg}

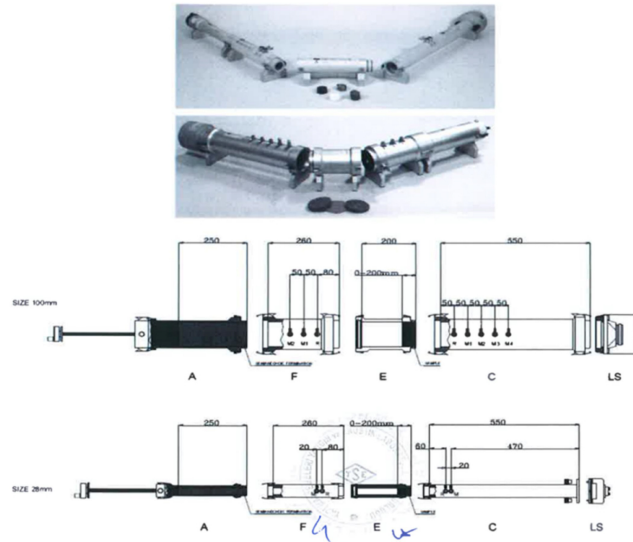


Fig. 4. The impedance tube used in this study.

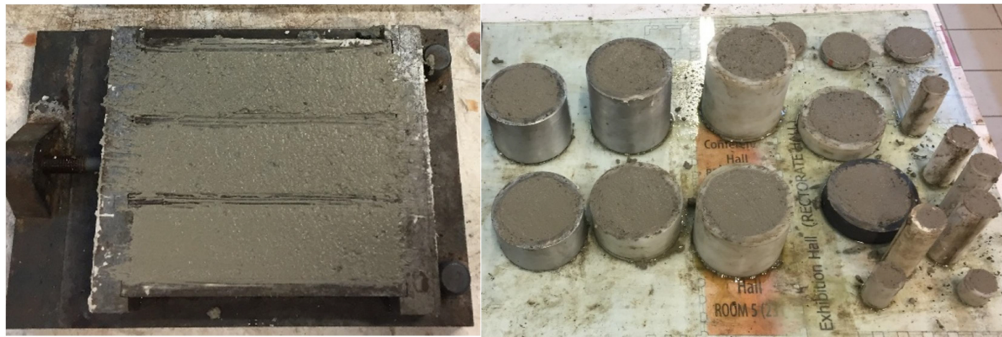


Fig. 5. Samples prepared for physical-mechanical tests (left) and STL tests (right).

and R_{sim} . The R_{avg} value represents the sound reduction index referenced to the 500 Hz frequency band. The R_{sim} (a single-number descriptor) was calculated from *INSUL* 1/3 octave band STL data, following the contour-fitting procedure of EN ISO 717-1 [48].

In this part of the study, the following formulas were used to calculate the critical frequency (f_c) (Eq. 1), the speed of longitudinal waves (Eq. 2) and the natural (resonance) frequency (f_{11}) (Eq. 3) of the mortars. C_L represents the speed of longitudinal waves, D represents the diameter of the sample, h represents the thickness of the sample, c represents the speed of air around the panel, ρ_w represents the density of the wall or panel, E represents the elastic modulus, and σ represents Poisson's ratio. Since the specimens produced for testing in the impedance tube are cylindrical, the formulas have been selected to suit circular samples. The calculations for a circular panel with diameter D and thickness h are as follows:

$$f_c = \frac{\sqrt{3}c^2}{\pi c_L h} \quad (1) \quad [33]$$

$$C_L = \sqrt{\frac{E}{\rho_w (1 - \sigma^2)}} \quad (2) \quad [49]$$

$$f_{11} = \frac{10 \cdot h^2 c_L}{\pi \sqrt{3} D^2} \quad (3) \quad [33]$$

For *INSUL* prediction software, a standard test area of 10 m² is assumed to represent large-scale building elements, whereas impedance tube measurements are conducted on small-scale cylindrical specimens. This difference in specimen scale and boundary conditions further limits the direct comparability between numerical predictions and laboratory impedance tube results. Since computer simulations can produce results close to room-scale data, the *INSUL* software model was also employed as a predictive tool for assessing noise control and sound transmission through building elements such as walls, floors, ceilings, and roofs. This software models materials based on classical elastic plate theory, incorporating corrections for thick panel behavior as described by Ljunggren [50], Rindell [51], and others. More complex

multilayered partitions are simulated following the theoretical approaches developed by Sharp [52–54], Cremer [55, 56], and related researchers. *INSUL* estimates transmission loss (TL) values across 1/3 octave frequency bands. Originally developed and validated using a database of 20–30 representative materials, the model provides reliable estimations of sound insulation performance. In addition to its predefined database, *INSUL* software enables calculation of transmission loss (TL) for new or alternative materials by incorporating physical parameters. STL calculations were performed by entering density, surface area, surface mass, critical frequency, loss factor, and thickness values from experiments. Aksoylu et al. [57] conducted a comparative evaluation of simulation models such as Bastian, Akuzoft, *INSUL*, dBKAisla, and Comsol. Simulation outcomes revealed that the *INSUL* model exhibited the highest accuracy (91%), followed by dBKAisla (91%), Bastian (82%), Akuzoft (78%), and Comsol (61%). Similarly, Cambridge [58] compared *INSUL*, Bastian, ENC, Reduct, and Winflag systems using panel models in adjacent classrooms, and emphasized the combined reliability of *INSUL* and Bastian. Therefore, in addition to the impedance tube results, it was deemed appropriate in this study to use *INSUL* simulation. Approximate actual insulation values were obtained through simulation experiments and converted to single-number values (R_{sim}). Fig. 6 illustrates the experimental flowchart corresponding to the methodology described above.

3. Results and discussion

The results of the physical and mechanical tests are presented in Table 2. The frequency-dependent sound transmission loss (STL) values obtained from the impedance tube measurements in 1/3 octave bands are summarized in Table 3. To facilitate comparison between different mixes, an average STL value (R_{avg}), calculated over the mid-frequency range, is reported; however, this parameter is not a standardized sound insulation index. In parallel, numerical pre-

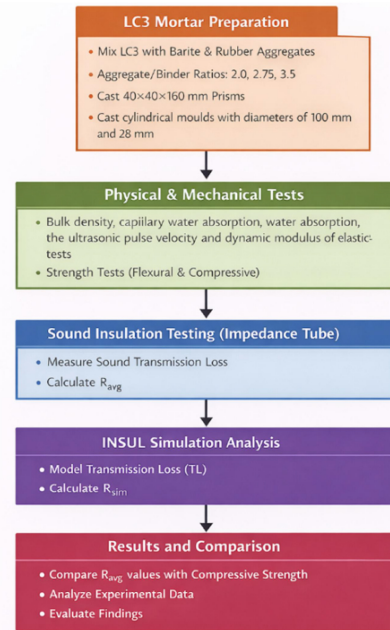


Fig. 6. Experimental process flow chart.

dictions were performed using the *INSUL* software, which assumes large-area building elements. The predicted sound reduction index curves were used to derive a single-number descriptor (R_{sim}), following the EN ISO 717-1 standard [48], solely for comparative purposes within the numerical analysis. These simulated single-number values are reported only to support relative comparison between configurations. Average sound reduction indexes (R_{avg} and R_{sim}) of the materials can be found in Table 4. Although the impedance tube method provides a practical and repeatable approach for evaluating the sound transmission behavior of materials at small scale, it should be noted that the measured STL values cannot be regarded as representative of the true sound reduction index of large-size specimens. Due to size effects, rigid boundary conditions, and the stiffness of small samples, impedance tube measurements may differ from and in some cases underestimate, the transmission loss obtained from standardized large-scale tests such as reverberation room methods. Consequently, the

Table 2. Physical and mechanical test results of the specimens.

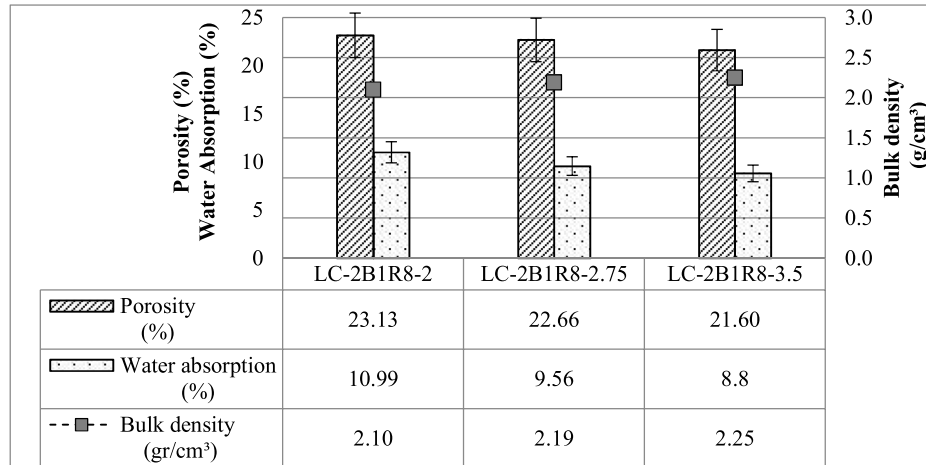
Specimen Code	Bulk density (g/cm ³)	Capillarity coefficient (C _c) (kg/m ² ·min ^{-1/2})	Water absorption (%)	Apparent porosity (%)	Porosity (%)	Ultrasound velocity (km/s)	Compressive strength (MPa)	Flexural strength (MPa)	Young's modulus of elasticity (MoE) (GPa)
LC-2B1R8-2	2.10	0.83	10.99	23.07	23.13	1.02	6.43	1.19	2.23
LC-2B1R8-2.75	2.19	0.59	9.56	21.30	22.66	1.12	7.9	1.35	2.80
LC-2B1R8-3.5	2.25	0.31	8.8	19.8	21.6	1.08	9.12	1.54	2.63
LC-2R1B8-2	1.65	0.36	9.92	16.37	17.64	1.16	7.4	1.52	2.26
LC-2R1B8-2.75	1.64	0.62	11.06	18.13	18.31	1.12	5.1	1.4	2.08
LC-2R1B8-3.5	1.55	0.71	11.60	18.42	18.63	1.08	4.74	1.59	1.88

Table 3. Sound transmission loss (STL, dB) test results measured with impedance tube.

Sample Code (sample thickness, mm)	Frequencies (1/3 Octave Bands)																		
	100	125	160	200	250	315	400	500	630	800	1000	1250	1600	2000	2500	3150	4000	5000	6300
LC-2R1B8-2.75 (60)	20.24	21.56	21.9	23.12	24.15	25.46	26.98	26.12	28	28.06	28.7	27.7	25.98	26.74	27.38	28.65	28.42	29.16	31.72
LC-2R1B8-2.75 (90)	21.24	21.5	22.62	23.82	24.78	25.35	26.56	25.93	26.67	26.33	26.03	26.93	29.59	29.83	30.92	31.16	31.75	32.66	33.14
LC-2R1B8-2.75 (120)	20.45	20.96	22.81	24.18	25.17	26.26	26.07	26.01	26.05	25.49	27.03	30.09	31.66	33.71	35.81	37.96	40.03	44.08	44.14
LC-2B1R8-2.75 (60)	23.46	23.96	24.81	25.47	26.29	27.41	27.3	27.24	28.57	29.37	29.5	30.55	30.53	30.55	32.5	34.76	36.43	36.75	37.82
LC-2B1R8-2.75 (90)	30.53	31.45	32.14	32.02	32.38	33.14	33.42	30.18	33.32	34.81	36.32	37.23	39.26	41.74	42.64	45.86	46.96	47.81	45.75
LC-2B1R8-2.75 (120)	20.48	21.67	22.6	23.65	24.7	25.63	25.58	25.31	25.32	25.03	26.02	29.85	30.63	26.62	28.37	29.85	32.39	35.16	35.94
LC-2B1R-8-2 (60)	16.52	17.04	19.01	20.08	21.25	22.52	23.4	23.26	24.85	26.18	26.88	27.38	28.46	29.25	31.2	33	34.26	35.79	36.79
LC-2B1R-8-2 (90)	16.88	18.51	19.62	21.34	21.93	23.47	24.32	25.4	25.98	26.16	24.45	22.68	23.58	25.71	25.99	26.33	27.11	27.57	27.96
LC-2B1R8-2 (120)	20.74	21.48	23.38	24.54	25.74	26.72	26.97	27.74	27.53	27.52	28.49	31.83	41.37	46.79	47.22	50.39	50.38	47.72	55.49
LC-2B1R8-3.5 (60)	19.11	20.99	22.26	22.88	24.54	25.74	27.11	25.99	27.51	29.02	27.44	24.49	20.38	21.84	24.12	24.71	25.97	26.99	30.67
LC-2B1R8-3.5 (90)	23.78	24.83	24.8	26.18	27.37	26.31	27.77	28.6	28.61	28.59	27.49	28.15	30.12	32.38	34.4	36.21	38.86	40.32	47.14
LC-2B1R8-3.5 (120)	22.52	22.91	24.8	25.63	26.9	26.49	27.07	27.01	26.06	26.07	28.63	31.06	32.03	35.28	37.56	40.33	44.45	48.98	51.97
LC-2R1B8-2 (60)	9.51	11.19	12.16	13.45	15.31	16.44	17.97	18.05	19.86	21.45	21.61	20.81	18.88	20.97	24.04	24.61	25.21	27.55	28.5
LC-2R1B8-2 (90)	16.27	17.26	18.84	20.19	21.58	22.92	24.01	24.82	25.35	25.81	24.76	23.8	27.87	29.86	30.71	32.53	33.22	34.39	33.96
LC-2R1B8-2 (120)	18.85	19.94	21.43	22.73	22.76	24.58	24.55	24.98	24.45	23.17	23.93	27.64	30.93	32.6	36.5	40.94	43.86	46.79	45.12
LC-2R1B8-3.5 (60)	13.44	13.55	15.18	15.69	16.79	17.66	18.95	20.01	20.85	21.94	20.85	19.07	15.44	14.3	17.01	17.93	16.86	18.76	20.95
LC-2R1B8-3.5 (90)	15.33	16.8	17.99	18.82	20.13	21.27	22.33	21.46	22.17	21.58	20.09	21.43	24.05	26.19	29.45	32.11	31.31	32.99	37.35
LC-2R1B8-3.5 (120)	16.98	18.11	19.08	20.35	21.24	22.19	22.34	22.33	21.36	19.62	22.54	26.75	29.49	29.76	30.88	33.59	41.19	43.09	44.88

Table 4. Average sound reduction indexes (R_{avg} for impedance tube and R_{sim} for *INSUL*) of the materials.

Sample Code (sample thickness, mm)	R_{avg} (Impedance tube, dB)	R_{sim} (<i>INSUL</i> , dB)
LC-2B1R8-2 (60)	23.26	45
LC-2B1R8-2 (90)	25.4	47
LC-2B1R8-2 (120)	27.74	49
LC-2B1R8-2.75 (60)	27.24	45
LC-2B1R8-2.75 (90)	30.18	48
LC-2B1R8-2.75 (120)	25.31	50
LC-2B1R8-3.5 (60)	25.99	45
LC-2B1R8-3.5 (90)	28.6	48
LC-2B1R8-3.5 (120)	27.01	50
LC-2R1B8-2 (60)	18.05	42
LC-2R1B8-2 (90)	24.82	44
LC-2R1B8-2 (120)	24.98	46
LC-2R1B8-2.75 (60)	26.12	43
LC-2R1B8-2.75 (90)	25.93	45
LC-2R1B8-2.75 (120)	26.01	47
LC-2R1B8-3.5 (60)	20.01	42
LC-2R1B8-3.5 (90)	21.46	44
LC-2R1B8-3.5 (120)	22.33	46

**Fig. 7.** Comparison of physical test results for barite and rubber aggregate samples (2B1R8).

results obtained in this study should be interpreted as indicative or comparative rather than as absolute STL/SRI values applicable to full-scale building elements [59].

3.1. Effect of aggregate-to-binder ratio on the mortar with 2 volumes barite and 1 volume rubber aggregate mortar (2B1R)

In the 2B1R8 mortar with an aggregate-to-binder ratio of 2.0, the bulk density was 2.1 g/cm³, increasing by factors of 1.04 and 1.07 at ratios of 2.75 and 3.5, respectively. Correspondingly, the mortar with a 3.5 aggregate-to-binder ratio exhibited a denser structure compared to those with ratios of 2.0 and 2.75. Porosity was 23.13% at a 2.0 ratio, decreasing by factors of 0.98 and 0.93 at ratios of 2.75 and

3.5, respectively (Fig. 7). Water absorption by weight and the capillary coefficient (C_c) also decreased in parallel with porosity. The increased C_c indicates that the mortar contained narrow, well-connected pores, resulting in higher capillary pressure. Decrease in porosity from 2 mortar to 2.75 and 3.5, resulted in decrease in C_c values of the samples. The C_c value of the 3.5 mortar (0.31 kg/m²·min^{1/2}) satisfies the threshold ($C \leq 0.40$) specified in EN 998-1 [60]; however, 2 (0.83 kg/m²·min^{1/2}) and 2.75 (0.59 kg/m²·min^{1/2}) samples do not meet the standard requirements for external applications indicating a faster moisture ingress rate once they contact with water.

Due to barite's high density, an increase in its volume fraction in the mortar increases bulk density, compressive strength, and flexural strength while decreasing porosity and water sorption, as expected; however, the 2B1R8-2.75 mixture deviates from this

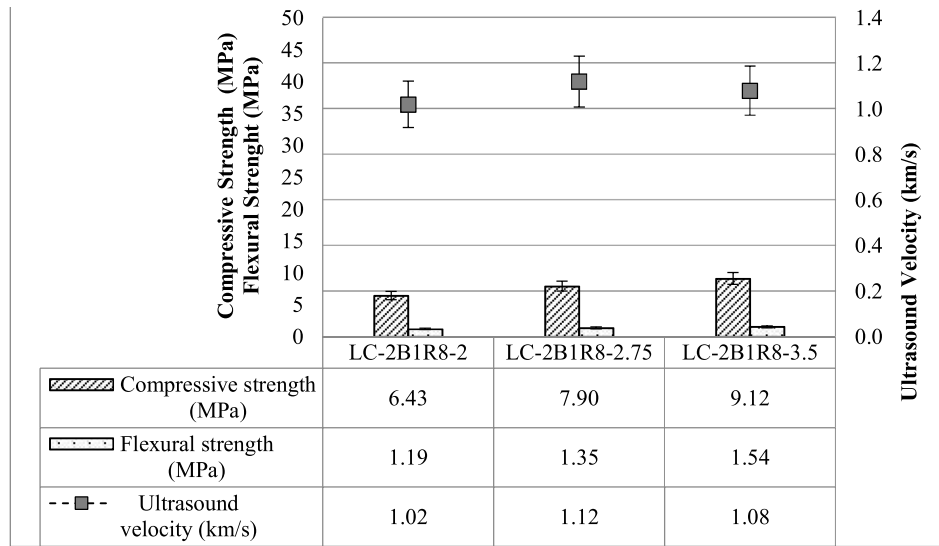


Fig. 8. Comparison of mechanical test results for samples containing barite and rubber aggregate (2B1R8).

Table 5. Mass, unit surface mass, resonance frequency (f_{11}) and critical frequency (f_c) data for samples (with 2, 2.75 and 3.5 aggregate to binder ratio) with different thicknesses (60–90–120 mm).

Specimen Code (thickness-mm)	Mass (g), unit surface mass (g/cm ²) for 98 mm and 28 mm		resonance frequency	critical frequency
	98	28	f_{11} (Hz)	f_c (Hz)
LC-2B1R8-2 (60)	981.59, 13.02	75.08, 12.20	12.23	1070.66
LC-2B1R8-2 (90)	1488.59, 19.74	109.92, 17.87	18.34	713.78
LC-2B1R8-2 (120)	1966.13, 26.07	121.31, 19.72	24.46	535.33
LC-2B1R8-2.75 (60)	1038.91, 13.78	64.78, 10.53	11.22	982.22
LC-2B1R8-2.75 (90)	1552.7, 20.59	96.07, 15.62	16.83	654.81
LC-2B1R8-2.75 (120)	2050.91, 27.20	133.95, 21.78	22.44	491.11
LC-2B1R8-3.5 (60)	1047.23, 13.89	81.35, 13.22	13.00	1008.72
LC-2B1R8-3.5 (90)	1558.22, 20.66	118.06, 19.19	19.50	672.48
LC-2B1R8-3.5 (120)	2065.95, 27.40	150.77, 24.51	26.01	504.36

trend, exhibiting the highest ultrasonic pulse velocity (UPV) and MoE values. The elastic modulus (MoE), a stiffness indicator, confirms that this mortar exhibits greatest resistance to elastic deformation under applied loads (Fig. 8).

Mass, unit surface mass, resonance frequency (f_{11}) and critical frequency (f_c) data of mortars with different thicknesses are shown in Table 5. In parallel with the MoE values, the LC-2B1R8-2.75 mixture, containing a 2:1 barite-to-rubber aggregate ratio and an aggregate-to-binder ratio of 2.75, exhibited the highest sound reduction index ($R_{avg} = 30.18$ dB) at a 90 mm thickness, with a compressive strength of 7.9 MPa which meets the 7-day strength requirement for ternary blended cements classified as Type IT ($S < 25$) (ASTM C595/C595M– 24 [40]). Changing the aggregate to binder ratio from 2.75 to 2 and 3.5 enabled the enhanced R_{avg} value to be obtained at 120 mm, and no improvement was observed due to decreasing or increasing thickness in other ratios (Fig. 9).

The dashed lines represent the fitted mass law behavior in Fig. 10. The theoretical mass law predicts a much higher STL (ranging from ~35 dB at 100 Hz to ~65 dB at 6300 Hz). The experimental results (solid lines) are significantly lower than the theoretical limit (by roughly 20–25 dB) as expected. The difference between the theoretical mass law and actual performance at a thickness of 60 mm is quite clear. In particular, the coincidence dip around 1600 Hz is very pronounced in the LC-2B1R8-3.5 sample. As the thickness increases, the mass law lines shift upward. The 90 mm thick LC-2B1R8-2.75 (green solid line) stands out as the sample that most closely approaches the theoretical mass law after 1600 Hz. The heaviest samples are 120 mm thick. Interestingly, the LC-2B1R8-2 sample has captured the theoretical mass law at high frequencies (above 1600 Hz) and even shows a tendency to exceed it. This may indicate that the material performs at those frequencies not only with its mass but also with its internal damping

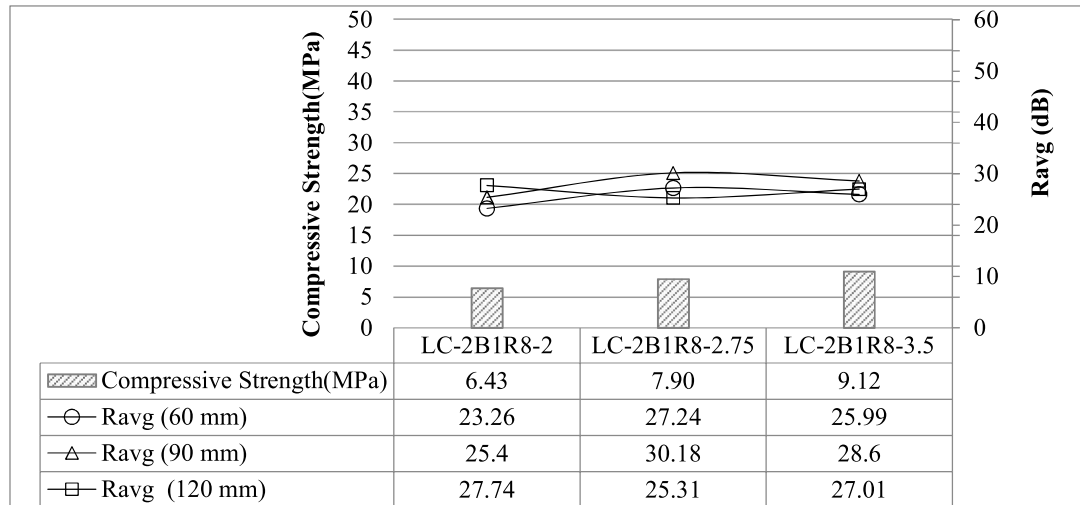


Fig. 9. Compressive strength and weighted sound reduction indexes (R_{avg}) of samples produced with different aggregate-to-binder ratios (2, 2.75 and 3.5).

properties. In all graphs, the experimental data at low frequencies (100–400 Hz) is much lower than the theoretical data. This is because at low frequencies, insulation depends not only on mass but also on the stiffness of the sample and the mounting conditions (stiffness-controlled region).

3.1.1. Sound transmission loss of 60 mm thick samples

The resonance and critical frequencies, determined by using the diffuse sound field formula, are illustrated in Fig. 11. For 60 mm-thick specimens, the resonance frequencies of mortars with ratios of 2, 2.75, and 3.5 were calculated as 12 Hz, 11 Hz, and 13 Hz, respectively—frequencies that lie below the measurement range. The corresponding critical frequencies were 1070 Hz, 982 Hz, and 1008 Hz. No substantial decline in STL was observed beyond these critical points, except for the 3.5 mortar. Despite variations in the aggregate-to-binder ratio, the resonance and critical frequency values remained relatively close, indicating consistent vibrational behavior among the samples.

In the low-frequency region, the key factors influencing sound transmission are the material's damping capacity and stiffness. Among the three mortar types, the specimen with an aggregate-to-binder ratio of 2.75 exhibited a higher modulus of elasticity than those with ratios of 2 and 3.5. The sound transmission loss (STL) of the mortar with a ratio of 2 ranged between 16.52 and 36.79 dB, while the mortar with a ratio of 2.75 showed values between 23.46 and 37.82 dB, and the 3.5 mixture ranged from 19.11 to 30.67 dB, all measured within the 1/3 octave frequency band. Overall, the 2.75 mortar demonstrated the highest STL performance across all frequencies

(Table 3 and Fig. 11). Although the 3.5 mixture yielded a denser structure, its STL values were up to 10 dB lower than those of the 2.75 mixture. In contrast, 2 mortar, characterized by the highest porosity, exhibited the lowest STL values up to 1000 Hz. Based on the findings of Kim et al. [61], sound absorption should also be considered in STL analyses of concrete specimens due to their relatively large thickness. Regardless of concrete type (heavyweight or lightweight), the coincidence (resonance) frequency that causes a sudden reduction in STL typically occurs at low frequencies, generally within the range of 300–600 Hz. This behavior is further influenced by specimen thickness, elastic modulus, and the angle of sound incidence.

3.1.2. Sound transmission loss of 90 mm thick samples

The resonance and critical frequencies calculated via the diffuse sound field equation are presented in Fig. 12. For specimens with a 90 mm thickness, the resonance frequencies of mortars with aggregate to binder ratios 2, 2.75, and 3.5 were determined as 18 Hz, 16 Hz, and 19 Hz, respectively—all below the measurable frequency range. The corresponding critical frequencies were calculated as 713 Hz, 654 Hz, and 672 Hz, and a decline in STL was observed for the 3.5 mixture beyond its critical frequency of 672 Hz. In the low-frequency range, the dominant parameters are the material's damping characteristics and stiffness. In the mid-frequency range, sound insulation performance is primarily governed by the mass of the material. At high frequencies, stiffness, thickness, and mass collectively influence the acoustic behavior. The sound transmission loss (STL) of mortar 2 ranged from 16.88 dB to 27.96 dB across

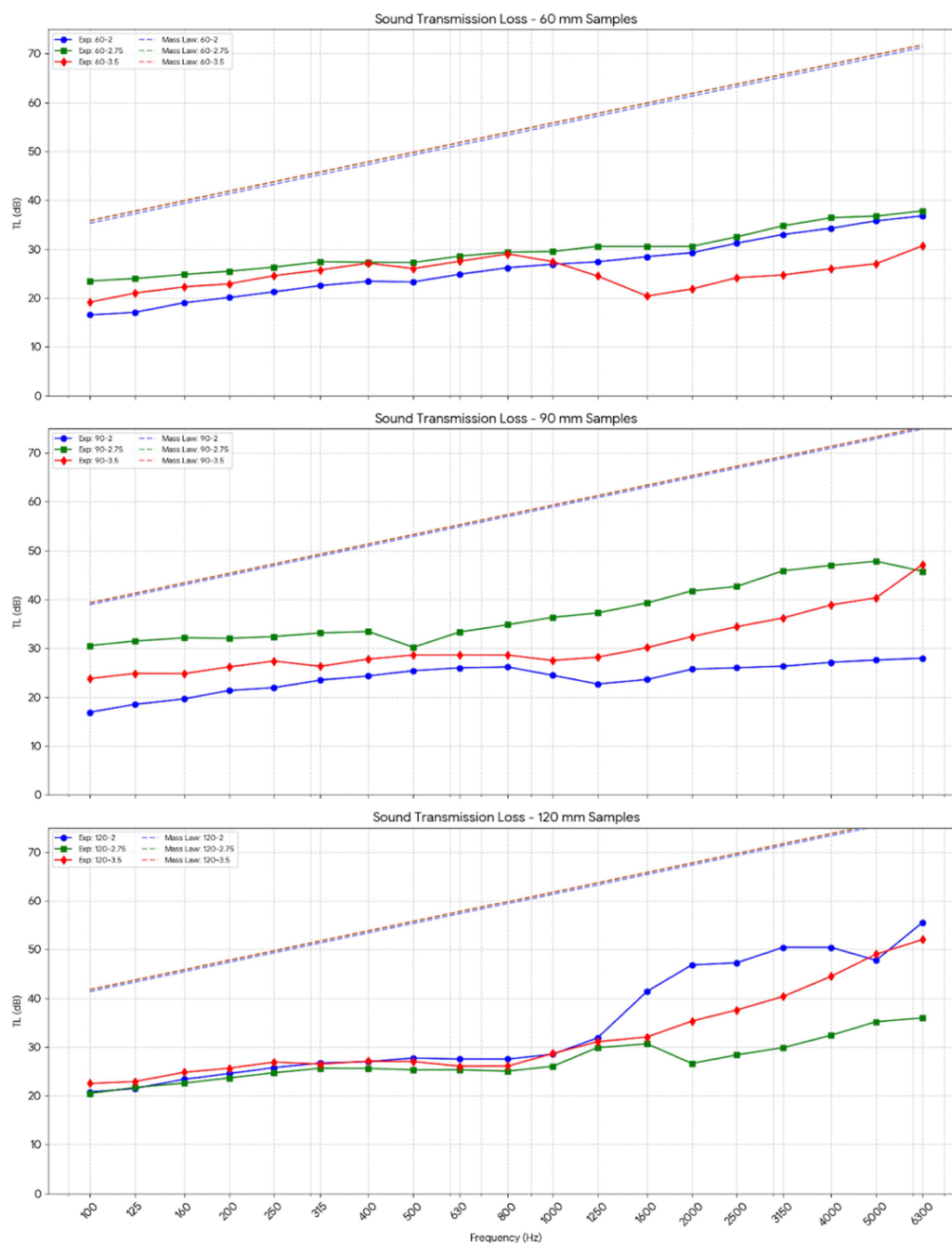


Fig. 10. Comparison of mass law curve and experimental STL results of LC-2B1R mortars.

the tested frequencies, while mortar 2.75 exhibited values between 30.53 dB and 45.75 dB, and mortar 3.5 showed a variation from 23.78 dB to 47.14 dB (Table 3 and Fig. 12). Altering the aggregate-to-binder ratio did not yield any notable improvement in acoustic performance at a thickness of 90 mm. The LC-2B1R8-2.75 mixture again achieved the highest STL values at all frequencies, followed by mortar 3.5, whereas mortar 2 displayed the lowest sound insulation, corresponding to its lower modulus of elasticity

and surface density, which aligns with expectations. Although the 3.5 mixture contained a higher barite proportion, its structure, unlike that of mortars composed solely of barite [30] was insufficiently stiff to provide effective stiffness control, resulting in a lower STL performance.

3.1.3. Sound transmission loss of 120 mm thick samples

The resonance and critical frequencies, determined by using the diffuse sound field equation, are

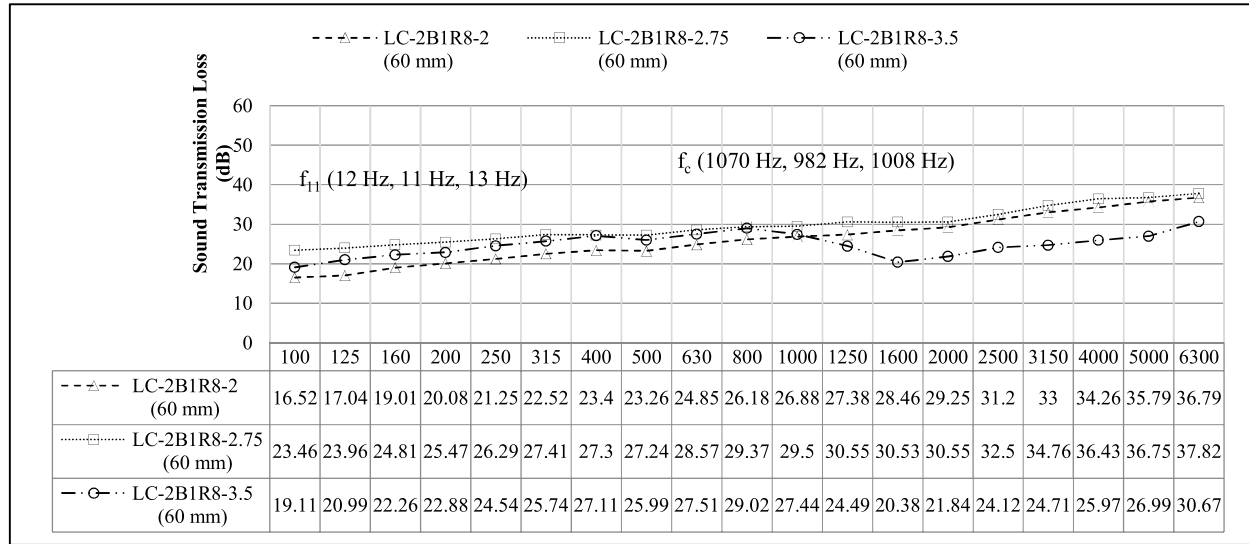


Fig. 11. Impedance tube sound transmission loss (STL) results (60 mm) in 1/3 octave bands depending on the increase and decrease of the aggregate-to-binder ratio of 2B1R samples.

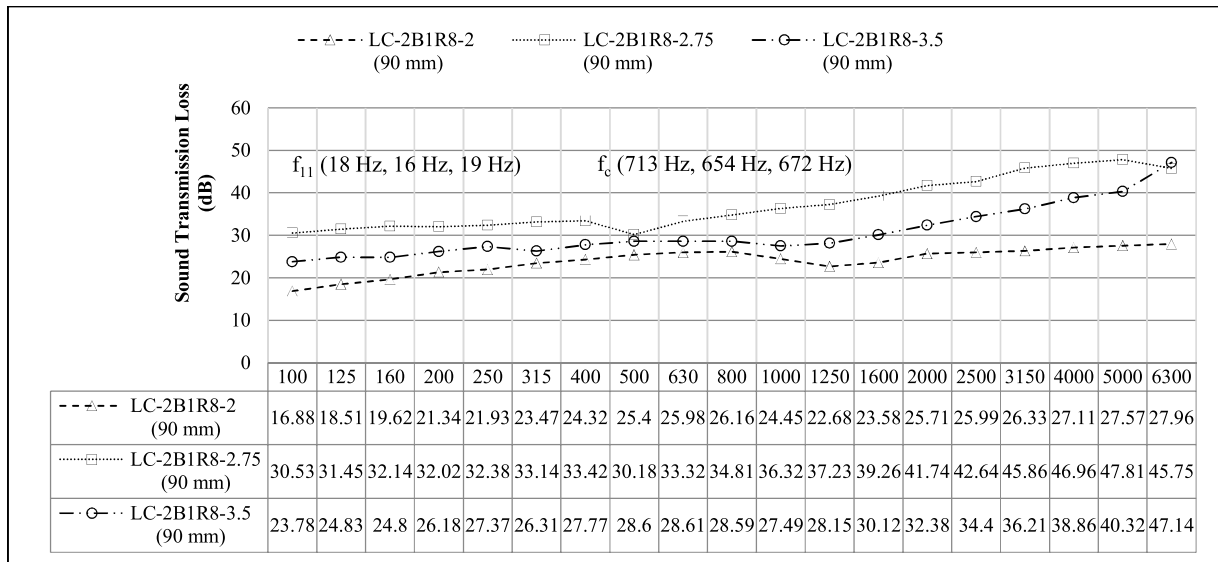


Fig. 12. Impedance tube sound transmission loss (STL) results (90 mm) in 1/3 octave bands depending on the increase and decrease of the aggregate-to-binder ratio of 2B1R samples.

illustrated in Fig. 10. For 120 mm-thick specimens, the resonance frequencies of the 2, 2.75, and 3.5 mortars were calculated as 24 Hz, 22 Hz, and 26 Hz, respectively, all of which lie outside the measurement frequency range. The corresponding critical frequencies were determined as 535 Hz, 491 Hz, and 504 Hz, and a slight decline in STL was observed for all mixtures beyond their respective resonance frequencies.

The sound transmission loss (STL) of mortar with aggregate to binder ratio 2 varied between 20.7 dB and 55.5 dB across the frequency range, whereas mortar 2.75 exhibited STL values between 20.5 dB and 35.9 dB, and mortar 3.5 ranged from 22.5 dB to 52

dB (Table 3 and Fig. 13). A reduction in the aggregate-to-binder ratio led to an improvement in acoustic performance at a thickness of 120 mm, with mortar 2 achieving the highest STL values particularly in for all frequency ranges. Similarly, increasing the aggregate-to-binder ratio from 2.75 to 3.5 further improved the overall sound insulation across all frequency bands. In short, while 2.75 had the lowest value, mortars 2 and 3.5 gave better and close STL results. Despite its lower modulus of elasticity and surface density, the relatively better performance of mortar 2 was unexpected. Although mortar 3.5 contained a higher proportion of barite, its composition—similar to

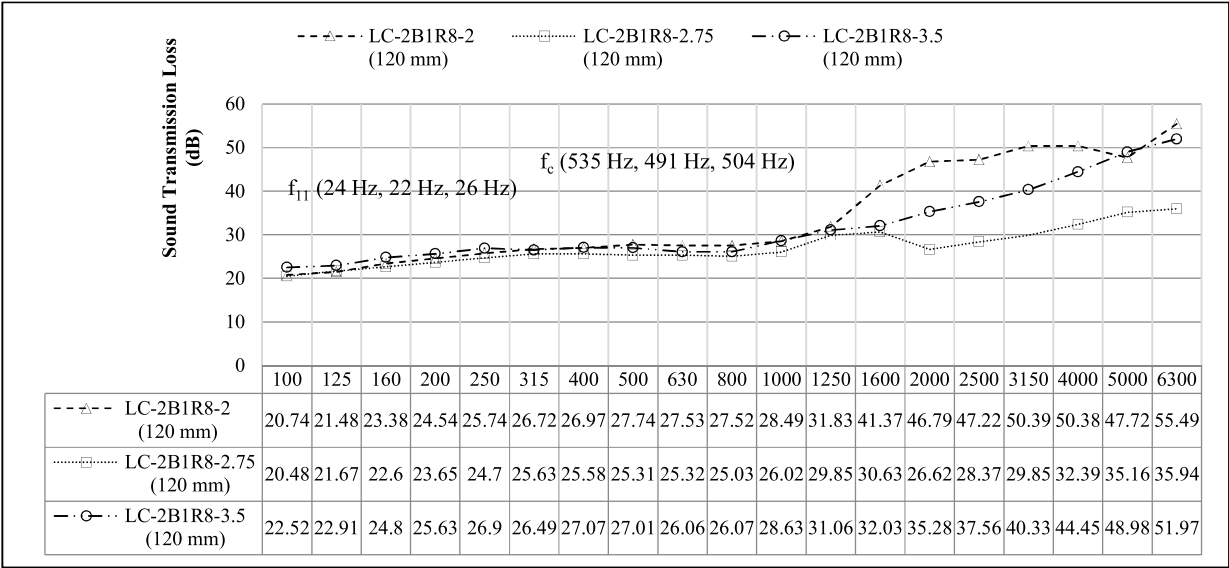


Fig. 13. Impedance tube sound transmission loss (STL) results (120 mm) in 1/3 octave bands depending on the increase and decrease of the aggregate-to-binder ratio of 2B1R8 samples.

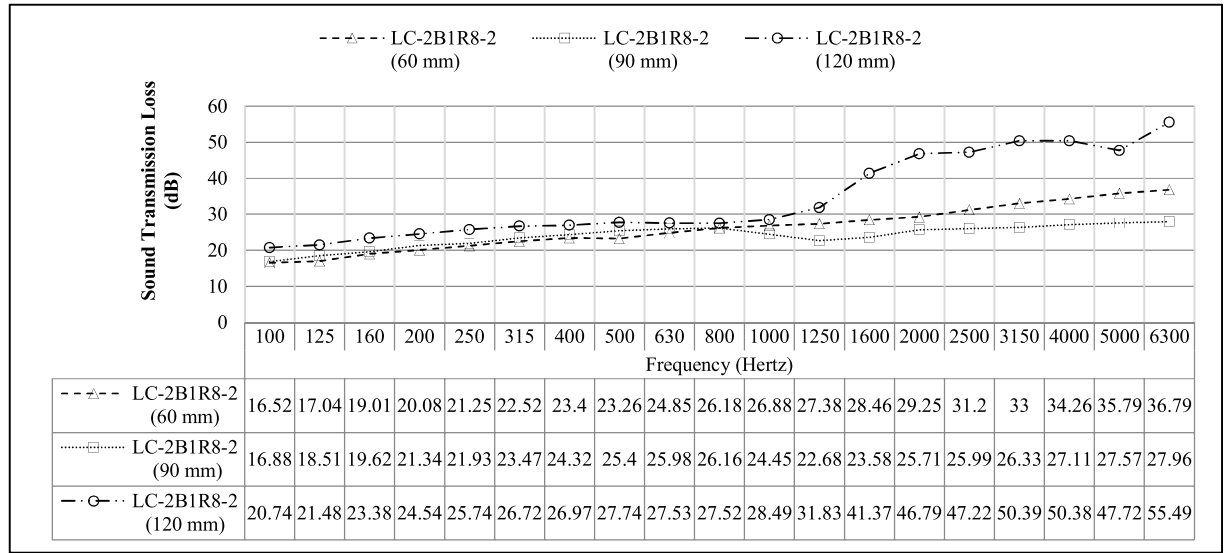


Fig. 14. Impedance tube sound transmission loss (STL) results of 2B1R8-2 samples at different thicknesses (60-90-120 mm) in 1/3 octave bands.

mortars made only with barite [30] was insufficient to provide effective stiffness control, resulting in a failure to achieve the highest STL values.

3.1.4. Effect of increasing thickness on sound transmission loss

In the previous analysis of Söyek Abay and Tanaçan [30] combined barite- and rubber-based mortars (2B1R8 and 2R1B8), with the aggregate to binder ratio of 2.75 was evaluated under varying thicknesses to assess its influence on sound transmission loss (STL). In this present section, the effect of the

aggregate-to-binder ratio (2–3.5) on the acoustic performance of mortars is examined as the specimen thickness increases. For mortar 2, the 120 mm-thick sample exhibited the highest STL values across all frequencies (Fig. 14). At low and mid frequencies, the 60 mm and 90 mm specimens showed comparable behavior, while at high frequencies, the 60 mm sample demonstrated an improvement in STL relative to the 90 mm specimen. These findings indicate that, consistent with previous observations, an optimum thickness exists for achieving maximum sound insulation efficiency. Similarly, for the mortar with

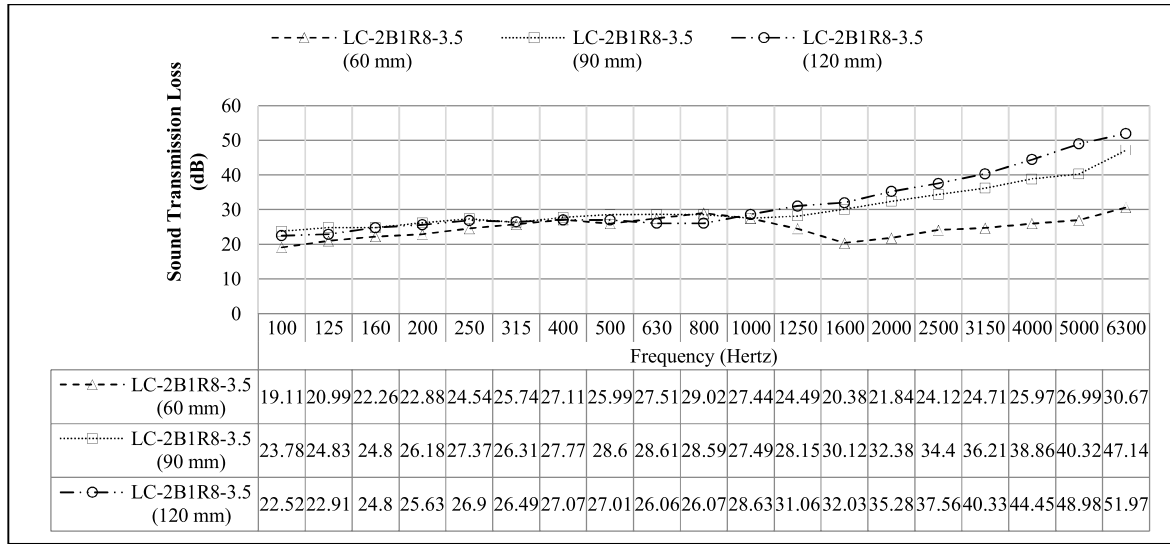


Fig. 15. Impedance tube sound transmission loss (STL) results of 2B1R8-3.5 samples at different thicknesses (60-90-120 mm) in 1/3 octave bands.

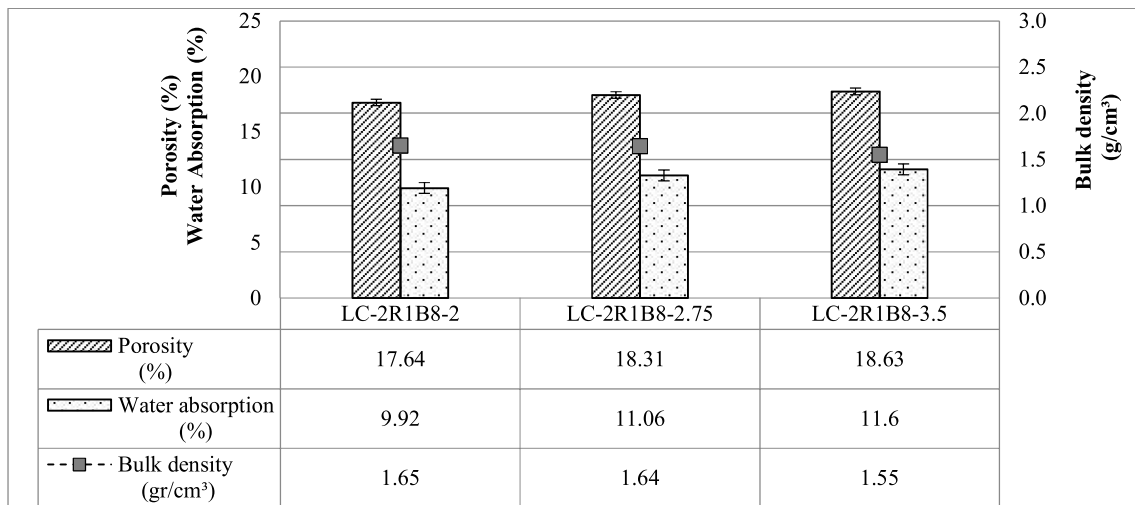


Fig. 16. Comparison of physical test results for barite and rubber aggregate samples (2R1B8).

an aggregate-to-binder ratio of 3.5, STL values were comparable at low and mid frequencies, whereas the 120 mm-thick sample yielded the highest insulation performance at high frequencies (Fig. 15).

3.2. Effect of aggregate-to-binder ratio on the mortar with 2 volumes rubber and 1 volume barite aggregate mortar (2R1B)

The highest bulk density was achieved in mortar with an aggregate-to-binder ratio of 2 (1.65 gr/cm³). In the 2.75 mortar, quite similar values were obtained, with a 0.99-times decrease. In the 3.5 mortar, there was a 0.94-times decrease. In parallel with the bulk density data, the mortar with an aggregate-to-

binder ratio of 2 had a denser structure compared to the mortars with ratios of 2.75 and 3.5. While the porosity values were found to be 17.64% in the 2 mortar, they slightly increased by a factor of 1.04 in the 2.75 mortar and by a factor of 1.06 in the 3.5 mortar. Water absorption by weight and C_c results also increase parallel to the porosity results (Fig. 16). The C_c value of the mortar 2 (0.36 kg/m²·min^{1/2}) satisfies the threshold ($C \leq 0.40$) specified in EN 998-1 [60]; however, 2.75 (0.62 kg/m²·min^{1/2}) and 3.5 mortar (0.71 kg/m²·min^{1/2}) samples do not meet the standard requirements for external applications.

In mixtures with 2R1B aggregates, as the waste rubber content increases (i.e., as the aggregate-to-binder ratio rises from 2.0 to 3.5), porosity increases, while

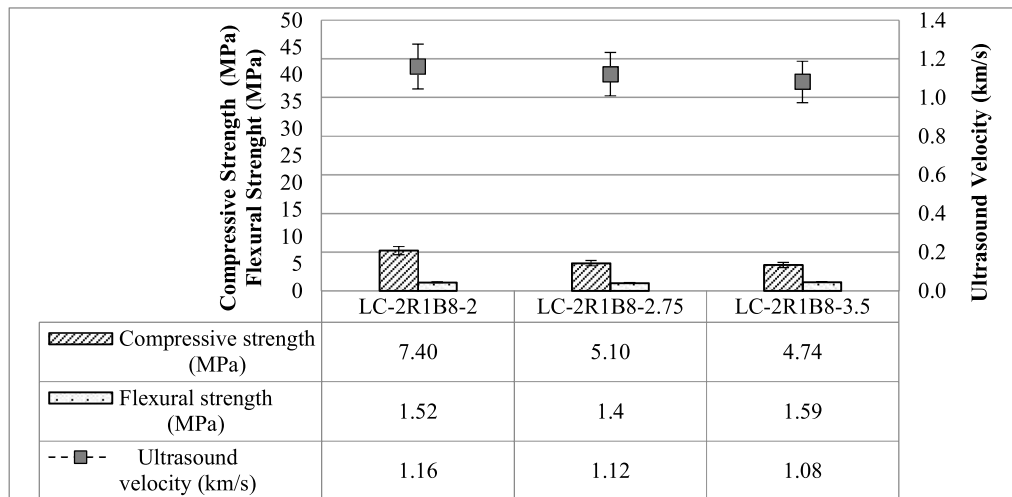


Fig. 17. Comparison of mechanical test results for samples containing barite and rubber aggregate (2R1B8).

Table 6. Mass, unit surface mass, resonance frequency (f_{11}) and critical frequency (f_c) data for samples (with 2, 2.75 and 3.5 aggregate-to-binder ratio) with different thicknesses (60-90-120 mm).

Specimen Code (thickness-mm)	Mass (g), unit surface mass (g/cm ²) for 98 mm and 28 mm		resonance frequency	critical frequency
	98	28	f_{11} (Hz)	f_c (Hz)
LC-2R1B8-2 (60)	744.27, 9.87	60.96, 9.91	14.28	1046.61
LC-2R1B8-2 (90)	1156.87, 15.34	89.20, 14.50	21.42	697.74
LC-2R1B8-2 (120)	1564.46, 20.75	115.63, 18.80	28.56	523.30
LC-2R1B8-2.75 (60)	780.33, 10.35	40.46, 6.57	9.4	1196.68
LC-2R1B8-2.75 (90)	1175.36, 15.59	73.22, 11.90	14.11	797.79
LC-2R1B8-2.75 (120)	1559.83, 20.69	101.46, 16.49	18.81	598.34
LC-2R1B8-3.5 (60)	727.64, 9.65	57.44, 9.33	13.58	1101.57
LC-2R1B8-3.5 (90)	1117.06, 14.81	83.70, 13.60	20.37	734.38
LC-2R1B8-3.5 (120)	1488.71, 19.74	112.69, 18.32	27.16	550.78

bulk density, compressive strength, ultrasonic pulse velocity (UPV), and stiffness progressively decrease. This is expected, as rubber aggregates, being highly elastic and less stiff than rigid barite, to reduce the mortar's compactness. However, in flexural testing, where tensile stresses predominate, the higher rubber content in the 2R1B8-3.5 mortar, enhanced by strong interfacial bonding with the LC³ binder, likely promotes energy absorption and dissipation, delaying crack initiation and propagation, thus increasing flexural strength (Fig. 17). This aligns with studies on rubberized mortars, which demonstrate improved flexural properties due to rubber's crack-bridging effects, despite reduced compressive strength [62].

Mass, unit surface mass, resonance frequency (f_{11}) and critical frequency (f_c) data of mortars with different thicknesses are available in Table 6. Mortar 2, with the least rubber content, received the highest compressive strength value, while mortar 3.5, the most porous mortar, received the lowest value. In terms of acoustic properties, the highest R_{avg} value was obtained in the mortar of 2.75 in all thicknesses.

Changing the aggregate-to-binder ratio between 2 and 3.5 could not improve the R_{avg} value in this mortar either. It can be said that the 2.75 aggregate-to-binder ratio used in the mortar standards gave the highest value in terms of R_{avg} value (Fig. 18).

The surface densities in the 2R1B series (approximately 9.6-20.7 g/cm²) are lower than those in the 2B1R series, therefore the theoretical mass law curves (dashed lines) are positioned slightly lower (Fig. 19). The "coincidence" drop around 1600 Hz for 60 mm (LC-2R1B8) is also evident in these mortars. Particularly in the LC-2R1B8-3.5 (red) sample, this effect causes the insulation to drop below 15 dB at 1600 Hz. As thickness and mass increase at 120 mm, the performance at high frequencies (>1250 Hz) approaches the theoretical mass law much more closely, even exceeding the theoretical limit at some points. This indicates that the material is quite successful in damping high-frequency sounds. The 120 mm thick samples provide around 20 dB of insulation even at low frequencies, while the 60 mm samples remain in the 10 dB range.

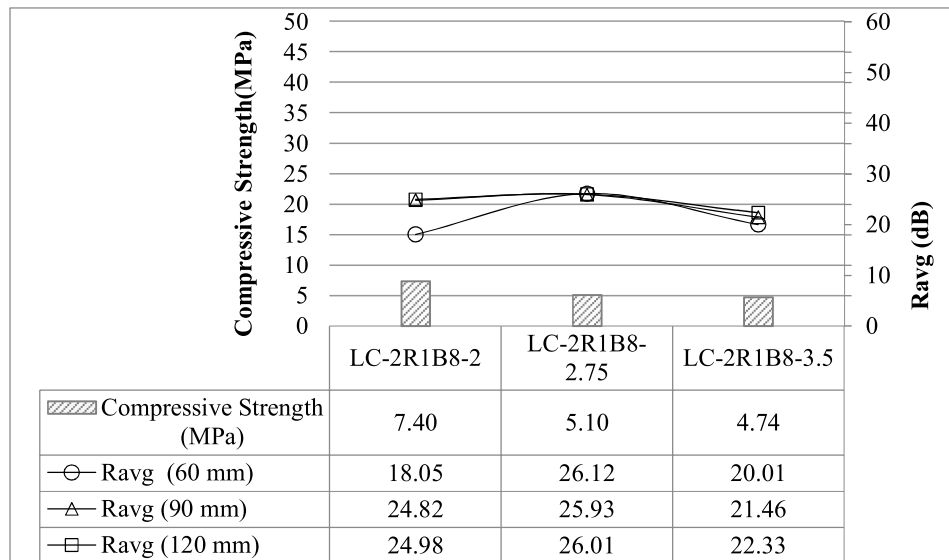


Fig. 18. Compressive strength and weighted sound reduction indexes (R_{avg}) of samples produced with different aggregate-to-binder ratios (2, 2.75 and 3.5).

3.2.1. Sound transmission loss of 60 mm thick samples

The resonance and critical frequencies, calculated using the diffuse sound field equation, are presented in Fig. 20. For samples with a thickness of 60 mm, the resonance frequencies of the 2.0, 2.75, and 3.5 mortars were determined as 14 Hz, 9 Hz, and 13 Hz, respectively—all of which fall outside the measurement frequency range. Beyond the resonance point, all mixtures exhibited a slight decline in STL, corresponding to their respective critical frequencies of 1046 Hz, 1196 Hz, and 1101 Hz.

The mortar with an aggregate-to-binder ratio of 2.75 achieved the highest sound transmission loss (STL) across all frequencies, indicating superior acoustic efficiency. This mixture exhibited a denser and more compact structure, with STL values exceeding those of the other mortars by up to 11 dB. The mortar with the aggregate to binder ratio of 2 showed the lowest STL performance below 800 Hz, but beyond this frequency, it demonstrated improved insulation, ranking second after the 2.75 mixture. Conversely, the 3.5 mortar, distinguished by its more porous microstructure, yielded the lowest sound insulation performance above 800 Hz (Table 3 and Fig. 20).

3.2.2. Sound transmission loss of 90 mm thick samples

The resonance and critical frequencies, calculated using the diffuse sound field equation, are presented in Fig. 19. For samples with a thickness of 90 mm, the resonance frequencies of the 2.0, 2.75, and 3.5 mortars were determined as 21 Hz, 14 Hz, and 20 Hz, respectively—all of which fall outside the measurement frequency range. For the 90 mm-thick

specimens, the mortar with an aggregate-to-binder ratio of 2.75 demonstrated the highest sound transmission loss (STL) up to 2500 Hz, whereas similar STL values were observed among all mixtures beyond 500 Hz. This trend can be attributed to the higher surface density of the 2.75 mixture. Above 2500 Hz, the STL values of all mortars became almost identical. At high frequencies, the effect of the aggregate-to-binder ratio on STL was less pronounced than that observed in the 60 mm-thick samples (Table 3 and Fig. 21).

3.2.3. Sound transmission loss of 120 mm thick samples

The resonance and critical frequencies, calculated using the diffuse sound field equation, are presented in Fig. 20. For samples with a thickness of 120 mm, the resonance frequencies of the 2.0, 2.75, and 3.5 mortars were determined as 28 Hz, 18 Hz, and 27 Hz, respectively—all of which fall outside the measurement frequency range. Although the 2.75 mortar with a 120 mm thickness achieved the highest sound transmission loss (STL) value up to 2000 Hz, the overall STL performance of all mortars remained comparable within this frequency range. Beyond 2000 Hz, the 2 mortar exhibited the highest STL values, whereas the 3.5 mortar showed variations of up to 7 dB between its STL measurements (Table 3 and Fig. 22).

3.2.4. Effect of increasing thickness on sound transmission loss

Increasing the specimen thickness from 60 mm to 120 mm led to an overall increase in sound transmission loss (STL) for the 2, 2.75, and 3.5 mortars. This improvement is primarily attributed to the higher surface density, which enhances the material's resistance

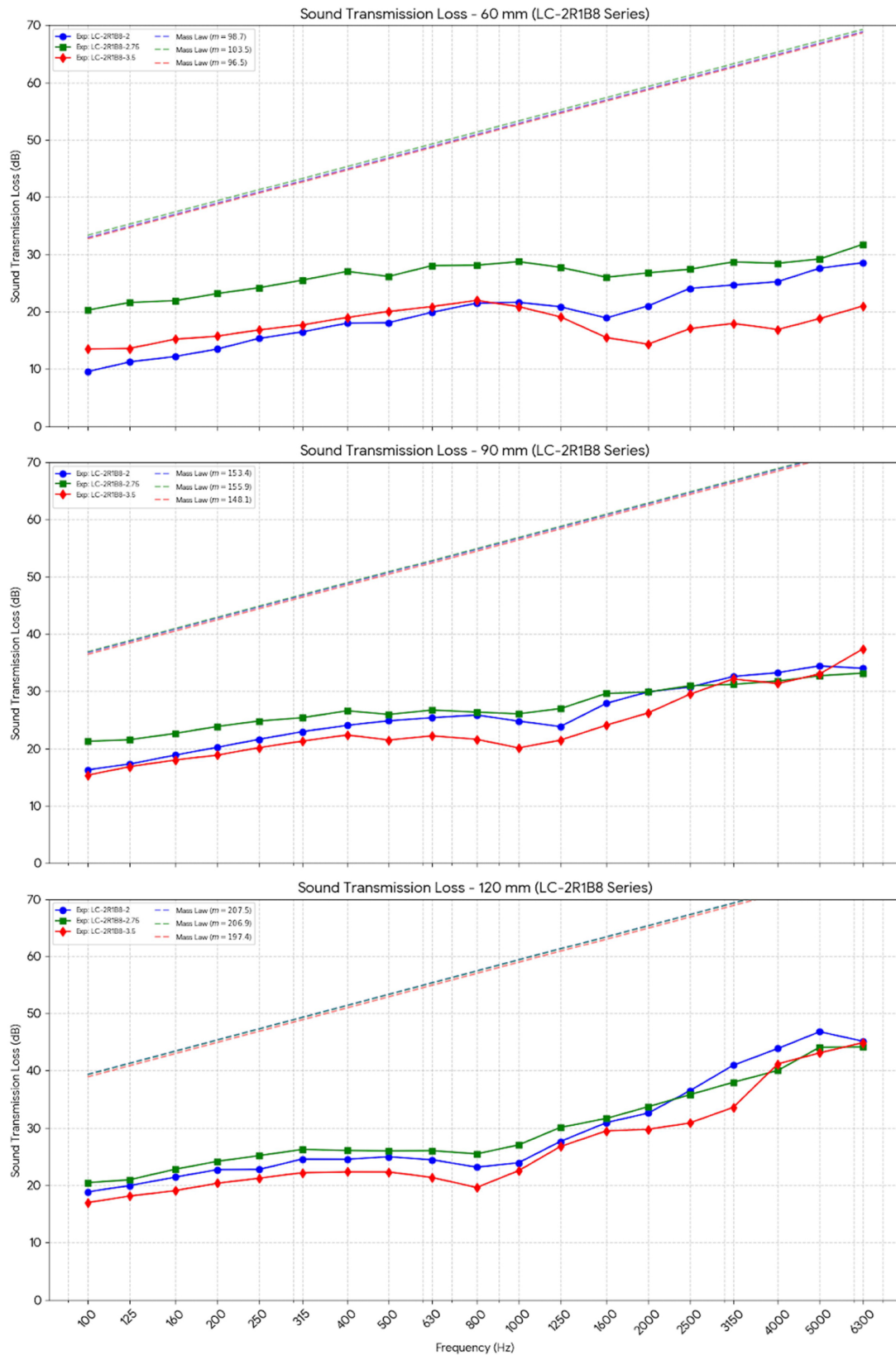


Fig. 19. Comparison of mass law curve and experimental STL results of LC-2R1B mortars.

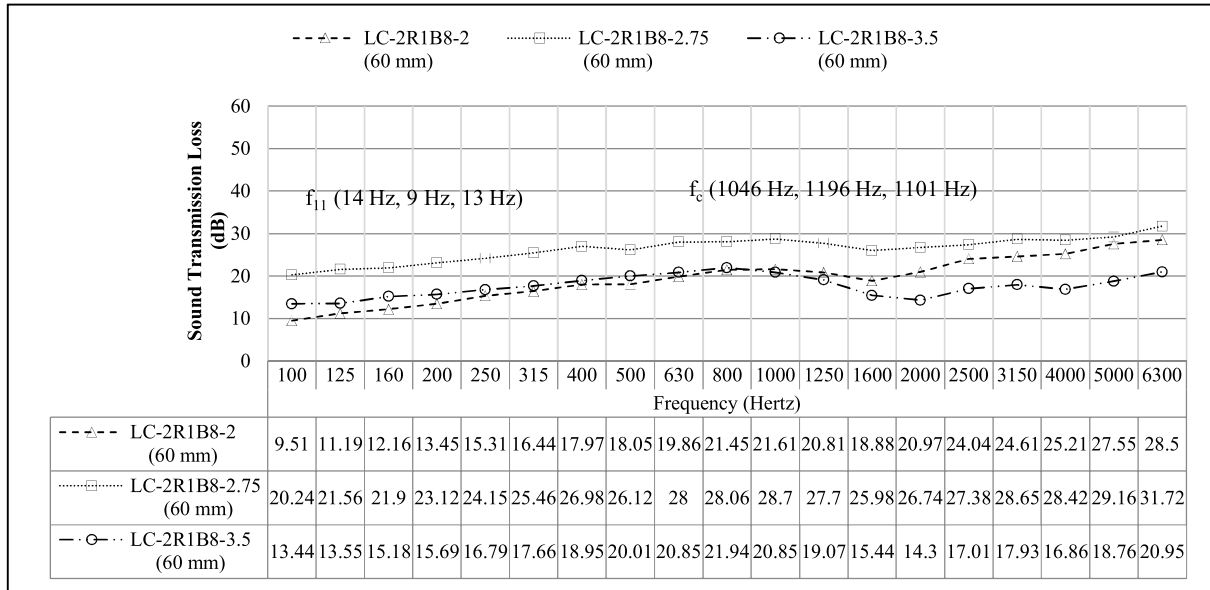


Fig. 20. Impedance tube sound transmission loss (STL) results (60 mm) in 1/3 octave bands depending on the increase and decrease of the aggregate-to-binder ratio of 2R1B samples.

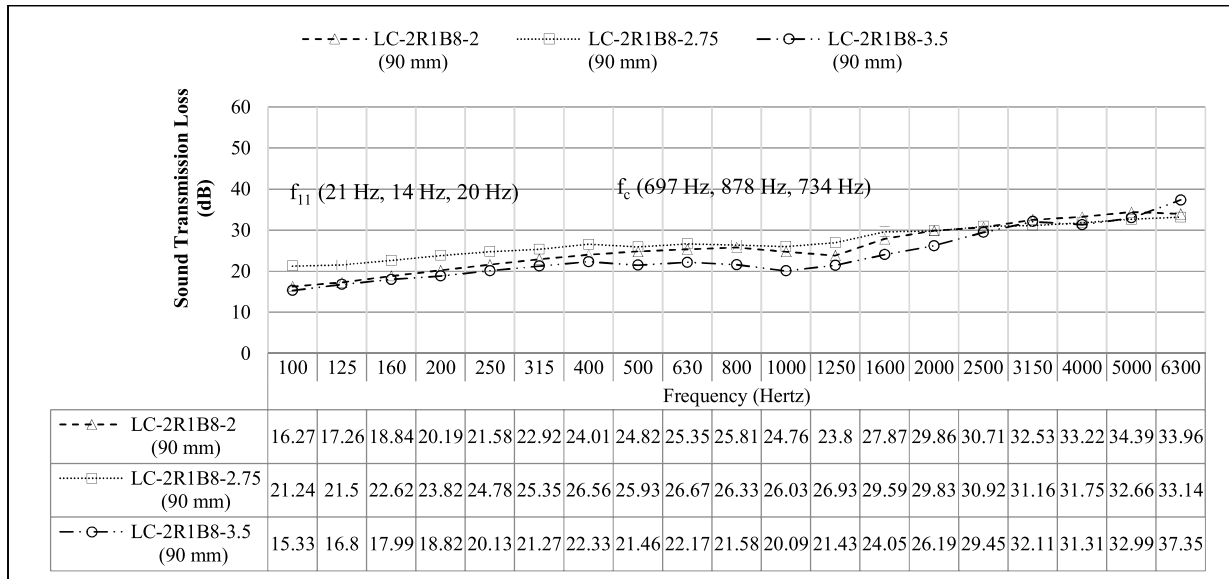


Fig. 21. Impedance tube sound transmission loss (STL) results (90 mm) in 1/3 octave bands depending on the increase and decrease of the aggregate-to-binder ratio of 2R1B samples.

to sound transmission. The effect of thickness was most evident in the 2.75 mortar at higher frequencies, whereas the STL values at low and mid frequencies remained largely consistent across all thickness levels (Figs. 23 and 24).

To summarize the section according to frequency ranges:

- Low Frequency Range (100 Hz - 400 Hz): This region is generally affected by the stiffness of the material. Sound transmission loss (STL) values are

at their lowest levels in all samples (average range of 10–25 dB). A significant increase in TL values is observed when moving from 60 mm to 120 mm. For example, in the LC-2B1R8 series, 60 mm samples start at around 16 dB, while 120 mm samples start at around 20 dB. The LC-2B1R8-2.75 mix ratio exhibits more stable and higher initial performance than other ratios at both 60 mm and 90 mm thicknesses.

- Mid-Frequency Range (500 Hz - 1600 Hz): This region is a transition zone where the mass of

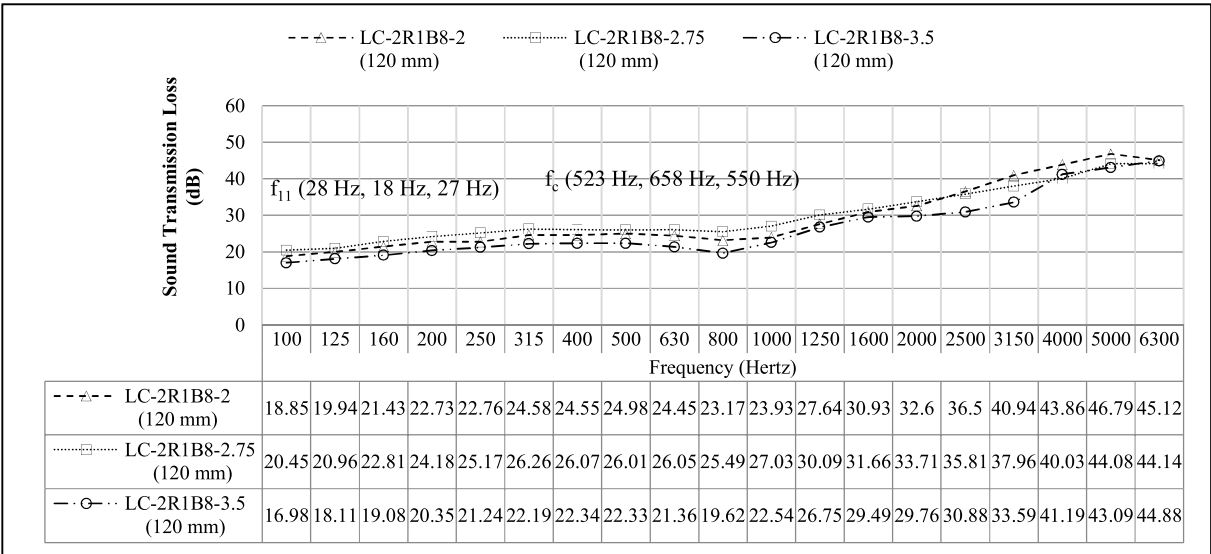


Fig. 22. Impedance tube sound transmission loss (STL) results (120 mm) in 1/3 octave bands depending on the increase and decrease of the aggregate-to-binder ratio of 2R1B samples.

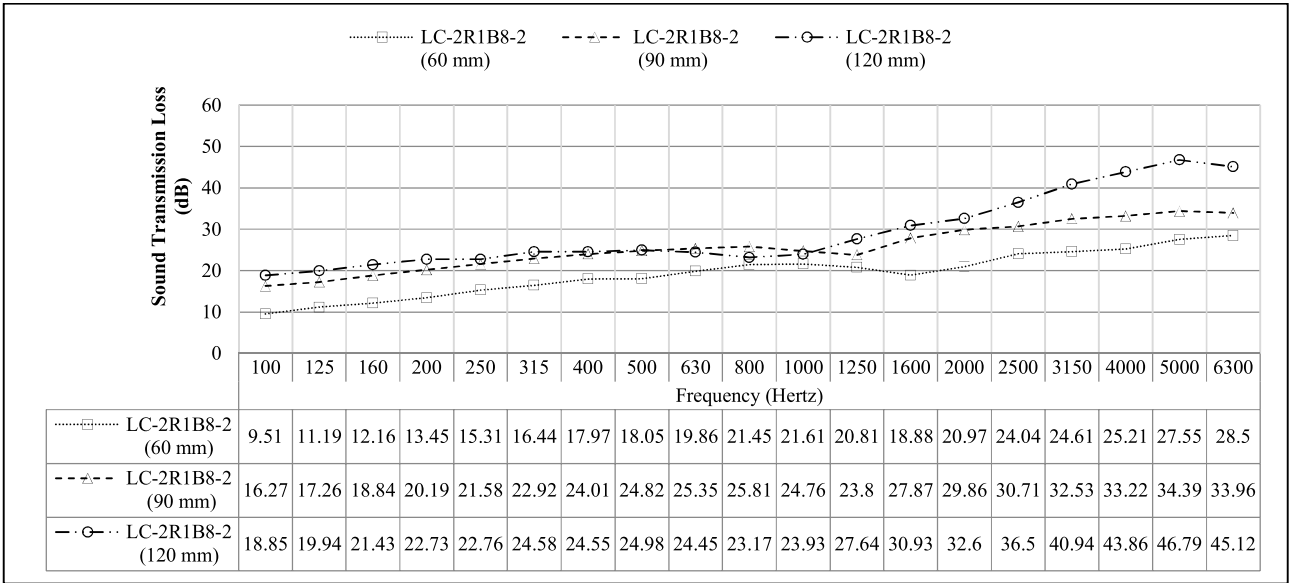


Fig. 23. Impedance tube sound transmission loss (STL) results of 2R1B8-2 samples at different thicknesses (60-90-120 mm) in 1/3 octave bands.

the material begins to dominate, but resonances also come into play. The most notable event in this range is the drops caused by the resonance frequency (f_c). In 60 mm samples, this drop is very clear in the 1600 Hz band (especially in the LC-2B1R8-3.5 and LC-2R1B8-3.5 samples). As the thickness increases (120 mm), this critical frequency shifts towards the 500-800 Hz band. This is consistent with the theoretical expectation that the critical frequency decreases as the material thickens. The LC-2B1R8-2.75 sam-

ple provides more reliable insulation with less fluctuation at mid-frequencies compared to other mortars.

- High Frequency Range (2000 Hz - 6300 Hz): This region is entirely dependent on the mass and internal damping properties of the material. After the critical frequency threshold is exceeded, the STL values rise rapidly in all graphs. The 120 mm thick samples achieve 45–55 dB levels at high frequencies, delivering the best performance in this range. The LC-2B1R8-2 and LC-2B1R8-3.5

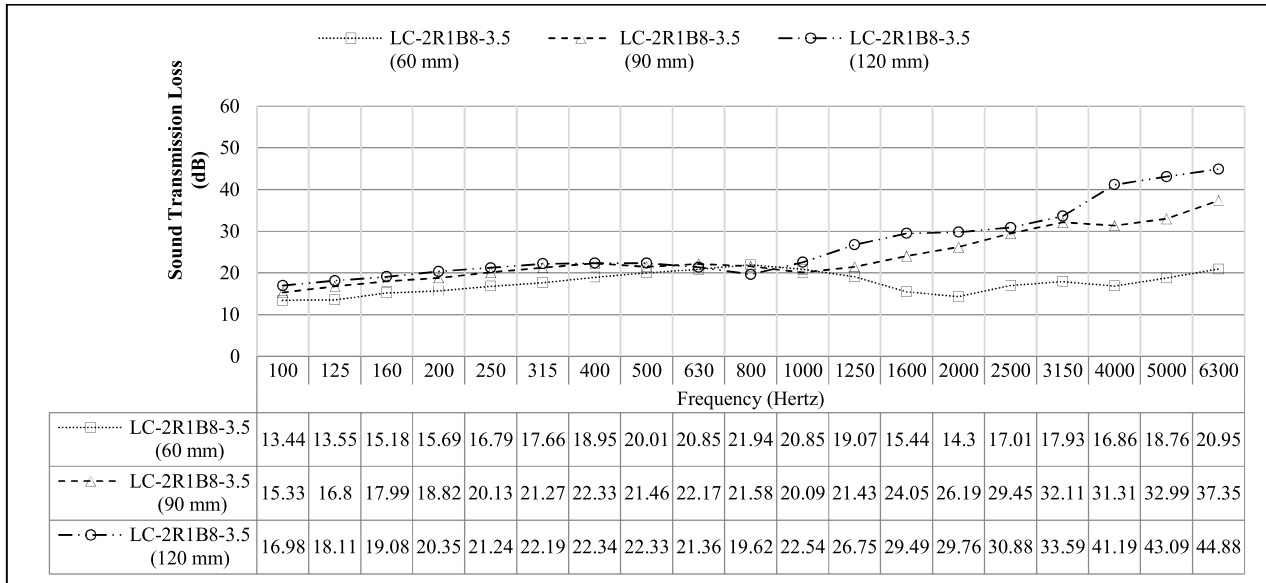


Fig. 24. Impedance tube sound transmission loss (STL) results of 2R1B8-3.5 samples at different thicknesses (60-90-120 mm) in 1/3 octave bands.

samples show a tendency to merge at high frequencies (especially after 5000 Hz).

The present study's result measured with an impedance tube of $R_{\text{avg}} = 30.18$ dB at 90 mm thickness for LC³ mortar with hybrid barite–rubber aggregates (2B1R8-2.75) situate it competitively among partition systems, demonstrating that sustainable binder systems can approach conventional partition performance in airborne sound insulation.

3.3. Assessment of material applications for built environment performance

This study investigated the potential use of LC3-based mortars with barite and rubber aggregates as acoustic materials. In the initial phase of the research, comparisons were made between Portland cement-based mortars and LC3-based mortars in subsequent phases in terms of mechanical and acoustic properties. It was observed that all LC3-based mortars are suitable for use in construction in terms of mechanical properties. When the environmental impact of barite mining is examined, barite mining is associated with land disturbance, waste generation and water and air pollution, with environmental impacts largely governed by mining method, ore-associated impurities, and the effectiveness of site management [63]. However, these environmental impacts can be reduced through proper mining methods. Another aggregate used in the study; rubber particles in concrete, particularly when untreated, may cause local

imperfections in cement hydration, leading to reductions in mechanical properties. Surface treatments such as sodium hydroxide enhance the hydrophilicity of rubber particles, improving water transfer, hydration efficiency, and consequently compressive strength [64]. In the long term, untreated rubber may continue to adversely affect hydration and structural integrity, whereas treated rubber can provide improved durability and performance. Rubber-modified cement composites generally exhibit enhanced crack resistance, energy absorption capacity, and moisture resistance due to the flexibility of rubber particles. However, potential long-term challenges remain, including rubber degradation under environmental exposure and the gradual weakening of rubber–cement bonding, even when chemical treatments are applied [65]. Therefore, further optimization of rubber treatment methods is necessary to ensure stable long-term performance of rubberized concrete.

The study by Júnior et al. [15] presents an evaluation of the sound insulation of simple walls built with solid and hollow plaster blocks of different thicknesses and densities, as well as double walls with acoustic absorbent materials and non-acoustic materials. Plaster blocks are elements widely used in the internal vertical partitions of buildings in Europe and especially in Brazil. In this research, tests were conducted in a standard laboratory, and the sound reduction index of 22 partitions was analyzed. The results showed that hollow plaster blocks weighing over 70 kg/m² tend to exhibit higher acoustic efficiency than solid blocks. The R_w results of blocks with

thicknesses ranging from 50 mm to 100 mm vary between 29 and 39 dB. When the research results of Júnior et al. [15] are compared with the R_{sim} results calculated with the *INSUL* program in our study, the R_{sim} results of the 2B1R mortar with LC³ binder and barite rubber combined aggregate reach up to 50 dB. Dönmez and Türker's study [66] investigated composite panels produced by recycling waste fibers from yarn factories to assess their sound insulation (sound transmission loss) performances. Panels were made from textile waste fibers (0.1–25 mm), with varied density, fiber type, and waste fiber content. Tested results showed that the sound transmission loss (STL) values were measured between 21.4 and 32.6 dB, showing measurable acoustic insulation performance. Yeşilyurt's study [67] investigated the effect of incorporating recycled waste soda glass powder into polyurethane (PU) foams on their sound transmission loss (STL) performance. The inclusion of soda glass significantly enhanced STL values across nearly the entire frequency range compared to neat polyurethane foam. The sample with the highest filler content demonstrated the best acoustic performance, achieving STL improvements of approximately 9 dB at low and mid frequencies and up to 13 dB at high frequencies. Overall, the findings show that waste soda glass fillers effectively improve the sound insulation performance of polyurethane foams, highlighting its potential as a sustainable filler material for acoustic insulation applications. When compared with these state-of-the-art sustainable acoustic materials, the LC³-based mortars investigated in the present study exhibit comparable sound transmission loss levels, while offering higher density. Although polymer-based and fibrous systems generally provide higher sound insulation, the proposed mortar system in our study offers a complementary solution for sound insulation applications where sustainability is required. In the study by Qu et al. [68], the airborne sound insulation performance of lightweight double-leaf walls was investigated, and the type of stud, stud spacing, material used in the cavity (type and thickness of infill materials), type of panel layers, number of layers, thickness, and mass effect were examined. The effect on the airborne sound insulation performance of the lightweight wall was analyzed. The experimental results show that the airborne sound insulation performance of the lightweight double-layer wall can be improved by the following five measures: increasing the interlayer cavity, increasing the panel size, using rock wool or glass wool as the cavity filler material, increasing the number of panel layers or the panel mass, and reducing the number of structural connection elements. The R_w results ranged from 45 to 57.1 dB [68]. This study revealed that

the 2B1R mortar obtained showed sound insulation performance (R_{sim} : 50 dB) close to that of the layered lightweight wall material, and that the produced barite and rubber combined mortar could be used in buildings as a single layer and thin section.

4. Conclusions

LC³ mortars with hybrid aggregates achieved high and competitive acoustic insulation while reducing Portland cement consumption by approximately 45%. Moreover, the incorporation of waste rubber further enhanced the environmental sustainability of the composites.

Results demonstrated that porosity played a decisive role in both mechanical and acoustic behavior and the findings verify that R_{avg} and R_{sim} improvement can be achieved by optimizing both aggregate composition and binder type:

- In the 2B1R mortar, where the barite content by weight was higher, reducing the aggregate-to-binder ratio from 2.75 to 2.0 led to an increase in porosity and a decrease in compressive strength. Accordingly, the R_{avg} value decreased for specimens with 60 mm and 90 mm thicknesses. However, at 120 mm thickness, the increased cross-section resulted in a higher R_{avg} value. Conversely, increasing the aggregate-to-binder ratio from 2.75 to 3.5, reduced porosity and improved compressive strength. Although this enhancement in strength did not increase the R_{avg} values for the 60 mm and 90 mm specimens, a notable improvement was observed at 120 mm.
- In the 2R1B mortar, decreasing the aggregate-to-binder ratio from 2.75 to 2.0 caused a reduction in porosity and an increase in compressive strength; however, the R_{avg} values decreased across all thicknesses. Increasing the ratio from 2.75 to 3.5, on the other hand, resulted in higher porosity and lower compressive strength. Nevertheless, the 2.75 mixture yielded the highest R_{avg} value at all thicknesses.
- Among all mortars, the mortar mixture with an aggregate-to-binder ratio of 2.75 and a 2:1 barite to rubber aggregate combination (LC-2B1R8-2.75) achieved a higher sound reduction index (R_{avg} = 30.18 dB) at a 90 mm thickness compared to mixtures with aggregate-to-binder ratios of 2.0 and 3.5 with the compressive strength of 7.9 MPa satisfying the 7-day strength requirement for Type IT (Slag < 25) ternary blended cements. At the thickness of 90 mm, this composition provided optimal performance, confirming that an effective thickness threshold exists for single-layer

partitions. Based on these findings, the combined influence of barite, contributing to mass, and rubber aggregate, providing damping, demonstrates that neither weight nor damping alone is sufficient to enhance sound insulation—both must act together. Furthermore, it was observed that increasing thickness or compressive strength does not always improve R_{avg} , indicating the presence of an optimum thickness and aggregate-to-binder ratio.

Importantly, the study also bridged the “model–experiment” gap in the literature by presenting the impedance tube and *INSUL* simulation results. Although no relationship has yet been established between experimental R_{avg} and simulated R_{sim} values, presenting the results of both methods together may pave the way for examining the relationship between them in the future studies. According to the Regulation on the Protection of Buildings against Noise [69] and *INSUL* simulation results, LC³ mortars with combined aggregates satisfied the minimum sound insulation requirement for class C buildings, demonstrating practical compliance. Class A represents the best acoustic performance, while class F represents the lowest performance class. The regulation requires that new buildings meet at least class C performance.

Overall, the results confirm that:

- A novel single-layer LC³-based hybrid mortar incorporating barite and rubber aggregates can function as an alternative partition wall material with enhanced airborne sound insulation.
- The proposed hybrid design establishes a new approach linking material microstructure and acoustic behavior, uniting building physics and materials science perspectives.
- The combined use of the model-experiment method through *INSUL* simulations has demonstrated methodological robustness and practical predictability for acoustic performance.

Within the scope of this study, some compositions exhibited sound insulation performance that was similar to or lower than expected. Nevertheless, the acoustic performance of LC³ ecological binders could be enhanced through further research by varying aggregate type, particle size, and wall thickness. The study assesses sound insulation performance mainly using R_{avg} and R_{sim} indices. The absence of D_nT measurements limits the direct representation of in-situ building conditions. Inclusion of both R values and D_nT measurements in future studies would enhance the overall robustness of the evaluation framework. Additionally, the fire resistance and durability under

humidity or temperature variations of these materials warrant investigation in future studies.

Ethics

There are no ethical issues with the publication of this manuscript.

All experimental procedures, measurements, and data analyses were carried out by the authors, while language editing tools were used only to improve clarity and readability.

Conflict of interest

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Author's contributions

Begüm Söyek Abay: Drafted and wrote the manuscript, performed the experiment and result analysis.

Leyla Tanaçan: Supervised the experiment's progress and helped in manuscript preparation.

Data availability statement

There is a data set associated with this submission.
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