EXPERIMENTAL STUDY OF AIRBORNE SOUND INSULATION OF REINFORCED RECYCLED AGGREGATE CONCRETE WALLS

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ABSTRAKT

Vzduchová neprůzvučnost je jednou z hlavních posuzovaných vlastností u dělících konstrukcí bytových staveb. Beton s recyklovaným kamenivem je stále více využíván i pro tento typ konstrukcí a proto je nutné vedle základních mechanických vlastností betonu ověřit i akustické parametry výsledné betonové konstrukce. Článek předkládá výsledky experimentálního měření vzduchové neprůzvučnosti železobetonových stěn tloušťky 200 mm s využitím recyklovaného kameniva v betonu a výsledky jsou porovnány s požadavky normy ČSN 73 0532 na vzduchovou neprůzvučnost konstrukce mezi obytnými místnostmi sousedních bytů. Dále jsou změřeny akustické parametry (dynamický modul pružnosti a ztrátový činitel) využívané pro modelové výpočty vzduchové neprůzvučnosti, které jsou porovnány s tabulkovými hodnotami z literatury. Současně byly ověřeny základní mechanické vlastnosti všech betonových směsí.

KLÍČOVÁ SLOVA

beton • recyklované kamenivo • stavební a demoliční odpad • akustická neprůzvučnost • ztrátový činitel

ABSTRACT

Airborne sound insulation is one of the main assessed properties of partition structures in residential buildings. Recently, recycled aggregate concrete has been used more frequently for these types of structures, and therefore, it is necessary to check the acoustic parameters of these structures in conjunction with the mechanical properties of concrete. The article describes experimental results of airborne sound insulation of the 200 mm thick reinforced recycled aggregate concrete walls, which are compared with the requirements of ČSN 73 0532 standard for the partition structures of two units of a residential building. Additionally, the acoustic parameters (dynamic modulus and loss factor), which are used for the calculation of the sound reduction index, are compared with the values stated in the literature. Furthermore, the basic mechanical properties of all concrete mixtures are tested and compared with previous work.

KEYWORDS

concrete • recycled aggregate • construction and demolition waste • sound reduction index • loss factor

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1. INTRODUCTION

Rapid development in the field of recycled aggregate concrete (RAC) is associated with its implementation in new structures. Currently, RAC is mostly used for non-load bearing structures e.g. base concrete, infill structures, or prefabricated elements made of plain concrete used for gravity retaining walls. One of the main obstacles to the use of RAC is the restrictive policies of current standards for the production of concrete and the design of concrete structures, which implies lower credibility in the eyes of investors and designers who are reluctant to use this material in new structures.

The mechanical properties and durability of RAC are the main research topic in most scientific papers in recent time, and, for example, the effect of recycled aggregate (RA) on the strength of concrete is already a very well-known phenomenon. Less emphasis is placed on the serviceability properties of the material, such as sound insulation, which can be even more important under certain conditions than the main mechanical properties of concrete. Airborne sound insulation is one of the most important properties of structures in residential buildings. Insufficient airborne sound insulation between two apartment units in a residential building is often the reason for complaints and disputes between the owners and the developer. The structural system of most of the new residential buildings that are being built is a combination of a reinforced concrete core structure with additional masonry walls, where the concrete walls serve as non-bearing partition walls be-

Figure 1: *RMFA (left); RMCA (right).*

tween individual apartment units and to stiffen the entire structure. The airborne sound insulation of these concrete walls is an important property that should be assessed to meet the requirements of current standards and future inhabitants of the building.

To assess the suitability of RAC for the partition walls of residential buildings according to the requirements of the ČSN 73 0532 standard, a practical experiment was carried out. Laboratory measurements of airborne sound insulation were performed in conjunction with basic mechanical properties and additional acoustic parameters.

2. EXPERIMENTAL PROGRAMME

2.1. General overview

The main objective of this study is to investigate the influence of RA on the acoustic properties of structural concrete. For this purpose, the measurement of airborne sound insulation of reinforced concrete walls made of different concrete mixtures was carried out under laboratory conditions. In addition to obtaining these results, an assessment of the suitability of this material can be made for partition wall structures between two rooms of different apartment units in residential buildings.

For the experiment, three reinforced concrete walls with dimensions of 3.57 m x 0.2 m x 3.73 m were manufactured. The walls were reinforced with 10 mm rebars with 100 mm spacing in both directions on each surface. The concrete parameters were specified according to CSN EN 206+A2 and CSN P 73 2404 as follows: strength class C 25/30, exposure class XC2, workability S4 and maximum aggregate grain size 22 mm. It should be noted that concrete mixtures of this specification made with RA cannot be produced according to the standards mentioned above.

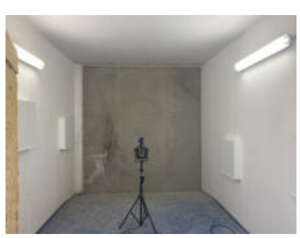
(a) *Concreting of reinforced concrete wall specimens.*

(b) *Curing of wall specimens under the plastic foil.*

(c) *Loading and transportation of wall specimens.*

(d) *Manipulation with wall specimens in the laboratory.*

(e) *Wall specimens placed between the testing rooms.*



(f) *Inside the sound receiving testing room.*

Figure 2: *The process of manufacturing prefabricated reinforced concrete walls and the testing of airborne sound insulation under laboratory conditions.*

2.2. Materials

Aggregates

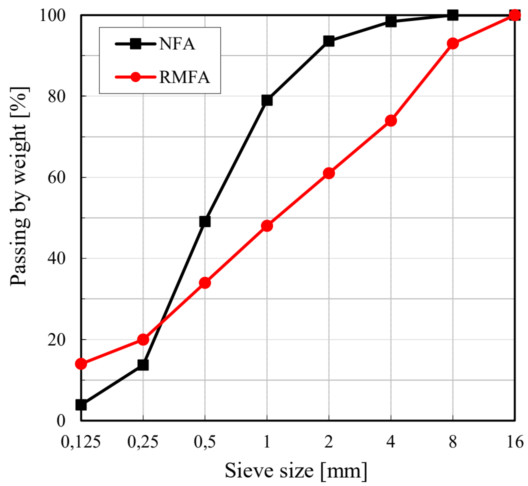
In this experiment, four different kinds of aggregate were used, including natural aggregate (NA): coarse (NCA) and fine (NFA); and two types of recycled mixed aggregate (RMA): coarse (RMCA) and fine (RMFA). The river stone and sand, used as NA, were provided by a local quarry near Prague, Czechia. RMAs were manufactured from construction and demolition waste (C&DW), which was produced after the demolition of an old bakery complex in Prague. RA manufacturing was carried out on the demolition site and delivered directly to the concrete plant where the specimens were produced for the experiment. Following this production scheme, the cost and environmental impact of RAC production were significantly reduced. However, the conditions at the demolition site influenced the quality of the RMA since there was a higher chance of contamination with impurities during the manufacturing process. Figure 1 shows the pictures of the RMAs used in the experiment. The pictures indicate slight contamination of the RMCA by wooden splinters, which could influence the sound insulation properties of the concrete structure. All types of aggregates were subjected to elementary property tests according to valid standards, and the results are presented in Table 1. The graphs in Figure 3 show the particle size distribution of the aggregates. Both RMCA and RMFA have higher water absorption and higher fine-particle content. This observation had to be taken into account in the mixture design process. Additionally, the lower apparent density of RA influences the density of hardened concrete and thus the airborne sound insulation of the final structure.

Table 1: *Properties of aggregates used in the experiment.*

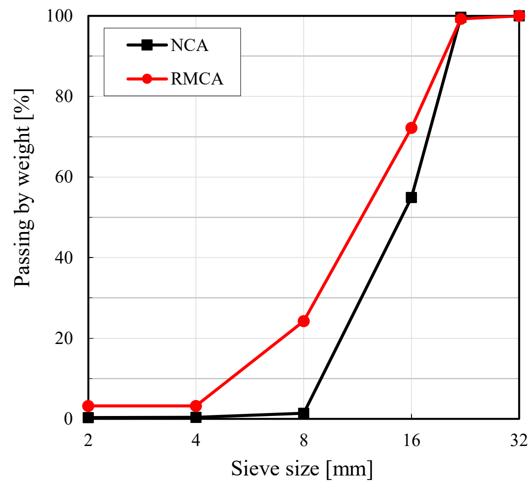
Aggregate type	Apparent density ($kg\,m^{-3}$)	Water absorption (%)	Moisture content (%)	Fine particles (%)
NCA	2640	0.4	0.6	0.3
RMCA	2450	6.3	4.5	1.2
NFA	2610	1.2	3.8	0.9
RMFA	2380	11.7	9.8	9.2

Other materials

Portland slag cement CEM II/B-S 32,5 R (cement plant Radotín, Czechia) according to ČSN EN 197-1 ed. 2 was used as a binder. This type of cement is the most commonly used in Czechia for the construction of urban structures. A portion of the cement was substituted by adding fly ash (coal power plant Mělník, Czechia) according to ČSN EN 450-1. A modified polycarboxylate-based superplasticizer that meets the requirements of ČSN EN 934-2+A1, was used to improve the workability of all concrete mixtures.



(a) *Particle size distribution of fine aggregates.*



(b) *Particle size distribution of coarse aggregates.*

Figure 3: *Particle size distribution of the aggregates used in the experiment.*

2.3. Mix proportions

Three concrete mixtures with different aggregate combinations were designed for this experiment. The reference mixture, NAC, contains only NA and its composition corresponds to the concrete delivered to most construction sites for this concrete specification. The second mixture, RAC-50, contains NFA and RMCA, which is roughly 50 % RMA content. The third mixture, RAC-100, contains RMFA and RMCA, and therefore the NA is completely replaced with RMA. To mitigate the effect of RMA on the strength of the concrete, a higher amount of cement with a higher content of RMA was used in the mixture. The portion of fly ash was reduced with increasing cement content. Due to the higher water absorption of RMA, mixing water was added during the mixing process to achieve the specified workability. Furthermore, a higher dose of superplasticizer was used to mitigate the higher content of fine particles in RMA.

2.4. Specimen preparation

Concrete specimens in this study were poured at the ready-mix concrete plant in Prague. After casting, the specimens for test of hardened concrete were placed in an indoor environment with stable conditions to harden. Subsequently, after 24 hours, all specimens for the hardened concrete tests were transported to the laboratory to cure in a controlled environment (temperature 20 ± 2 °C and relative humidity $\geq 95\,\%$).

All three prefabricated concrete walls were manufactured outdoors on the same day to mitigate any adverse influence of weather conditions or fluctuation of material properties. After the concrete had set, the prefabricated walls were covered with plastic foil to minimise the evaporation of water from their surface. The prefabricated walls were left to cure for 56 days until the day of testing.

2.5. Testing methods

Properties of fresh and hardened concrete

The workability of fresh concrete was tested following the slump test procedure according to ČSN EN 12350-2 immediately after mixing the concrete. The density of fresh concrete was determined by weighing a specimen with a known volume. The temperature was measured with a contact thermometer.

The compressive strength of concrete was tested on cubes with an edge length of 150 mm at the specimen age of 2, 7 and 28 days. The depth of penetration of water under pressure was tested on cubes with an edge length of 150 mm. The flexural strength of concrete was tested on beams with dimensions of 100x100x400 mm. The bulk density of each specimen was determined prior to the test. All the above tests were conducted according to the testing procedures described in ČSN EN 12390 standards. Additionally, the static modulus of concrete was tested on cylinders (150x300 mm) according to ČSN ISO 1920-10. Except for the cubic strength of concrete, all tests were conducted after 28 days of curing of the specimen.

Sound reduction index

The sound reduction index was measured according to ČSN EN ISO 10140-2 and ČSN EN ISO 10140-4. Measurements were carried out on three prefabricated reinforced concrete walls described in the previous section, where each wall was made of a different concrete mixture (NAC, RAC-50 and RAC-100). The tests were carried out in the accredited laboratory TZÚS Teplice. During the test, specimens were placed between the source room and the receiving room. In the source room, a diffuse sound field was created and the average level of acoustic pressure is measured in both rooms in the range of 1/3 octave middle frequencies between 100 and 5000 Hz. The transmission of sound through external pathways was eliminated during the test, and the measured value represents the sound reduction index of the tested specimen. To determine the sound reduction index from the measurement, the following equation was used:

$$R = L_1 - L_2 + 10 \cdot log \frac{S}{A} \tag{1}$$

where L_1 is the average level of sound pressure in the source room (dB), L_2 is the average level of sound pressure in the receiving room (dB), S is the surface of the tested specimen (m^2) and A is the equivalent absorbed area of the receiving room (m^2).

Table 2: *Properties of fresh and hardened concrete.*

Parameter	NAC	RAC-50	RAC-100	SI
Fresh concrete				
Slump test	140	210	220	mm
Bulk density	2320	2180	2080	$kg\,m^{-3}$
Temperature	22,3	21,5	22,1	°C
Hardened concrete				
Bulk density	2330	2210	2100	$kg\,m^{-3}$
Depth of water penetration	19	14	17	mm
Flexural strength	5,5	5,4	5,4	MPa
Cylinder strength	38,5	40,0	33,5	MPa
Modulus of elasticity	31,1	25,5	18,9	MPa

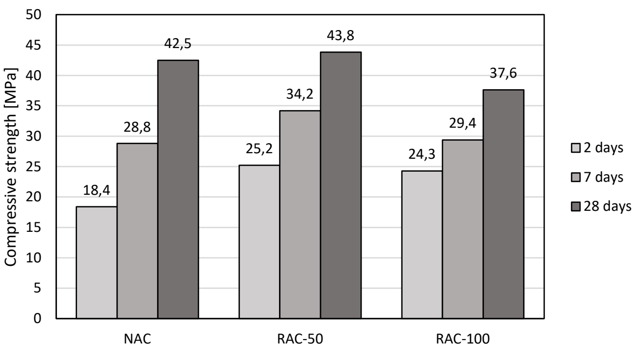


Figure 4: *The cubic strength of concrete of all concrete mixtures at the age of 2, 7 and 28 days.*

Loss factor

Additionally to the sound reduction index, the loss factor of concrete used for the calculation of the sound reduction index was determined following the resonance method procedure in the methodical handbook P 04 0013 - VÚPS 22/548/79 developed by ITC a.s. The test method also determines the dynamic modulus of elasticity and the propagation of longitudinal waves through the material. The tests were carried out on specimens with dimensions of 100x50x150 mm. The specimens did not contain reinforcement due to their small thickness. This could influence the final result, and the values could differ with the prefabricated wall specimens.

3. RESULTS AND DISCUSSION

The results of fresh and hardened concrete are listed in Table 2. The results of the compressive strength of concretes are shown in Figure 4. The specified strength class C 25/30 was achieved with all three concrete mixtures. The RAC-100 concrete mixture had the lowest compressive strength, about 5 MPa less than the reference mixture of NAC. The bulk density of the two RMAC concrete mixtures was lower by 5 % to 10 %. An even more significant decrease was observed in the modulus of elasticity, where RAC-50 was lower for about 18 % and RAC-100 was lower up to 39 %. The lower values of the bulk density and the modulus of elasticity correspond to the previous results. The impact of RMA on the tensile strength of concretes was negligible. The depth of penetration of water under pressure was similar to that of the NAC, with even slight improvement.

Table 3: *The results of sound reduction index measurements on reinforced concrete wall specimens.*

Parameter	NAC	RAC-50	RAC-100	SI
Weighted sound reduction index R_w	58	55	55	dB
Spectrum adaptation term C	-3.4	-2.1	-1.9	dB
Spectrum adaptation term C_{tr}	-7.9	-7.2	-6.4	dB

Table 4: *The results of acoustic material constant measurement.*

Parameter	NAC	RAC-50	RAC-100	SI
Bulk density	2391	2165	2109	$kg\,m^{-3}$
Dynamic modulus	12.1	11.1	9.0	GPa
Longitudinal wave propagation	2246	2274	2038	$m\,s^{-1}$
Loss factor	0.021	0.023	0.023	-

The results of the sound reduction index are plotted in Figure 5. The values of the weighted sound reduction R_w and the spectrum adaptation terms C and C_{tr} are listed in Table 3. The measured curves show that the biggest difference between the NA mixture and the RMA mixture is around the range of 100 Hz and 250 Hz where the sound reduction index of NAC is higher by 15 dB and 10 dB respectively. The rest of the frequency range shows similar values. The weighted sound reduction index of the mixtures RAC-50 and RAC-100, determined by the shifted curves of the reference values according to ČSN EN ISO 171-1, is therefore 3 dB lower than that of NAC. Although airborne sound insulation is mainly governed by the bulk density of the material, the 110 $kg\,m^{-3}$ difference between RAC-50 and RAC-100 has not induced a further decrease in the sound reduction index of the RAC-100 mixture.

To determine the apparent sound reduction index R'_w of a structure, a correction k_1 that accounts for the transfer of sound through external pathways must be extracted from the weighted sound reduction index. The ČSN 73 0532 standard sets this correction value for monolitic concrete with surrounding structures made of heavy material (e.g. concrete or bricks) at 2. The limit of the standard for partition walls between two living rooms of different units is 53 dB. Therefore, the three tested structures would meet the standard requirements. It should also be noted that the tested reinforced concrete walls did not include any additional layers, e.g. plaster. Therefore, a slight improvement in airborne sound insulation could be expected after applying these additional layers in the real structure.

The results of dynamic modulus, propagation of longitudinal waves and loss factor are listed in Table 4. The dynamic modulus of RAC-50 and RAC-100 decreased by approximately 8 % and 28 % respectively, compared with that of the reference mixture NAC. The influence of RMA on the dynamic modulus is less than that of the static modulus. The propagation of longitudinal waves differed only with the RAC-100 mixture, which is about 200 $m\,s^{-1}$ lower than that of other mixtures. The loss factor increased with the content of RMA in the mixture to 9 %.

The more important comparison of the values obtained is with the values from in the literature. Two sources commonly used for the sound reduction index calculation are the ČSN EN ISO 12354-1 standard and either ČVUT or VUT scriptum. The recommended values of these documents are listed in Table 5. The measured

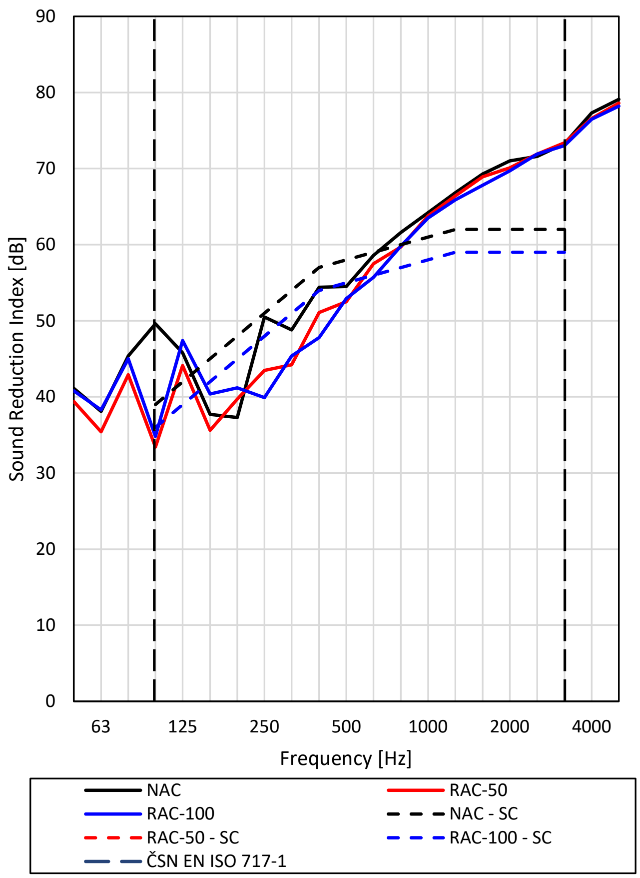


Figure 5: *The results of airborne sound insulation measurement according to ČSN EN ISO 10140-2 with the curve of shifted reference values according to ČSN EN ISO 717-1.*

longitudinal wave propagation is about a third lower than recommended in the literature. The loss factor is about four times higher than the values recommended in the literature, and even in the case of the mixture with NA. The discrepancy between the measured values and the values in the literature, which were published for the first time in 1998, could be caused by several factors. First, the method used for the measurement in this experiment could be different from the method used to determine the values stated in the literature. Second, concrete technology has developed since the values were published, and therefore a more thorough revision could be considered. Finally, the results could be influenced by the measurement procedure, where a perfect insertion into the testing jig is needed to get the results. The insertion is influenced by the flatness of the specimen, which is, in the case of concrete specimens with RA, not so easy to achieve. The tests should then be repeated and the results confirmed.

4. CONCLUSIONS

The article presents the results of an experimental assessment of the sound reduction index of reinforced concrete walls made of concrete with a content of 0, 50 and 100 % recycled mixed aggregate which was recovered from construction and demolition waste. In addition to the sound reduction index, the properties of fresh and hardened concrete were determined along with the acoustic parameters of the concrete following the guidelines of valid standards.

Table 5: *The values of longitudinal wave propagation and loss factor stated in the literature.*

Parameter	ČSN EN ISO 12354-1	Scriptum ČVUT and VUT	SI
Bulk density	2200	2300 - 2500	$kg\,m^{-3}$
Longitudinal wave propagation	3800	3162 - 3286	$m\,s^{-1}$
Loss factor	0,005	0,005	-

Although the recycled mixed aggregate was contaminated with a high content of fine particles and impurities in the form of wooden splinters, the final parameters of the concrete and the measurement of the sound reduction index showed that this material is suitable for the structures of partition walls in residential buildings and will meet the requirements of ČSN 73 0532. The sound reduction index of 200 mm thick reinforced concrete walls made of recycled mixed aggregate is lower by 3 dB than that made of natural aggregate.

In addition, the acoustic parameters of all concrete mixtures were determined. The results of longitudinal wave propagation and loss factor did not correspond to the widely used values in the literature. The longitudinal wave propagation was underestimated compared to the literature and the loss factor was overvalued compared to the literature. The tests should be repeated in the future to confirm the presented results.

ACKNOWLEDGEMENTS

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