Improving the sound insulation of construction boards with a high damping glue

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ABSTRACT

Lightweight building boards are being commonly used in various wall and floor structures because of their easy use and low costs. The sound insulation of a single board alone is not good enough so the constructions are mainly composed of multilayered structures. The thickness and weight of the structures are being minimized while the sound insulation properties should be optimized as well. With light weight building boards such as plaster boards, wood based boards and minerits, one constraining problem is the coincidence phenomenon. The dip in the sound insulation properties is quite deep, depending on the board properties, and it is located at the important frequency area concerning human perception. With visco-elastic high damping epoxy layer used in multilayered constructions, it's possible to get rid of the dip and increase the sound insulation above the critical frequency by several decibels. With the use of epoxy-based viscoelastic, high damping glue the sound insulation tests of plywood structures show that without any significant add of mass the total R_W can be improved 2…4 dB and above critical frequency even 7…8 dB improvements are seen.

Keywords: Damping, Insulation, Visco-elastic I-INCE Classification of Subjects Number(s): 47.2

1. INTRODUCTION

Lightweight building boards are being commonly used in various wall and floor structures because of their easy use and low costs. Insufficient sound insulation properties make builders and constructers to use multilayered structures. The thickness and weight of the structures are being minimized while the sound insulation properties should be optimized as well. With light weight building boards such as plaster boards, wood based boards and minerits, one constraining problem is the coincidence phenomenon. The dip in the sound insulation properties is quite deep, depending on the board properties, and it is located at the important frequency area concerning human perception.

Adding mass and increasing the thickness of the structure are commonly used to increase the sound insulation properties, but they usually mean more costs, smaller room sizes, heavier structures etc. One way to influence on the sound insulation and the transmission loss of different structures, with a minimal effect on the total weight, is to increase the internal damping of the materials and structures. This study is partly based on the previous research work on the high-damping epoxy materials and constrained-layer damping (CLD) systems in heavy machinery structures [1].

2. SOUND INSULATION

Some basic equations concerning the sound insulation behavior of a thin single building board are presented in this section for easier interpretation of the measurement results of laboratory tests presented in the section 5. More detailed information on the sound insulation of wall structures can be found e.g. from reference [2].

Sound reduction index R [dB] is defined as the logarithm to the base 10 of the ration of the sound power incident to the board W_1 to the sound power transmitted through the board W_2 (assuming that there is no flanking transmission through any other component than the board being tested):

$$R = 10\log_{10}\frac{W_1}{W_2} \qquad [dB]. \tag{1}$$

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A simplified prediction model can be used with good accuracy up to the critical frequency, if the board is assumed to be thin and infinite. At frequency f [Hz] sound reduction index depends on the surface mass m [kg/m^2] of the board according to:

$$R(f) = 20\log_{10}(mf) - 42 - 10\log_{10}\left(\ln\left(\frac{2\pi f}{c_0}\sqrt{S}\right)\right) \qquad [dB]. \tag{2}$$

A Sewell's correction term, which depends on the frequency and the area S [m^2] of the board and the velocity of sound in air c_0 (343 m/s), was used in the equation (2) because of the finite size of the test sample. Equation (2) is commonly called the field incidence mass law. It is valid in reverberant rooms where sound reaches the specimen evenly from all directions. According to the mass law, only the wall's mass matters. It usually gives a good estimate when considering very heavy materials and structures such as dense concrete walls without leakage and flanking transmission that yet always do exist. [3]

2.1 Coincidence phenomenon

The mass law is still valid only below the half of the critical frequency f_c of the specimen. At the critical frequency f_c, the wavelength of the bending wave in the panel coincides with the wavelength of the sound propagating in air. Because bending waves of different frequencies travel at different speeds, for every frequency above a certain critical frequency, there is an angle of incidence for which the wavelength of the bending wave can become equal to the wavelength of the impacting sound in air. That is why at and above critical frequency, the sound energy is efficiently transmitted through the element causing a dip in the sound insulation curve. This is called the coincidence phenomenon. The critical frequency can be calculated according to equation (3):

$$f_c = \frac{c_0^2}{2\pi}\sqrt{12\left(1-\nu^2\right)}\sqrt{\frac{m}{Eh^3}}\,, \tag{3}$$

where ν is Poisson's ratio, E is Young's modulus [Pa] and h is the thickness of the board [m]. [2, 3]

The depth and width of the coincidence dip are determined by losses of sound energy in the material and energy transfer to the supporting structure. The greater these losses are, the shallower and broader the coincidence dip is, and the less it affects the transmission loss. The most effective way to increase energy losses of the panel is to increase damping, thus, increasing the transformation of mechanical energy into heat energy. Added damping capacity of the panel therefore decreases coincidence dip and also panel resonances that affect the transmission loss at low frequencies. [2, 3, 4]

The coincidence dip may be shifted up or down the frequency range by altering stiffness, boundary conditions and changing thickness of the material. Wooden panels, such as plywood boards, are interesting, because their coincidence dips affect frequencies most sensitive to ear. Usually greater stiffness means steeper coincidence dip. For example, plywood has a deeper coincidence dip than plasterboard, at least partly because it's stiffer. On the other hand, if two layers of material such as plasterboard are glued firmly together using regular glue, not highly damping and visco-elastic glue, they behave like a single thick layer with an associated lowering of the coincidence frequency. If the layers are only held together loosely (with screws for example), so that they can slide over each other to some extent during bending motions, then the coincidence frequency does not move to lower frequencies and the friction between the layers can introduce some extra energy losses, giving higher transmission loss near critical frequency. [2, 4]

3. VIBRATION AND DAMPING

Vibration controlling efforts can be focused on different fields: excitation, transfer paths, joints, damping and sound radiation. One attractive way to solve the vibration problems is to increase the damping capacity of structural materials.

With components that exhibit low inherent material damping, noise and vibration problems are often generated by vibrating surfaces. Internal material damping, the transformation of mechanical energy into heat, is often described using a quantity called the loss factor, which indicates the fraction of the vibratory energy lost in one cycle of the vibration. This damping mechanism, as all the other damping mechanisms, is dependent on various factors like frequency, temperature and material composition. [2]

3.1 Damping

Structural damping, the transformation of mechanical energy into heat, is usually described using a quantity called the loss factor (η), which indicates the fraction of the vibratory energy lost in one cycle (radian) of the vibration. Some other terms like damping ratio (ζ), half power bandwidth (b), decay time (T), logarithmic decrement (Λ), tan δ and sharpness of resonance (Q) are also used to describe the amount of damping in a structure. The relation between all these quantities is [4]

$$\eta = 2\zeta \Big/ \sqrt{1-\zeta^2} = b/f = 2.2/T_D f = \Lambda/\pi = \tan\delta = Q^{-1}. \tag{4}$$

Typically the measured damping is a combination of several damping mechanisms which are not separable. The effect of (total) damping to the velocity level of a point force excited structure is presented in the Figure 1 as well as the effect of damping to the transmission loss of a wall structure.

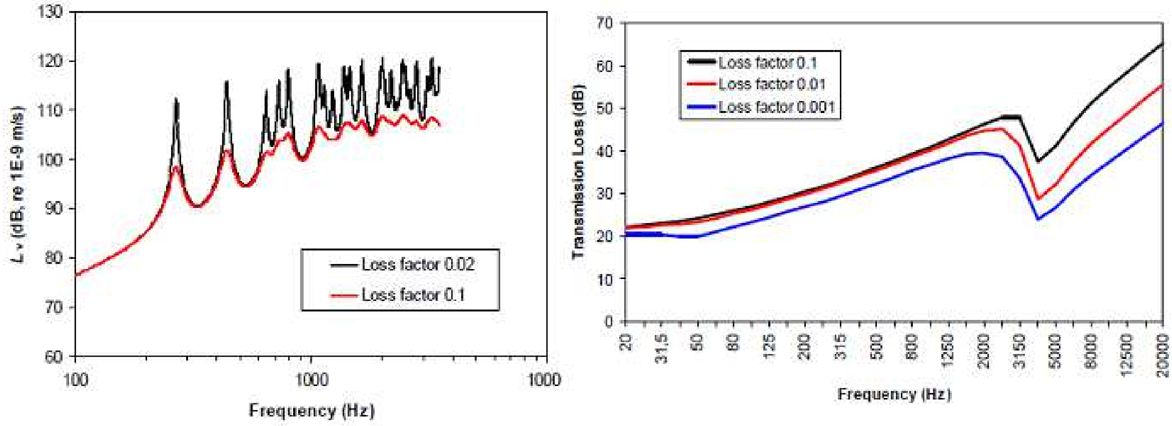

Figure 1 – The effect of damping on the mean velocity level of a structure (left) and on the transmission loss of a wall structure. [1]

Results in the Figure 1 are obtained using finite element method (FEM) simulations. The example structure used to demonstrate the effect of damping is a thin steel plate with varied loss factor value.

The simulated results show that clear improvement of transmission loss is observed around and above the critical frequency of the chosen panel. Similar effect is hoped to achieve from the sound insulation tests using construction boards. The internal damping in the steel plate used in simulations is smaller than with the construction boards and plywood boards used in the following tests. This could weaken the effect gained with added damping compared to the steel structure.

3.2 Free-layer and constrained-layer damping

Damping materials can be used for a wide variety of noise and vibration applications. To take full advantage of their vibration-reducing potential, product designers often must make a choice between using free-layer or constrained-layer damping (CLD) systems. While either system will provide good results for thin substrate panels; thick, heavy or stiff structures require a CLD system to achieve high damping and effective noise reduction. Considering stiff construction boards and adding damping without excess mass, constrained-layer damping was obvious choice to start the testing.

Most CLD applications use a three-layer “sandwich” system that is formed by laminating the base layer to a damping layer and then adding a third constraining layer on the top. Typically, the constraining layer is of the same material as the base layer, but exceptions are common. In these structures with multiple layers, when the system flexes during vibration, the damping material layer is forced into a shape that shears adjacent material sections. This alternating shear strain in the CLD material dissipates the vibration as frictional heat more efficiently than the extension and compression in the free-layer damping system. [1]

4. MATERIAL DEVELOPMENT

Damping materials can be used for a wide variety of noise and vibration applications. Polymer based damping treatments are one of the most common methods to increase damping of the structure and thereby to decrease resonant vibration and noise. The material development was focused on CLD materials to get great results using only small amounts of damping material.

The properties of polymers are highly dependent on temperature and also on excitation frequency, and as a result, one damping material cannot cover all of the needs. The need for an adjustable damping material in both temperature and frequency scale was pinpointed initially by the heavy machine industry. Adjustable epoxy based materials were developed and the utilization is based on very accurate control of location of glass transition temperature region.

4.1 ELASTE high damping epoxies

Epoxy systems are versatile because of the large number of potential epoxy resin, curing agent and modificator combinations. Examples of typical applications of epoxy materials include adhesives, functional joints, shock absorbing pads, abrasion resistant coatings and flexible laminates.

These novel ELASTE high damping visco-elastic epoxy materials by NMC Cellfoam Oy, formerly Noisetek Oy, provide high mechanical damping properties in the middle of glass transition region and are relatively easy to adjust with regard to the location of the glass transition region by altering the ratios of the components of the epoxy material. In practice, the properties of a given cured epoxy system are designed so that the maximum peak of damping is set to appear in the property window of predetermined thermal and mechanical vibration conditions. Additionally a review for the dimensions (shape of the damper and thicknesses of the different layers) of a particular damper must be made to achieve optimal damping in the desired frequency range.

Glass transition temperature region is a phenomenon featured especially in polymeric materials. When rising the temperature to reach this transition region, the modulus of elasticity undergoes a significant change from glassy state of high modulus (a state below T_g region) to rubbery state (a state above T_g region). In about the middle of the glass transition region, there occurs an intensive rise of mechanical damping. Maximum damping loss factor values over 1.2 are common with the novel developed materials. More detailed information about the developed materials can be found e.g. from reference [1].

5. CASE STUDY AND RESULTS

The potential of ELASTE high damping epoxies in construction industry and with lightweight building boards was initially tested by determination of airborne sound insulation of glued boards in laboratory conditions. Theory tells us that added damping should increase the airborne sound insulation at especially around and above the critical frequency as mentioned in sections 2 and 3.

Wood based plywood boards where chosen as the base of the testing due to the quite vast knowledge of them and the availability of the samples from the manufacturer. Wood based boards such as the birch plywood are quite stiff construction boards and they are known to have a quite deep dip in the airborne sound insulation due to the coincidence phenomenon.

The target was to evaluate the effect of the added viscoelastic epoxy layer between the plywood layers. The glued specimens were tested with standard plywood products manufactured at the same thickness (and weight class) as the glued specimen. The density of the epoxy glue is around 1 kg / dm^3, so the glue doesn't have a big impact on the total weight of the samples. The wet thickness of the epoxy glue was less than 1 mm and the epoxy was spread almost to the whole area of the sample.

Two viscoelastic ELASTE epoxies with different optimum damping frequency area at room temperature were used. Two slightly different materials were chosen to see if the minor change would have an effect on the sound insulation results. With two materials we could always have an optimized test sample (in damping material vice) as the critical frequency of the plywood board varies due to the total thickness.

The sample thickness varied from 21 mm to 45 mm and standard plywood board thicknesses were used. The effect of using two glue layers instead of one layer was also tested with the thickest sample. The 45 mm sample was constructed either using 15 mm thick layers or 21 mm and 24 mm thick plywood boards.

The tested samples were glued at room temperature under limited and a bit uneven pressure due to the restricted equipment available during the sample manufacturing. The edges of the boards were clamped and a thick steel plate was used on top of the board to give uniform pressure. The surfaces of the plywood boards are not flat and there were also some variance in the boards and thicknesses, so in the end the epoxy layer was not constant on the whole area. The excess epoxy glue between the boards was let to drip. All the manufactured and tested samples with their mass per unit area values are listed on table 1.

Table 1 – Test samples and constructions

Sample	Structure and Name	Nominal thickness, mm	Mass per unit area, kg/m^2
1.	K45	45*	32.2
2.	K21 + E1 + K24	45	30.5
3.	K21 + E2 + K24	45	30.3
4.	K15 + E1 + K15 + E1 + K15	45	32.8
5.	K15 + E2 + K15 + E2 + K15	45	33.0
6.	K21	21	14.5
7.	K9 + E1 + K12	21	15.3

Names of each tested sample are composed of the abbreviations of used structure components. The K means that the material is birch plywood and the number after it is the thickness of the single board in millimeters. The used viscoelastic ELASTE damping materials are coded E1 and E2. The main difference between the materials is the different optimal damping frequency area at room temperature. The E1 is optimized to a bit lower frequency area (500 – 700 Hz) than the E2 (around 1000 Hz). The shear modulus G of the E1 compound is also slightly lower than the modulus of E2 at room temperature. Both damping compounds are unfilled materials with basically same chemical structure and long term properties.

Samples 1. and 6. were unmodified, standard plywood boards for comparison and to determine the starting point. The standard 45 mm sample was measured to be 1…2 mm thicker than the nominal thickness of 45 mm. That also explains the higher mass per unit value of 32.2 kg/m^2. The specimen was weighed with a 150 kg precision weighing machine (PM 150).

5.1 Test method

The test methods for determination of airborne sound insulation in laboratory conditions were ISO 10140-2:2010 for sound reduction index within 100 – 5000 Hz and ISO 717-1:2013 for weighted sound reduction index.

The area of every test element was (2100 x 1230 mm) 2.6 m^2. The specimen was attached to the built in frame of the test opening using 20 x 20 mm wood laths. Specimen was mounted between two laths. The distance of the wood lath was 230 mm measured from the source room. The distance from the surface of the specimen varied between 182 …209 mm, depending on the thickness of the specimen. The perimeters of the specimen were sealed using acryl mastic.

The volume of the source room used in the measurements was 81 m^3 and the volume of the receiving room 113 m^3. The operating conditions were static. Air temperature in test rooms was 22 °C and relative humidity 8 % while static pressure was measured to be 1002 hPa.

More detailed information about the acoustical measurements used in the test can be found from the related ISO standards.

5.2 Results

As the tests were not made for any final product or real life structure, we were more interested in the behavior of airborne sound reduction index R in the frequency scale than the final weighted R_W values of the specimens.

The following results and conclusions are based on the measurements made in the laboratory test and using only one test specimen, so great uncertainties are present because of the material samples, mounting etc.

5.2.1 Significance of damping glue

The significance of added damping to the airborne sound insulation properties can be seen when standard plywood plates are compared to the glued ones. In figure 3 airborne sound insulation results of a standard 21 mm thick birch plywood, sample 6, is compared to the sample 7 that is constructed using 9 mm and 12 mm thick boards and high damping epoxy glue E1.

The effect of added damping can be seen clearly in the figure 3. The sound insulation dip around the critical frequency of the 21 mm birch plywood specimen, f_c = 1250 Hz, is greatly reduced when damping is added. The measured weighted sound reduction indexes R_W are 28 dB for standard 21 mm thick specimen and 31 dB for the glued specimen number 7. All the test results are listed in table 2.

The mass per unit area for samples 6. and 7. differ by 0.8 kg/m^2. That is mostly due to the added epoxy glue between the two boards and partly due to the changes in the standard plywood boards. The increased mass explains partly the better sound reduction index of the glued specimen, but the greatly increased sound insulation around the critical frequency is caused by the added damping. The difference between the two samples at 1250 Hz, centre frequency of the third octave band, is up to 8 dB.

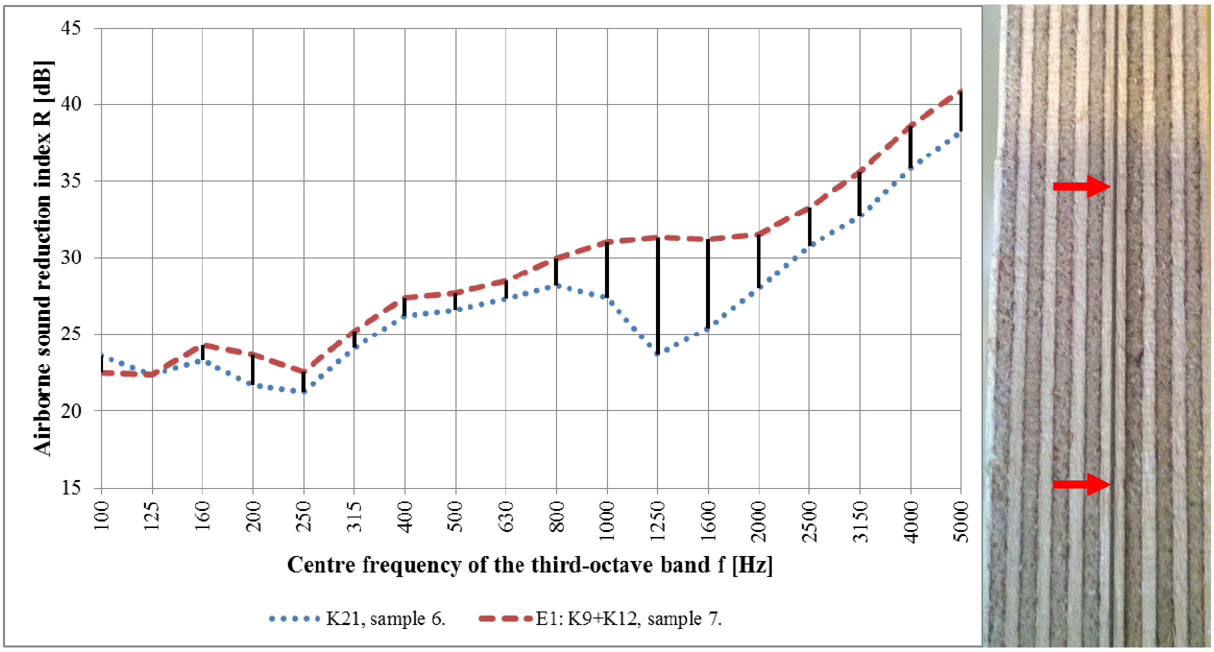

Figure 3 – Comparison of sound reduction index values of 21 mm thick plywood specimens in frequency domain on the left. Side of the glued sample, with red arrows pointing the glue line, is presented on the right.

The difference between the samples 6. and 7. at lower frequencies are supposedly due to the difference in the mass per unit area and the uncertainties in the measurement method.

Table 2 – Airborne sound insulation measurement results

Sample	Structure and Name	R_W [dB]	C [dB]	C_{tr} [dB]	Mass per unit area [kg/m^2]
1.	K45	32	-1	-3	32.2
2.	K21 + E1 + K24	35	-1	-3	30.5
3.	K21 + E2 + K24	34	-1	-3	30.3
4.	K15 + E1 + K15 + E1 + K15	36	-1	-3	32.8
5.	K15 + E2 + K15 + E2 + K15	35	0	-3	33.0
6.	K21	28	-1	-2	14.5
7.	K9 + E1 + K12	31	-1	-2	15.3

The results listed in table 2 show a change of few decibels in the final weighted sound reduction indexes R_W. More interesting and significance results can be seen when comparing the results of different measurements in the frequency band as in figure 3.

5.2.2 Significance of the number of damping layers

In Figure 4 results of a standard 45 mm, measured thickness ranged from 46 to 47 mm, plywood is compared to the glued samples 2. and 4. according to the table 1. The sound insulation dip around the critical frequency of the 45 mm birch plywood specimen, f_c = 630 Hz, is greatly reduced when damping is added.

The gain using two damping layers instead of one is also seen from the results, but the difference between those is not as big as it is between the standard specimen and the glued ones. The weighted sound reduction indexes R_W are 32 dB for standard 45 mm thick specimen, 35 dB for the glued specimen number 2. and 36 dB for the glued specimen number 4.

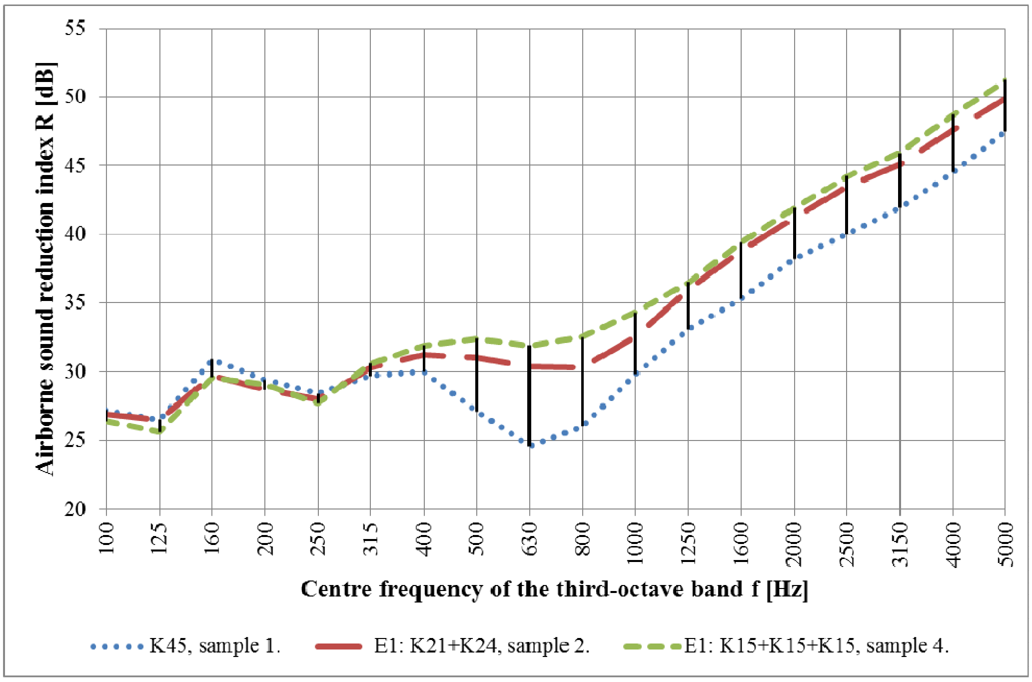

Figure 4 – Comparison of sound reduction index values of 45 mm thick plywood specimens in frequency domain.

The results in table 2 and in figure 4 show that increasing the number of glue layers, the airborne sound insulation results get better. The graph in figure 4 shows that the improvement is around the critical frequency as expected. A slight dip is still observed with 45 mm thick plywood when only one glue layer is used. With two glue layers the sound reduction index is steady around the critical frequency area.

It’s good to notice that while the two glue layers increase the amount of damping material in the construction, the damping layer are also in different positions in thickness wise. In sample 2 with one glue layer, the damping material is situated very near the middle height of the whole structure. In sample 4 with two glue layers, the both layers are evenly far from the middle of the construction. The position of the damping glue could have some impact on the results, but it was not yet considered in this set of tests.

Even though the mass per unit area is much larger for the unglued construction K45, the sound insulation ability is greatly behind to the glued ones around and after the critical frequency area. The weighted sound reduction indexes are listed on table 2. The improvement of sound reduction index around the critical frequency is up to 7…8 dB.

5.2.3 Significance of damping material

In the tests series two slightly different high damping epoxy compounds were used. The damping ability of the E1 epoxy compound was optimized to slightly lower frequency area than the compound

E2 as mentioned in table 2.

In figure 5 measurement results of samples 4. and 5. are shown and compared to the unglued 45 mm thick plywood specimen, sample 1. Both glued specimens are constructed using 15 mm thick plywood boards with two damping glue layers. As the E1 epoxy is optimized to the frequency area where the critical frequency of 45 mm thick plywood is situated, the results of sample 4. are expected to be better.

Looking at the measurement results in figure 5, one can see that the difference using E1 or E2 damping glue is very narrow. The difference in the R_W is only one decibel and of course the uncertainties in the measurements could already explain that. The same 1 dB difference is also noticed when samples 2. and 3. are compared. That could also mean that the E1 damping compound works slightly better, as expected, due to the more optimized damping ability.

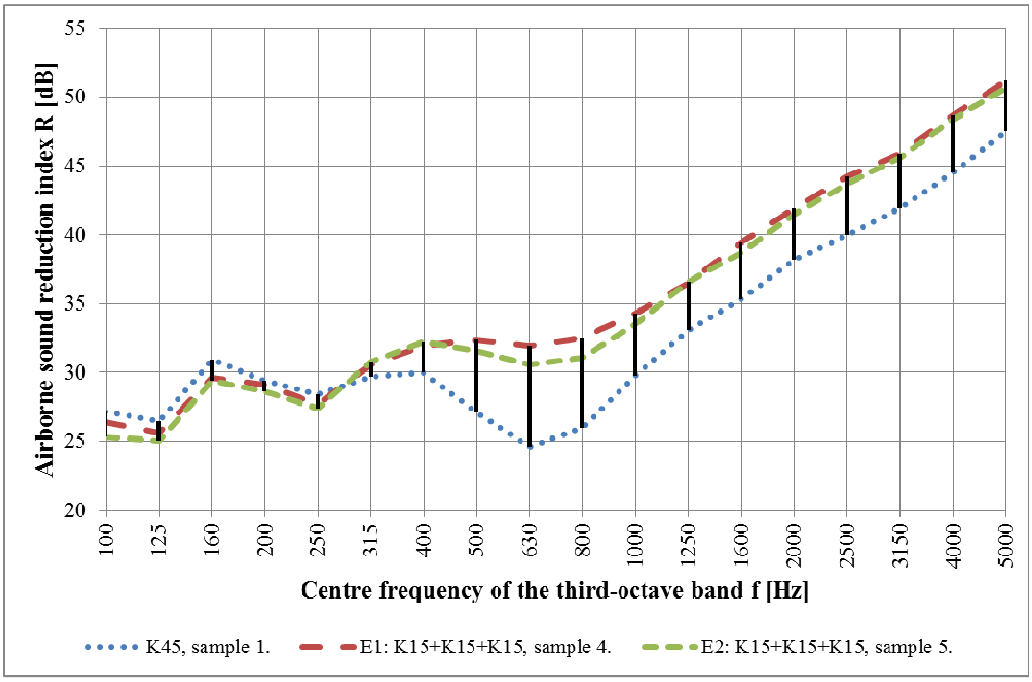

Figure 5 – Comparison of sound reduction index values of 45 mm thick plywood specimens in frequency domain. The damping glue used in samples 4. and 5. is slightly different.

The difference between the results gained with damping materials E1 and E2 is very small compared to the all possible uncertainties in these measurements starting from the sample manufacturing.

6. CONCLUSIONS

The focus on this project and the measurements based on birch plywood construction boards was to observe and determine the influence of added high damping ELASTE epoxy glue between boards on airborne sound insulation properties. Tested samples were based on layered structures using two different, optimized damping materials. The plywood boards were glued together using the epoxy damping material.

Results from measurements were partly expected, as the airborne sound insulation improved a lot around and also above the critical frequency of every tested board. Increasing the number of damping layers from one to two improved the results but only a bit compared to the effect of the first damping layer. The results were very similar using either one of the damping materials. The more optimized material gave a little bit better results.

The improvement on airborne sound reduction index around the critical frequency area was found to be up to 8 dB. Best results were received with thinner 21 mm plywood structure and using two damping glue layers when measuring thicker 45 mm plywood board structures.

The structures used in this project are not final product structures. These test results will help to determine new possible structures and products for construction industry, other wood based industry and also other applications were coincidence phenomenon is limiting the sound insulation properties such as different frame and door structures. The same phenomenon is observed with almost every construction board when lightweight structures are targeted.

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