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Heavy fillings on CLT floors II – correlation of the material properties and its acoustic performance

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Abstract

Elastically bound granular chippings are widely used in cross-laminated timber (CLT) floor constructions to improve the impact sound insulation of the construction. Although laboratory measurements often demonstrate very low normalized impact sound pressure levels for such systems, significant variability has been observed in practice. Previous research [1, 2] also supports the assumption that the type of the chippings and their binding agent strongly influence the acoustic performance. In addition to the impact sound pressure measurements of different chipping types (loose, elastically bound, mechanically bound, etc.; shown in [3]), the material properties of the different heavy fillings and binding mechanisms were also investigated in the present study. Specifically, the longitudinal wave velocity c_L in m/s and the loss factor η were determined experimentally and correlated with their acoustic performance in CLT floors. In this paper a short overview of the measurement method and its development is provided. The impact sound pressure measurements already showed that the type of binding agent has a greater effect on the impact sound pressure level than the thickness (i.e., mass) of the filling itself (see [3]). Furthermore, the findings indicate that the internal damping behavior (loss factor η) of bound fillings is a key parameter for predicting the acoustic performance of timber floor systems.

Keywords: *cross-laminated timber (CLT) floors, impact sound pressure level, elastically bound fillings, loss factor, longitudinal wave velocity*

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1. Introduction

Cross-laminated timber (CLT) floor constructions with floating screeds and granular chippings (Figure 1) are commonly used in multi-storey timber buildings. Elastically or mechanically bound (loose chippings in a slatted grid or honeycomb cardboards) fillings are frequently applied as levelling layers and additional mass to enhance airborne and impact sound insulation.

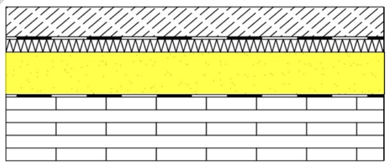

Figure 1. Cross-laminated timber (CLT) floor structure with a ballast layer (yellow) and floating screed. Component gdmnxn06 on dataholz.eu [4].

Despite generally favourable laboratory results, considerable variability in acoustic performance is reported back from the field. Previous laboratory measurements according to EN ISO 10140-3:2021 [5] at the Akustik Center Austria [6] have shown that floor assemblies with apparently identical configurations show significantly different impact sound pressure levels [7] (see Figure 2).

A difference in the single-number quantity (SNQ) $L_{n,w}$ of more than 10 dB was observed, depending primarily on the binding type of the granular filling. The correct binding ratio can also have a significant effect; in the worst case, elastically intended fillings behave acoustically similar to rigid cement-bound layers due to improper binder ratios or unsuitable material properties. However, the threshold at which a filling can be considered as "elastically bound" is not yet clearly defined, and no (standardized) classification scheme exists.

Other research showed that certain material properties of the filling may have an influence on the acoustic performance of the floor. Specifically, the longitudinal wave velocity (e.g. dynamic modulus) and the loss factor (damping) are mentioned in [1] and very different values of the mechanical properties in dependence of the binding agent were observed. A direct correlation to impact sound pressure measurements was not included in [1], but these findings suggest a strong influence on the impact sound insulation.

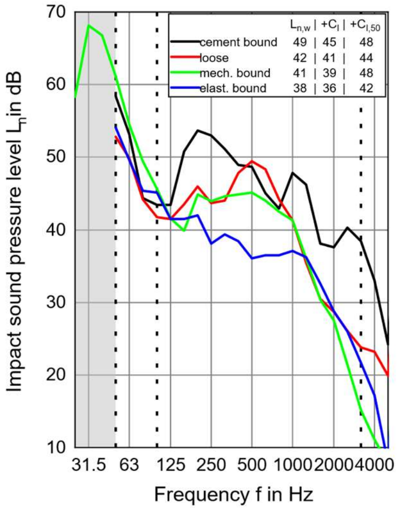

Figure 2. Impact sound pressure levels of very similar CLT floors with different bound heavy fillings measured in the laboratory from 25 Hz to 5000 Hz.

To test this hypothesis, systematic laboratory investigations were conducted as part of a bachelor's thesis [8]. Small-scale tests enabled a controlled variation of the binding agents, aggregate types and the filling heights in a short period of time. The results of the impact sound measurements are shown in part I of this paper [3].
In addition, material characterization, more precisely the determination of longitudinal wave velocity and loss factor of the fillings, was done. In this paper, the material characterization and its correlation with the impact sound pressure levels is shown and will be discussed as part II of the study.

2. Material and method

2.1 Determination of Material Parameters

To quantify mechanical properties of the fillings, the following two parameters were determined:

- **Longitudinal wave velocity in m/s (c_L)**, directly related to the stiffness (e.g. the dynamic modulus).
- **Loss factor (η)**, representing internal damping.

Measurements were conducted using a resonance method based on EN 14146:2004 [9]. Beam-shaped specimens (500 × 50 × 50) mm³ were elastically supported and excited at one end while acceleration was measured at the opposite end (Figure 3).

Figure 3. Test stand to measure the acceleration of beam shaped specimens by transient excitation with a pendulum visible in the backend.

The longitudinal wave velocity was derived from the first eigenfrequency. The loss factor was determined from the first eigenfrequency peak width shown in the figures below. This procedure worked well for stiff samples with low damping, respectively loss factors (Figure 4), showing clear eigenfrequencies, whereas it was more difficult for samples with very high internal damping (Figure 5).

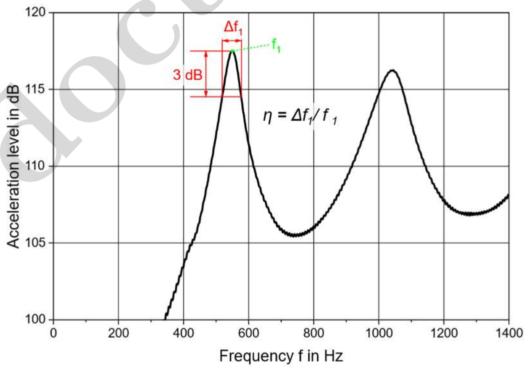

Figure 4. The graph represents the acceleration level in dependence of the frequency by transient excitation of a specimen with low internal damping, showing the eigenfrequencies very clearly.

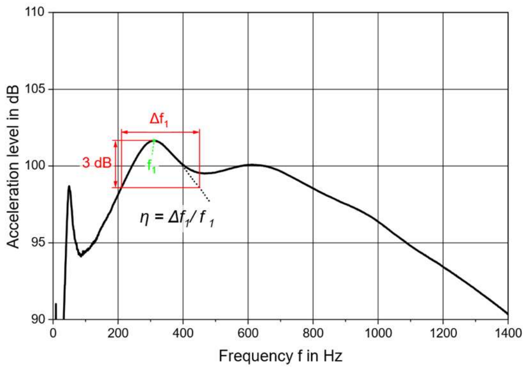

Figure 5. The graph represents the acceleration level in dependence of the frequency by transient excitation of a specimen with very high internal damping, which makes it difficult to identify the eigenfrequencies.

Therefore, as the level difference of 3 dB at the first eigenfrequency could not be measured, the second leg of the parabola was extended symmetrically (dotted line) to the first leg to measure the frequency width Δf_1.

2.2 Development and verification of the measurement

The measurement system was built to measure the longitudinal wave velocity of 500 mm samples according to the standard EN 14146:2004 [9]. Therefore, the excitation of the sample happened by a transient impulse of a custom-built hammer, while the acceleration level was measured on the other side. A detailed description of the development of the measurement system and its validation can be found in [8].

Overall, the measurement works similarly to the method described in [1]. As some samples with very low amount of adhesive/binding component had very low stiffness, the samples were placed flat on an elastic layer to prevent fractures instead of the decoupled mounting on elastic bands shown in [1]. The elastic layer underneath decouples the specimen from the background and prevents the measurement to be influenced by background vibrations. During preliminary tests no difference in the measurement results between the method with the elastic layer and the elastic bands was observed.

The preliminary tests were also carried out to validate the setup. On the one hand the derived values are compared with those reported in [1], on the other hand two common materials (concrete and gypsum) were measured and compared to literature. The measured values and those reported in the literature [10] are shown in Table 1 The densities of the concrete and gypsum samples were slightly different to those reported in literature. However, the measured wave velocity c_L is similar to the values given in [10]. The lower density of the concrete samples may explain the lower stiffness; interestingly for the gypsum samples it shows the opposite trend (higher density → lower c_L). The measured loss factors are doubled compared to the values in the literature, but it must be considered that the values are quite low in total for both materials. As the measured material properties seem to be in the correct range (considering also the unknown differences between the ingredients of the samples of this study and those reported in the literature), the measurement method provides reliable results.

Table 1. The table shows the density ρ and material properties c_L and η of concrete and gypsum samples, measured in the recent project and from literature [10].

Material	ρ in kg/m³	c_L in m/s	η
Concrete (meas.)	2016	3085	0.0135
Concrete [10]	2300	3400	0.004-0.008
Gypsum (meas.)	1372	2145	0.0135
Gypsum [10]	1200	2400	0.006

2.3 Impact sound pressure measurements

All impact sound measurements were performed according to EN ISO 10140-3:2021 [5]. The small-scale impact sound pressure measurements are discussed in the first part of this paper in [3]. Systematically the filling was varied to measure the acoustic influence of different adhesives and fillings. The sample size was 1.45 m². In this study, the correlation of the measured material properties of fillings (see above) with the impact sound pressure measurements was investigated. Additionally, its correlation with existing impact sound pressure measurements according to the standard with a sample size of 22.2 m² from the internal database was investigated. Those constructions with 22.2 m² measured 160-180 mm in thickness of the CLT, the (varying) filling had a height of 100 mm (with 2-4 mm grain size) and the dynamic stiffness s' of the sound insulation mat (mineral wool) under the prefabricated cement screed was 6 MN/m³ to 7 MN/m³ (according to the datasheets, own measurements of s' were done as well). Overall, the main difference between the constructions was the adhesive in the filling, which seems to be responsible for very different impact sound pressure levels (see Figure 2).

3. Results

3.1 Measured values for c_L and η

The material properties of the heavy filling as a function of grain size respectively type and binding agent were measured based on vibration measurements according to EN 14146:2004 [9] (see above). The lowest values for the dynamic stiffness were obtained by loose fillings with longitudinal wave speeds c_L down to 40 m/s. The highest value (= highest stiffness) with 1600 m/s was measured for a filling bound with cement. The internal damping of the latex-bound filling reached a loss factor of 0.76, which was almost twice as high as the second-highest value in damping behaviour (0.43 for polymer-bound filling). The lowest loss factor was measured for cement-bound fillings with 0.03. Overall, it was observed that cement-bound variants were thus significantly stiffer and exhibited substantially lower internal damping than elastically bound or loose systems. The results for the measured material properties of all filling variants are listed in Table 2.

3.2 Correlation with the impact sound pressure level

The aim of this study was not just to measure the dynamic stiffness and the internal damping of heavy fillings. A primary objective was to find a correlation between these mechanical properties and their influence on the acoustic performance of CLT-floors. For this purpose, these values were compared both visually and statistically to each other in scatter plots. As characteristic value the coefficient of determination R^2 for the linear regression was used. These scatter plots including the R^2 values are shown in the following figures.

Table 2. Measured longitudinal wave velocities c_L and loss factors η of different fillings varying in the binding agent and the gravel.

Binding agent & gravel type	c_L in m/s	η bei f_1
loose & paving chippings (2-4 mm)	41.8	0.280
loose & round grain (4-8 mm)	44.4	0.316
loose & round grain (3-5 mm)	45.8	0.325
loose & basalt chippings (2-4 mm)	54.3	0.269
cement & paving chippings (2-4 mm)	989.8	0.067
cement & round grain (4-8 mm)	1609.4	0.030
cement & round grain (3-5 mm)	1343.0	0.061
cement & basalt chippings (2-4 mm)	882.8	0.091
Paving chippings (2-4 mm) bound with:		
Polyurethan 1	565.2	0.107
Polyurethan 2	374.4	0.188
Polyurethan 3	238.3	0.294
Latex	298.2	0.764
Polymer + cement 1	1180.1	0.076
Polymer	682.4	0.431
Polymer + cement 2	470.3	0.367
Polymer + cement 3	788.3	0.092

3.2.1 Small-scale tests

To evaluate the relationship between mechanical properties and acoustic performance, normalized impact sound levels were correlated with c_L and η. The sample size was n = 12. As shown in Figure 6, the coefficient of determination R^2 was higher for the correlation between $L_{n,w}$ and the loss factor η ($R^2 = 0.62$) than with c_L ($R^2 = 0.28$). The same trend is observed for the sum level between 100 Hz and 2500 Hz (which is equal to $L_{n,w} + C_{I,50\text{-}2500}$ by a 15 dB shift) with even higher R^2-values.

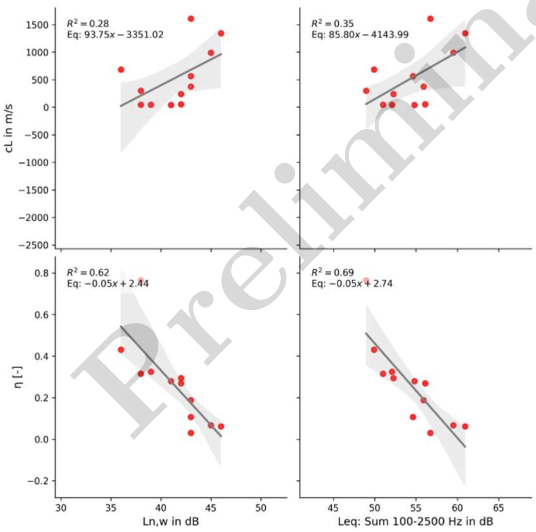

Figure 6. Relationship between the weighted standard impact sound level $L_{n,w}$ (left) and the sum level of L_{eq} from 100 Hz to 2500 Hz (right) from the small-scale tests with the longitudinal wave velocity c_L (top) and the loss factor η (bottom).

Also, a frequency dependent analysis was done. The R^2-values at every octave band in dependence of the material properties c_L and η are shown in Table 3. Low values of R^2 are highlighted in red/orange, while higher values are highlighted in green. The results again show higher correlation of the loss factor η to the sound pressure levels compared to the wave velocity c_L. The highest correlation is achieved at 500 Hz with a R^2 of 0.67. The scatter plot of this correlation is shown in Figure 7 including a linear regression line.

Table 3. Frequency dependent coefficients of determination R^2 for the relationship between the longitudinal wave velocity c_L and the loss factor with the impact sound pressure levels of the small-scale tests.

R^2 (n = 12)	Energetically summed octave bands from the standard impact sound levels in Hz					
	125	250	500	1000	2000	4000
c_L in m/s	**0.61**	**0.26**	**0.26**	**0.31**	**0.00**	**0.21**
η [-]	**0.39**	**0.60**	**0.67**	**0.40**	**0.14**	**0.15**

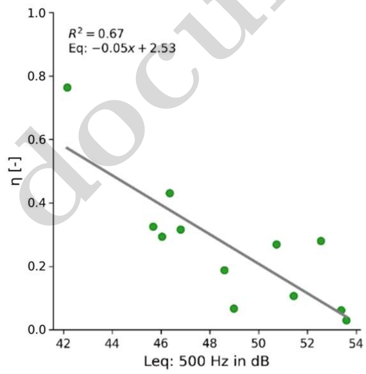

Figure 7. Relationship between the impact sound pressure level at the octave band 500 Hz from the small-scale tests with the loss factor η.

3.2.2 Full-scale tests

A similar analysis was conducted using the results from the normative full-scale measurements with a sample of n = 6. Despite the smaller dataset, comparable trends were observed. As illustrated in Figure 8, the correlation between the normalized impact sound pressure level and the loss factor η again showed higher coefficients of determination than the correlation with the longitudinal wave velocity c_L. This indicates that the internal damping of the filling material also plays a more significant role in the acoustic performance under normative test conditions.

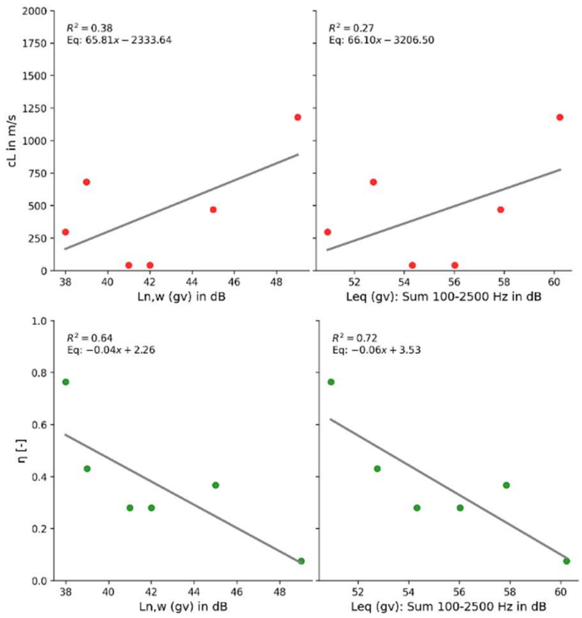

Figure 8. Relationship between the weighted standard impact sound level Ln,w (left) and the sum level of Leq from 100 Hz to 2500 Hz (right) from full-scale tests (gv) with the longitudinal wave velocity cL (top) and the loss factor η (bottom).

A frequency-dependent analysis was performed in the same manner as for the small-scale tests. The resulting coefficients of determination R^2 for each octave band are summarized in Table 4. As before, higher correlations are generally observed for the loss factor η than for the longitudinal wave velocity c_L. The strongest relationship was observed again in the mid-frequency range around 500 Hz, where the highest R^2 values are obtained ($R^2 = 0.86$ at 500 Hz; see Figure 9). Although the limited sample size requires cautious interpretation, the results from the full-scale measurements support the trends identified in the small-scale investigations.

Table 4. Frequency dependent coefficients of determination R^2 for the relationship between the longitudinal wave velocity c_L and the loss factor with the impact sound pressure levels of full-scale tests.

R^2 (n = 6)	Energetically summed octave bands from the standard impact sound levels in Hz					
	125	250	500	1000	2000	4000
c_L in m/s	**0.20**	**0.44**	**0.03**	**0.24**	**0.52**	**0.39**
η [-]	**0.14**	**0.68**	**0.86**	**0.78**	**0.22**	**0.25**

The circled data point in Figure 9 corresponds to the loose filling that was mechanically constrained using a batten grid. Without the batten grid, a higher normalized impact sound level is obtained, although the loss factor stays the same. The same loss factor with a different impact sound pressure level results in a horizontal shift of the data point in the diagram. As the acoustic measurements with and without the batten grid differ, it can be assumed that additional factors beyond the longitudinal wave velocity c_L or the loss factor η influence the normalized impact sound level.

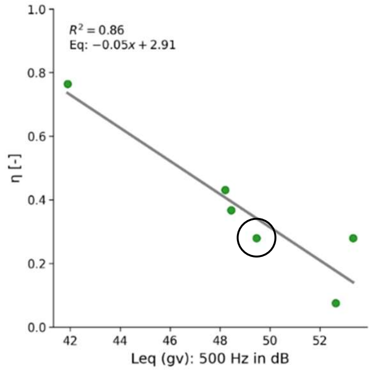

Figure 9. Relationship between the impact sound pressure level at the octave band 500 Hz from full-scale tests with the loss factor η.

In [11] lower impact sound levels were also observed for board-stacked timber floors when concrete slabs were installed instead of loose gravel chippings with a comparable surface mass. It is therefore assumed that the segmentation of the loose filling may have a beneficial effect on the normalized impact sound level. For similar reasons, segmentation caused by cracks in bound fillings could also lead to improved impact sound performance, as observed in the small-scale tests [3].

4. Discussion

In both scales, the mid-frequency range around 500 Hz showed the strongest relationship between impact sound level and loss factor (Tables 3 and 4). This finding agrees with other studies, which also detected the same frequency range as influenced by the filling [2].

Longitudinal wave velocity exhibited weaker and inconsistent correlations across frequency bands. These findings indicate that internal damping (loss factor η) is more relevant for the impact sound performance than stiffness alone. The obtained results from the small- and full-scale tests and their correlation, e.g. the R^2-values are consistent; therefore, it is reasonable to assume that the internal damping has a greater effect on the impact sound insulation of a heavy filling compared to its stiffness.

However, during the small-scale tests other effects were observed [3]. Most notably, the mechanical segmentation effects (e.g., batten grids or fractured specimens) suggest that additional structural parameters influence acoustic behavior beyond c_L and η. Further research is required to be done by testing other mechanical parameters; also, a systematic approach for the full-scale tests with a higher sample size should be carried out to prove the hypothesis.

5. Conclusions

Full-scale tests at the Akustik Center Austria showed that the stiffness and the type of adhesive of the filling interlayer has a greater influence on the impact sound pressure level than the thickness (weight) itself or even the dynamic stiffness of the impact sound insulation mat. The Laboratory measurements showed a difference of 11 dB of the SNQ $L_{n,w}$ for the same construction with different binding agents. Therefore, systematic small-scale tests were carried out to outline the influence of the fillings (thickness, binding, grain size), which is discussed in the first part of this study [3]. Additionally, the impact sound pressure levels are compared with the material properties stiffness (longitudinal wave velocity c_L) and damping (internal loss factor η) of the filling. The measurements were carried out based on the standard EN 14146:2004 and led to the following conclusions:

1. Cement-bound fillings exhibit high stiffness and low damping, resulting in higher impact sound pressure levels.
2. Elastically bound fillings with high internal damping can achieve improved acoustic performance. Due to their higher internal damping behaviour, the acoustical performance can even surpass the one of loose chippings.
3. The loss factor η correlates more strongly with impact sound pressure levels than the longitudinal wave velocity c_L, particularly in the mid-frequency range around 500 Hz.
4. Structural segmentation (mechanical binding or cracking) may influence acoustic performance independently of material stiffness and damping.

Although the results strongly indicate the relevance of damping behaviour, the limited sample size requires cautious interpretation. Future work should include systematic full-scale tests with identical binder systems and simultaneous determination of material parameters to validate predictive relationships.

6. Acknowledgments

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