Acoustical renovation of beam-and-block Ackermann floor in Cracow residential building from 1940

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Abstract. During the renovation works one of the apartments, in a tenement house in the center of Cracow, we had the opportunity to conduct measurements of airborne and impact sound insulation of existing and newly designed floors between apartments (before and after replacing the floor layers). Article presents results of these measurements along with the analysis of floor solutions used in the interwar period and the comparison of their effectiveness with solutions used nowadays.

1. Introduction
In a tenement building built in 1940 in Cracow, the owner of one of apartments intended to perform a general renovation. One of the authors was asked to provide guidelines for the execution of new floor layers in this apartment. During the renovation works, the authors had the opportunity to conduct measurements of airborne (weighted sound reduction index in the field R’w(C;Ctr)) and impact (weighted normalized impact sound pressure level in the field L’nw) sound insulation. The results of these measurements, along with the analysis of floor solutions used in the interwar period and the comparison of their effectiveness to solutions used today are the subject of this article.

2. Building
The discussed apartment is located on the fourth floor of a multi-family, five-story residential building located at Sereno Fenna str. in the center of Cracow. The building was designed in 1938 on behalf of the company "Henryk Franck Sons - Fabryka Środków Kawowych Spółka Akcyjna" from Skawina. The company began construction of a tenement building in 1939, which was interrupted by the outbreak of war. The construction was completed by Germans in 1940 and German officers settled in the building. The building has been designed as a mixed structural system, with load-bearing (or stiffening) brick walls of thickness equal to 51cm and reinforced concrete columns and girders. A bomb shelter was located in the basement. The building was equipped with an elevator, central heating and central hot water with a recirculation system from its own boiler house, delivered to each of the flats.

3. Before renovation state
Individual residential floors were separated from each other by structural ceilings made beam and block floor system using Ackermann bricks [1, 2, 3]. Based on the measurements of the thickness of structural ceilings, it was found that structural floors consisted of Ackermann blocks of 20cm height, with Griffel 25mm steel reinforced ribs and approx. 4cm layer of concrete topping. Floor thickness was increased by 3cm on the 120cm wide area centered along non load-bearing dividing walls. Figure 1 shows the floor layers and the longitudinal and transverse cross-section through the system in the
discussed apartment before renovation. Layout of the floor layers in the discussed apartment shown in Figure 1 remained unchanged from 1940 until the renovation in 2017.

The floor layers had total thickness of approx. 15 cm, which consisted of floor joists, with cross-section of 7x7 cm, spaced every 80 cm, to which subfloor planks, with thickness approximated 20 mm, spaced approximately 20 mm, were nailed. The oak parquet, of thickness about 20 mm, was laid on the boards. Space between the joists was filled with a sand mixed with brick debris.

**Figure 1.** Plan and cross-section of floor slab before renovation (1940).
Noteworthy is the method of supporting the floor joists. Floor joists were not supported on the top of the Ackermann floor along its entire length. They were supported only on both ends by small wooden chocks with dimensions of section about 30x30mm, in such a way that they worked as simply supported beams (deflecting), not as joists. As a result, the contact area of these beams with the Ackermann floor was limited only to the surface of wooden chocks. Floor beam periodically deflected under the weight, compacting the 30mm layer of the sand, which was under the joist, additionally minimizing the contact area of the beams with the ceiling. Joist scheme is shown in Figure 2.

![Figure 2. Schematic drawing of joist supported by wooden chocks of height 30mm (1940).](image)

In Figure 3, an axonometric diagram of the cross-section of the structural ceiling in the discussed building is shown in the before renovation state.

![Figure 3. Axonometric view with cross-section of floor slab with floor layers before renovation (1940).](image)
4. After renovation state

The owner of the apartment described earlier repaired the second apartment, which was on the same floor, but on the opposite side of the staircase. In second apartment, the renovation company replaced existing floor layers (similar as described in chapter 2) with OSB floor, based on joists placed directly on the Ackermann floor, with mineral wool filling space between joists. The use of such a floor system was dictated (according to renovation company opinion) by the ease of assembly and economic factors. Unfortunately, such floor design resulted in a distinct feeling of impact sounds in the flat below. The Authors were able to perform additional measurements of impact sound insulation just recently, therefore the analysis of this solution was not included in this article. However, the very fact of problems reported by the renter, the owner of the apartment above, prompted the latter to consult one of the authors on the acoustic issue.

Analyzing the available possibilities of floor renovation, two solutions were considered. A "lightweight" solution, similar to that described above, using OSB boards, but with the support of joists on the ceiling through the elastic elements. And a "heavyweight" solution using a cement screed as a pressure layer and underlying resilient layer made of mineral wool or elastic expanded polystyrene. The owner and contractor's arguments for the "lightweight" solution were low cost, quick assembly and no need to wait for screed to dry out, which is necessary to start the installation of the parquet. One of the authors arguing against the "lightweight" solution was significant reduction in the weight of the existing system, resulting from the removal of approx. 10 cm layers of sand and brick, which surface mass was estimated at approx. 140 kg / m2 with a sand and debris density of approx. 1,400 kg / m3. With a relatively small surface mass of Ackermann floors (approx. at 300-330 kg / m2), acoustic performance considered as airborne sound insulation of Ackermann floor together with layers of debris and sand was estimated at approx. RW = 59dB. The lack of these additional 140kg / m2 could significantly reduce the roof sound insulation, especially in the low frequency range. This reduction was estimated at approx. ΔRW = -6 dB, which would translate into the RW value = 53 dB for the Ackermann floor alone. According to [4], beam and block floors of similar surface mass amounting to 305-314kg / m2 are characterized by acoustic insulation from airborne sounds at RW = 51dB, and therefore slightly lower than RW = 52 ~ 53dB, as it would appear it is from the mass law [in 4, Table 4, point 1].

The expected impact sound level for a floor with a mass of approx. 300kg / m2 is approx. 82dB. According to [4], beam and block floors of similar surface mass from 305-314kg / m2 are characterized by impact sound level LnW, eq = 77 ~ 78dB, which is measured according to standards from 1980-1990, not exactly in the same way as values currently used.

A comparison of the estimated airborne sound insulation for a floor with a surface mass of 300 and 440 kg / m2 and a typical reinforced concrete slab with a thickness of 20 cm and a weight of 470 kg / m2 is shown in Figure 4.
Figure 4. Comparison of estimated airborne sound insulation for Ackermann floors with surface mass of 300 kg/m² (red curve) with floor of surface mass 440 kg/m² (blue curve) and typical reinforced concrete floor 20 cm thick and with surface mass 440 kg/m² (green curve).

Second argument against the use of the "lightweight" floor layer solution was fear of "rumbling" of a single layer of OSB boards when users walk and jump on them.

Finally, the "heavyweight" solution was chosen, with mineral wool acoustic insulation and a pressure coating made of cement screed. Due to the need to distribute installation in the floor layers, acoustic insulation in two layers, 5 cm + 2 cm was applied, with the assumption that the installations will be carried out in the bottom 5 cm layer of mineral wool. Choice of mineral wool instead of elasticized expanded polystyrene resulted mainly from desire to maximize airborne sound insulation and the use of wool as a resilient material in a layered system (ceiling-screed). In the areas where Ackerman floor topping was thicker, 2 cm layer of acoustic insulation was omitted.

The area of the renovated apartment was approx. 90 m², so it was estimated that approximately 100 m² of 5 cm thick mineral wool panels will be needed and the same number of 2 cm thick panels. For the total sound insulation thickness of 70 mm used in the discussed solution, dynamic stiffness should amount to approximately 8.5 MN / m³ [according to 5, see pg. 84].

As a pressure layer, a cement screed was used, with density of approx. 2000 kg / m³ and thickness of approx. 70 mm, which translated into a surface mass of approx. 140 kg / m², the same as the sand and brick pugging weighed. Maintaining the mass of ceilings during the renovation of old tenement buildings is an important point of view of the safety of the structure.

For a combination of insulating material with dynamic stiffness of approx. 8.5 MN / m³ and pressure layer with a surface mass of approx. 140 kg / m², based on EN 12354-2 [6], Annex C predicted reduction of impact sound level (Weighted impact sound reduction improvement index) should be approx. ΔL_w = 36 dB, at the resonance frequency f₀ of the pressure layer, depending on the calculation method, approx. 39 Hz [in 6, Annex C1] or 47 Hz [in 7, Annex D2]. At the same time,
calculation of increase in insulation from airborne sound (Weighted sound reduction improvement index) due to the use of additional massive layer on the ceiling should amount to approx. $\Delta R_w = 9\text{dB}$.

In order to maximize the impact sound insulation of designed floor layers, an additional layer of so-called "rubber-cork", 4.5 mm thick was glued between the screed and the parquet.

Figure 5 shows plan of floor layers and the longitudinal and transverse cross-section through the structural ceiling in the discussed apartment after renovation. In Figure 6, an axonometric diagram of the cross-section of the floor in the discussed building is shown in the current state and after renovation.

Figure 5. Floor layers plan and cross-section of floor after renovation (2017).
5. Results of acoustic insulation measurements
Before renovation and during the renovation works, authors made impact and airborne sound insulation measurements of the ceiling between the renovated apartment on the fourth floor and the apartment located directly under it. The results of these measurements together with the comparison to the requirements of PN-B 02151-3 from 2015 [9] are presented in Table 1.

Table 1. Results of acoustic insulation measurements carried out before, during and after renovation compared to requirements of PN-B 02151-3:2015 [9].

| Floor system | R’<sub>W</sub> [dB] | R’<sub>A1</sub> [dB] | R’<sub>A2</sub> [dB] | L’<sub>n,W</sub> [dB] |
|--------------|---------------------|---------------------|---------------------|---------------------|
| Ackermann floor (without floor layers) | 50 | 49 | 47 | 86 |
| With floor layers 1940 | 57 | 55 | 51 | 53 |
| With floor layers 2017r (no parquet) | 59 | 58 | 55 | 57 |
| With floor layers 2017r (with parquet and rubber-cork mat) | 62 | 61 | 57 | 47 |

6. Discussion
As can be seen from the analysis of the results given in Table 1, tested Ackerman floor without any additional layers (Table 1, item 1) does not meet the requirements in the field of airborne sound insulation (1dB deficit) or impact sound insulation (deficit 31dB). After considering 2dB corrections for the differences between the laboratory and the construction, the measured airborne sound insulation
insulation is consistent with the predicted value ($R'W = 50\text{dB}$ in relation to the predicted $RW = 51 \sim 53\text{dB}$). The measured impact sound level is very similar to the predicted value ($L'nW = 86\text{dB}$ in relation to the predicted $LnW = 83\text{dB}$).

The most interesting result of measurements is the fact that Ackermann floor together with wooden floating floor made in 1940 (Table 1, item 2) met the present (2015) [9] acoustic requirements. Airborne sound insulation requirement is fulfilled with 4dB surplus, and impact sound insulation—with a reserve of 2dB, both in relation to the requirements of the 2015 standard [9]. Compared to the requirements of the 1999 standard [8], impact sound level is 5dB better than required by the standard. Requirements in field of air sounds for floors between flats are the same in both standards. The measured airborne sound insulation is in line with predicted value including a 10cm layer of sand and brick pugging ($R'W = 57\text{dB}$ compared to predicted $RW = 59\text{dB}$). The measured impact sound level is very similar to predicted value ($L'nW = 86\text{dB}$ in relation to predicted $LnW = 83\text{dB}$).

Another interesting result is the fact that floating floor without top layers (Table 1, item 3), i.e. without rubber-cork and parquet floor, did not meet the modern requirements in the field of impact sound when laid on the Ackermann floor. The deficit is not large (-2dB) and may be due to the fact that when measuring, the screed was not loaded with furniture or elements that simulated it, which could contribute to lowering the measurement result. What is more important measured impact level reduction was only $\Delta L'W = 29\text{dB}$, with the predicted value equal to $\Delta LW = 36\text{dB}$. It can be seen that Ackermann floor used in this building is characterized by very high values of the impact level ($L'nW = 86\text{dB}$), which means that it is necessary to use very effective sound insulation materials. Nevertheless, this result is a certain surprise, although weaker than the predicted impact sound level reduction could also result from a partial thinning of the ceiling in one of the analyzed rooms, resulting from the need to compensate for inequalities of the existing ceiling. The measured airborne sound insulation is consistent with the calculated value, taking into account the additional weight of the screed, ($R'W = 59\text{dB}$ in relation to the predicted $RW = 59\text{dB}$). In addition, the predicted increase of 9 dB airborne sound insulation of ceiling after using floating floor proved to be accurate ($R'W = 50\text{dB}$ for Ackermann floor itself in relation to $R'W = 59\text{dB}$ for ceiling with floating floor).

The last of the results are measurements made on a fully finished floor, together with oak parquet stuck to the screed through the rubber-cork layer and a typical load of furniture. Designed and made floating floor (Table 1, item 4) fulfilled with great reserve all modern requirements in terms of both airborne sound (11dB reserve) and impact sound (8dB reserve). However, what is more important for users of flat below, new floor is better soundproof than the one from 1940, by 6dB in both airborne and impact sound.

In order to better analyze changes in the acoustic insulation of subsequent examined systems, Fig. 7 shows diagrams of from airborne sound insulation (a) and impact sound level (b) of individual examined layer systems.
a) airborne sound insulation

b) impact sound level

Figure 7. Comparison of measured airborne sound insulation (a) and impact sound level (b) for 4 examined layer systems. Numbering of systems according to Table 1.

As it can be seen from comparison of measurement results shown in Figure 7a, the airborne sound insulation of Ackermann floor with original layers from 1940 (No. 2 in the graph) is almost equal to
insulation of floor itself without floor layers (No. 1 in the graph) in terms of 50 Hz to 200 Hz one-third octave bands. Above these bands "lightweight" floor layers begin to affect the insulation of the entire system. In Figure 7a it can also be seen that "heavyweight" floor layers begin to affect acoustic insulation from much lower frequencies, above the resonant frequency of the entire system (about 50 ~ 80Hz). It can also be seen that furniture load on the screed (No. 4 in the graph) compensated slightly the course of the insulation curve in relation to the value for screed itself (No. 3 on the graph).

Comparison of results of impact sound insulation measurements shown in Figure 7b shows that "lightweight" floor from 1940 (No. 2 in the graph) is effective as impact sound insulation for frequencies above 125 Hz one-third octave band. In contrast, the "heavyweight" solution currently designed (No. 3 and No. 4 in the graph) reduces impact sound for frequencies above 50Hz band, above the resonant frequency of the floating floor system. The increase in impact level of the "heavyweight" floor in frequency band 500Hz is clearly visible. This is probably related to the critical frequency of the screed, which for the 50-70mm screed ranges around 400-500Hz, which is probably the cause of the deterioration of results shown in Figure 7b (No. 3 and No. 4 in the graph).

Finally, it is worth paying attention to the subjective aspect of receiving changes in impact sound insulation of original solution from 1940, and its contemporary version. Despite clear improvement of acoustic parameters of new solution in relation to original floor from 1940, subjective reception of changes is not unambiguous. The subjective tests of receiving footsteps of a person walking on both floors in shoes and barefoot showed that new solution causes a strengthened feeling of low frequency penetration, audible in form of low-frequency rumbling of the screed layer around 40-50Hz. This frequency is marked on the Figure 8 with an arrow. Paradoxically, the increase of impact sound insulation in above the resonant frequency - visible in Figure 8 from about 100Hz, where impact sound insulation after a renovation is lower, marked in brown, than analogous level, marked in blue, for floor solution before renovation - caused that after refurbishment to the dwelling below, the audible noises of footsteps in higher frequencies penetrate to a much lesser extent, which masked the lower frequencies to some extent. Currently, for solution after renovation, due to the lack of footsteps from frequencies above 100Hz, people conducting subjective tests heard only low-frequency rumbling, which was perceived by some as more onerous. This is shown in Figure 8.

![Scanned Selection](image.png)

a) walking in shoes
Figure 8. Comparison of perceptible impact sound level in the flat below tested ceiling, for person walking in shoes (a) and bare feet (b) for floor layers before renovation (item 2 in Table 1, blue in the graph) and after renovation (item 4 in Table 1, brown in the graph).

Another possible reason for appearance of such rumble is difference between a locally reactive layer of a light floor in the solution before renovation and a resonant reactive layer of a heavy screed in the solution after renovation. This means that in first case, force from impact of tapping machine or the steps of walking person is transmitted from top layer to ceiling only around point of impact, while in second case a reverberating bending wave field is created [10]. Due to lack of dilatation in screed layer on a large area of the renovated flat (due to later possibility of changing the partition walls) the resonance of the screed layer due to impacts can be more clearly heard.

7. Summary
This paper discusses the process of renovation of floor layers in an apartment from the interwar period. It has been shown that solutions used in residential buildings of last century meet modern requirements in the field of sound insulation. What is more modern solution presented in this article has not fulfilled impact sound level requirement. Additional layers had to be done to provide satisfying results. Awareness of connections between solutions in the field of general construction and their acoustic function is a key element in the process of acoustic renovation of existing buildings. This applies especially to older constructions, such as the 1940 tenement building described in this article.

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