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Research paper

Effectiveness of preventive structural protection against mining impacts and Maintenance Management on technical state of masonry buildings

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Abstract: This research paper presents the results of the analyses of the course of technical wear over time carried out for residential masonry buildings located in the mining area of the Lublin Coal Basin (LCB). As a result of the conducted analyses, models of the course of technical wear over time were obtained for the entire building development and for groups of buildings, taking into account the conducted renovation works and preventive structural protection. By comparing the parameters of the developed models, statistically significant differences in the course of technical wear resulting from the quality of maintenance and the use of preventive measures were identified. In addition, the durability of individual groups of structures was estimated and compared. Based on a comparison of the course of technical wear of 22-year-old building structures, unrenovated and with similar structural and material solutions, it was found that the rate of increase in technical wear after 50 years of use is on average 3.5% lower than in the case of unprotected buildings. In addition, the use of preventive structural protection extends the durability of the analysed building structures by an average of over 13 years. The obtained results may e.g. help owners or managers optimise the Maintenance Management of building structures.

Keywords: mining areas, masonry buildings, technical wear, durability, Maintenance Management, preventive structural protection

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1. Introduction

The measure of the technical condition of a building structure is its technical wear, i.e. material (physical) wear related to changes occurring in the structural matter, interpreted as a decrease in the functional properties or the value of its individual components [1].

In order to maintain appropriate technical efficiency and a proper level of utility values of a building structure, periodic inspections and assessment of its technical condition are carried out, which form the basis for planning and carrying out the necessary renovation works. In recent years, with the increase in the number of complex building structures, the importance of this issue has been steadily growing. This phenomenon is reflected in the development of scientific research on Maintenance Management [2], especially with the use of BIM tools [3]. They are aimed at determining the optimal moment of renovation due to changes in the reliability level of the structure related to the damage intensity function [4] or assessment of the costs of renovation and repair works on a building at a given stage of its use, and their relationship with the value of the technical wear [5].

It is particularly important to correctly assessment the technical condition of building structures in areas subject to the harmful effects of underground mining of raw materials. Underground mining interferes with the rock mass and also leads to the formation of stresses and strains inside the rock mass, which may result in the occurrence of deformations on the ground surface and mining tremors which, in turn, may have an adverse impact on building structures [6–10]. These impacts may appear in the form of damage to finishing elements and, less frequently, structural members, deteriorating the technical condition and functional properties of the building. Thus, comprehensive preventive structural protection is routinely applied in mining areas, which is aimed at improving structural health of buildings in a way that allows to mitigate or completely eliminate adverse mining impacts. The application of preventive structural protection in mining areas consists in the adaptation of structures to the predicted impacts of mining exploitation. It consists in selection of appropriate solutions to strengthen the structure (e.g. additional longitudinal reinforcement of footings), proper location of the building, selection of the size and shape of the building, and in the case of larger or elongated buildings – dividing them into segments.

In recent years, AGH University of Science and Technology has conducted research on the effect of preventive structural protection against mining impacts and executed renovation works on the technical condition of building structures located in the area of Legnica-Głogów Copper District (LGCD) and Upper Silesian Coal Basin (USCB) (e.g. [11–14]).

This publication presents the analyses carried out for a group of 413 buildings located in the mining area of Lublin Coal Basin (LCB). The aim of the described research was to quantify the effects of construction interventions, including preventive structural protection against mining impacts and performed renovation works on the technical condition and durability of residential masonry buildings subjected to the unfavourable effects of underground mining.

The obtained results can be used for further research on the effectiveness of construction interventions in the life cycle of building structures [15], including the costs of renovation works and preventive structural protection against mining impacts.

2. Materials and methods

2.1. Characteristics of database

The research was based on a database containing information on 413 residential masonry buildings located in eastern Poland, in the mining area of Lublin Coal Basin. This database was created based on inventory works carried out in 2018 by the staff of the Faculty of Mining Surveying and Environmental Engineering of AGH University of Science and Technology in Krakow. It contains information e.g. on the age, geometric and construction features of individual buildings as well as on the implemented preventive structural protection against mining impacts. In addition, the following information of the buildings was collected: the technical condition, damage intensity, quality of maintenance as well as the scope of renovation works carried out in individual objects and of their parts.

Based on the performed analysis, it was found that as a result of the underground mining activity carried out in the studied area, surface deformations occurred with indices of the mining area category I or II [16]. Only a few buildings were located in the area with the mining tremors intensity index between the mining area category II and III. Moreover, in the analysed area, mining tremors have been reported in recent years, including several with intensity indices corresponding to the upper limit of the tremor intensity grade I according to the Mining Seismic Intensity Scale GSIS-2017 [17].

The most numerous group in the created database included buildings between 40 and 50 years old (100 structures). The youngest ones had been built in the year of the inventory works, and the oldest were 68 years old (the average age is 33).

The vast majority (97.3%) were detached buildings. Buildings with a straight shape of the floor plan dominated (43.1%); those with a fragmented shape constituted 30.3% and strongly fragmented – 26.6%. A compact body was characteristic of 57.6% of the analysed structures.

The examined buildings had a masonry load-bearing structure. 72.6% of them were built on a constant level. A little more than half of them (231 structures) had cellars under the whole building or under part of it. The foundations, in most cases, were made of concrete (58.8%), and less frequently of reinforced concrete (40.9%). In most cases (74.3%), the cellar (or foundation) walls were concrete monolithic or made of concrete blocks. In 24.0% of the cases, cellar walls were built of ceramic bricks, especially in older buildings. The load-bearing walls of the ground floor and the upper floors were made mostly of aerated concrete blocks (71.2%), and a significant part of slag concrete blocks (18.9%). In the remaining buildings, walls were made of ceramic bricks (5.8%), ceramic hollow bricks (3.1%) or silicate blocks (1.0%) (Fig. 1).

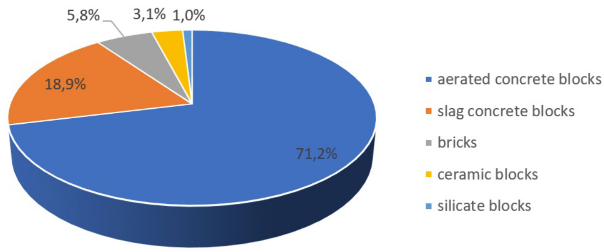

Fig. 1. Division of load-bearing walls according to the materials used

The analysed group of buildings was characterised by great diversity in terms of the structure of ceilings. The ceilings over the first floor were predominantly monolithic reinforced concrete, ribbed, prefabricated or concrete slabs on steel beams (80.7%), in some cases wooden (12.1%), Klein (7.0%) and section (0.2%). Almost half of the buildings (46.0%) had one ceiling. In most cases (61.7%), continuous perimeter beams were used at the ceiling support on the walls.

The database included 57 buildings (13.8%) that had been protected against mining impacts at the design and construction stages (e.g. Fig. 2 and Fig. 3). The foundations of 51 protected buildings were made as reinforced concrete continuous footing with additional longitudinal reinforcement. The diagonal braces of continuous footing were used in 68.4% of cases. Three buildings were founded on a reinforced concrete foundation slab and in other three cases anchor diaphragms were used. In addition, as part of preventive measures taken, 21 buildings had walls reinforced with concrete studs, and all protected buildings had continuous perimeter reinforced concrete beams in the ceilings.

Fig. 2. Example of a renovated building without preventive structural protection

Fig. 3. Example of a unrenovated building with preventive structural protection

The shape of the floor plan and the solid as well as the type of foundations, walls and ceilings affect the stiffness of the building structure and the ability of the facility to absorb the forces generated by mining operations. The criteria described in the "Principles of using alternative construction in mining areas" [18] were adopted to assess the stiffness. Based on the collected data, 365 buildings (88.4%) were classified as *stiff*, 45 buildings (10.9%) as *slightly stiff* and 3 (0.7%) as *not stiff*.

It was found that due to the renovation works carried out in the analysed group, two sets of buildings should be distinguished: *renovated*, which had at least once been subject to significant construction interference in the course of their use (major renovation, upward extension or outward extension), constituting 42.6% of the objects contained in the database, and *unrenovated* which constituted over half of the set, i.e. 237 objects.

2.2. Research methodology

2.2.1. Weighted average technical wear

The first stage of the research work involved the determination of the degree of technical wear of building structures with the highest possible accuracy. Most of the methods used, for the assessment were based on the assumption that technical wear, increases over time and depends on the maintenance quality (e.g. [1]). The so-called time formulas were formulated therefrom. However, these formulas can only be used for a preliminary estimate of the value of technical wear. Therefore, in this research, the weighted average method was used to assess the degree of technical wear of buildings, which accounted for the wear of individual elements and their value proportionally to the cost of restoring the whole structure. The weighted average degree of technical wear of a building is determined using this formula:

$$s_z = \sum_{i=1}^{n} \frac{u_i \cdot s_{ze_i}}{100} \tag{2.1}$$

where: s_z – the weighted average degree of technical wear of the structure, u_i – the value of the i-th element to the cost of restoring the whole structure, s_{ze_i} – the degree of technical wear of the i-th element.

The distribution of the obtained values of the degree of technical wear s_z of the analysed building structures depending on their age and accounting for their division into *renovated* and *unrenovated* ones is presented graphically (Fig. 4).

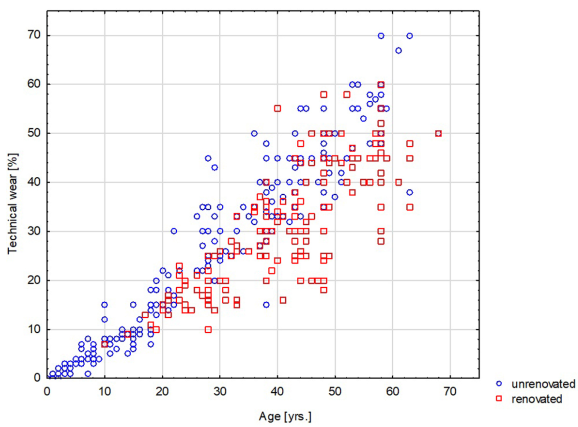

Fig. 4. Scatter plots of $s_z(t)$ buildings in the database, accounting for renovation works performed

2.2.2. Technical wear process

In the next stage, trends in technical wear were determined in each group of the buildings. The trend analysis detects trends in a defined data set. These dependencies can already be detected based on the data scatter plot, the distribution of which indicates a general trend (decreasing or increasing). Such analysis allows to determine the character of the trend function that properly describes the data set. When selecting a trend model, the physics of the studied phenomenon should also be remembered. On the other hand, in order to determine the parameters of the model – equations of the trend line that best describes the analysed data, the regression line should be fitted into them [19].

Each time when starting a research, it is advisable to select the simplest model possible, which has a physical justification and fits well to the analysed data.

The regression model is determined using the least squares method, which consists in fitting such a line into the data set so that the sum of the squared distances of points (representing individual values of the variable) from the regression line is as small as possible. The model determined in this way represents the most accurate trend describing the analysed data.

For the above-described reasons, the search for the optimal model in this research was limited to simple, quadratic, polynomial and exponential functions. The research was performed with the use of the Matlab programme [20].

3. Results

The main purpose of the research described was the quantitative assessment of changes in the value of technical wear of building structures resulting from construction interventions, including the renovation works and preventive structural protection.

3.1. Selection of the best model for comparison

As part of the preliminary study, an analysis of the course of technical wear over time was performed using the non-linear regression method and the least squares method for the selection of model parameters. This approach allowed for direct comparison of optimal models in different classes of functions. The results of the analysis are summarised in Table 1. The third degree polynomials with different values of the slope coefficients were the best fitted, which significantly limited the possibility of their comparison. This resulted in the need to find a uniform solution, thanks to which it would be possible to directly compare selected trends determined for individual groups of buildings. In the course of further research, it was found that the linear trend models (3.1) has a course similar to the best-fitted ones and their accuracy was sufficient for comparative studies of the technical wear of selected groups of buildings. This was confirmed by the values of the correlation coefficient obtained for linear models, which were almost equal to those determined for the best-fitted models (Table 1).

$$s_z = b \cdot t \tag{3.1}$$

where: s_z – the degree of technical wear, b – the slope coefficient, t – age of the building structure.

Table 1. Summary of the best-fitted models and models selected for comparison

Group of buildings	Number of objects	Best practice formula of technical wear [%]	Correlation coefficient	Chosen formula of technical wear [%] ($s_z = b \cdot t$)	Correlation coefficient
renovated	176	$s_z = 3.0775 + 0.3456 \cdot t + 0.0128 \cdot t^2 - 0.0001 \cdot t^3$	0.784	$s_z = 0.7508 \cdot t$	0.783
unrenovated	237	$s_z = -0.0719 + 0.4721 \cdot t + 0.0231 \cdot t^2 - 0.0003 \cdot t^3$	0.963	$s_z = 0.9473 \cdot t$	0.958
all	413	$s_z = -0.2399 + 0.5973 \cdot t + 0.0121 \cdot t^2 - 0.0001 \cdot t^3$	0.902	$s_z = 0.8353 \cdot t$	0.900

3.2. Evaluation of the effectiveness of building renovation

The analysed group of building structures was divided with regard to construction interventions (renovation works). Out of the 413 buildings contained in the database located in the LCB mining area, 176 were renovated at least once. Renovation of a building should be understood as restoring its utility value, consisting in comprehensive repair or replacement of worn, destroyed or damaged structural or secondary elements and fittings. These activities lead to the improvement of the technical condition of the building.

In order to present the course of changes in the values of the mean technical wear over time, in the compared groups of buildings divided according to the renovation works performed, absolute differences in the mean degree of technical wear $s_{zśr}$ after 25 and 50 years (Table 2) between the studied groups were determined.

First, the parameters of the linear model of the course of technical wear were determined for all 413 buildings (c.f. Fig. 1), in which the value of the slope coefficient b was 0.8353, which gave the value of the degree of technical wear of 20.9% after 25 years (Table 2). Then, the course of technical wear was determined with the division of the analysed building structures accounting for their renovation. In the *renovated* group, the average value of technical wear after 25 and 50 years of use was 18.8% and 37.5%, respectively. This value was lower than in the *unrenovated* group by 4.9% and 9.9%, respectively. The obtained results made it possible to estimate the durability of the studied building structures, which for renovated facilities is 133.2 years, i.e. 20.7% higher than for unrenovated facilities. This confirms the positive effect of renovations on the technical condition and durability of building structures.

Table 2. Summary of model parameters and values of mean technical wear after 25 and 50 years, accounting for performed renovations

Group of buildings	Number of objects	Course of technical wear model parameter ($s_z = b \cdot t$)	Average wear $s_{zśr}(t)$ and absolute differences $\Delta s_{zśr}(t)$			
			t = 25 years		t = 50 years	
	[number]	b	$s_{zśr}(t)$ [%]	$\Delta s_{zśr}(t)$ [%]	$s_{zśr}(t)$ [%]	$\Delta s_{zśr}(t)$ [%]
renovated	176	0.7508	18.8	**4.9**	37.5	**9.9**
unrenovated	237	0.9473	23.7		47.4	
all	413	0.8353	20.9	–	41.8	–

3.3. Evaluation of the effectiveness of preventive protection

In the group of 176 renovated buildings, only 5 had preventive structural protection against mining impacts implemented. Such a number did not allow for the analysis of the trend of technical wear of buildings, which were protected and were subject to renovation works at the same time. On the other hand, out of 237 unrenovated structures, 52 had preventive structural protection provided for at the design stage and implemented during their construction, aimed at counteracting harmful mining impacts. A short description of the protected building structures is presented in Section 2. The remaining 185 objects did not have preventive structural protection. A large group of objects in the technical condition undisturbed by construction interventions allowed for subsequent analyses to be performed without the need to take into account the differences resulting from the scope of the renovation works carried out (Table 3 and Table 4).

The results presented in Table 3 demonstrate that the technical wear of unprotected buildings is 23.8% and, over the period of 25 years, increases by 6.7% faster than those of protected buildings.

The reasons for such large differences in the average wear s_z after 25 and 50 years (Table 3) between the examined groups of unrenovated buildings lie in the variability of the structural and material solutions used, related to their age structure. The group of protected buildings contains objects up to 22 years old (the average age is 8), while among the unprotected buildings, the oldest are even 68 years old (the average age is 32). It should be remembered that the function (3.1), which was used for the comparisons, defines only an approximate course of technical wear. Moreover, it should be noted that in the group of 52 protected buildings up to 22 years old, the values s_z after 25 and 50 years are obtained by extrapolating the function, which is a linear one.

For the reasons described above, subsequent comparative analyses of the course of technical wear were carried out for the buildings up to 22 years old, taking into account their division into those with preventive structural protection against mining impacts and the unprotected ones (Table 4).

Table 3. Summary of model parameters for unrenovated buildings accounting for preventive structural protection

Unrenovated buildings	Number of objects	Course of technical wear model parameter ($s_z = b \cdot t$)	Average wear $s_{zśr}(t)$ and absolute differences $\Delta s_{zśr}(t)$			
			t = 25 years		t = 50 years	
	[number]	b	$s_{zśr}(t)$ [%]	$\Delta s_{zśr}(t)$ [%]	$s_{zśr}(t)$ [%]	$\Delta s_{zśr}(t)$ [%]
with preventive structural protection	52	0.6849	17.1	**6.7**	34.2	**13.4**
without preventive structural protection	185	0.9522	23.8		47.6	

Table 4. Summary of model parameters for unrenovated buildings up to 22 years old, accounting for preventive structural protection

Unrenovated buildings	Number of objects	Course of technical wear model parameter ($s_z = b \cdot t$)	Average wear $s_{zśr}(t)$ and absolute differences $\Delta s_{zśr}(t)$			
			t = 25 years		t = 50 years	
	[number]	b	$s_{zśr}(t)$ [%]	$\Delta s_{zśr}(t)$ [%]	$s_{zśr}(t)$ [%]	$\Delta s_{zśr}(t)$ [%]
with preventive structural protection	52	0.68049	17.1	**1.8**	34.2	**3.5**
without preventive structural protection	64	0.7551	18.9		37.8	

The difference in the mean degree of technical wear demonstrated in Table 4 applies to protected and unprotected buildings up to 22 years old with similar structural and material solutions. The obtained results allow to conclude that the use of preventive structural protection at the design and construction stages allows to mitigate the technical wear of buildings by an average of 1.8% over 25 years and by 3.5% over 50 years when compared to unprotected buildings.

For the analysed groups of buildings, the obtained models of technical wear also allow for the assessment and comparison of their durability (Fig. 5).

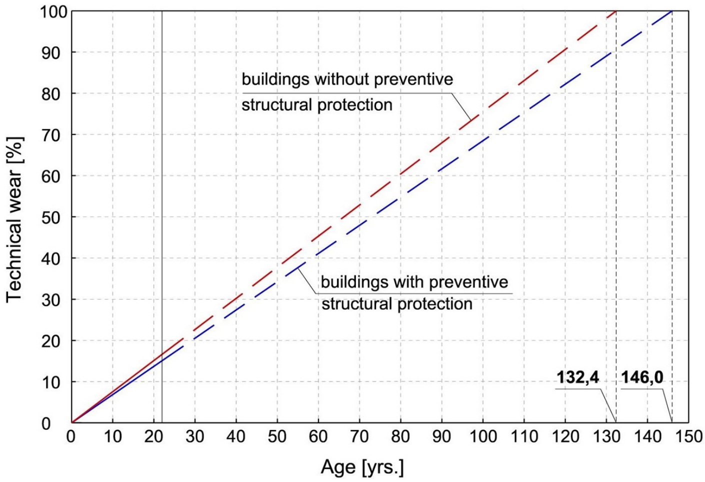

Fig. 5. Course of technical wear summarised in Table 4 of unrenovated buildings with and without preventive structural protection, located in the LCB

Based on the analysis of the obtained models (Table 4) illustrated in Figure 5, it can be concluded that for the analyzed development the use of preventive structural protection results in extended durability of detached masonry houses by 13.6 years on average.

4. Conclusions

The aim of the described research was to quantify the effect of the construction interventions, including preventive structural protection against mining impacts and renovation works, on the technical condition of residential buildings subject to the unfavourable impacts of underground mining.

The research was based on a database containing information on 413 masonry buildings located in the mining area of Lublin Coal Basin.

As a result of the conducted analyses, models of the course of technical wear were obtained for the entire building development and for groups of buildings, taking into account the conducted renovation works and preventive structural protection. Subsequently, comparative analyses of the technical wear trends made it possible to evaluate the effectiveness of construction interventions.

It was found that the renovation works performed, consisting in the comprehensive repair or replacement of worn, destroyed or damaged structural or secondary elements and fittings, resulted in the decreased value of technical wear of the analysed structures by an average of nearly 10 percentage points over the period of 50 years of their use (Table 2). Then, based on the performed extrapolation, the durability of renovated buildings was determined at the average level of 133.2 years, which is the lower limit of the estimate and may increase in the case of subsequent renovations.

It was also found that out of 237 unrenovated structures, 52 had preventive structural protection against mining impacts implemented and were characterised by a much slower course of technical wear over time when compared to the unprotected ones (Table 3). Then, a comparative analysis of trends in the technical wear of 22-year-old buildings with similar structural and material solutions and unrenovated ones was carried out. This analysis showed that the technical wear of protected buildings after 50 years of their use is on average 3.5 percentage points lower than in the case of unprotected ones (Table 4). Another finding was that the use of preventive structural protection extended the durability of building structures by an average of 13.6 years (from 132.4 to 146.0 years).

Moreover, the comparison of the course of technical wear of renovated buildings (Table 2) and of unrenovated ones but with preventive structural protection (Table 4) demonstrated a slower rate of technical wear over time for protected structures.

The presented research results confirmed the statistically significant effects of renovations and preventive structural protection on the course of technical wear in the building structures located in the mining area of the Lublin Coal Basin. The obtained results indicate that although the use of preventive structural protection is associated with significant costs, it effectively reduces the extent of damage and slows down the rate of wear over time, which translates into a reduction in renovation costs and extends the durability of building structures.

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Efektywność zabezpieczeń profilaktycznych przeciw wpływom górniczym oraz remontów na stan techniczny budynków murowanych

Słowa kluczowe: tereny górnicze, budynki murowane, zużycie techniczne, trwałość, zarządzanie remontami, profilaktyczne zabezpieczenia konstrukcji

Streszczenie:

W artykule przedstawiono wyniki analiz przebiegu zużycia technicznego w czasie przeprowadzone dla budynków mieszkalnych o konstrukcji murowanej, zlokalizowanych na terenie górniczym Lubelskiego Zagłębia Węglowego LZW (Lublin Coal Basin LCB). W efekcie przeprowadzonych analiz uzyskano modele przebiegu zużycia technicznego w czasie dla całej badanej zabudowy oraz dla grup budynków wydzielonych z uwzględnieniem zastosowanych remontów i profilaktycznych zabezpieczeń konstrukcyjnych. Porównując parametry uzyskanych modeli stwierdzono istotne w sensie statystycznym różnice w przebiegu zużycia wynikające z jakości utrzymania oraz stosowania zabezpieczeń profilaktycznych. Ponadto oszacowano i porównano trwałość poszczególnych grup obiektów. W szczególności porównano przebieg zużycia technicznego budynków w wieku do 22 lat, o podobnych rozwiązaniach konstrukcyjno-materiałowych oraz nieremontowanych. Stwierdzono, że tempo przyrostu zużycia technicznego w czasie jest po 50 latach użytkowania średnio o 3,5% niższe niż w przypadku budynków niezabezpieczonych. Ponadto wykazano, że stosowanie zabezpieczeń profilaktycznych wydłuża trwałość badanej zabudowy średnio o ponad 13 lat. Uzyskane wyniki mogą m.in. pomóc właścicielom lub zarządcom w optymalizacji gospodarki remontowej budynków (Maintenance Management).

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