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Tests of loading efficiency of worm-type cutting drums in longitudinally inclined longwall working

This article presents the execution and results of tests of the loading efficiency of worm-type cutting drums as a function of the slope of a longwall working. The tests were carried out at various angles of longitudinal inclination of a longwall within a range of 0° to 9° along the strike. In real conditions, the separation of the two basic processes that take place during operation of a longwall shearer (i.e., milling and loading) is not possible; therefore, the research was carried out under laboratory conditions at the Department of Mining, Dressing, and Transport Machines at AGH University of Science and Technology in Krakow. The tests were carried out on a special station that allowed for the gradual change of the longitudinal and transverse slope of a longwall working. Based on the conducted tests, it was found that the inclination of a longwall working influences the loading efficiency; i.e., that, along with an increase in the angle of the longitudinal inclination, loading resistance increases while the loading efficiency decreases.

Key words: *laboratory tests, spoil loading, worm-type cutting drums*

1. INTRODUCTION

Hard coal mining in most European countries (including Poland) is practically carried out by longwall methods (in particular by longwall shearers). The longwall system has many advantages, which include low operational losses, a small amount of preparatory work, a reduction of the risk of rock bursts (due to the convenient stress distribution in the rock mass), a reduction in the risk of fires due to the clean bed selection, and the possibility of ventilation by means of a circulating air current [1]. However, each longwall working is characterized by individual hazards and difficulties in coal mining. Such threats include the so-called co-existing hazards: fire, rock burst, temperature, and methane [1]. Meanwhile, the technical difficulties certainly include walls with heights of less than 1.5 m and a slope in the excavation (the dip angle of the seam). As in the case of determining the height ranges of walls in particular categories, the slope of the seam is also a matter of convention. The most frequent divisions are as follows [2, 3]:

- horizontal <5°,
- almost horizontal 5–15°,
- slightly inclined 15–30°,
- strongly inclined 30–45°,
- steep >45°.

Bearing in mind the heading longwall excavations, their direction in reference to the slope of the seam, and the direction of the exploitation, we can distinguish between longitudinal and transverse wall slopes. If the face of the wall moves perpendicularly to the inclination of the seam (Fig. 1), such a wall is called a longitudinal wall. However, when the face of the wall moves in a parallel fashion along the strike or dip to the inclination of the seam, such a wall is referred to as a transverse wall (Fig. 2) [4].

In mining practice, excavation in the case of inclined seams is oriented in such a way that the transverse inclination angle of the wall is as small as possible, permitting higher values of longitudinal inclination (even 45°). This is mainly due to the operational capabilities of the machines and devices working in the wall [4]. An example of longwall shearers working at a large longitudinal inclination are Beijing HOT Mining Tech shearers (Fig. 3) [5, 6].

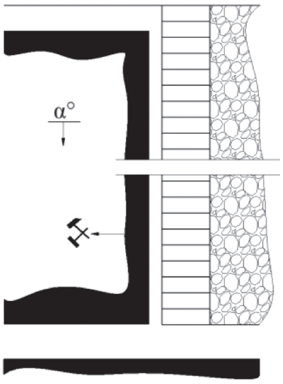

Fig. 1. Longitudinally inclined wall

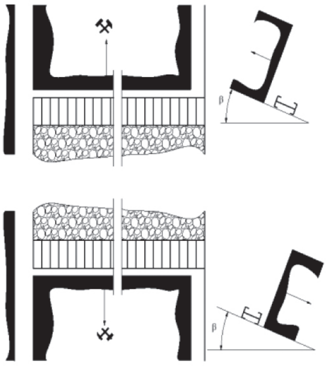

Fig. 2. Transversely inclined wall

Fig. 3. Classic longwall shearer for strongly inclined seams at testing grounds of Beijing HOT Mining Tech [5]

As can be seen from the literature, the ranges of the permissible slopes for mechanized longwall systems is up to 45° longitudinally and up to ±20° transversely. It should be noted that the best results are obtained by mechanized walls in horizontal or slightly inclined seams; as the inclination increases, the efficiency of the walls decreases significantly [6].

Therefore, given the above literature-derived data, it was checked to what extent the angle of inclination of a longitudinal longwall working influences the loading process of worm-type cutting drums, thus to obtain the efficiency of this process.

The loading process is crucial, as there is a need for the continuous transport of the spoil produced in the mining process onto the longwall conveyor. The cleaning of the shearer path enables the shearer to be moved to a new field by a full swath. Leaving the spoil on the shearer path can lead to the so-called loss of swath; i.e., moving the conveyor by a swath smaller than assumed (required). This situation affects the fact that the drums cannot work across the entire width, which results in the failure to achieve the target daily production. The second undesirable effect is the so-called elevation of the conveyor, consisting of lifting it on the remaining spoil. This can cause difficulties in continuing the shearer's operation at the height assumed for a given wall. In addition, this may lead to a reduction in the durability of the picks due to the fact that the cutting heads cut into the roof rocks [7].

2. AIM AND FOUNDATION OF RESEARCH

The purpose of the research was to determine the influence of the longitudinal angle of a longwall working on the loading efficiency. As we find in the literature [3], the maximum longitudinal slope of medium walls can be 35°, while a transverse slope can range up to 20° along the strike and 15° along the dip. Therefore, the angle values selected for the tests will be representative of nearly horizontal walls. The tests were carried out for four angles of inclination of the excavation. As these are pilot studies on the topic, the lowest values of inclination angles were tested; first for a horizontal excavation with an angle of 0°, then three longitudinal inclination angles: 3°, 6°, 9°. Also, the station at which the loading efficiency measurements were carried out has the possibility of applying these angles during the tests. During the tests, the values of the fill factor of the drum (k_w) and the coefficient of the loosening of the output spoil (k_r) have been taken into account, which affect the efficiency of the loading. The ranges and values of these coefficients have been determined on the basis of empirical studies and are adopted within the limits of $k_w = 0–1$, $k_r > 1$, [8]. The analytical model of the process of loading using worm-type cutting drums has been adopted for the interpretation of the test results [4, 9]. In accordance with the assumed objective of the study, it was assumed that the loading process will be separated from the milling process so that the study could focus only on the loading process. This assumption was possible to be included only under laboratory test conditions.

In connection with the above, the tests of the loading process were laboratory tests and were carried out at a specially prepared test station. The test station in question enables us to carry out the loading process as well as to use different angles of the longitudinal and transverse inclination of a longwall working. A specially designed worm-type cutting drum was used for the tests with a specific angle of the winding of the thread.

3. RESEARCH PLAN AND METHODOLOGY

The main assumption for testing the efficiency of a loading with worm-type cutting drums was to check to what extent the longitudinal slope of a longwall working impacts the quality (efficiency) of the loading process. The tests needed to be carried out in accordance with the dependencies defining the proper course of the loading process; i.e., that the internal volume of the drum (V_o) is greater than the quantity of the spoil produced during the mining (V_u) for one or two drums. These dependencies have been described in the literature [4] for the operation of drums with and without loaders. In the equations (described in the literature [4]), there are parameters such as the volumes of the front and rear drum, which can be described as follows:

- spoil volume for the front drum:

$$V_{up} = V_u \frac{D_s z v_p k_r k_L}{n} \tag{1}$$

- spoil volume for the rear drum:

$$V_{ut} = \frac{(H - D_s) z v_p k_r k_L}{n} \tag{2}$$

where:

V_u – mining efficiency of the drum [Mg/h],
D_s – diameter of the drum [m],
H – height of the mined wall [m],
Z – swath [m],
k_r – loosening coefficient of the output spoil [–],
k_L – coefficient defining the amount of spoil loaded with no participation of the drum [–],
k_w – drum filling coefficient [–].

Due to the above, only one front drum was designated for the tests, because it always machines the face with its whole diameter. Coefficient *kL* was adopted as equal to 1; this means that all of the spoil will be loaded using a worm-type cutting drum. From Relationship (1), it follows that:

$$k_w \geq \frac{D_s \cdot z}{v_o} \cdot \frac{v_p}{n} \cdot k_r \tag{3}$$

where:

$\frac{D_s \cdot z}{v_o}$ – construction parameters of the drum,
$\frac{v_p}{n}$ – kinematic parameters.

From Formula (3), the construction parameters of the drum without the pick system required for the given conditions were determined.

For the needs of the laboratory tests, it was necessary to create a spoil with a previously assumed grain composition. The use of a spoil with a specific grain composition allowed for obtaining different values of spoil loosening coefficient k_r. For a given spoil and a given worm-type drum, the change of the feed speed and the rotational speed of the drum determines the value of the filling factor of the drum k_w.

The parameters measured in the tests will be as follows:

- power consumption of loading resistance *Np* measured on the feed motor as a function of loading efficiency of the drum η_l,
- power consumption of loading resistance N_o measured on the drum's engine as a function of loading efficiency of the drum η_l,
- loading efficiency of the drum η_l, measured as the cross-section of the spoil heap [9, 11].

The range of rotational speed n and feed rate v_p was determined based on the actual structural and kinematic parameters of the drum used for testing.

Table 1

Values of drum fill factor k_w and spill loosening factor k_r

No.	Spoil loosening factor k_r (granulation)	Rotational speed of the drum n [rpm]	Feed speed v_p [m/min]							
			1	2	3	4	5	6	7	8
1	1.69 (0–45 mm)	40	0.322	0.644	0.967	1.289	1.611	1.933	2.256	2.578
2		80	0.161	0.322	0.483	0.644	0.806	0.967	1.128	1.289
3		120	0.107	0.215	0.322	0.430	0.537	0.644	0.752	0.859

The values of these parameters are included in Table 1 and reflect the values of the parameters used under real conditions (rotational speed of the drum, feed rate). Dependence (3) was used to compile this table. The table illustrates the theoretical values of fill factor k_w of the drum depending on feed speed v_p and the rotational speed of organ n for different spoil loosening coefficients k_r. This allows for the easy and quick selection of the feed and rotational speeds of the drum in order to obtain the fill factor required for the test.

The values presented in Table 1 allow us to carry out tests for three angles of longitudinal inclination of a longwall working; namely, 3°, 6°, and 9°. On the basis of the tests and the results obtained, it will be possible to analyze and assess the influence of the angle of inclination of the excavation on the loading efficiency as a function of the rotational speed of the drum and feed rate, taking into account drum fill factor k_w and spill loosening factor k_r.

4. LABORATORY STATION FOR TESTING LOADING PROCESS USING WORM-TYPE CUTTING DRUMS

The laboratory station (Fig. 4a) intended for testing the loading process consists of a structural part and a measuring system. The structural part of the station is a sliding frame, with the body of the cutting drum mounted on it (Fig. 4b). The feed drive (toothed wheel and toothed rack) allows the frame to move along guide rails, thus realizing the movement of the drum during operation.

The feed drive motor allows for adjusting the linear speed of the frame. Two guide rails allow the frame to travel over a distance of 1200 mm. The power supply system of the rotor enables the changing of directions and regulation of the rotational speed of the drum. The construction of the sliding frame makes it possible to place a heap of the loaded spoil between its sheets [3].


a)
b)

Fig. 4. Station for testing loading process: a) view of test bench from side of feed motor and rail; b) view from drum: 1 – station base, 2 – toothed rack, 3 – guide rails, 4 – drum drive motor, 5 – sliders, 6 – feed drive motor, 7 – gear cog, 8 – cutting drum, 9 – sliding frame

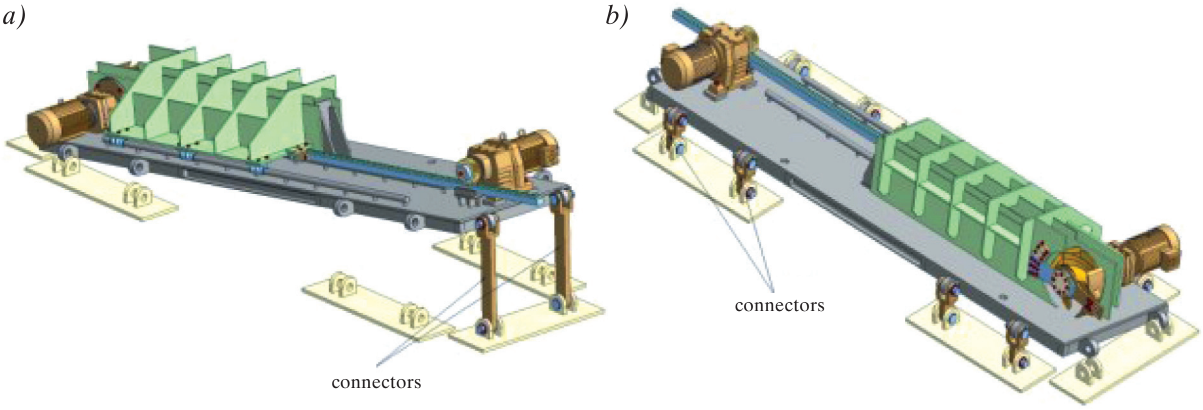

Fig. 5. Station for testing loading process: a) longitudinal inclination; b) transverse inclination

The station makes it possible to regulate the basic kinematic parameters of the station elements, such as:

- linear speed of the frame (feed speed),
- rotational speed of the drum,
- direction of the drum's rotation,
- feed direction (frame movement).

The position allows for setting the longitudinal and transverse inclination angle as shown in Figure 5. The inclination of the station can be achieved through connectors that have different lengths and correspond to the appropriate angles.

A quadruple-entry worm-type cutting drum with normal threads without a shielded loader was used for testing. The selection of the organ for the research was based on the professional literature and previous research, which was described in Item [10]. The drum in question is characterized by the following parameters:

- $Z_U = 0.133$ m,
- $D = 0.334$ m,
- $d = 0.2$ m,
- $b = 0.012$ m,
- $i = 4$,
- $\alpha_2 = 28.33°$,
- $k_{kp} = 1$,

where:

Z_U – swath of the drum without the cutting disc (the mining-loading part) [m],
D – diameter of the drum, including the loading extensions [m],
d – drum's hub diameter [m],
b – thickness of the thread [m],
i – number of threads [–],
α_2 – thread twist angle [°],
k_{kp} – coefficient taking into account the shape of the drum's hub, defined as the relationship between volume other than cylindrical to the volume of the hub cylinder (d) [–].

The measuring part of the station was a specially designed measuring system that allows for measuring and registering the power consumption of both engines.

The measuring system used on the test bench was equipped with current transformers, active power converters, a measurement module, and a measuring computer (Fig. 6).

Rotational speed measurement on the rotors (S) was carried out by the encoders (E), from which the signals were transmitted to the power box.

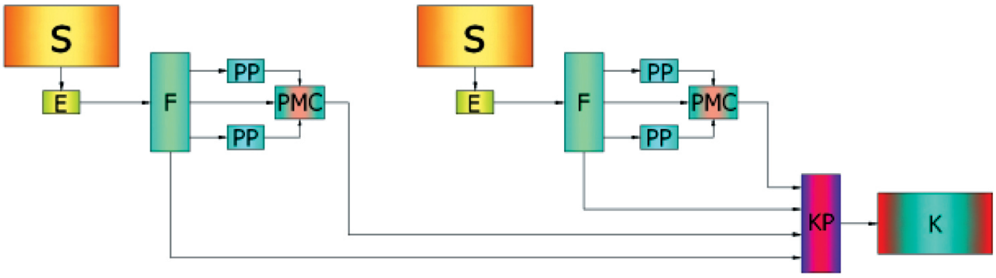

Fig. 6. Diagram of test bench measuring system [10]

In the power box, the signal is transferred to the inverter (F) and through the current transformers (PP), active power converters (PMC), and measurement card (KP) (docking station) to the computer (K) in which the data is saved.

5. PRELIMINARY TESTS

It was also assumed that the research will be two-staged; namely, it would consist of preliminary and primary tests. The initial tests were aimed at determining whether the measuring system works properly, whether the assumptions for testing are correct, and whether the necessary number of repetitions of the measurements are performed during the primary tests. In connection with the above, three measurements were taken for the constant rotation of the drum and feed speed. The results were analyzed statistically according to the Stein method [14]. Then, from the *t*-Student distribution, it was assumed that it is sufficient to perform two tests for each set of parameters.

Based on the preliminary research, a number of conclusions have been formulated. During the operation of the drum without a loader, no increase in power consumption was observed in any of the motors. However, it was observed that as the value of filling factor k_w increases, the shape and position of the output spoil heap changes.

In connection with the above, it was assumed that the main criterion for assessing the loading process for the drum without a loader will only be its loading efficiency.

The efficiency of the loading was defined as the ratio of the cross-sectional area of the heap of the spoil loaded to the area of the total cross-section of the dislocated spoil [8]. Therefore, it was assumed that the cross-section of the heap will be illustrated by a triangle (Fig. 7), which would be determined by the following values: a, b, h. Through this, it would be possible to determine the loading efficiency for a given measurement. The 145 mm dimension visible in Figure 7 results from the swath of the cutting drum and is a delimitation between the loaded and unloaded spoil. The efficiency of loading $\varsigma_{ł}$ was calculated in the same way for all samples; that is, as the quotient of the cross-sectional area of the spoil loaded $P_{łśrd}$ and average cross-section area $P_{c\ średnie}$ of the total spoil multiplied by 100%. To calculate the loading efficiency, the following dependence was used:

$$\eta_{ł} = \frac{P_{ł\,mean}}{P_{c\,mean}}100\% \tag{4}$$

6. PRIMARY TESTS

Coal from one of the Polish mines was used for the tests. The coal to be tested was selected in terms of its properties and granularity class for the test cutting drum.

The preparation of the spoil was carried out at the Accredited Laboratory for Research and Property of Stone Products at AGH University of Science and Technology. The aim of preparing the spoil was to isolate the fractions and determine the bulk density in the loose state. On the basis of the volume density of the coal grains (i.e., the density that coal has in the seam and the bulk density of its granulation), it was necessary to determine the so-called spoil looseness coefficient k_r. The volume density was determined in accordance with the PN-EN 1097-6 standard and the bulk density in accordance with the requirements of the PN-EN 1097-3: 2000 standard. While determining the k_r coefficient, the geometrical parameters of the drum used for the tests were also taken into account [10]. The coal to be tested had a granulation of 0–45 mm and a looseness coefficient of k_r = 1.69. The k_r coefficient was assumed on the basis of the experimental studies and literature data [11–13].

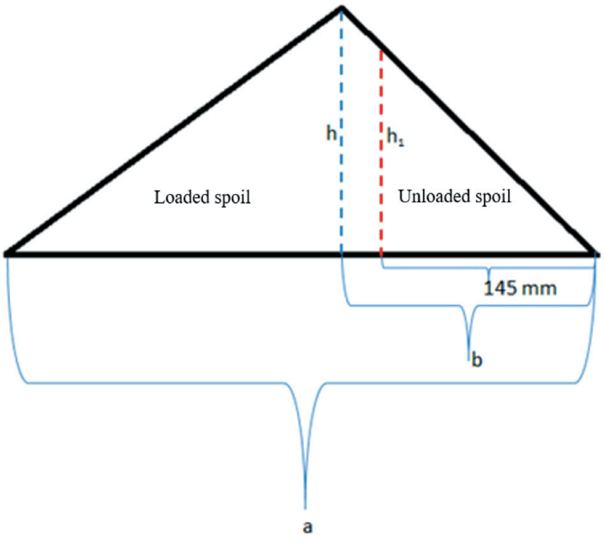

Fig. 7. Diagram of cross-section of spoil heap

The tests were carried out in accordance with the following plan:

- a spot located within the sliding frame of the station was filled with the spoil of a specified and known granulation corresponding to the k_r coefficient;
- the appropriate angle of the longitudinal inclination of the longwall working was set by using connectors of the appropriate length (Fig. 5);
- the feed drive and rotor of the drum were started in accordance with Table 1;
- the frame was stopped after having moved 1200 mm, and the quantity of the spoil loaded was measured in accordance with Figure 7 (measurement of the geometry of the heap).

After performing the above-mentioned activities, the test procedure was repeated twice for all of the parameter values specified in Table 1.

7. TEST RESULTS STUDY AND ANALYSIS

In accordance with the test procedure described above, the drum without a shield loader was tested first, and the test station was set horizontally (0° angle of the excavation slope). Then, the tests were carried out for three settings simulating the inclination of the longwall working for angles of 3°, 6°, and 9°. The loading process was carried out along the strike for each of the inclination angles. The test results obtained after testing for the horizontal working served as a reference for the remaining slope settings.

After conducting a whole series of tests for each of the kinematic parameters (feed speed, rotational speed of the drum) and each setting of the angle of inclination of the working, all of the results were compiled in a graphical and tabular manner. This allowed for an easier comparison and determination of the dependencies between them and an evaluation of the loading efficiency for the individual inclination angles.

Presented below are selected combinations of the test results. Figure 8 and Table 2 summarize the test results for the horizontal position and the drum without a loader. Figure 8 shows loading efficiency η_l as a function of the fill factor of the drum for different feed speeds v_p. As can be seen in the chart below, the highest loading efficiency was obtained at the lowest feed speed and at the lowest filling of the drum. In addition, at a feed speed of v_p = 2 m/min, loading efficiency is the highest. However, for a feed speed of v_p = 6 m/min, the efficiency decreases with increases in the fill factor of the drum. In connection with the above, it can be assumed that, as the filling of the drum increases, the loading resistances increase accordingly and, thus, the loading efficiency decreases.

Comparing the results summarized in Table 2, we can conclude that the highest loading efficiency was obtained for a feed speed of v_p = 2 m/min and the lowest fill factor of the drum k_w. However, the lowest loading efficiency was recorded for the highest k_w coefficient and the highest feed speed (v_p = 6 m/min).

The next stage of the research was to conduct tests for various longwall slopes. Presented below is an example graph of the loading efficiency (Fig. 9) as a function of the drum's fill factor and feed speed. The graph presented in Figure 9 clearly shows that, with increases in the feed speed v_p, as the drum becomes increasingly filled, there is a significant reduction in the loading efficiency. Similar dependencies were observed for the remaining inclination angles of the station (wall), an example of which is shown in Figure 10.

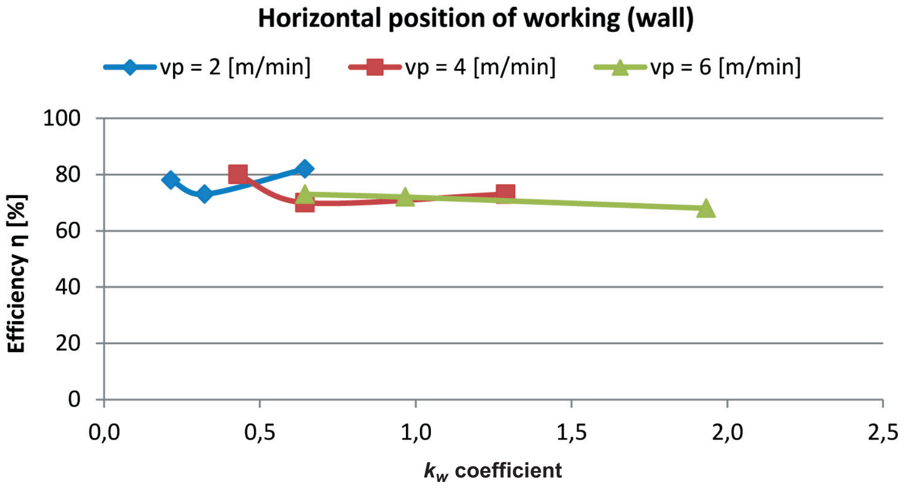

Fig. 8. Efficiency of loading η in function of drum fill factor k_w for different feed speeds v_p for horizontal longwall

Table 2

Test results for various kinematic parameters set during tests

No.	v_p [m/min]	n [rpm]	k_w	a [mm]	b [mm]	h [mm]	h_1 [mm]	P_{c_2} [cm^2]	P_{z_2} [cm^2]	η [%]
1	2	40	0.644	48	24.2	15	9	357	292	82
2	2	80	0.322	42.3	18.6	19	15	396	290	73
3	2	120	0.215	45.8	21.1	18	12	407	319	78
4	4	40	1.288	42.2	18.5	14	11	306	223	73
5	4	80	0.644	41.1	17.1	14	12	294	206	70
6	4	120	0.429	46.5	22.2	11	8	267	213	80
7	6	40	1.933	39.2	17	15	13	301	206	68
8	6	80	0.966	41.7	18.2	14	11	290	210	72
9	6	120	0.644	43	17.9	14	12	307	223	73

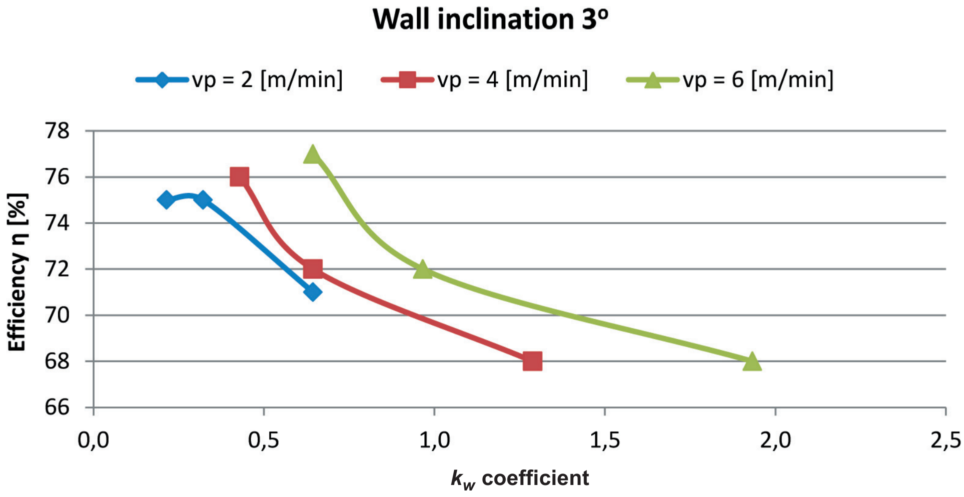

Fig. 9. Loading efficiency $\eta_ł$ as a function of the drum fill factor k_w for different feed speeds v_p for a 3° wall inclination

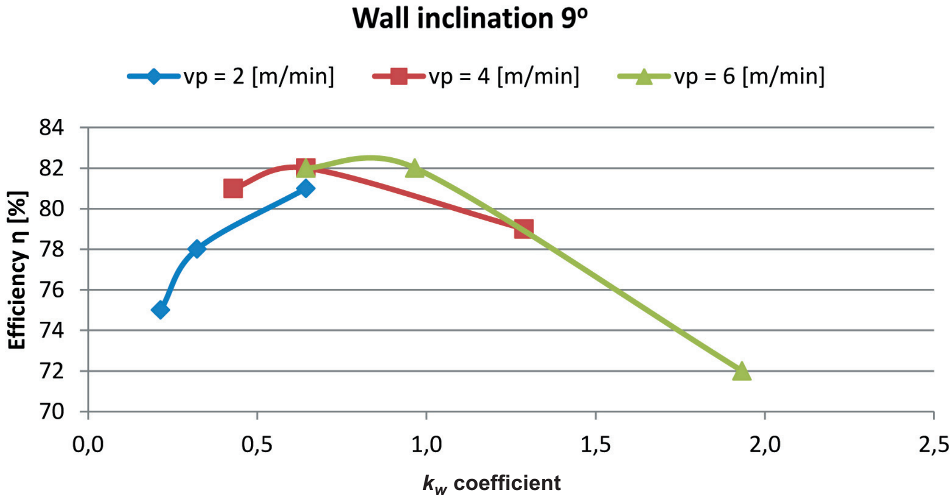

Fig. 10. Loading efficiency $\eta_ł$ as function of drum fill factor k_w for different feed speeds v_p for 9° wall inclination

The graph shown in Figure 10 also shows that, at a 9° wall inclination and for higher feed speeds, the drum's fill factor increases and, thus, the loading efficiency is significantly reduced.

8. CONCLUSIONS

As mentioned earlier, the conducted research should be considered as a pilot study on the subject of the loading of spoil with worm-type cutting drums for inclined workings. The laboratory tests carried out and the subsequent analysis of the test results allowed us to draw conclusions and indications for further research (tests) on this topic. The main conclusion from the research is that the inclination of the working impacts the loading process because, with increases in the inclination angle, the efficiency of the loading with a drum without a loader decreases slightly. All of the experiments were carried out to simulate a shearer moving along the spike. The tests also indicate that, with increases in the feed speed and angle of inclination of the wall, the filling of the drum increases, thus affecting the efficiency of the loading.

These tests were the first tests of the loading process with a longitudinal inclination of a wall conducted at the Department of Mining, Dressing and Transport Machines of AGH. Previously, only tests for horizontal walls had been carried out. In connection with the above, tests should be continued for the longitudinal inclination of a station for greater angles and for drums with shield loaders. Perhaps for larger wall inclinations and with the use of a shield loader, an increase in power of the drum's rotor and feed motor will be visible during the tests. It is also suggested to introduce a system for collecting the spoil at the station, which could better illustrate the loading process.

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