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GEOMECHANICAL PROPERTIES OF ROCKS FROM THE ROCKBURST HAZARD VIEWPOINT

GEOMECHANICZNE WŁASNOŚCI SKAŁ W ASPEKCIE ZAGROŻENIA TĄPANIAMI

Studies carried out over many years by the Central Mining Institute on the geological properties of the Coal Measure rocks in the Upper Silesian Coal Basin have resulted in the acquisition of a substantial data base of mechanical parameters of rocks over the total strain range. Among the parameters are the following: peak strength or maximum stress, modulus of elasticity, drop modulus determined from the post-peak range of the stress-strain curve.

The post-peak rock properties are closely related with the peak strength and the pre-peak properties. Hence, the relationship between the uniaxial compressive strength R_C, the drop modulus M, and the relationship between the modulus of elasticity E and the drop modulus M have been determined. The fundamental mechanical properties of rocks described are needed to predict the "host rock-coal seam" system dynamic failure (rockburst) incidence from the laboratory-based "testing machine platen-rock specimens" system-failure experiment.

The paper considers a double roof-seam-floor system, namely, $M_{coal} < E_{rock}$ (Table 1, variant 1) and $M_{coal} > E_{rock}$ (Table 1, subvariants 2a and 2b) that have been identified through the relationship between E_{rock} and M_{coal}. A proposed classification of the liability of rocks to rockbursts based on the M_{coal}/E_{rock} index is suggested. A prognosis of the variation of the "host rock–coal seam" system-failure patterns related to an increase in strain rate has been elaborated, using knowledge of the variation of drop modulus post-peak values obtained for various strain rates, mostly in the 10^{-4}–10^{-1} s^{-1} range. In the paper, the possibility to use the proposed M_{coal}/E_{rock} index for the analysis of the triaxial compression testing results with regard to the rockburst hazard is suggested.

Key words: rock mass, rockburst, relationship definition, research method

Budowa geologiczna, w tym litologia wraz z naturalną skłonnością węgla i skał płonnych do tąpań, należy do czynników naturalnych wywołujących tąpnięcie. Prowadzone w Głównym Instytucie Górnictwa wieloletnie badania własności geomechanicznych skał, stanowiących formację węglonośną Górnośląskiego Zagłębia Węglowego (GZW) pozwoliły na zebranie bogatej bazy danych parametrów mechanicznych skał w pełnym zakresie ich odkształcenia. Są wśród nich: naprężenie krytyczne, moduł sprężystości oraz moduł spadku wyznaczany z pokrytycznej części charakterystyki naprężeniowo-

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-odkształceniowej. Własności pokrytyczne są ściśle związane z naprężeniem maksymalnym oraz z własnościami przedkrytycznymi. Stąd określono zależności pomiędzy wytrzymałością na jednoosiowe ściskanie R_c a modułem spadku M skał karbonu produktywnego GZW oraz zależność między modułem sprężystości E a modułem spadku M. Zależności $M = f(R_c)$ oraz $M = f(E)$ mają postać funkcji potęgowej o wysokich współczynnikach korelacji od 0,72 do 0,93 (rys. 2–6). Traktując węgle górnośląskie jako samoistnie nietąpiące, przedstawiono podstawowe własności mechaniczne skał, które są niezbędne do oceny możliwości zaistnienia zjawiska dynamicznego rozpadu (tąpnięcia) układu „skały otaczające–pokład" jako odpowiednika w warunkach laboratoryjnych układu „płyty maszyny wytrzymałościowej–próbka skalna". W dalszej części przedstawiono wyniki analizy rzeczywistych układów „skały otaczające–pokład" jako stabilnych lub niestabilnych, a w konsekwencji zdolnych do przeskoku energii odkształcenia sprężystego, które jest jednym z mechanizmów inicjujących tąpnięcie. Traktując tąpnięcie jako utratę stateczności skał wokół wyrobisk górniczych, o jego zaistnieniu decydują własności sprężyste skał zalegających w stropie i w spągu pokładu ($E_{skał}$) oraz własności pozniszczeniowe pokładu ($M_{węgla}$). W zależności od relacji między $E_{skał}$ i $M_{węgla}$, wyróżniono dwa układy stropowo-spągowo-pokładowe, a mianowicie: gdy $M_{węgla} < E_{skał}$ (tabl. 1, wariant1) oraz gdy $M_{węgla} > E_{skał}$ (tabl. 1, wariant 2a i 2b). Z uwagi na możliwość zaistnienia dynamicznego zniszczenia skał wokół wyrobiska za niebezpieczny uznano układ drugi z zastrzeżeniem, że skały otaczające nie mogą cechować się zbyt niską wytrzymałością na jednoosiowe ściskanie, ponieważ nie mają zdolności do gromadzenia energii sprężystej o wysokiej wartości (wariant 2b). Eneregia sprężysta skał płonnych wraz z własnościami pokrytycznymi węgla decyduje o dynamice jego zniszczenia. Na podstawie wskaźnika $M_{węgla}/E_{skał}$ przedstawiono propozycję klasyfikacji skłonności do tąpań. Zaproponowano trzy przedziały jego zmienności oceniając układ „skały otaczające–pokład" pod względem możliwości jego dynamicznego zniszczenia jako niesklonny bądź skłonny do tąpań (rozdz. 4). Korzystając z danych doświadczalnych dotyczących wartości modułów sprężystości i modułów spadku skał formacji węglonośnej GZW stwierdzono, że z uwagi na stosunek $M_{węgla}/E_{skał}$ teoretycznie jest możliwość zaistnienia dynamicznego zniszczenia pokładu we wszystkich grupach pokładów. Ocena skłonności do tąpań wymaga zatem, oprócz analizy stanu naprężenia panującego w górotworze, również analizy konkretnych układów stropowo-spągowych w konfrontacji z wartościami parametrów pozniszczeniowych pokładu. W dalszej części przedstawiono ocenę skłonności do tąpań na podstawie wskaźnika $M_{węgla}/E_{skał}$ w konfrontacji ze stosowanymi dotychczas niektórymi wskaźnikami skłonności skał do tąpań, wykazując niezgodności w ocenie możliwości zajścia zjawiska dynamicznego niszczenia pokładu. Wykorzystując zdobytą wiedzę na temat zmian wartości modułu spadku (pokrytycznego) M dla różnych prędkości odkształcenia, głównie w zakresie prędkości 10^{-4}–10^{-1} s^{-1}, wykonano prognozę zmian sposobów niszczenia układu „skały otaczające–pokład węglowy" ze wzrostem prędkości odkształcenia. Dokonana analiza wpływu prędkości odkształcenia na dynamikę niszczenia pokładu węglowego wykazała, iż ze wzrostem prędkości odkształcenia, w zakresie prędkości odkształcenia 10^{-4} s^{-1} odpowiadającej odkształcaniu się skał w sąsiedztwie wyrobisk eksploatacyjnych do prędkości 10^{-1} s^{-1}, wzrasta zagrożenie tąpaniami. W artykule zasygnalizowano możliwość zastosowania proponowanego wskaźnika $M_{węgla}/E_{skał}$ w analizie wyników badań w trójosiowym ściskaniu w aspekcie zagrożenia tąpaniami.

Słowa kluczowe: górotwór, tąpnięcie, określenie zależności, metoda badań

1. Introduction

One of the basic natural hazards encountered in the coal and copper ore mining industries is mine tremors and rockbursts generated in rock masses possessing high strength parameters. Among the factors conducive to the occurrence of rockbursts, the critical stress state of a given rock mass region induced by both natural stress fields (geostatic and tectonic stresses) and the secondary, mining-induced stress fields (remnants, excessive panelling, inadequate face line advance rate, etc.), as well as the mechanical properties of the rocks surrounding mine workings expressed by the following parameters: modulus of elasticity, uniaxial compressive strength and drop modulus may be cited. The laboratory-based determination of the rock's mechanical properties can be obtained using old-generation testing machines or the so-called "soft testing" machines and the new generation high-stiffness presses with servo-system control capabilities. The results of laboratory experiments form a basis for the development of various criteria of the proneness of rock to rockbursts. In recent years, these criteria have also taken into account the rock's post-peak properties studied by means of stiff: testing machines capable of yielding a complete stress-strain response describing the behaviour of rocks in both pre-peak and post-peakphases. The stress-strain response may form a basis for evaluating the proneness to rockbursts of the coal/country rock system, a model of which can be evaluated through the testing machine/rock specimen interaction.

2. The testing machine-rock specimen system as a rock mass-coal seam system analog

The earliest Upper Silesian rockburst report dates back to the year 1858 and relates to events that occurred in the former *Fanny* coal mine (Gottwald, Polska and Siemianowice mines lease cross-border area). At that time, the rockburst phenomenon was understood to be spalling and flaking of coal along side-walls, which were accompanied by various acoustic events such as knocking and cracking. As the coal extraction increased and the mining was conducted at deeper and deeper levels, the number of coal mines at risk of rockburst also increased. Thus, the principal concept of the rockburst phenomenon was gradually being verified. Although many rockburst definitions can be encountered in world literature, they differ little from each other. Hereunder, I should like to illustrate the definition with a quotation from a working group of the International Bureau of Strata Mechanics (1979): "Rockburst is a brittle failure of the portion of a coal seam or rock in a critical stress state, adjacent to a mine working, which occurs in conditions when the energy release rate exceeds the ultimate rate of the irrecoverable strain-related energy dissipation. The energy involved in the rockburst consists of the coal seam or country rock failure-related elastic energy. The rockburst may be accompanied by loud sounds, coal outbursts, damage to supporting structures, installations and machines, as well as by dust and air movements. The elastic strain of the rock mass adjacent to the failure epicentre generates seismic waves which, in the case of a strong event, may be propagated over distances of tens or even hundreds of kilometres." This definition, compared with others quoted in the literature, can be taken as being more significant because it mentions the energy release and attenuation rates, as well as the participation in the event by both the mineral sediment seam rocks and the country rocks.

Among the rocks, the following may, be distinguished: spontaneously bumping and spontaneously non-bumping rocks (Filcek, Kłeczek, Zorychta 1984). The coals occurring in the Polish coalfields can be considered to be spontaneously non-bumping, except the cannel coal which, due to its petrographic structure and homogeneity, can be considered to be spontaneously bumping. W. Szuścik and his team advanced the concept of the "rockburst of the coal material" and its recurrence rate (Szuścik, Zastawny 1980; Szuścik, Zastawny, Bobkowski 1984). W. Konopko defines the coal material liability to rockbursts as one of the parameters, in addition to the properties of the surrounding rocks, characterizing the bumpiness of a seam and as one of many factors contributing to the rockburst occurrence in a mine working (Konopko 1994). Considering the rockburst definition provided by Filcek, Kłeczek and Zorychta (1984), the rockburst may be the stability loss process of the strata adjacent to mine workings. This suggests existing of the following rockburst mechanisms: energy jump and bearing capacity loss. The energy jump, i.e., stepwise changes in the: "roof-seam-floor" system's stability state, can be determined by the elastic properties of the strata adjacent to a coal seam and the past failure properties of the seam because the energy jump will be induced by the transmission of the roof elastic energy to the seam comprising a mine working, which implies that the amount of energy stored in the roof can be greater than that absorbed by the seam.

Considering, further on, the liability of the "roof-seam-floor" system to rockbursts, one may relate it, under laboratory conditions, to the "testing machine platen-rock specimen" system with respect to both the elastic properties of waste rocks determined from the pre-peak region of the stress-strain response and the post-peak properties of coal. From the point of view of the "testing machine platen-rock specimen" system, the two following systems can be distinguished: (a) unstable and (b) stable, that are dependent on the testing machine ability to receive the energy stored in the rock specimen.

Assuming the soft testing machine stiffness value to be 0.175 MN/mm and the rigidity of the Upper Silesian Coal Basin Carboniferous sedimentary rock specimen of the base side and slenderness ratio equal to 50 mm and 1.0, respectively, to be ranging from about 0.25 to 0.9 MN/mm, we may deduce that the testing machine can store more energy than the specimen. Therefore, the "soft testing machine-rock specimen" system corresponds to the unstable system which may dynamically lose its equilibrium because the elastic energy stored in the testing machine will abruptly be released and converted info the kinetic energy of the fractured rock specimen. In the second case, in order that the rock specimen failure process should continue, an additional, external energy would be needed. This effect can be observed by comparing the plots of force F versus strain x of the rock specimens for the soft testing machine k_1 and the stiff testing machine k_2 equipped with the servo-system control facility (Fig. 1).

The nature of the rock failure depends on the kinetic energy values. The kinetic energy may be derived from the energy balance equation during the rock specimen failure in uniaxial compression. There the strain energy both elastic and irrecoverable can be taken into account in the pre-critical and post-critical regions of the stress-strain relationship, which, in the case of the abrupt failure, can be expressed as (Minh 1989):

$$E_k = W_p + E_{eb} - E_{sp} - E_{pp} \tag{2.1}$$

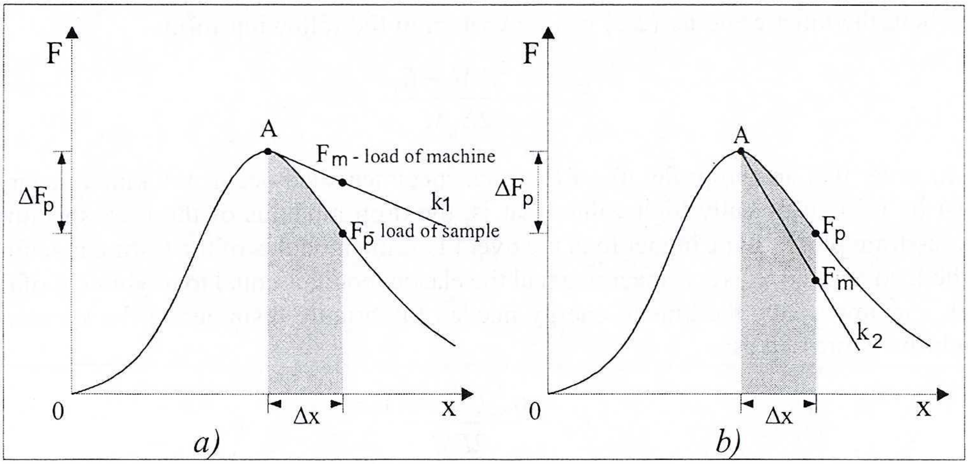

Fig. 1. Post-critical loading of the system:
a — soft testing machine–rock specimen system; b — stiff testing machine–rock specimen system

Rys. 1. Pokrytyczne obciążenie układu: maszyna wytrzymałościowa–próbka przy zastosowaniu:
a — miękkiej; b — sztywnej maszyny wytrzymałościowej

where:

W_p — energy provided by the external load in the post-peak phase,
E_{eb} — elastic strain energy,
E_{sp} — energy needed to create a new surface in the post-peak region,
E_{pp} — irrecoverable strain energy in the post-peak region.

In the post-peak region of the stress-strain curve, the elastic energy E_{eb} stored in the rock specimen can chiefly be converted into the energy E_{sp} of the new surface. Hence

$$E_k = W_p - E_{pp} \tag{2.2}$$

The above equation reveals that the abrupt failure of a rock specimen would only be possible if the external load-related energy in the post-peak phase were higher than the irrecoverable post-peak yield point strain energy. Assuming that the relations defined by the overall elastic modulus of testing machine E_1 and the rock specimen's post-peak stress-strain response curve slope defined by drop modulus M are linear, the following equations can be obtained:

a) energy provided by loading of the machine:

$$W = \frac{\sigma_{cr}^2}{2E_1} \tag{2.3}$$

b) energy of the post-peak irrecoverable strain:

$$E_{pp} = \frac{\sigma_{cr}^2}{2M} \tag{2.4}$$

Then, the kinetic energy (2.2) can be written in the following form:

$$E_k = \frac{\sigma_{cr}^2 (M - E_1)}{2E_1 M} \tag{2.5}$$

In order that an abrupt failure of the rock specimen shall occur, the kinetic energy must be of a sufficiently high value, that is, the drop modulus of the rock specimen stress-strain plot must be higher than the overall elastic modulus of the testing machine. If the load applied to a rock specimen had the elastic modulus equal to modulus E of the rock specimen, then the kinetic energy needed to abruptly disintegrate the specimen might be expressed as:

$$E_k = \frac{\sigma_{cr}^2 (M - E)}{2EM} \tag{2.6}$$

It follows from the above relation that in order that the rocks shall abruptly fail, their drop modulus M must relatively be greater than the elastic modulus E of the surrounding strata.

3. Mechanical properties of rocks, in the total strain range, necessary to assess the possibility of the occurrence of a dynamic failure of the "roof-seam-floor" system

In the current laboratory experiments, the liability of coals and rocks to rockbursts has been estimated based on their mechanical properties determined from the pre-failure region of the rock material behaviour characteristics during the uniaxial compression tests. This fact arose from the lack of possibility of examining the processes taking place in the rock specimen disintegration phase. Significant expansion of the possible rock mechanical properties research scope became visible due to the application of the stiff testing machines with the servo-system control facility. Of the few indices of the rock proneness to rockbursts taking into account the rock specimen post-failure characteristics, the following ones can be worth-while to note:

- rockbursts hazard mitigation index involving rock specimen's elastic energy and post failure disintegration energy (Krzysztoń 1989; Bukowska 2000);
- dynamic disintegration period index (Kidybiński, Smołka 1988);
- energy dissipation rate index involving rock specimen disintegration time (Bukowska, Smołka 1994);
- rock disintegration dynamics index involving the pre-and post-critical properties in the uniaxial compression tests and being defined by the ratio of Young's modulus and drop modulus (vide Minh 1989, vide Bukowska 1996).

The majority of the used indices of rock proneness to rockbursts can be determined based on the pre-peak stress-strain relation. That is why they cannot be related to the post-peak properties of rocks or mineral sediment seams that are crucial to the rockburst generation because the process of rock mass stability loss takes place in the post-critical region (Zorychta 1999).

Of the many indices of rock proneness to rockbursts determined in laboratory from the pre-peak stress-strain relation, only the energy index of susceptibility of coal to rockbursts, W_{ET} (Szecówka, Domżał, Ożana 1973) was included in the mining regulations. The limited amount of coal material designed for laboratory investigations (poor availability of coal and its disadvantageous structural features favouring disintegration of specimens) does not always allow conducting investigations into the determination of the coal proneness to rockbursts based on the W_{ET} index. W. Konopko defined the $W_{ET} = f(R_C)$ relation as $W_{ET} = -6.4672 + \exp(1.8867 + 0.0174\,R_C)$ based on the determination of both values using the same coal specimens (Konopko 1994).

Some researchers such as, among others, A. Kidybiński and J. Smołka question the significant role attributed to the W_{ET} index as the index of coal proneness to rockbursts (Kidybiński, Smołka 1988).

Among the mechanical parameters being fundamental for assessing the possibility of the occurrence of the "roof-seam-floor" system's dynamic failure event, we can mention the following ones:

- elastic properties of rocks adjacent to coal seams, including the elastic modulus,
- peak strength and the related elastic energy value,
- post-peak properties of coal expressed chiefly by values of drop modulus obtained from the stress-strain response's post-peak region.

Drop modulus M can be calculated either from the tangent line to a decreasing portion of the stress-strain curve or from the respective secant in the region between the peak strength σ_{cr} and the residual stress σ_r corresponding to the total strain of a rock specimen. The values of drop modulus shown further in the paper have been calculated from the tangent of the angle of inclination of the tangent line to the post-peak decreasing branch of the curve according to the following formula:

$$M = \frac{\Delta\sigma}{\Delta\varepsilon}\ [\text{MPa}] \tag{3.1}$$

where:

$\Delta\sigma$ — stress drop in the region corresponding to the decreasing portion of the stress-strain curve,

$\Delta\varepsilon$ — increase in strain corresponding to the decreasing portion of the stress-strain curve.

Of the characteristic stress-strain parameters, the most difficult and subjective to determine are the post-peak parameters such as drop modulus and the residual stress--related strain (Bukowska, Krzysztoń 1994; Bukowska 1997, 2000). In particular, in determining drop modulus, a substantial difference in its values can be made by a small difference in values of the post-peak strain. The "testing machine platen-rock specimen" system corresponding to the "roof-seam-floor" system under natural conditions can be considered as the latter system's best fit model. From the point of view of the stress jump induced by the transmission of elastic energy from the strata adjacent to a seam to the seam, this case can be extremely dangerous and its laboratory-performed test easiest. Therefore, the characteristic stress-strain parameters can be analyzed based on the results of the uniaxial compression test using perpendicular to bedding loads with strain rates ranging from 10^{-5} s^{-1} to 10^{-3} s^{-1}. It corresponds to the strain rates of the strata adjacent to mine workings (vide Kwaśniewski 1986).

Many years' experience in conducting uniaxial tests by using the MTS-810 testing machine has led to defining a relationship between different mechanical parameters obtaining from the pre-peak region of the stress-strain response of the rock specimens considered to be a basis for analyzing the "roof-seam-floor" system with respect to its proneness to rockbursts. Also, defined separately was the $M = f(R_c)$ relation for the main waste rocks of the Upper Silesian Coal Measures. Defining a relationship between the peak strength and the post-peak properties of rocks displayed by the stress-strain curve's post-peak region slope, may be of use for the primary assessment of the dynamic failure hazard occurrence in rocks surrounding a mine working.

The relations between the parameters determined from the pre- and post-peak regions of the stress-strain plot have been defined for the following four kinds of Carboniferous rocks from the Upper Silesian Coal Basin: (1) sandstones, (2) mudstones, (3) claystones, and (4) coals using a strain rate equal to 10^{-4} s^{-1}. The following relationships have been derived: linear, power, exponential and polynomial, including the related correlation coefficients and standard errors. The best relationship was considered to be the power function due to the highest correlation coefficient and the lowest standard error. Figs. 2–5 show the $M = f(Rc)$ relationship described by the power regression equations obtained based on the performed statistical analysis. Each Figure shows the plot of given relationships, including regression equations, correlation coefficients, r, and the power

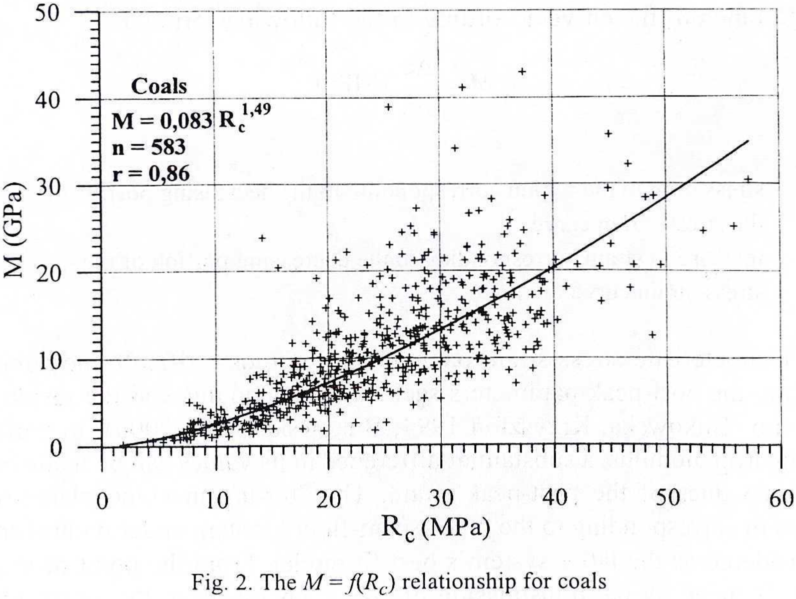

Fig. 2. The $M = f(R_c)$ relationship for coals

Rys. 2. Zależność $M = f(R_c)$ dla węgli

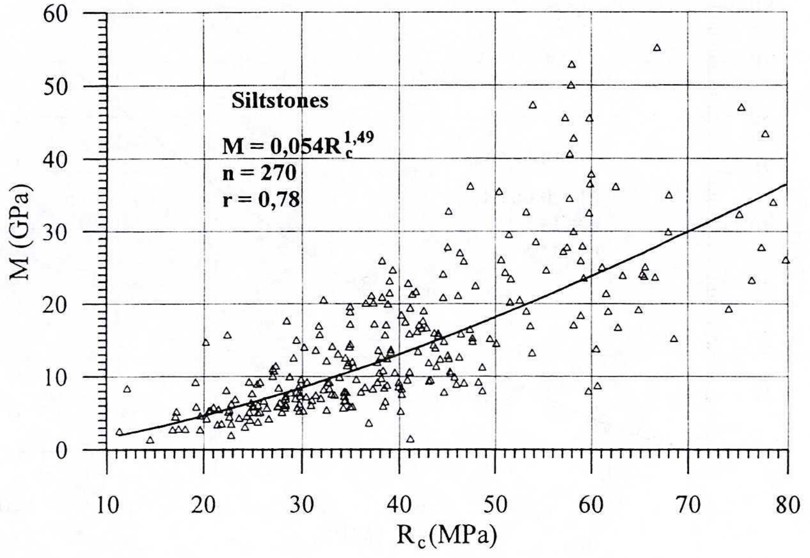

Fig. 3. The $M = f(R_c)$ relationship for siltstones

Rys. 3. Zależność $M = f(R_c)$ dla iłowców

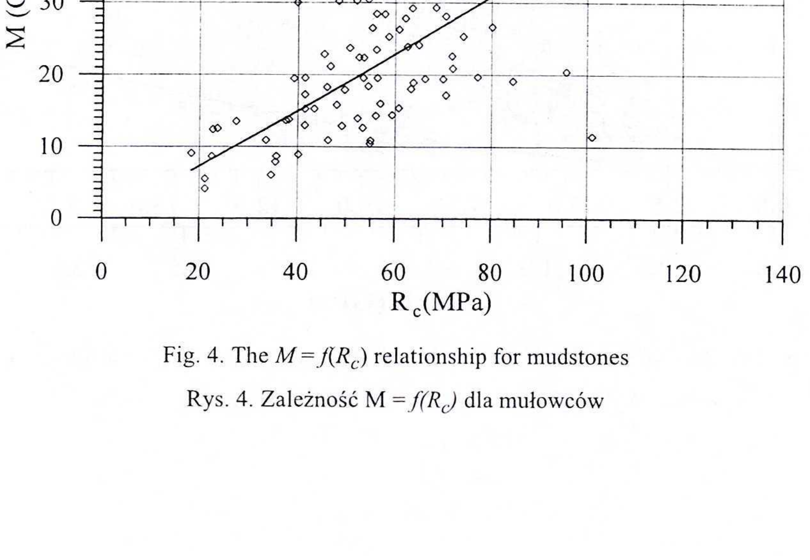

Fig. 4. The $M = f(R_c)$ relationship for mudstones

Rys. 4. Zależność $M = f(R_c)$ dla mułowców

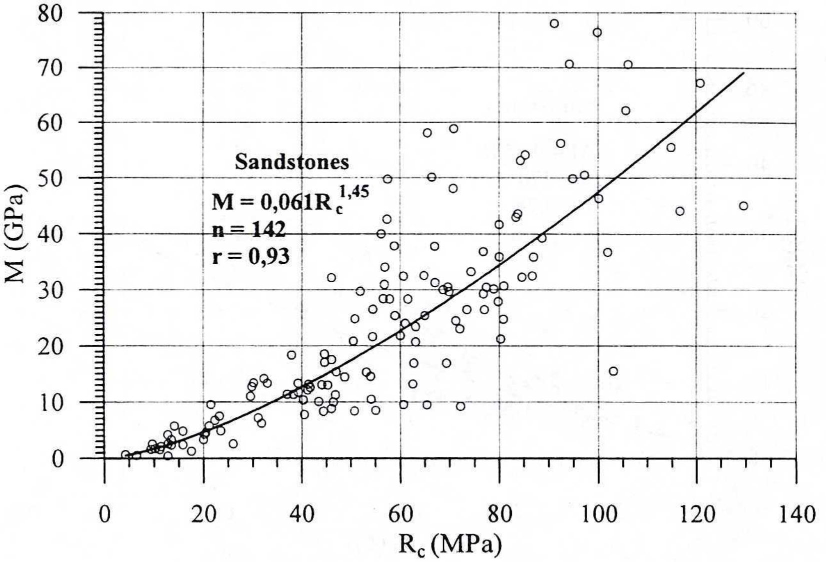

Fig. 5. The $M = f(R_c)$ relationship for sandstones

Rys. 5. Zależność $M = f(R_c)$ dla piaskowców

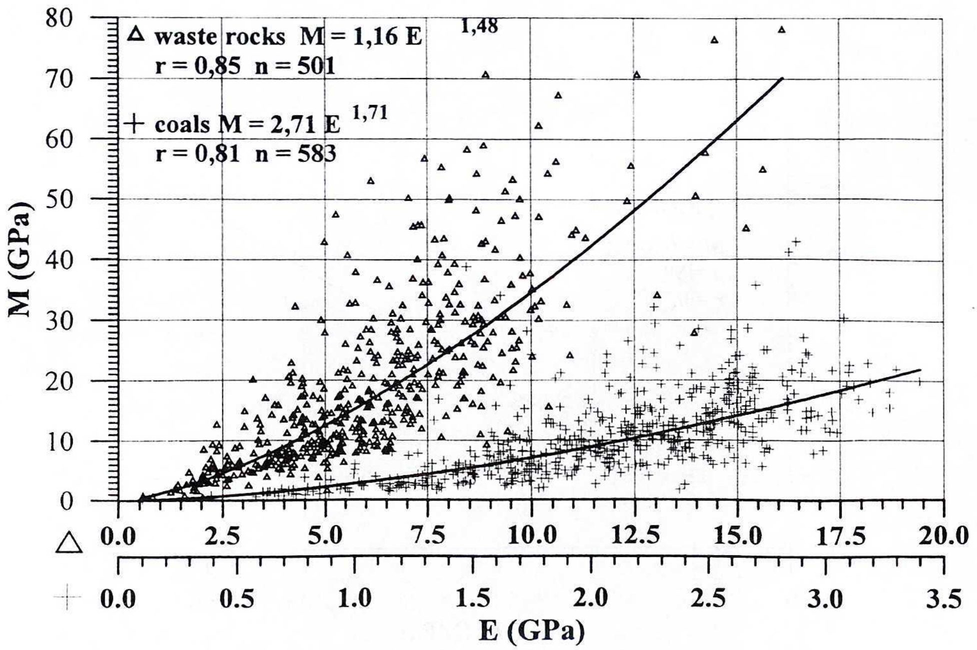

Fig. 6. Plots of the $M = f(E)$ relationship for coals and waste rocks from the Upper Silesian Coal Basin

Rys. 6. Wykresy zależności $M = f(E)$ węgli i skał płonnych GZW of a set, n. The $M = f(Rc)$ relationship is of power nature as far as both coal and strata adjacent to coal seams are concerned with the correlation coefficients ranging from 0.78 for claystones (very high correlation value) to 0.86 for coals (Fig. 2) to 0.93 for sandstones (almost full correlation) (Figs. 3–5). Coals usually show high values of drop modulus at lower values of σ_{kr}. Waste rocks, generally, attain the same values of the M modulus mostly at higher values of the peak strength.

It follows from both theoretical and experimental studies that the rock failure process depends on both pre- and post-peak properties of rocks (Bukowska 1994, 1997).

The $M = f(E)$ relationships were determined based on the pre- and post-peak regions of the stress-strain response curves for the Upper Silesian Coal Measures rocks using 2900 coal specimens (583 average values) and 25000 waste rock specimens (sandstones, mudstones and claystones) (501 average values) (Fig. 6).

4. A proposed method for predicting the abrupt rock failure in the "strata-seam" system

The rockburst definition takes into account the following fundamental causes leading to the rockburst origin:

- adequately high strength of the coal seam adjacent to a mine working (Konopko 1994) and its proneness to dynamic failure after exceeding some peak strength value (Szuścik, Zastawny 1980; Szuścik, Zastawny, Bobkowski 1984; Konopko 1994);
- elastic energy of a coal seam or rocks within the source of failure;
- elastic energy of the host rocks mass;
- energy release rate exceeding its dissipation rate as a result of irrecoverable strains;

Some of the rockburst-related causes may be analyzed based on the test results obtained from the testing machine constituting an analog of the "roof-seam-floor" system.

In order that the dynamic failure of a seam shall occur, bearing in mind the mechanical properties of rocks, there must be a relationship between the elastic modulus of the host rock mass and drop modulus of the coal seam of the other mineral substance, as described in Part 2 of this paper. Due to the complex geology of the Carboniferous strata and the remnant and edge interactions and the overmining or undermining — induced destressing extent, it should be advisable in the rockburst hazard assessment to take into account a considerable variability of the strata surrounding a mine working ranging from 100 m above the roof of the seam to 30 m underneath the seam (Konopko 1994).

Let us consider two cases of the relationship between the elastic modulus of the host rock mass and drop modulus of the coal (coal pillar). When the elastic modulus of the immediate roof rocks is much higher than the drop modulus of the coal being subject to the process of failure ($E_{\text{rock}} > M_{\text{coal}}$), the seam of low or medium strength undergoes strain due to the load of overlying rocks. Thus parts of the seam showing the low peak strength fail. Such conditions lead to the static failure of the seam. On the other case, when the modulus of elasticity roof is lower than the drop modulus of coal

(E_{rock} < M_{coal}) the "seam-host rock mass" system is behaving like a rock specimen loaded using the soft testing machine. After the ultimate strength of the coal had been exceeded, the dynamic effect became enhanced through the release of the elastic energy stored in the roof. In such a case, we are faced with a dynamic model of the seam failure.

Considering the above facts, we have examined a dozen or so "roof-seam-floor" systems from the Upper Silesian Coal Basin sites both under and not under rockburst hazard in order to compare the real situation in the rock with the simulation system such as the laboratory-based testing machine and a rock specimen. These systems have been examined from the point of view of the ratio of elastic modulus of waste rocks to drop modulus of coal while taking into account a very wide range of coal strength from 8.0 to 42.0 MPa (coal ranks from bright through semi-bright to dull). Various relations between the compressive strength of the coal seam and host rock mass, values of the elastic energy stored in waste rocks and the depth of coal deposition also have to be taken into account. These factors are summarized in Table 1. The cases of M_{coal} < E_{rock} (variant 1) are considered as not hazardous from the point of view of possibility of occurrence of the coal seam dynamic failure. In such cases coal can display a wide range of the compressive strength, from 8.0 to 26.3 MPa. These are the coals considered weak to medium strength. The country rocks adjacent to coal seams show varying ability to store elastic energy due to different compressive strength and different elastic moduli. Assuming that the coal seams are chiefly underlain by the weak clayey formations, we may distinguish, as regards the compressive strength and the kind of roof rocks, the following 5 "roof-seam-coal" systems:

1. Very weak coal–medium-strength roof.
2. Weak coal–weak roof.
3. Weak coal–medium-strength roof.
4. Weak coal–strong roof.
5. Medium-strength coal–strong roof.

The cases of M_{coal} > E_{rock} (variant 2) can be related to the coal with the compressive strength ranging from 16.7 to 42.0 MPa. We may distinguish the following two subvariants:

2a. $M_{coal} > E_{rock}$.

2b. $M_{coal} >> E_{rock}$.

The subvariant 2a is considered to be hazardous from the physical point of view due to the possible occurrence of the stepwise changes in the equilibrium state, which can lead to the dynamic failure of the seam. The host rock masses adjacent to such seams show varying abilities to store elastic energy. Among the roof-seam systems we may distinguish with respect to strength the following types:

- Medium-strength coal–medium-strength roof.
- Strong coal–strong roof.
- Strong coal–medium-strength roof.

Among the cases of M_{coal} > E_{rock}, we may distinguish the following strata:

- Ruda Series (seams Nos. 416, 401, 418 of the Śląsk, Wujek and Mysłowice coal mines, respectively).

TABLE 1

The selected roof-seam-floor systems from the Upper Silesian Coal Basin sites of both under rockburst hazard and not under rockburst hazard

TABLICA 1

Wybrane układy stropowo-pokładowo-spągowe w Górnośląskim Zagłębiu Węglowym w rejonach zagrożonych i niezagrożonych tąpaniami

Coal mine	$R_{c\ coal}$ [MPa]	$R_{c\ roof}/R_{c\ floor}$	*PES* [kJ]	E_{roof}/E_{floor}	Relationship between *M* and *E*	M_{coal}/E_{rock}	Depth [m]
1	2	3	4	5	6	7	8
Jankowice 410	8.0	64.6(c//m //s)/54.5(c//m)	105	9772/8847	Variant 1 $M_{coal} < E_{rock}$	0.10	400–600
Borynia 403/1	9.3	66.3(c)/30.3(c)	213	7350/3311		0.55	838
Makoszowy 412/1	12.4	110.7(m)/34.9(c)	240	11925/5072		0.46	500–830
Bytom II 418	14.0	89.2(m)/ -	249	9758/ -		0.51	540
Jankowice 411/1	14.2	47.8(c)/56.6(c)	104	6112/7118		0.48	400–600
Knurów 402/2	15.5	70.6(s)/ -	166	9256/ -		0.49	~1000
Rydułtowy 713/1-2	18.8	71.5(c//s, co)/57.8(c//s)	150	8728/6726		0.78	1185
Brzeszcze 404	18.2	43.2(c//m)/38.1(c)	75	5000/4672		0.8	900
Szczygłowice 403/1	18.6	68.4(c//s)/70.8(c)	169	7063/8180		0.12	650
Makoszowy 416	26.3	135.2(s)/76.0 (m)	384	12241/8578		0.83	370–950
Wujek 401	16.7	50.3(c)/41.5(c//m, s)	111	5575/5120	Subvariant 2a $M_{coal} > E_{rock}$	1.14	130
Mysłowice 418	21.5	41.2(c)/31.4(c)	99	5098/4230		1.28	500–700
Śląsk 416	25.2	35.4(c)/45.6(c)	97	6010/7058		1.69	~700
Bielszowice 501*	20.8	46.2(c)/ -	145	6855/ -		1.56	800

cont. table 1

cd. tablicy 1

1	2	3	4	5	6	7	8
Mysłowice 501*	33.1	41.9(s)/37.9(c//s)	116	4975/4130	Subvariant 2a $M_{coal} > E_{rock}$	1.64	400–500
Bielszowice 502*	21.4	51.4(c//s i m)/ -	140	7252/ -		1.38	800
Polska Wirek 504*	17.7	51.5(c//s i m)/23.2(c)	116	6815/3000		1.59	680
Niwka-Modrzejów 510*	30.0	72.8(m //s i con)/90.5(s//m)	299	8174/10125		1.24	650
Piekary 510*	30.4	104.1(s, c)/ -	476	10356/ -		1.10	570
Wesoła 510	31.5	43.0(s/ c, co)/62.8(m/ c/s)	129	5957/7759	Subvariant 2b $M_{coal} > E_{rock}$	2.03	850
Grodziec 816	40.5	78.5(m // c, s)/81.0(m //s// c)	240	7919/8262		2.50	500
Ziemowit 205/4	42.0	11.1(s)/ -	20	1810/ -		7.99	450–470
Ziemowit 207	39.0	14.3(s)/ -	31	2029/ -		6.89	350–460 590–632
Ziemowit 215	36.3	23.6(s)/ -	46	3826/ -		3.64	364–414
Ziemowit 308	26.2	28.5(c)/ -	72	2991/ -		6.13	410–457
Chwałowice 404/9	31.2	53.5(c/m, s)/56.0(c/m, s)	75	6660/6902		3.00	~670

* The recorded rockbursts, s-sandstone, m — mudstone, c — claystone, con — conglomerate, co — coal.

- Saddle Series (seams Nos. 501, 501/502, 504, 510 and 510 of the Mysłowice, Bielszowice, Polska-Wirek, Niwka-Modrzejów and ZG Piekary coal mines, respectively).

The 2b variant, generally, includes the following systems:

- Strong coal–weak roof (seams Nos. 205/4, 207, 215 and 308 of the Ziemowit coal mine; seam No. 404/9 of the Chwałowice coal mine; seam No. 510 of the Wesoła coal mine).
- Strong coal–strong roof (seam No. 816 of the Grodziec coal mine).

On comparing the above data with the list of rockbursts from coal mines and seams recorded over a period from 1970 to 1999 and collected by Central Mining Institute, we may conclude that in the above mentioned coal mines over that time period the rockbursts only occurred within the coal seam group 500, composed of very thick seams and surrounded by sandstones and mudstones able to store large amount of elastic energy, which, if were transmitted to a seam and converted into the kinetic energy, would induce its dynamic failure. In the other cases, the "seam host rock mass" system, despite the high strength of coal, will not be in considered dangerous in terms of rockburst occurrence due to the host rocks showing poor mechanical parameters and consequently low ability to store elastic energy. A good example may be coal seams Nos. 205/4, 207 and 215 of the Łaziska Series from the Ziemowit coal mine, which are lying among weak sandstones locking ability to store high elastic energy. Below, a relationship between the elastic modulus of host rocks and drop modulus of coal is described. The ratio M_{coal}/E_{rock} for the examined "host rock mass–coal seam" system assumes values ranging from 0.1 to 7.99. In the case of the systems (variant 1) free of the coal seam dynamic failure (rockburst) hazard, that is, when $M_{coal} < E_{rock}$, this index can be lower than 1.0; however, when $M_{coal} > E_{rock}$, this index can be in excess of 1.0 (subvariants 2a and 2b). From the point of view of the abilities to store elastic energy and to transmit it to a coal seam, the most dangerous will be subvariant 2a if $M_{coal} > E_{rock}$. However, the difference between the values of the moduli is not significant enough to show poor elastic properties of the host rock mass. In other words, the host rock mass can transmit great amounts of elastic energy to a coal seam and the coal seam with respect to its mechanical properties has a reduced ability to absorb it. In this case, the values of the M_{coal}/E_{rock} index can be in the range from 1.10 to 1.69. However, for the subvariant 2b when $M_{coal} >> E_{rock}$, the values of the M_{coal}/E_{rock} index can be in the range from 2.03 to 7.99.

As follows from the discussed analysis of various "roof-seam-floor" systems, a value of the M_{coal}/E_{rock} index equal to 2.0 indicates the upper bound of the interval containing the index values for the rockburst prone systems. The "host rock mass–coal seam" system, above the upper bound, is considered to be non-bumping because the system loses its energy transmission capability due to poor elastic properties of the host rock mass.

We may conclude that the occurrence of a rockburst within the "host rock mass–coal seam" system depends, among others, on the elastic properties of host rock mass and the post-peak properties of coal. Table 2 shows the proposed classification of the "host rock mass–coal seam" system's proneness to rockbursts.

TABLE 2

Proposed classification of the "host rock mass–coal seam" system's proneness to rockburst

TABLICA 2

Propozycja klasyfikacji skłonności do tąpań — układ: górotwór–pokład węglowy"

$\frac{M_{coal}}{E_{rock}} < 1$	The "host rock mass–coal seam" system not prone to rockbursts
$1 \leq \frac{M_{coal}}{E_{rock}} < 2$	The "host rock mass–coal seam" system prone to rockbursts
$\frac{M_{coal}}{E_{rock}} \geq 2$	The "host rock mass–coal seam" system not prone to rockbursts

The above discussion may also refer to the other roof-seam systems outside of coal mining industry, where the rockburst hazard exists. As an example, consider the cooper ore mining industry where systematically recorded strong mine tremors and rockbursts occur incurring risk to miners' health and doing damage to mine workings.

The extensive experiment — based database allowed determining drop modulus M variation regions for each stratigraphic unit of the Upper Silesian Coal Basin.

Fig. 7 shows drop modulus M variation regions, including the average values.

Due to large regions of variation of the elastic modulus and drop modulus, there is a probability of the coal seam dynamic failure occurrence for an the stratigraphic units of the Upper Silesian Coal Measures. The above statement was confirmed by a rockburst in seam No. 209 of the Piast coal mine that occurred in 1986 and was accompanied by a mine tremor of energy $E = 5 \times 10^6$ J, and by a rockburst in seam No. 414/1 of the Śląsk coal mine that occurred in 1993 and was accompanied by a mine tremor of energy

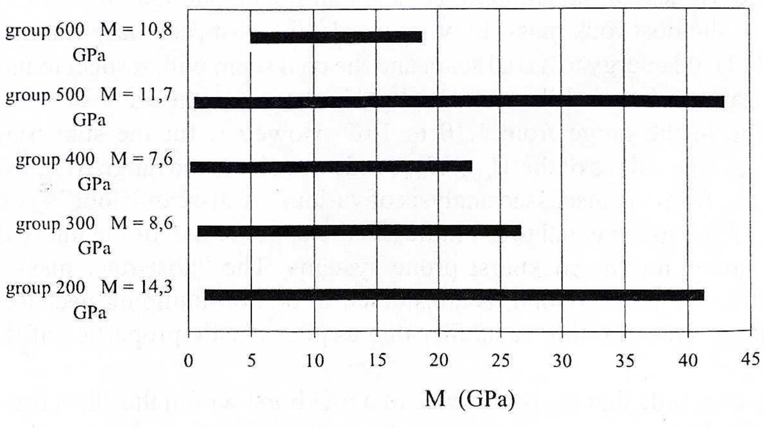

Fig. 7. Drop moduli of coal from the Upper Silesian Coal Basin

Rys. 7. Moduły spadku węgli Górnośląskiego Zagłębia Węglowego

$E = 4 \times 10^5$ J. Thus, we may conclude that an estimate of the liability to rockbursts requires analyzing each case of the "roof-seam-floor" system with respect, among others to the rock stress-strain relationship examined in total strain domain. Considering the mechanical properties of rocks, the rockburst prevention requires performing special operations both in a coal seam and in the host rock mass, aimed to change the stress-strain behaviour of rock.

5. Assessment of the host rock mass — coal seam system's proneness to rockbursts according to selected geotechnical drilling data in comparison with the related current laboratory methods

The M_{coal}/E_{rock} index has been compared with certain indices of the coal and waste rock proneness to rockbursts. Among them we may number the following ones:

- energy index of susceptibility of coals to rockbursts W_{ET},
- index of potential elastic energy *PES*,
- rock mass number L_g that takes into account the properties of rocks up to 100 m above the seam and up to 30 m beneath the seam, which is essential from the rockbursts hazard state point of view (Konopko 1994; Dubiński, Konopko 2000).

The comparison between the estimates of the rock proneness to rockbursts performed based on the above — mentioned indices was preceded by the mechanical properties — related characteristics of waste rock and coal (Tables 3, 4) and by the rock mass characteristics showing the role of dominant Carboniferous rocks played in the Upper Silesian Coal Basin geology (Figs. 3–9).

TABLE 3

Coal characteristics of seams Nos. 713/1-2, 501/510, 404/9

TABLICA 3

Charakterystyka węgli pokładów 713/1-2, 501/510 i 404/9

Coal characteristics	Seam No. 713/1-2	Seam No.501/510	Seam No. 404/9
Lithotype of coal	bright and semibright	semibright and dull	semibright and dull with bright intercalations
Depth of coal seam	1 185 m	~850 m	~670 m
Thickness of coal seam	2.67 m	10.8 m	1.72 m
Uniaxial compressive strength R_c	18.8 MPa	31.5 MPa	31.2 MPa
Elastic modulus E	1 291 MPa	2 634 MPa	2 369 MPa
Drop modulus M	6 685 MPa	12 949 MPa	20 222 MPa
Energy index of susceptibility of coals to rockbursts W_{ET}	2.32	5.21	3.68

TABLE 4

Characteristics of rock masses adjacent to coal seams Nos. 713/1–2, 501/510 and 404/9

TABLICA 4

Charakterystyka skał otaczających pokłady 713/1–2, 501/510 i 404/9

Characteristics of host rock masses	Host rock masses		
	Seam No.713/1-2	Seam No.501/510	Seam No.404/9
Uniaxial compressive strength of roof rocks R_c	71.5 MPa	44.8 MPa	53.5 MPa
Uniaxial compressive strength of floor rocks R_c	57.8 MPa	62.9 MPa	56.0 MPa
Elastic modulus of waste rocks E	8 609 MPa	6 375 MPa	6 721 MPa
Potencial elastic energy index PES	150 kJ	129 kJ	75 kJ

The following coal seams and adjacent rock masses with respect to their proneness to rockbursts have been taken into account:

- seam No. 713/1-2 of the Rydułtowy coal mine (boreholes Nos. G-38/2000, G-19/95, G-22/95);
- seam No. 501/510 of the Wesoła coal mine (boreholes Nos. G-704/2000, G-714/2000);
- seam No. 404/9 of the Chwałowice coal mine (boreholes Nos. G-695/2000, G-693/2000).

The rock mass characteristics according to the following core drilling data are described as follows:

1. Boreholes Nos. G-38/2000, G-19/95 and G-22/95 of the Rydułtowy coal mine.

In the sedimentary complex overlying and underlying the coal seam No. 713/1-1 up to 100 m and 30 m, respectively, 17 layers, each less than 1.0m thick, have been found, which was 37% of the total number of 46 layers. In the vertical profile, the sandstone and mudstone beds ranging from 0.36 m to 9.0 m thickness amount to 27% of the total thickness of the complex. No sandstone and mudstone beds of thickness in excess of 10 m have been found. This ground is lithologically varied. No excavations have been carried out up to 100 m above the coal seam. Fig. 8 illustrates the percentage shares of lithologic forms in the host rock mass complex, according to the core drilling data obtained from boreholes Nos. G-38/2000, G-19/95 and G-22/95.

2. Boreholes Nos. G-704/2000 and G-714/2000 of the Wesoła coal mine.

The sedimentary complex composed of 44 layers includes 7 layers of less than 7 m thickness. The strata surrounding the coal seam predominantly comprise the arenaceous sediments (sandstones and mudstones) constituting 58% of the rock mass. Among the sandstones the following ones have been found: fine-grained, medium-grained, coarse-grained and conglomerates of thickness ranging from 0.7 to 11.3. In the roof of seam No. 510, up to 100 m, two sandstone beds, each more than 10.0 m thick can be found (one bed 11.3 m thick, R_c = 54.0 MPa, around 15 m spaced; another bed 11.0 m

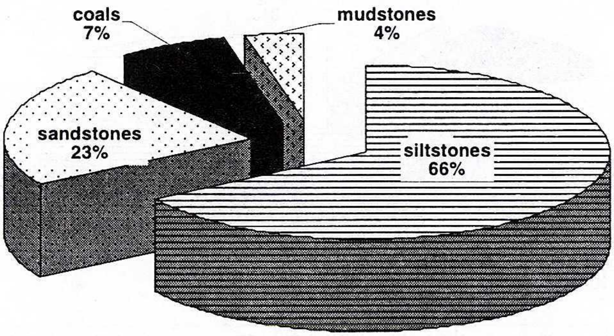

Fig. 8. Share of Carboniferous rocks in the geological cross-section comprising coal seam No.713/1-2

Rys. 8. Udział skał karbońskich w profilu pionowym względem pokładu 713/1-2

thick, $R_c = 52.6$ MPa, around 80.0 m spaced). Because sandstones and mudstones series constitute a large part of the complex, a coefficient $\xi = 1.0$ (Konopko 1994) was used in the calculation of the potential elastic energy index *PES*. The *PES* values showed that the host rock masses were highly prone to rockbursts. The rock mass quality was estimated to be weak/medium strength — the *RQD* index was 49%. No mining operations have so far been conducted in the roof up to 100 m.

Fig. 9 illustrates the percentage share of Carboniferous rocks in the vertical profile up to distances of 100 m above coal seam No. 510 and 30m below the seam calculated based on the core drilling data obtained from boreholes Nos. G-704/2000 and G-714/2001.

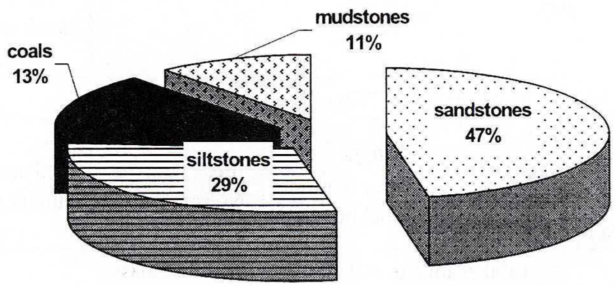

Fig. 9. Share of Carboniferous rocks in the geological cross-section comprising coal seam No. 501/510

Rys. 9. Udział skał karbońskich w profilu pionowym względem pokładu 501/510

3. Boreholes Nos. G-695/2000 and G-693/2000 of the Chwałowice coal mine.

In the sedimentary complex 42 layers, each less than 1.0 m thick, have been found, which was 53% of the total number of 80 layers. This complex is highly stratified and lithologically varied (more than 10 alternately deposited rock layers) with the 50% share of the sandstone and mudstone beds. The determined rock quality designation index

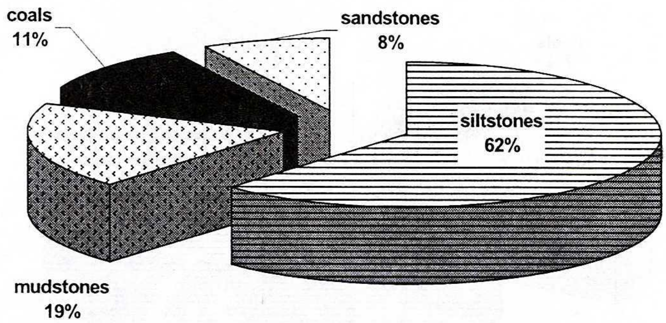

Fig. 10. Share of Carboniferouse rocks in the geological cross-section comprising coal seam No. 404/9

Rys. 10. Udział skał karbońskich w profilu pionowym względem pokładu 404/9

RQD = 53% indicates, according to Deere classification, a weak/medium strength rock mass. Fig. 10 illustrates the percentage share of lithologic forms in the rock mass complex comprising coal seam No. 404/9 according to the core drilling data obtained from boreholes Nos. G-695/2000 and G-693/2000.

TABLE 5

Summary of the index of rock proneness to rockbursts W_{ET} and the assessment of rockburst hazard state

TABLICA 5

Wskaźniki skłonności skał do tąpań wraz z oceną stanu zagrożenia tąpaniami

W_{ET}	*PES*	$M_{\text{coal}}/E_{\text{rock}}$	L_g	Information on the classification and the assessment of rockburst hazard state
Coal seam No. 713/1-2 and host rock mass				
2.32 Coal slightly prone to rockbursts	150 kJ Rocks significantly prone to rockbursts	0.78 System not prone to rockbusrts	Less than 50 No rockbursts	Coal seam No.713/1-2 not under rockburst hazard
Coal seam No. 501/510 and host rock mass				
5.21 Coal heavily prone to rockbursts	129 kJ Rocks significantly prone to rockbursts	2.03 System prone/not prone to rockbursts	More than 50 Rockbursts occur	Coal seam No. 510 under III degree of rockburst hazard throughout the whole mine
Coal seam No. 404/9 and host rock mass				
3.68 Coal slightly prone to rockbursts	75 kJ Rocks slightly prone to rockbursts	3.0 System not prone to rockbursts	Less than 50 No rockbursts	Coal seam No. 404/9 not under rockburst hazard

In Table 5 are summerized the values of selected indices of rock proneness to rockbursts and the assessment of rock proneness to rockbursts.

For the two cases mentioned above, namely, (a) coal seam No. 404/9 of the Chwałowice coal mine and (b) coal seam No. 713/1-2 of the Rydułtowy coal mine, the assessment of coal proneness to rockbursts based on the W_{ET} index approved by mining authorities, classifying it among the "coal slightly prone to rockbursts" does not agree with the assessment of proneness to rockbursts of the "host rock mass–coal seam" system obtained based on the M_{coal}/E_{rock} index, classifying it among the "system not prone to rockbursts". The lack of rockbursts hazard can be confirmed by the so-called "rock mass number Lg" index which is 50 for the analyzed systems and considered to be an ultimate value above which rockbursts occur. In the case of the roof-seam-floor system applied to coal seam No.501/510 of the Wesoła coal mine, the M_{coal}/E_{rock} index assumes a value of 2.03. It means that the system is in the neighbourhood of the two following classes: (a) prone to rockbursts and (b) not prone to rockbursts. Because of a substantial share of the sandstone and mudstone beds in vertical profiles of the G-704/2000 and G-714/95 boreholes, amounting to more than 50%, the L_g index can be in excess of 50, which according to W. Konopko classification scheme, indicates a rockburst hazard (Konopko 1994).

6. Influence of strain rate on the host rock mass–coal seam system's proneness to rockbursts

There are well known, often controversial, opinions on the variation of drop modulus M with an increase in strain rate $\dot{\varepsilon}$. According to some opinions, an increase in strain rate leads either to an increase (Bieniawski 1970) or to a decrease (Peng 1970) in drop modulus. The uniaxial compression tests with a strain rate ranging from 10^{-4} s^{-1} to 10^{-1} s^{-1} conducted by the Central Mining Institute using a stiff testing machine confirmed the ambiguous behaviour of rocks in the stress — strain curve post — peak region (Bukowska 1996). This behaviour can be defined as follows:

(1a) drop modulus for coal, R_c, lying in the range between 14.0–20.0 MPa increases with the increase in strain rate by a value of 100%,

(1b) drop modulus for coal, R_c, lying in the range between 20.0–40.0 MPa either decreases with the increase in strain rate equal to 30% to 45%, averaging about 40%, or does not vary for certain kinds of coal (certain dull coals).

Elastic modulus E for the investigated Carboniferous clastic rocks from the Upper Silesian Coal Basin varies as follows (Bukowska 1996):

(2a) claystones — the increase in elastic modulus E lies in the range between 15–32%, averaging about 20%,

(2b) sandstones, conglomerates and partly mudstones — no influence of the strain rate on the elastic modulus has been found.

Considering the information above, the prognosis of the failure manner variation for the "host rock mass–coal seam" system with the increase in strain rate has been accomplished in the range from 10^{-4} s^{-1} corresponding to the strain of rock mass adjacent, to mine working to 10^{-1} s^{-1} corresponding to the rockburst incidence (10^{-2} to 10^{2} s^{-1}) (vide Kwaśniewski 1986).

Example 1

TABLE 6

Influence of strain rate on the "host rock mass–coal seam" system's proneness to rockbursts according to the core drilling data obtained from borehole No. G-38/2000, coal seam No. 713/1-2, Rydułtowy coal mine

TABLICA 6

Wpływ prędkości odkształcenia na skłonność do tąpań układu „skały otaczające–pokład węglowy" według otworu G-38/2000 w KWK Rydułtowy, pokład 713/1-2

$\dot{\varepsilon} = 10^{-4}$ s^{-1}	$R_{c\ coal} = 18.8$ MPa $M_{coal} = 6685$ MPa	$E_{rock} = 8609$ MPa Up to 100 m above coal seam and up to 30 m beneath coal seam. Siltstones composition –66%	$M_{coal}/E_{rock} = 0.78$ (variant 1) The system not prone to rockbursts
$\dot{\varepsilon} = 10^{-1}$ s^{-1}	$M_{coal} = 13\ 370$ MPa ↑ by 100% (point 1a)	$E_{rock} = 10\ 330$ MPa ↑ by 20% (point 2a)	$M_{coal}/E_{rock} = 1.29$ (subvariant 2a) The system prone to rockbursts

As follows from the above example, the "host rock mass–coal seam" system passes from the not prone to rockbursts state $M_{coal}/E_{rock} < 1$ to prone to rockbursts state $1 \leq M_{coal}/E_{rock} < 2$.

Example 2

TABLE 7

Influence of strain rate on the "host rock mass–coal seam" system's proneness to rockbursts according to the core drilling data obtained from borehole No. G-704/2000, coal seam No. 501/510, Wesoła coal mine

TABLICA 7

Wpływ prędkości odkształcenia na skłonność do tąpań układu „skały otaczające–pokład węglowy" według otworu G-704/2000 w KWK Wesoła, pokład 501/510

$\dot{\varepsilon} = 10^{-4}$ s^{-1}	$R_{c\ coal} = 31.5$ MPa $M_{coal} = 12\ 949$ MPa	$E_{rock} = 6375$ MPa Up to 100 m above coal seam and up to 30 m beneath coal seam. Sandstone and mudstone beds composition — 58%	$M_{coal}/E_{rock} = 2.03$ (subvariant 2b) The system not prone to rockbursts
$\dot{\varepsilon} = 10^{-1}$ s^{-1}	$M_{coal} = 7\ 771$ MPa ↓ by 40% (point 1b)	$E_{rock} = 6375$ MPa (point 2b)	$M_{coal}/E_{rock} = 1.22$ (subvariant 2a) The system prone to rockbursts

As follows from the above example, the "host rock mass–coal seam" system passes from the not prone to rockbursts state $M_{coal}/E_{rock} \geq 2$ to prone to rockbursts state $1 \leq M_{coal}/E_{rock} < 2$.

Example 3

TABLE 8

Influence of strain rate on the "host rock mass–coal seam" system's proneness to rockbursts according to the core drilling data obtained from borehole No. G-695/2000, coal seam No. 404/9, Chwałowice coal mine

TABLICA 8

Wpływ prędkości odkształcenia na skłonność do tąpań układu „skały otaczające–pokład węglowy" według otworu G-695/2000 w KWK Chwałowice, pokład 404/9

$\dot{\varepsilon} = 10^{-4}$ s^{-1}	$R_{c\ coal} = 31.2$ MPa $M_{coal} = 20\ 222$ MPa	$E_{rock} = 6721$ Mpa Up to 100 m above coal seam and up to 30 m beneath coal seam. Siltstones — 62%	$M_{coal}/E_{rock} = 3.00$ (variat 1) The system not prone to rockbursts
$\dot{\varepsilon} = 10^{-1}$ s^{-1}	$M_{coal} = 12\ 133$ MPa ↓ by 40% (point 1b)	$E_{rock} = 8064$ MPa ↑ by 20% (point 2a)	$M_{coal}/E_{rock} = 1.50$ (subvariant 2a) The system prone to rockbursts

As follows from the above example, the "host rock mass–coal seam" system passes from the not prone to rockbursts state $M_{coal}/E_{rock} \geq 2$ to prone to rockbursts state $1 \leq M_{coal}/E_{rock} < 2$.

From the analysis of the influence of the strain rate in uniaxial compression on the proneness of the "host rock mass — coal seam" system to rockbursts, we may conclude that the rockburst hazard increases with the increase in strain rate in the 10^{-4} s^{-1} to 10^{-1} s^{-1} range.

7. Influence of the confining pressure on the M_{coal}/E_{rock} index value

Triaxial compression tests have been carried out in a 70 MPa high-pressure chamber. The chamber allows conducting tests in conditions of 70 MPa confining pressure. To determine the M_{coal}/E_{rock} index value for the "rock mass–coal seam" system, the sandstones overlying coal seam No. 502/II of the Polska-Wirek coal mine and the coal from this seam have been tested. Table 9 shows values of the peak strength, drop modulus for coal and elastic modulus for sandstones. It should be noted that these values were determined from the tests on speciments with a strain rate of 10^{-4} s^{-1} performed in a manner similar to those using the uniaxial compression technique previously discussed.

TABLE 9

Mechanical parameters for coal and sandstones obtained from triaxial compression tests. Coal seam No. 502/II, Polska-Wirek coal mine

TABLICA 9

Parametry mechaniczne węgla i piaskowca drobnoziarnistego w trójosiowym ściskaniu — KWK Polska Wirek, pokład 502/II

Confining pressure	Seam No. 502 coal	Roof sandstone	$M_{coal}/E_{roof\ rock}$
p = 0 MPa	σ_{kr} = 45.0 MPa M = 40 250 MPa	σ_{kr} = 126.7 MPa E = 24 634 MPa	1.63
p = 10 MPa	σ_{kr} = 56.2 MPa M = 27 944 MPa	σ_{kr} = 177.1 MPa E = 14 339 MPa	1.95
p = 20 MPa	σ_{kr} = 113.4 MPa M = 25 233 MPa	σ_{kr} = 231.4 MPa E = 13 102 MPa	1.93
p = 30 MPa	σ_{kr} = 128.1 MPa M = 22 813 MPa	σ_{kr} = 310.7 MPa E = 15 567 MPa	1.47
p = 50 MPa	σ_{kr} = 147.8 MPa M = 18 530 MPa	σ_{kr} = 379.1 MPa E = 14 798 MPa	1.25

The values of confining pressure correspond to the following coal seam deposition depths: ~400, ~800, ~1200 and ~2000 m. The latter value considerably exceeds the current depth of mining in the Upper Silesian Coal Basin area, but because the mining operations are getting deeper and deeper into the ground, it allows predicting the values of rock mass parameters for depths greater than 1200 m.

Figs. 11 and 12 shows the relationships $\sigma_{kr} = f(p)$, $M = f(p)$ for sandstones and coals, respectively. These relationships are defined by the second order polynomial function of the form $y = ap^2 + bp + c$ with very high correlation coefficients ranging from 0.97 to 0.99, where p is the confining pressure.

The triaxial compression tests on sandstone and coal specimens showed an increase in peak strength with an increase in confining pressure (p = 20 MPa and p = 50 MPa) by an amount of 64% for sandstones and 30% for coals, which is lower than in the case of granite where the difference between the respective values of confining pressure may be 100% (Li H. and Li T. 1999). As follows from Fig. 12, the values of drop modulus M_{coal} decrease with an increase in confining pressure.

It is worth-while to comment upon the M_{coal}/E_{roof} index values obtained based on the triaxial compression test data using a strain rate of 10^{-4} s^{-1} and the pressures in the 0–50 MPa range (see Table 9). The values of the index corresponding to the respective values of confining pressure are contained in the (1–2) range as defined by

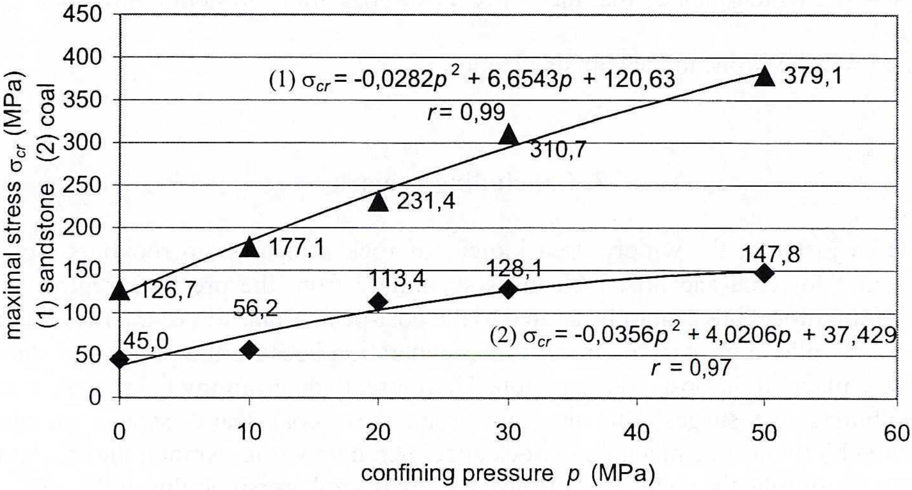

Fig. 11. Relationship between the peak strength and the confining pressure for sandstone and coal. Coal seam No. 502/II, Polska-Wirek coal mine

Rys. 11. Zależność naprężenia krytycznego od ciśnienia okólnego dla piaskowca drobnoziarnistego i węgla — KWK Polska Wirek, pokład 502/II

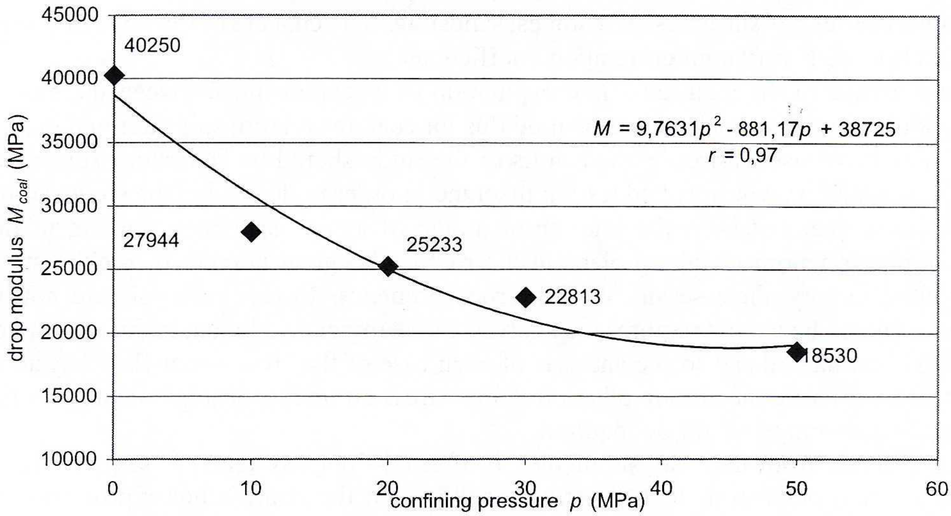

Fig. 12. Relationship between drop modulus and the confining pressure for coal. Coal seam No. 502/II, Polska-Wirek coal mine

Rys. 12. Zależność modułu spadku węgla od ciśnienia okólnego — KWK Polska Wirek pokład 502/II

$1 \leq \frac{M_{\text{coal}}}{E_{\text{rock}}} < 2$ which implies that the "rock mass–coal mine" system (subvariant 2a — Table 1) will be prone to rockbursts (Table 2).

8. Concluding remarks

The majority of the widely used indices of rock proneness to rockbursts can be determined for coal and host rock mass separately from the pre-peak region of the stress-strain plot. Thus cannot be related to the post-peak properties of the rock and coal seam which play a crucial role in rockburst generation because the process of stability loss takes place in the post-failure region. Therefore, in determining the rock proneness to rockbursts, we suggest that the "host rock mass–coal seam" system should be simulated by the testing machine — rock specimen interaction. Among the mechanical parameters, the elastic modulus of the host rock mass and drop modulus of the coal seam can be fundamental for the "rock mass–coal seam" system analysis involving prediction of the coal seam dynamic failure (rockburst) incidence.

The accomplished analysis allows coming to the following conclusions:

1. Many years' studies on mechanical properties of the Coal Measures' sedimentary rocks from the Upper Silesian Coal Basin using a stiff, servo-controlled testing machine have allowed us to define the relationship between drop modulus of the stress-strain curve's post-peak portion and the peak strength. The relations for such kinds of rocks as siltstones, mudstones, sandstones and coal are of the form of power function with very high correlation coefficients.
2. In the case of the required initial evaluation of a relationship between the elastic modulus for waste rocks and drop modulus for coal, the relationships defined in Part 3 may be of use. However, the results of the study should be laboratory supported using a stiff, servocontrolled testing machine in order to determine the strees-strain response parameters in the total strain range of a rock specimen. Owing to the complex phenomena taking place in the rock and a great number of rockburst — related factors, the assessment of the rock proneness to rockbursts should not be generalized because it requires the analysis of the mineral sediment in the area under rockburst hazard and so the analysis of each case of the "roof-seam-floor" system, taking into account, among others the rock stress-strain response parameters in the total strain range would be required.
3. As follows from the analysis of the "roof-seam-floor" systems, if $M_{\text{coal}} < E_{\text{rock}}$, the system behaves as a stiff testing machine and the seam is not exposed to the hazard of dynamic failure. However, if $M_{\text{coal}} > E_{\text{rock}}$, then the $M_{\text{coal}}/E_{\text{rock}}$ ratio is in excess of 1.0. In this case, the "host rock mass–coal seam" system behaves as a soft testing machine and we face the coal seam dynamic failure event. The practice shows (see Table 1) that to some extent, the probability of incidence of the coal seam dynamic failure phenomenon could be reduced. To this end, the host rock mass must

show the elastic properties closely related to the post-failure properties of the seam, which implies that the M_{coal}/E_{rock} ratio should only little be in excess of 1. Three regions of the M_{coal}/E_{rock} index variation are proposed by classifying the "host rock mass-coal seam" system with respect to its dynamic failure probability into either not prone to rockbursts or prone to rockbursts (see Part 4). The values of the M_{coal}/E_{rock} index were compared with the rock mass number L_g, for definite cases, and it was found that the assessments of rock proneness to rockbursts defined from both indices were consistent. On the other hand, no consistency has been found when the assessments of rock proneness ro rockbursts defined from the afore-mentioned indices were compared with the corresponding assessment defined from the currently used and recognized by mining authorities index of natural proneness to rockbursts W_{ET}.

4. The M_{coal}/E_{rock} index, in addition to coal properties, takes into account the participation of each kind of rock layer defined by the elastic properties, which allows to identify the seismogenic layers, i.e,. The layers that are able to store large amounts of elastic energy which, when converted into the kinetic energy, can play an essential role in the rockburst hazard of mine workings.
5. As follows from the performed analysis of the influence of the strain rate on the coal seam failure dynamics, the rockburst hazard increases with an increase in the strain rate in the (10^{-4} to 10^{-1} s^{-1}) range.
6. The triaxial compression tests (confining pressure ranging from 0.0 to 50.0 MPa) on rock specimens from the "rock mass-coal" system have confirmed the increase in peak strength and revealed a decrease in drop modulus M_{coal} for coal with an increase in confining pressure. The value of the M_{coal}/E_{rock} index for coal seam No.502 of the Polska-Wirek coal mine, obtained from the triaxial tests, is contained in the range pertaining to the rockburst prone "rock mass–coal seam" system (part 4). This was confirmed by the real mining situation where in the workings of coal seam No. 502 four rockbursts were recorded in the period 1970–1999. Due to the limited scope of studies and the related ambiqnous results, these relationships should be considered to be approximate. Further studies on the above problems conducted by the authoress are currently under way at the Central Mining Institute.
7. The M_{coal}/E_{rock} index taking into account simultaneously the post-peak properties of coal and elastic properties of waste rocks can be a new measure of the rock mass proneness to rockbursts. However, the studies on the assessment of rock proneness to rockbursts require further developments that should take into account, among others:
   - shape (slenderness) of rock specimens,
   - strain rates approximately corresponding to rockburst phenomena,
   - mineral sediment seam structure and
   - rock mass stresses, in order to gain insight into the stress states the generate rockbursts.

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