Mining Science, vol. 30, 2023, 63–81

www.miningscience.pwr.edu.pl

Mining Science

(Previously Prace Naukowe Instytutu Gornictwa Politechniki Wroclawskiej, ISSN 0370-0798)

ISSN 2300-9586 (print)
ISSN 2353-5423 (online)

Received March 21, 2023; Reviewed; Accepted September 25, 2023

UNDERGROUND TESTING OF LOAD BEARING CAPACITY OF ROCK BOLTING AS PART OF THE VERIFICATION OF ITS PROPER SELECTION

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Abstract: The results of an underground study of the interaction of expansion bolts with the rock mass, aimed at the improvement of rock bolting selection principles in copper ore mines in the LGOM (Legnica and Głogów copper industry district) area are presented in this paper. Although the grouted bolts are generally suitable for use in most types of rock mass, expansion bolting still accounts for a significant share of underground mine workings in two of the three LGOM copper ore mines. This is mainly due to the simplicity of installation and the resultant higher bolting performance, which, among other things, has its economic benefits. Based on the research carried out, it was concluded that in conducive geo-mechanical conditions, mechanically fixed bolts work correctly with the rock mass, however, the correct selection of the bolt design for specific roof conditions is crucial. In order to verify the proper interaction of expansion bolts of different designs with rock mass with varying properties, 6 typical designs of expansion bolts used in the LGOM mines were selected and 7 underground test sites were prepared where the bolts had been installed. The tests were performed in a crosswise manner, i.e., each tested bolt design was tested on each of the test sites. For the mentioned 42 bolt-rock mass systems, the underground performance tests of rock bolting were performed immediately after its installation and then, after 1 and after 2 years from installation. Based on the results of the tests, the selected expansion bolts of different designs were evaluated for proper interaction with rock mass of varying properties.

Keywords**:** *bolt, expansion bolt, rock bolting, selection*

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doi: 10.37190/msc233004

1. INTRODUCTION

Rock bolting is currently used in underground mining all over the world (Małkowski et al. 2015; Song et al. 2017). The first attempts to use rock bolting in LGOM (Legnica and Głogów copper industry district) were made in 1965 at the Lubin Mine in cooperation with the Experimental Department of KGHM and the Central Mining Institute (Juszyński et al. 2018). As opposed to coal mining, bolting in ore mining soon became the primary and ultimate means of securing mine workings (Madziarz, 2002). For example, a total of 400 000 bolts were installed in LGOM in 1969, and by 1980 that figure had risen to 2.3 million (Kidybiński et al. 1997), while and currently around 3 million bolts are installed annually in the three active copper ore mines in the LGOM area.

For the copper ore deposit in the LGOM area, in stratified roof conditions, a model was adopted for the bolting interaction with the rock mass, involving binding of rock layers with low strength and deformation characteristics and binding them with a layer with higher performance (Cała et al. 2001, Grzebyk et al. 2016). The mechanism of rock-bolting interaction with the rock mass is now quite well researched and extensively discussed in literature in Poland and worldwide (Cała et al. 2001). However, despite decades of research into this issue, the selection of rock bolting is based primarily on practical experience gained from underground observations.

The stability of workings secured with rock bolting depends to a large extent on the proper selection of bolting components, as well as the technology adopted and care exercised during the installation (Piechota et al. 2002). According to Głuch (2008), the design of rock bolting requires a comprehensive analysis of a number of elements, including the geological structure of the rock mass, geotechnical parameters of the rocks around the working and others. The methods for the selection of rock bolting and its design are always subject to uncertainty due to the simplification of the actual conditions (Juszyński et al. 2018). The threat of cave-in remains one of the major hazards in the underground mining industry. It depends directly on the local geology, the presence of horizontal strains and the type of mining method and performance of the bolting employed (Fuławka et al. 2002).

According to the researchers (Juszyński et al. 2018; Hoek et al. 1993; Brady et al. 2006) never can the rock bolting in workings be assumed to be fully effective due to the risk of local roof conditions being deteriorated. In particular situations, due to the geological conditions or the purpose of the working, cable rock bolting with cement binder or tube and friction bolts are additionally used (Grzebyk et al. 2016). Furthermore, note that in the mining plants of KGHM Polska Miedź S.A., maintaining the stability of workings secured by independent rock bolting at depths of around 1000 m and above is a complex and costly solution (Pawelus 2013).

According to the valid "Guidelines for the selection, installation and inspection of rock bolting in mining plants at KGHM Polska Miedź S.A." (*Wytyczne* 2017) bolts of various rod lengths and an appropriate bolting grids are selected, depending on the type and geometry of the workings, the class of roof rock (for dog headings and longwalls) or the category of roof rock package (for special-purpose chamber workings), etc. However, no normative acts refer to the selection of a specific bolt design depending on the rock mass properties or other factors. The Guidelines (*Wytyczne* 2017) stipulate that both, expansion bolts and grouted bolts may be used in longwalls as well as in dog headings (access-preparation). Expansion bolts, on the other hand, should not be used in long-term workings and in rock with a risk of poor head expansion in the hole. However, it is stated that "the criteria for selecting a particular type of bolt do not take into account all the factors determining the maintenance of stability of the workings (...) and should therefore not be considered mandatory".

2. APPLICATIONS OF GROUTED AND EXPANSION BOLTS IN THE LGOM AREA

According Skrzypkowski (Skrzypkowski 2019), rock bolting can be divided, among other things, according to the criterion of the mechanism of interaction with the rock mass, into grouted, expansion and friction bolts. Currently, depending on different geological and mining conditions, mainly grouted or expansion (with mechanical fixing, in points) bolting solutions are used in the mines of LGOM.

Since the 1980s, the researchers' interest and industrial applications have focused on rock reinforcement using bolts. The effectiveness of such a solution has been widely studied worldwide, mainly when it comes to resin-based systems (Feng et al. 2022). According to Cała et al. (2001), the researchers now agree that grouted bolts are a more effective way of securing workings than the expansion bolts. Resin adhesives are the most commonly used support material (Bačić et al. 2020), worldwide and the superiority of bolting using them is well known (Feng et al. 2022). Grouted bolts work well in most conditions present at LGOM mines (Pytel 2012), particularly in workings intended for long-term exploitation. However, where roof conditions do not allow the use of expansion bolts, the grouted bolts are used all along the site (Martyniak et al. 2003). The embedding depth of bolts is the key factor affecting the load-bearing capacity. Its mechanism is widely described in the world literature (Chen et al. 2023). It has been demonstrated that a linear relationship exists between the bolting strength and its embedding depth (Høien et al. 2021). Such a relationship has not been found for the expansion bolts analysed herein.

In the LGOM area, expansion bolts are more often used in mine workings with a shorter useful life and with a higher bolting performance desired. The use of such bolting is not recommended for loose and waterlogged rocks where it is at risk of corrosion (Pytel 2012).

In LGOM mines, expansion bolts were tested over a long span of service life (Rzepecki et al. 2005). It was proven that, outside the tectonic disturbance zone, in fresh air currents, expansion bolts retained the required strength even though they had been installed nearly 30 years before. The same researchers concluded that such bolting does not work well when exposed to corrosion or in areas of tectonic disturbance.

Depending on the function and purpose of the excavation (tunnel, mining), its projected maximum width and the roof class, expansive or resin bonded bolts with lengths ranging from 1.2 m to 2.6 m in roof bolting grids of 1.0 m × 1.0 m to 2.0 m × 2.0 m (*Wytyczne* 2017) are used as primary roof bolting. Cemented cable bolts are only used as secondary roof bolting. Only resins are used as binders in the adhesive bolts of the primary roof bolting, which has to do with the need to achieve full load-bearing capacity in a short period of time.

Under the conditions of the Lubin Mine, bolts of 1.8 m in length predominate, and the most commonly used roof bolting grid is 1.5 m × 1.5 m. Bolts of this length were used in the described studies. The standard diameters of holes drilled to install a roof bolting are 25 mm, 28 mm or 38 mm. Only expansive bolts with 36 mm and 25 mm head diameters were analysed in this study, as 28 mm expansive heads are not currently used. The diameter of the bolt heads does not have a significant impact on the load bearing capacity of the bolts, whereas each type of roof bolting requires a hole to be drilled with a strict dimensional tolerance, which, depending on the bolt design, is specified by the bolt manufacturer.

The data presented in Table 1 shows that the grouted rock bolting has been used almost exclusively at the Rudna Mine since 2016. In other LGOM mines (i.e., Lubin and Polkowice-Sieroszowice), expansion bolts currently account for a significant percentage of the bolting solutions applied due to the simplicity and low installation cost, and this trend will continue.

Table 1. Percentage application of grouted and expansion bolts in LGOM area mines (own compilation based on data from LGOM mines Rock Burst Departments)

"Lubin" Mine			"Polkowice-Sieroszowice" Mine			"Rudna" Mine		
year	grouted	expansion	year	grouted	expansion	year	grouted	expansion
2022	**54.3%**	**45.7%**	**2022**	**24.3%**	**75.7%**	**2022**	**100%**	**0%**
2021	**54.2%**	**45.8%**	**2021**	**26.4%**	**73.6%**	**2021**	**100%**	**0%**
2020	53.1%	46.9%	2020	32.9%	67.1%	2020	99.7%	0.3%
2019	33.6%	66.4%	2019	33.3%	66.7%	2019	99.2%	0.8%
2018	28.7%	71.3%	2018	31.3%	68.7%	2018	99.4%	0.6%
2017	33.7%	66.3%	2017	22.9%	77.1%	2017	92.2%	7.8%
2016	30.2%	69.8%	2016	24.7%	75.3%	2016	94.5%	5.5%

The significant share of expansion bolts in the total number of bolts used is primarily due to economic reasons. Expansion bolts are a sufficient means of ensuring the stability of workings in numerous sites with developed mining operations. Considering the fact that the cost of purchasing a single grouted bolt is similar to that of a mechanically fixed one, the key argument for the use of the expansion bolts appears to be the bolting performance, which has a direct impact on the unit cost of bolt installation. Refer to Fig. 1 for an example illustrating this.

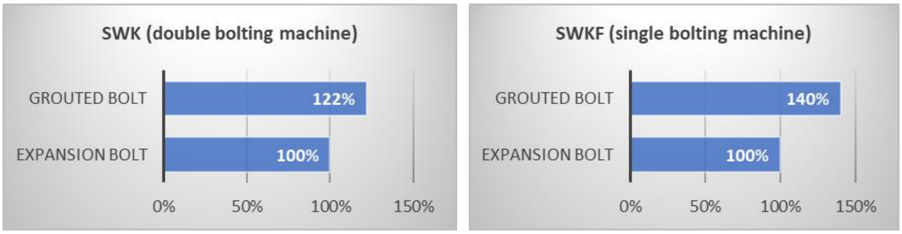

Fig. 1. Comparing the cost of grouted and expansion bolting at Lubin Mine in Q1 2020 (based on the data from the Standards Department of KGHM Polska Miedź S.A. "Lubin" Mine)

3. SELECTING THE DESIGN OF EXPANSION BOLTS DEPENDING ON THE ROCK MASS

Analysing the current knowledge in this area, bolts are generally suitable for use in most types of rock mass. The need to define selection criteria for individual bolt designs for the specific rock mass conditions is particularly relevant for expansion bolts. Based on the data analysed, expansion bolts are, and are likely to continue to be, a significant percentage of the bolting in LGOM mines due to easy installation, lower unit cost of bolting and higher bolting performance.

Expansion bolts were the subject of considerable researchers' interest in the 1970s (Jędrzejowski et al. 1997; Pochciał et al. 1976; Siewierski 1978). In recent the years, Skrzypkowski (2018) was engaged in the research on mechanically installed bolting by studying the energy absorption of expansion bolts, and Korean researchers analysed the strength of hydraulic expansion bolts (Kim et al. 2016). Despite that, the problem of restraining mechanically installed bolts, particularly with expansion heads, should be considered to have been researched insufficiently, particularity when it comes to the potential of modern numerical methods for modelling the bolt vs. rock mass interactions.

In particular, it is important to develop a method (rules) for the proper selection of the type and design of mining bolts for securing workings in copper ore mines of KGHM Polska Miedź S.A. in LGOM, primarily in order to:

- improve the state of work safety in the copper ore mines of KGHM Polska Miedź S.A. (OHS effects), as a result of improved stability of the roof of underground workings secured with this type of bolting,
- reduce the cost of excavation and maintenance, and therefore improve the economic effects of mining.

Cała et al. (2001) point out that the restraint of the head of a mechanically fastened bolt in the rock mass is affected by:

- the design, geometry and material of the head,
- geo-mechanical properties of the roof rock in the area of the bolt head installation,
- quality of bolting work (especially the pre-tensioning).

It is assumed that the diameter of the tool drilling the hole to install the expansive bolt should be (2012):

- 38 mm ±0.5 mm for 36 mm diameter heads,
- 26 mm ±0.2 mm for 25 mm diameter heads.

Single head spreaders are usually used. The use of double spreaders or double heads is not reflected in the normative acts of KGHM Polska Miedź S.A. and is dictated by the desire to achieve a certain contact between the head and the rock mass, especially in worse roof conditions. The results of this study, however, call into question the advisability of using such a solution.

4. TESTING INTERACTIONS OF EXPANSION BOLTS OF DIFFERENT DESIGNS WITH ROCK MASS OF VARYING PROPERTIES

The following studies are aimed at clarifying the rules (*Wytyczne* 2017) for selection of bolting in LGOM copper ore mines, by developing a method for selecting expansion bolts of different designs for roof rock with varying properties. These were carried out as part of an Industrial PhD Program entitled "The method of selection of type and design of bolts for different geological and mining conditions of underground copper ore mines of KGHM Polska Miedź S.A. in the LGOM area". In Polish copper ore mines, mainly dolomites and limestones are subjected to bolting. The regulations (*Regulations* 2016) require that the rock in the area to be reinforced by bolting in copper ore mines have an average divisibility of at least 20 mm and should not have a natural tendency to detach. Sandstone is not subject to bolting. Descriptions of bolt testing in sandstone and shales are encountered in the world literature such as the 181 bolts tested under Australian mine conditions in the Sydney region (Salcher et al. 2018).

The studies included the following:

- selection of 6 distinctive expansion bolt designs used in LGOM mines (bolts from a single production batch were tested so as to minimise potential production-related variations),
- selection of 7 underground test sites with varying roof conditions (in different parts of the mine),
- installing 3 times 6 bolts of different designs at each site,
- cyclic testing of the load-bearing capacity of the rock bolting in underground conditions at the previously selected sites,
- laboratory testing of the load bearing capacity of rock bolting for the bolt vs. rock relationship identical to the one used at the underground test sites (bolt

heads installed in cores from the underground test sites, from the depth they are embedded in the roof),

- strength tests on rock samples from the cores,
- strength tests of the rock bolting material.

In addition to the above-mentioned tests, a numerical analysis of bolt vs. rock mass interaction was carried out for the described bolt-rock mass relationships in order to properly interpret their results and identify the phenomena occurring. The modelling results will be presented in a separate publication due to the extensive amount of data involved.

5. IN SITU UNDERGROUND TESTS

5.1. SELECTION OF TEST SITES

Test sites were located in underground mine workings at the Lubin Mine. Locations with different roof conditions, in different parts of the mine were selected. One of the aspects considered, was the operating experience of the Rock Burst Department of the expansion rock bolting met the required load-bearing performance and those Lubin Mine, relating to the test of rock bolting load-bearing capacity – locations where

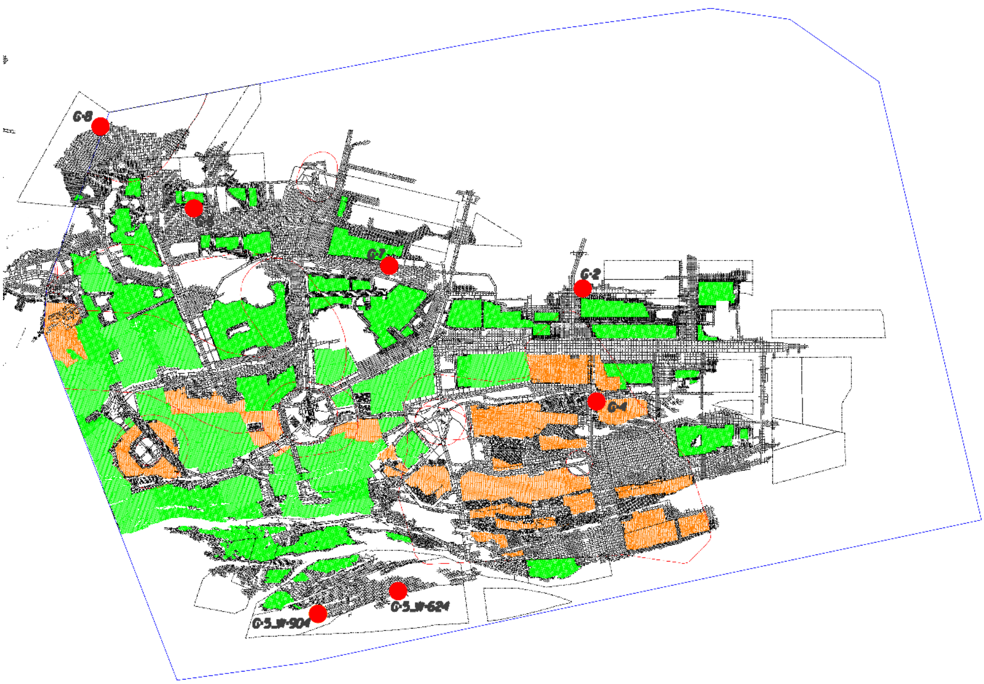

Fig. 2. Map of the Lubin mine with test sites indicated (red) and designated the relevant department (own compilation based on the Lubin mine data) – as of February 2023, without scale

where it did not, were selected for comparison. Documentation gathered at the Lubin mine was analysed to this end.

The roof conditions were assessed based on the strength of the roof rock at a height of approximately 1.8 m above the working roof. This height corresponds to the location of the heads of the expansion bolts installed. Data from 80 geotechnical boreholes located
in the Lubin mine was analysed for that purpose.

In view of the above, the test sites were located in the following areas of the ongoing mining works:

- in the Lubin East region – one site each in G-2 and G-4 departments,
- in the Lubin Central region (southern part of the mining area) – 2 test sites in the G-5 department for completely different roof conditions,
- in the the L-VI shaft area – one test site in the G-6 and G-7 departments and one site in the G-8 department that conducts mining work in the Rudna mine area.

The locations of the test sites are shown in Fig. 2, while the characteristics of the roof rock at the individual sites are presented in Section 6.1.

5.2. SELECTION OF BOLT DESIGN FOR UNDERGROUND AND LABORATORY TESTING

In order to prepare underground and laboratory tests of the interaction of various expansion bolt designs with rocks of varying properties, solutions for mechanical installation of rock bolting available and widely used in ore mining were analysed in terms of their suitability for underground conditions in LGOM copper ore mines.

Expansion bolts of various designs were selected and prepared for underground and laboratory testing. Typical various designs were selected taking into account the possibil-

Table 2. Parameters of rock bolting being examined (own compilation based on documentation from bolting manufacturers)

Symbol	Designation	Head type	Rod material	Head jaw material
A	RN 1.8 G36X2 KNW bolt kit	head dia. 36 double	Steel AP600V	Cast iron EN-GJMW-400-5
B	R18/G36x1/KW bolt kit	single head dia. 36	Steel AP600V	Cast iron EN-GJMW-400-5
C	RN18/G25X2/SNW expansion bolt kit	head dia. 25 double knurled (inside knurl)	Steel FER-K19	Steel R35
D	R18/G25X1/KMW bolt kit	head dia. 25 single knurled	Steel AP600V	Steel S235JR+AR

		(inside knurl)		
E	TR25/2L-1.8m/Rnw bolt kit	head dia. 25 single reinforced	Steel B500SP	Steel S355J2
F	RN18/G25X1W/KNW expansion bolt kit	head dia. 25 single reinforced	Steel AP600V	Steel S355J2H

ity of installation using the machinery available at KGHM Polska Miedź S.A. mines. They are presented in Table 2 and in Fig. 3.

All bolts were installed between existing bolts in a 1.5 m × 1.5 m grid, as shown in the diagram in Fig. 4. The length of all tested bolts is 1.8 m.

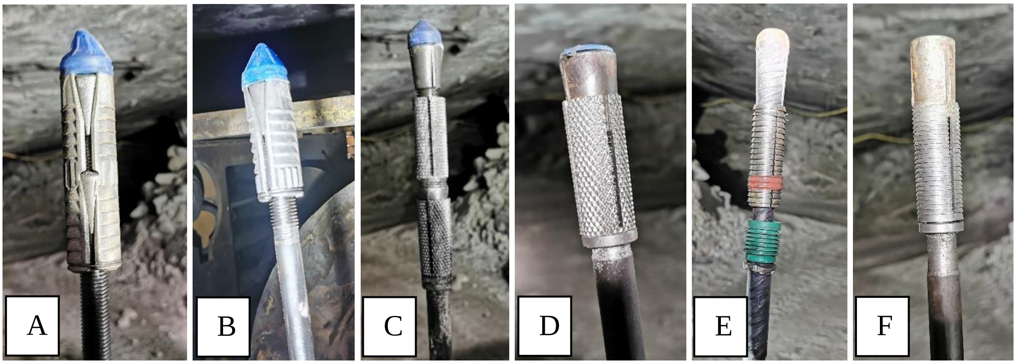

Fig. 3. Bolt designs selected for testing with symbols assigned (own photographs)

5.3. PREPARATION OF TEST SITES

At each of the underground test sites described above (Section 6.1), 3 groups of bolts were installed, each containing one bolt of a specific design.

The letters A, B, C, D, E, F stand for the bolt design according to Table 2. The bolts were installed at all sites accordingly.

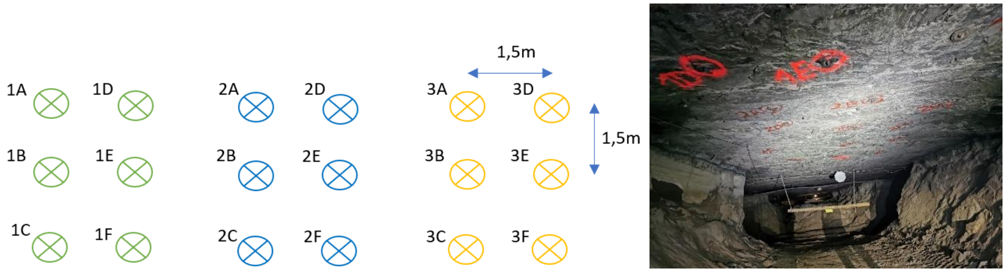

Fig. 4. Layout of bolt installation at the underground test site.
The photo on the right shows a test site in the G-6 department (own compilation)

The bolts were installed using an SWK machine with a Fletcher–Roof Master 1.7 turret from Mine Master. The machine can drill holes for bolts of different diameters and extract drill cuttings instead of using a traditional water flush, thus eliminating the "water logging" of the roof while drilling, which could have affected the results of the tests carried out.

In order to consider the influence of time (in particular the effects of corrosion and seismic vibration) on the interaction of the bolts with the rock mass, the tests of the load bearing capacity of the bolts (determination of performance characteristics of the bolts) were carried out periodically at the following intervals:

- 1A, 1B, 1C, 1D, 1E, 1F bolts – bearing capacity tests performed shortly after installation;
- 2A, 2B, 2C, 2D, 2E, 2F bolts – bearing capacity tests performed approx. 1 year from installation;
- 3A, 3B, 3C, 3D, 3E, 3F bolts – bearing capacity tests performed approx. 2 years after installation.

5.4. UNDERGROUND TEST METHODOLOGY

Prior to the in-situ testing of the rock bolting, the condition of the bolting was visually assessed and the bolt torque, which ranged from 250 Nm to 300 Nm according to the manufacturers' specifications, was monitored. The in-situ testing consisted of determining the bolt performance by measuring its retraction from the hole with increasing load (increasing axial force applied to the bolt in the vertical downward direction) according to the following scheme:

- 0 kN, 20 kN, 40 kN, 60 kN, 80 kN, 100 kN,
- after relieving the load.

Fig. 5. From the left: 1) checking the bolt tightening torque with a torque wrench, 2) cylinder with sleeve, 3) hydraulic dynamometer pump (own photos)

A hydraulic dynamometer (special hydraulic cylinder), standard in LGOM mines (03/TT/KGHM, 2008), was used to set a specific load level on the bolts, while a hand-held torque wrench was used to control the tightening torque. Internal regulations of KGHM Polska Miedź S.A. (*Wytyczne* 2017) require that both, the grouted and expansion bolting, up to 2.6 m in length, should provide a minimum load bearing capacity of 100 kN, and that the extension of the bolt after load removal should not exceed 10 mm. No load bearing capacity measurements were carried out by sub-
jecting the bolts load above 100 kN, so that the tests could be compared with those routinely carried out in LGOM mines, in accordance with the KGHM internal manual (03/TT/KGHM 2008).

6. RESULTS OF UNDERGROUND TESTS

6.1. STRENGTH TESTS OF ROCK SAMPLES

The rock cores for laboratory testing were taken from the underground test sites so that the laboratory tests reflect as closely as possible the underground conditions. Rock samples from 1.5 m to 2.0 m above the surface of the roof, with expansion bolt heads embedded in the holes, were tested. A geological description of these rock samples was prepared (Table 3) and their strength was determined in laboratory tests (Table 4). The tests were carried out at the Material Testing Laboratory of KGHM Cuprum Sp. z o.o. CBR.

Table 3. Geological description of the cores examined
(own compilation based on the data from Geological Department of the Lubin mine)

Core sampling site	Geological description of cores examined
G-2	Dark grey massive clay dolomite, cryptocrystalline, scattered calcite nests 2 mm in diameter, locally dark spots
G-4	Streaked grey/dark grey massive dolomite, cryptocrystalline, dark bands of organic matter and clay minerals, scattered calcite nests up to 5 mm in diameter
G-5_624	Streaked grey and dark grey dolomite, cryptocrystalline, cavernous (up to 10 mm), inclusions of dolomitic limestone, clay minerals and organic matter
G-5_904	Grey calcareous dolomite, weathered, strongly cavernous, fragile, cryptocrystalline, fissure-cavernous system, stilolites present
G-6	Dark grey calcareous dolomite, fractured, cryptocrystalline, gypsum meshes 5–30 mm in diameter, scattered

G-7	Streaked dark grey dolomite, cryptocrystalline, with inclusions of light grey dolomitic limestone, scattered gypsum meshes 1-10 mm in diameter, almost vertical cracks (at an angle of about 80 degrees) filled with gypsum
G-8	Streaked dark grey dolomite, cryptocrystalline, with inclusions of dolomitic limestone, almost vertical cracks (at an angle of about 80 degrees), gypsum meshes up to 10 mm, local fissures up to 20 mm filled with crystalline calcite, stilolite seams beginning to appear

Table 4. Parameters of roof rocks at locations where expansion heads interact with the rock mass (based on own study at the laboratory of CBR Cuprum sp. z o.o.)

Core sampling site	Volumetric density	Compressive strength	Tensile strength	Shear strength	Flexural strength	Modulus of elasticity	Poisson's ratio	Burst tendency index
	ρ_s	R_c	R_r	R_t	R_g	E_{sp}	ν	W_{et}
	[g/cm^3 = kg/dm^3]	[MPa]	[MPa]	[MPa]	[MPa]	[GPa]	–	-
G-2	2.68	**112.43**	**8.90**	20.64	22.12	**23.08**	**0.22**	2.54
G-4	2.68	**127.68**	**6.49**	33.40	26.97	**25.98**	**0.16**	2.77
G-5_624	2.74	**145.77**	**12.13**	44.48	20.31	**36.27**	**0.30**	5.11
G-5_904	2.51	**83.41**	**4.76**	26.86	11.26	**31.23**	**0.21**	3.17
G-6	2.75	**136.97**	**10.91**	37.42	27.27	**38.76**	**0.22**	3.95
G-7	2.69	**110.03**	**8.55**	24.04	28.59	**27.03**	**0.19**	2.79
G-8	2.73	**154.84**	**7.00**	42.46	21.93	**40.18**	**0.24**	5.28

6.2. RESULTS OF UNDERGROUND TESTS ON ROCK BOLTING LOAD-BEARING CAPACITY

As a result of underground testing of the load-bearing capacity of rock bolting, the performance characteristics of 6 different expansion bolt designs interacting with roof rock of varying properties were determined at 7 underground test sites. The performance curves for the bolts reflect the measured relationships between the axial load of the bolt and its measured retraction from the hole. Exemplary measurement results for the test site at G-6 department of the Lubin mine are presented in Table 5, and the characteristic curve of bolt performance is shown in Fig. 6.

Table 5. Exemplary results of the rock bolting load-bearing capacity measurement for the test site at G-6 department (own compilation)

Several days after bolt installation			One year after installation			Two years after installation		
Bolt no.	Tension [kN]	Extension [mm]	Bolt no.	Tension [kN]	Extension [mm]	Bolt no.	Tension [kN]	Extension [mm]

1A	20	0	2A	20	0	3A	20	1
	40	2		40	1		40	2
	60	5		60	3		60	4
	80	8		80	5		80	5
	100	11		100	7		100	7
	After load relieving	6		After load relieving	2		After load relieving	2

The performance characteristics of the rock bolting as a ratio of its retraction to the axial force tension of the bolt load) were derived from the above data.

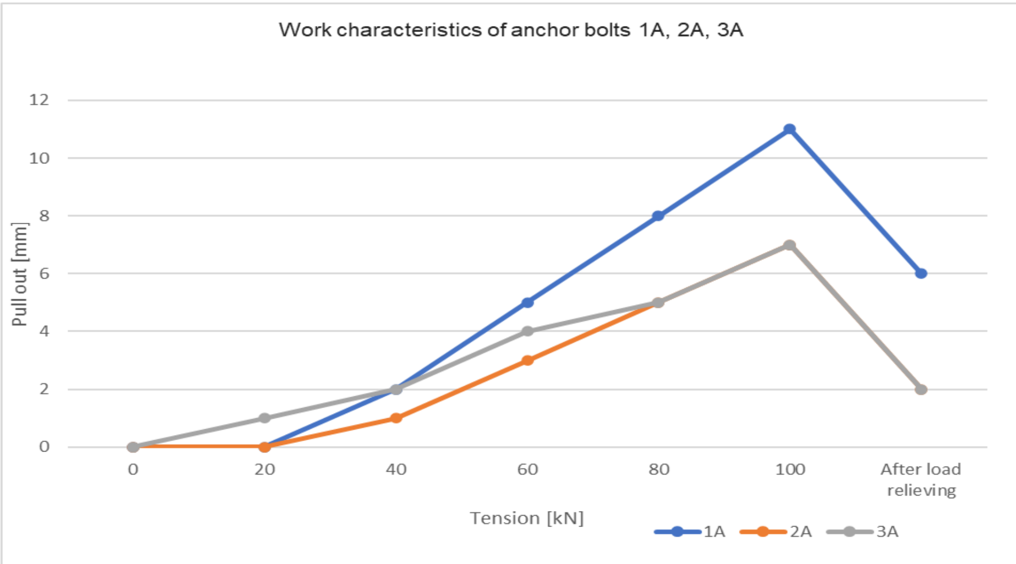

Fig. 6. Exemplary curve for rock bolting performance in the G-6 department for the A bolt in the first series of tests – blot extension [mm]

In a similar manner, test results were obtained for all 42 bolt-rock mass relationships analysed (6 bolts in 3 intervals at 7 test sites). The results were analysed taking into account laboratory tests of the bolting load-bearing capacity, strength tests of the rock samples and material tests of the bolts. This made it possible to identify those bolt-rock mass combinations which work properly together and those whose interaction is considered as risky or even incorrect. The results of the joint assessment of the interaction of the examined expansion bolts with the rock mass of different properties at the individual test sites are compiled in Table 6. Those bolt and rock mass sets whose correct interaction was not in doubt were identified as "useful". The sets G-5_W-624 for bolts A and B with a cast iron head were identified as "risky" (yellow colour in Table 6), which posed a risk of head slippage and loss of bolt load capacity, and the interaction with the rock mass of bolt C, which structurally poses a risk of loss of load capacity, as described in the conclusions. The interaction of all the heads with the rock mass at position G 5_W-904 was assessed as faulty (red in Table 6). It was concluded that none of the tested expansive head designs guarantees the maintenance of the required bolt load capacity in cavernous and scattered roof conditions. Bolt E, which generally works well with most of the tested roof rocks, was marked as the most versatile (green colour in Table 6).

Table 6. Joint assessment of the interaction of the examined expansion bolts with the rock mass of different properties (at individual test sites), based on underground and laboratory tests (own compilation)

Bolt symbol	Location of test sites						
	G-2	G-4	G-5_W-624	G-5_W-904	G-6	G-7	G-8
A	correct	correct	risky	incorrect	correct	correct	correct
B	correct	correct	risky	incorrect	correct	correct	correct
C	risky	risky	risky	incorrect	risky	risky	risky
D	correct	correct	correct	incorrect	correct	correct	correct
E	correct	correct	correct	incorrect	correct	correct	correct
F	correct	correct	correct	incorrect	correct	correct	correct

The results of the above study cannot be limited to a zero-one assessment of the suitability of a bolt for use in specific roof conditions. Factors affecting the proper, or improper, interaction of a particular bolt design, in particular the expansion heads, with the roof rock, must be identified. Analysing individual bolt-rock mass systems studied, it was found that:

- The bolt (head) design that performs best in a variety of roof conditions, and therefore the one that can be considered versatile and most likely to interact correctly with most roof rocks, is the one designated with "E". This is probably due to the fact that it does not have a typical expansion head (with the wedge being a separate component), and the jaws that engage with the walls of the hole are expanded during installation by the conically shaped end of the bolt rod which acts as a wedge. Thanks to such design, as the bolt tension increases, the head of the bolt becomes increasingly firm in the rock mass. The drawback, however, is the installation method of such a bolt which requires more care by the SWK operator since, unlike the other tested bolts, it is sufficient to tighten them with the correct torque, whereas the E anchor must be "jerked" downwards before tightening so that the jaws engage with the ceiling.
- The double-headed A bolt and the single-headed B bolt achieved almost identical load-bearing capacities in different ceiling conditions. Therefore, the use of double-headed or extended expansion bolt heads appears to be unjustified. In the tests

performed, no increase in the load bearing capacity of such bolt designs was found, nor was there any improvement in their restraint in the roof rock. Consequently, using them seems to be pointless, in particular due to the higher cost of such bolting solution.

- The 36 mm head diameter bolts (A and B) did not demonstrate better interaction with the rock mass than the smaller 25 mm head diameter ones (C, D, E, F) in different roof conditions at any of the test sites.
- For bolts with a "knurled" head, an "external" knurl, the convex one (B bolt) seems to be a better solution, with teeth protruding above the surface of the jaw, which penetrates (cuts in) well into the rock of the hole walls.
- For the C bolt, the risk of pulling the head mesh through the bolt wedge was established. This is due to the head mesh material being too thin, which can break, thus posing a risk of the entire bolt losing its load-bearing capacity.
- For the roof rocks at the G-5_W-624 site (Tables 3 and 4), i.e., hard dolomite (R_c above 140 MPa) with clay inclusions, the cast iron heads (A and B bolts) slipped in the hole, instead of expanding and cutting in its walls (rock). This poses the risk of the bolts not performing properly and losing their required load bearing capacity.
- At the G-5_W-904 site, brittle, cavernous dolomite with an R_c of ca. 80 MPa, instances of load-bearing capacity loss were found for all tested bolt designs. It was therefore proven that point-fixed bolting should not be used in such rock mass.
- At the G-2, G-4, G-6, G-7 sites with compacted dolomitic rock with R_c in the range 110 to 145 MPa, the expansion bolts were found to interact properly with the rock mass. It can be assumed that these are the optimum conditions for the use of mechanically fixed rock bolting.
- At the G-8 site (the hardest roof rock, with R_c above 150 MPa, no clay or organic matter inclusions), the proper interaction with the tested bolt designs was observed. However, the load-bearing capacities for the A, B, C, D bolts were lower than for the E and F bolts, whose head design causes them to jam into the hole walls as the tension increases

The tests acknowledged that care in the installation, along with with a proper tightening torque, is crucial to the load-bearing capacity of the bolts. The load-bearing capacity figures of all the bolt designs examined, installed under direct author's supervision, are significantly higher than for bolts installed in typical underground conditions, during mine operation.

Fig. 6. The test site located in the G-7 department: on the left – just after installation, on the right – after the the high-energy tremor (own compilation)

Note that in the immediate vicinity of the test site located at the G-7 department, between the first and second test cycle, a high-energy rock mass tremor classified as rock burst, occurred. The rock face was excavated and ejected into the working, resulting in a convergence of approximately 1 m. This made it possible to compare the results of the load-bearing capacity tests before and after this occurred, including the time just after the tremor. The first test was performed before the burst, the second one about 3 months later, and the third after more than 1 year. No "loosening", resulting in a loss of load-bearing capacity, was found for either of the bolt designs tested. It should be noted that, under conditions of rock bursting hazard, the roof bolting was characterised not only by adequate strength, but also by flexibility.

7. CONCLUSIONS

The presented underground tests of interactions of various expansion bolt designs with roof rock of varying properties carried out in the Lubin mine acknowledge that, for expansion bolts (with point installation), the proper restraint of the bolt head in the hole is of key importance, which is mainly affected by the design, geometry and material of the bolt head, geo-mechanical properties of the roof rock where the bolt head is installed, and the quality of bolt installation (in particular its proper pre-tensioning).

By analysing the results of the tests carried out, the following conclusions can be drawn:

- It is possible to select specific expansion bolt designs for specific roof conditions in order to achieve the most beneficial bolt vs. rock mass interaction conditions;

- It is possible to identify expansion bolt designs that work correctly with most of the roof rock types and those whose design does not guarantee the proper bolting performance (roof reinforcement);
- It is the quality of the bolt installation, particularly applying the correct bolt rod pre-tensioning, that is of key importance for the correct interaction of the bolts with the rock mass;
- For rock mass with low strength ($R_c \approx 80$ MPa), as for the LGOM conditions (cavernous, scattered rock mass), it is not advisable to use a mechanically fixed bolting, and the grouted bolting along the entire length of the bot rod should be used as a proper reinforcement method.
- For the majority of the 42 bolt and rock mass sets, the basic load-bearing capacity parameter, i.e., bolt extension after removal of a load of 100 kN not exceeding 10 mm, remained fulfilled, indicating correct bolt and rock mass interaction.

Furthermore, note that no trend of the loss of bolt pre-tension over time was observed at any of the sites over the approximately 2-year duration of the tests, which is probably due to the lack of negative effects of bolting corrosion.

For the G-7 test site in the vicinity of which the high-energy tremor (classified as a rock burst) was observed, no loss of bolt tension was observed between test cycles. On the contrary, the bolt tension increased, indicating that the bolting interacted properly with the rock mass and accepted the increased load. This was identified for all 6 tested bolt designs and it should be assumed that correct and highly accurate installation, including in particular the proper pre-tensioning, was a prerequisite for the proper interaction of the bolts with the rock mass. The results of the tests carried out demonstrate that the load-bearing capacity of the bolts is significantly higher than that of the bolts installed under typical operating conditions (out of this study).

As since the 1980s, the researchers' attention has primarily focused on the testing of the grouted bolting, it is the case of expansion bolts with point fixing that it makes sense to perform research work aimed at the proper selection of bolt design for specific roof conditions. The practical (operational) experience of the LGOM underground copper ore mines shows that the grouted bolting works well in a wide range of roof conditions, and its application ensures proper protection to the mine workings. However, due to the simplicity of installation, the lower unit cost of purchase and installation of the bolting and its higher performance, expansion bolts currently have, and are likely to continue to have in the future, a significant share of the total number of bolts installed. The simplicity of full installation mechanisation, compared to the grouted bolts, is also an argument in favour of their application.

The underground tests of interactions of various expansion bolt design vs. rock mass of varying properties (with supplementary laboratory tests), described in this publication, are part of a research project carried out by the first author under the Industrial PhD Program which also includes verification of proper interactions of the selected bolt-rock mass combinations by means of numerical modelling, with the use of results of laboratory strength tests of the bolting and rock samples obtained from bolt installation sites. The ultimate result of the work will be to develop principles for the selection of various expansion bolt designs for different roof conditions, in order to ensure the best conditions for bolt interaction with the rock mass, and thus improve the stability of the roof reinforced by this solution, improve safety in the copper ore mines of KGHM Polska Miedź S.A. (OHS effects) and reduce the cost of digging and maintenance of workings, and thus improve the economic effects of mining.

ACKNOWLEDGEMEMNTS

Many thanks to the Management of KGHM Polska Miedź S.A. Lubin Mine for providing machines and underground workings to perform the research described in this article.

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