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PROPERTIES OF WASTE FROM COAL GASIFICATION IN ENTRAINED FLOW REACTORS IN THE ASPECT OF THEIR USE IN MINING TECHNOLOGY

WŁAŚCIWOŚCI ODPADÓW ZE ZGAZOWANIA WĘGLA W REAKTORACH DYSPERSYJNYCH W ASPEKCIE ICH WYKORZYSTANIA W TECHNOLOGIACH GÓRNICZYCH

Most of the coal gasification plants based of one of the three main types of reactors: fixed bed, fluidized bed or entrained flow. In recent years, the last ones, which works as „slagging“ reactors (due to the form of generated waste), are very popular among commercial installations. The article discusses the characteristics of the waste from coal gasification in entrained flow reactors, obtained from three foreign installations. The studies was conducted in terms of the possibilities of use these wastes in mining technologies, characteristic for Polish underground coal mines. The results were compared with the requirements of Polish Standards for the materials used in hydraulic backfill as well as suspension technology: solidification backfill and mixtures for gob caulking.

Keywords: gasification, ash, slag, suspension, backfill

Większość przemysłowych instalacji zgazowania węgla pracuje w oparciu o jeden z trzech głównych typów reaktorów: ze złożem stałym, dyspersyjny lub fluidalny. W zależności od rodzaju reaktora oraz szczegółowych rozwiązań instalacji, powstające uboczne produkty zgazowania mogą mieć różną postać. Zależy ona w dużej mierze od stosunku temperatury pracy reaktora do temperatury topnienia części mineralnych zawartych w paliwie, czyli do temperatury mięknienia i topnienia popiołu. W ostatnich latach bardzo dużą popularność wśród instalacji komercyjnych zdobywają reaktory dyspersyjne „żużlujące". W takich instalacjach żużel jest wychwytywany i studzony po wypłynięciu z reaktora. W niektórych przypadkach oprócz żużla powstaje jeszcze popiół lotny, wychwytywany w systemach odprowadzania spalin. Może być on pozyskiwany oddzielnie lub też zawracany do komory reaktora, gdzie ulega stopieniu. Wszystkie z analizowanych odpadów – trzy żużle oraz popiół pochodzą właśnie z tego typu instalacji. Tylko z jednej z nich pozyskano zarówno żużel jak i popiół, z pozostałych dwóch jedynie żużel. Odpady te powstały, jako uboczny produkt zgazowania węgla lub węgla z dodatkami: bitumin (żużel S1), czy biomasy (popiół A2, żużel S2).

W polskim górnictwie podziemnym wyróżnić można kilka technologii podsadzkowych, w których do transportu materiału wykorzystywana jest woda. Tradycyjnie oraz ze względów historycznych, terminem „podsadzka hydrauliczna" określa się tę, która spełnia wymagania normy PN-93/G-11010. Do najważniej-

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szych cech takiej podsadzki hydraulicznej zaliczyć należy wypełnienia uprzednio wydzielonej pustki poeksploatacyjnej, materiałem o jak najmniejszej ściśliwości oraz o jak największej wodoprzepuszczalności. Materiał taki, po odprowadzeniu wody ma stanowić mechaniczna podporę stropu, a proces podsadzania jest ściśle powiązany z procesem eksploatacji, jako sposób likwidacji zrobów. Najczęściej stosowanymi materiałami są piasek podsadzkowy oraz odpady górnicze lub hutnicze (Lisowski, 1997).

Od ponad dwudziestu lat, w polskim górnictwie węgla kamiennego obecna jest również inna technologia podsadzkowa, w której do transportu materiałów wykorzystywana jest woda. W tym przypadku części stałe to materiały drobnoziarniste, najczęściej popioły różnych typów, które po wymieszaniu z wodą tworzą zawiesinę (stąd termin „zawiesiny popiołowo-wodne"). Polska norma PN-G-11011:1998 wyróżnia dwie odmiany takich zawiesin i definiuje je, jako „podsadzkę zestalaną" oraz „mieszaninę do doszczelniania zrobów". Podstawową ideą przyświecającą stosowaniu zawiesin drobnoziarnistych w technologiach górniczych była początkowo troska o zagospodarowaniu odpadów energetycznych, a następnie górniczych (Mazurkiewicz i in., 1998; Piotrowski i in., 2006; Piotrowski, 2010; Plewa i Mysłek, 2000; Plewa i Sobota, 2002). Obecnie technologia zawiesinowa na stałe zagościła w kopalniach węgla kamiennego stając się m.in. nieodzownym środkiem profilaktyki pożarowej i metanowej (Dziurzyński i Pomykała, 2006; Palarski, 2004; Pomykała, 2006).

W artykule przedstawiono analizę możliwości wykorzystania ubocznych produktów zgazowania, jako materiałów do podsadzki hydrauliczne (wg normy PN-93/G-11010), podsadzki zestalanej oraz mieszaniny do doszczelniania zrobów (wg normy PN-G-11011:1998) – technologii stosowanych w polskim górnictwie węgla kamiennego.

Podstawowe badania ubocznych produktów zgazowania obejmowały takie właściwości jak gęstość, wilgotność, skład ziarnowy, wymywalność zanieczyszczeń chemicznych oraz zawartość radionuklidów. Wybrane właściwości fizyczne ubocznych produktów zgazowania oraz ich oznaczenie zestawiono w tabeli 1. Składy ziarnowe żużli ze zgazowania, analizowanych pod kątem zastosowania w podsadzce hydraulicznej przedstawiono na rys. 1, a materiałów dla technologii zawiesinowej, czyli popiołu lotnego A2 oraz zmielonych żużli oznaczonych, jako S1m, S2m oraz S3m – na rys. 2. Żużle ze zgazowania zawierają nie więcej niż 6% ziaren mniejszych niż 0,1 mm, co odpowiada wymaganiom dla materiałów podsadzkowych I klasy. Analiza wymywalności zanieczyszczeń chemicznych wykazała przekroczenia wymagań jednej lub obu przywołanych norm w zakresie pH i/lub niklu dla próbek żużli S1 i S2 oraz popiołu A2 (tab. 2). Zwraca uwagę bardzo niska wartość pH oraz bardzo wysoka zawartość niklu dla żużla S1. Jest to rzecz nietypowa dla krajowych odpadów energetycznych powstających ze spalania węgla kamiennego. W zakresie zawartości radionuklidów wszystkie materiały spełniają nie tylko wymagania norm podsadzkowych, ale również wymagania stawiane materiałom budowlanym (tab. 3).

Ściśliwość żużli ze zgazowania kształtuje się na poziomie 11÷14%, co pozwala zakwalifikować je do materiałów podsadzkowych III klasy. Aby uzyskać materiał wyższej klasy, konieczne jest zmieszanie żużli z piaskiem podsadzkowych. W zakresie wodoprzepuszczalności wszystkie żużle kwalifikują się, jako materiał podsadzkowy klasy I (rys. 5, tab. 4).

W normie PN-G-11011:1998 określone zostały wymagania podsadzki zestalanej oraz dla mieszaniny do doszczelniania zrobów. (tab. 5), tylko dla części badań wskazane są konkretne wymagania ilościowe. Wyniki badań wymywalność zanieczyszczeń chemicznych oraz zawartości radionuklidów zostały omówione wcześniej. Właściwości zawiesin w stanie płynnym zestawiono w tabeli 6. oraz na rys. 7, 8 i 9., a parametry reologiczne wg modelu Binghama na rys. 10÷13.

Wymagania w zakresie właściwości zestalonych zawiesin tj. wytrzymałości na jednoosiowe ściskanie oraz rozmakalności zostały ściśle określone dla podsadzki zestalanej jak i mieszaniny do doszczelniania zrobów (tab. 5). Zawiesiny przygotowane na bazie odpadów ze zgazowania węgla nie wykazują właściwości wiążących. Zarówno ze względu na wytrzymałość na jednoosiowe ściskanie (rys. 14) jak i rozmakalność (rys. 15) kwalifikują się jedynie, jako mieszaniny do doszczelniania zrobów.

Przeprowadzone badania wstępnie potwierdziły możliwość zastosowania ubocznych produktów zgazowania pochodzących z instalacji bazujących na reaktorach dyspersyjnych, w technologiach górniczych charakterystycznych dla polskiego górnictwa podziemnego. Dla ostatecznego potwierdzenia konieczne są oczywiście badania dokładnie tych odpadów, które miałyby być stosowane w konkretnych kopalniach. Przyszłe wykorzystanie zastosowania odpadów z procesu zgazowania węgla, jako materiałów podsadzkowych zależy od wielu czynników, do których zaliczyć należą: dalszy rozwój technologii podsadzki hydraulicznej w górnictwie polskim, a także właściwości i dostępność tego typu materiałów powstałych ze zgazowania polskich węgli i/oraz w instalacjach na terenie Polski.

Słowa kluczowe: zgazowanie, popiół, żużel, zawiesiny, podsadzka

1. Introduction

Most of the industrial coal gasification plants work on the basis of one of the three main types of reactors: fixed bed, fluid bed or dispersing. Depending on the type of reactor and the specific installation solutions, the arising gasification by-products may take various forms.

It depends largely on the ratio of the temperature of reactor work to the melting point of the minerals contained in the fuel, or in other words to softening and melting temperature of the ash. In recent years, dispersion "slagging" reactors became very popular in commercial installations. Dispersion reactors are now one of the most popular solutions in solid gasification technology. Most of the 2,016 planned gasification reactors are based on this type (W*orldwide Gasification Database*, 2010; Chmielniak & Tomaszewicz, 2012). It can be assumed that in the near future, installation of coal gasification based of dispersion reactors will being built also in Poland.

In such systems slag is captured and cooled after outflow from bottom part of the reactor. Besides slag, fly ash are also formed and captured in the exhaust system. It may be extracted separately or returned to the reactor chamber, where it is melted. In the latter case, the only slag is a by-product (*Clean Energy*..., 2008; Higman & van der Burgt, 2008; Pomykała & Mazurkiewicz, 2011b).

So far, ash and slag from the gasification process are mainly used as aggregates in the building and road construction industry (Aineto et al., 2005; Higman & van der Burgt, 2008). Potential usefulness in the ceramic industry was also stated (Acosta et al., 2002; Aineto et al., 2006). Searching for new directions of applications this type of material is still going on.

The article presents an analysis of the possibilities of using by-products of gasification as materials for hydraulic backfill, solidification backfill and mixture for gob caulking – technologies used in the Polish underground coal mining industry.

2. Backfill technologies

Several backfilling technologies, which use water to transport the material can be distinguish in the Polish underground mining. Traditionally, and for historical reasons, the term "hydraulic backfill" refers to that which meets the requirements of Polish Standard PN-93/G-11010. The most important features of the hydraulic backfill include: filling the previously separated voids, using material with the low compressibility and high permeability. This material, after draining the water has a mechanical support of the roof, and the backfill process is closely linked with to exploitation process as a way of liquidation of gob (cavity behind a longwall). Sand and mining waste, rarely metallurgical waste, are the most commonly used types of materials for this technology (Lisowski, 1997).

For over twenty years, in the Polish coal mining industry is present also other backfill technology, in which hydro transport is used. In this case, the solid materials are fine-grained (with a predominance of dust fraction), which after mixing with water form a suspension. Such mixtures are often referred to as ash-water suspensions or fly ash suspension (because their main ingredient are different types of fly ashes), and technology as suspension backfill or suspension technology. Polish standard PN-G-11011:1998 distinguishes two types of such suspensions and defines them as "solidifying backfill " and "mixture for gob caulking."

The basic reason for the use of fine-grained suspensions in mining technologies was initially necessity of management of waste from mining and power industry (Mazurkiewicz et al., 1998;

Piotrowski et al., 2006; Piotrowski, 2010; Plewa & Mysłek, 2000; Plewa & Sobota, 2002). Currently, suspension technology entered very deeply and permanently in coal mines and became indispensable means of fire and methane prevention (Dziurzyński & Pomykała, 2006; Palarski, 2004; Pomykała, 2006). Most frequently suspensions are used for partially or completely fill the breaking down zone („gob filling" or „gob caulking") arising as result of the coal exploitation in longwall system. In this way, the effect of cooling and insulating is being achieved and thus – limiting the possibility of two-way gas flow, both: from exploitation zone (air) as well as from the gob (methane and gases – coal oxidation products). This is particularly important for reducing the risk of spontaneous endogenic fire, which are still present in Polish coal mines (Trenczek, 2008). Suspensions are used also in other mining technologies, among others to liquidation (fulfilling) of unnecessary roadways. Still an important goal of suspensions in the mining industry is the use of waste, this is particularly fine-grained mining wastes, such as tailings or slimes (Piotrowski, 2010; Pomykała et al., 2012).

While traditional hydraulic backfill is increasingly rare used in Polish coal mines, interest of use fine-grained suspensions continues to grow. A major barrier to the wider use of fly ash is its availability of a short distance from the mines. Mining here feels strong competition from the cement, building and road construction industry, especially in the summer months. Therefore, intensive activities and researches are carried, aimed at expanding the range of potential materials (preferably waste) available and feasible, as components of the backfill suspension technology.

Both referred Polish standards for hydraulic backfill and suspension backfill (solidification backfill and mixture for gob caulking) are constructed according to a similar pattern. First, the requirements on the basic physical and chemical properties of materials are defined followed by the technological properties of backfill mixtures. A similar arrangement is used in this paper: due to the fact that the basic requirements for the material properties of both standards are similar, or in some cases identical – are listed together. The rest of the properties are shown by-products of gasification, as components of mixtures backfilling.

3. Test Materials

For testing were used waste (by-products of gasification) origin from foreign installations, where coal is gasified, but also other additives such as bitumen (slag S1), and biomass (fly ash A2 and slag S2). All of the sample material obtained from the system are based on dispersion "slagging" reactors, in which the process temperature exceeds the melting point of the minerals contained in the fuel. In each of these installations the slag is primary by-product . Fly ash captured in the exhaust gas treatment systems are often recycled back into the reactor. Only from one of the installations both the slag and ash was obtained, from two remaining only slag.

Initial characterization of three (S1 and S2 slag, fly ash, A2) of four of the wastes has been presented previously (Pomykała & Mazurkiewicz, 2011a). For the conservation continuity the same sign have been left, where "S" stands for slag, A – ash, and the numbers from 1 to 3 were determined sequentially gasification installations.

Each of the two main types of backfill requires the use of other materials, especially in the field of granulation. For hydraulic backfilling are suitable materials containing mainly sand fraction (0.5÷2.0 mm) and gravel (2 to 40 mm). Strongly limited are content of grain less than 0.1 mm. Among the obtained materials only slags meet this condition, and only slags were analyzed in terms of fit for this technology.

In backfill suspension is usually used materials with smaller grains – there prevails dust fraction (0.002÷0.5 mm), which corresponds to most of the fly ash particle size. Materials of larger grains are used rarely, usually as a supplement – alone do not form stable suspensions of water, bigger grains sedimentate very easy, which is undesirable. Among the analyzed by-products of gasification only ash A2 resembles a typical material used in this technology. Therefore, for a complete determination of the properties of coal gasification by-products in terms of usefulness for the backfill suspension, slags was subjected to grinding process, and only in such a state were used to prepare suspensions.

4. The basic properties of the gasification by-products as backfill materials

Basic tests of gasification by-products include such properties as density, moisture content, grain composition, leachability of chemical contaminants and radionuclides content. Selected physical properties of the gasification by-products and the marking are presented in Table 1.

TABLE 1

Basic properties of wastes and their marking

Type of material	Marking	Moisture [%]	Colour	Specific density [Mg/m^3]	Bulk density [Mg/m^3]
Slag from coal gasification in installations I	S1	5.5	Black	2.52	1.44
Slag from coal gasification in installation II	S2	4.5	Black	2.55	1.47
Fly ash from coal gasification in installation II	A2	0.5	Grey	2.39	1.41
Slag from coal gasification in installation III	S3	5.5	Black	2.63	1.56

Grain composition

Determination of particle size distribution of slags were performed using sieve shaker. Particle size distribution of slags and, for comparison, two other backfill materials: sand and steel slag, is shown in Figure 1. The key limitation to use material in the hydraulic backfill, is content of particles of size below 0.1 mm. In all the analyzed slags the content of particles smaller than 0.1 mm does not exceed 6%, and the maximum size – 10 mm. Thus, due to the grain composition gasification slags comply the requirements for backfilling materials class I (Table 4).

Figure 2 shows the curves of grain distribution of A2 ash and the milled slags from coal gasification i.e. the materials used for the preparation of suspensions and for test their suitability for the solidifiaction backfill and mixture for gob caulking. Wherever the milled slags are used the index "m" is added to the mark: "S1m", "S2m" and "S3m".

Leachability of chemical contaminants

The results of chemical contaminants leaching together with requirements for waste used as hydraulic backfill material according to PN-93/G-11010 as well as for materials used in suspension backfill (solidification backfill and / or a mixture of the gob caulking) posed by PN-G-11011:1998, are summarized in table 2.

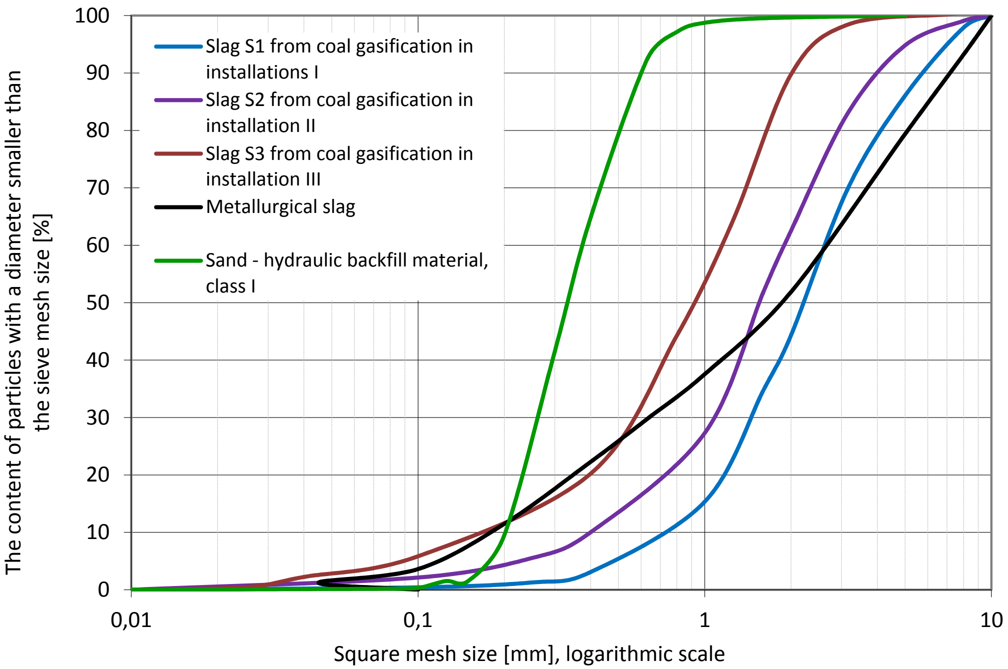

Fig. 1. Particle size distribution of slags from coal gasification, and other backfilling materials: sand I class

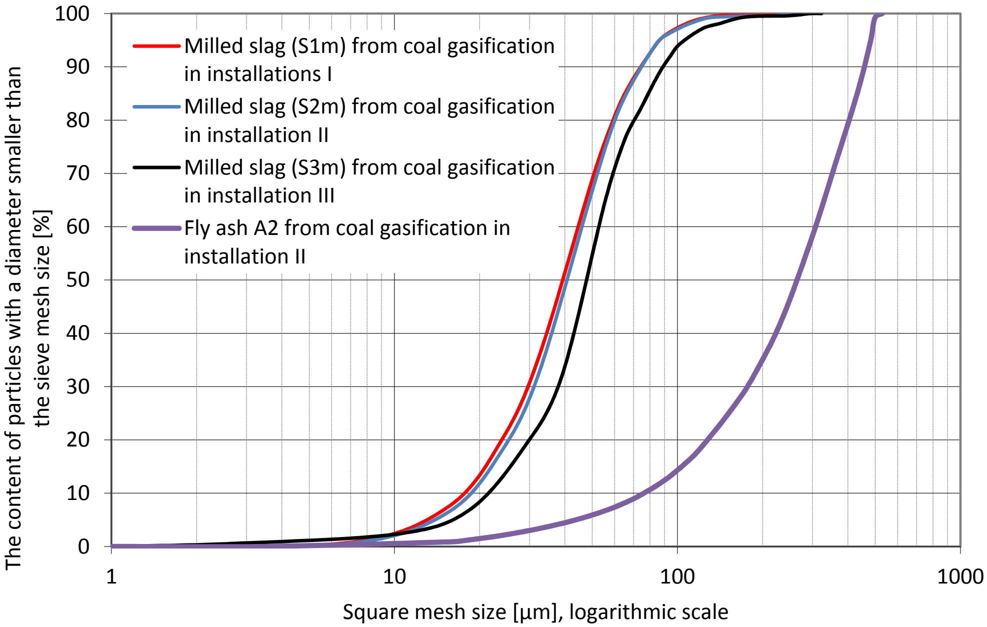

Fig. 2. Particle size distribution of fly ash A2 and milled slags from coal gasification, (with index “m”)

TABLE 2

Chemical leaching of coal gasification wastes (Pomykała & Mazurkiewicz, 2011a)

Indicator or type of contamination	**Unit**	**Requirements of:**		**Coal gasification slag S1**	**Coal gasification slag S2**	**Fly ash from coal gasification A2**	**Coal gasification slag S3**
		PN/G-11010	**PN-G-11011**				
pH		6.5 – 9.0	6.0 – 12.0	**3.92**	**6.35**	6.09	8.28
Chloride	mg/dm^3	1000	1000	2.5	6.8	11.7	3.7
Sulfur	mg/dm^3	500	500	64.97	28.10	105.31	9.3
Arsenic	mg/dm^3	n/d	n/d	<0.001	<0.001	0.031	<0.001
Chrome	mg/dm^3	0.7	0.7	<0.005	<0.005	<0.005	0.0051
Zinc	mg/dm^3	2.0	2.0	0.005	0.002	9.49	0.0090
Cadmium	mg/dm^3	0.1	0.1	0.0010	0.0003	0.0498	0.0003
Copper	mg/dm^3	0.5	0.5	0.057	0.001	<0.001	0.0049
Nickel	mg/dm^3	2.0	2.0	**15.769**	0.056	**2.797**	0.0014
Lead	mg/dm^3	0.5	0.5	0.0007	0.0001	0.0002	0.0025
Potassium	mg/dm^3	80	80	0.34	0.54	11.62	2.12
Mercury	mg/dm^3	n/d	0.02	0.0046	0.0020	0.0046	0.001
Sodium	mg/dm^3	800	800	1.35	0.82	36.94	1.85
Total hardness	mg $CaCO_3$/dm^3	n/a	n/a	8.3	41.9	77.2	30.9
Carbonate hardness	mg $CaCO_3$/dm^3	n/a	n/a	0.0	0.0	64.7	15.6
Non- carbonate hardness	mval/dm^3	n/a	n/a	0.17	0.84	0.25	0.3
Electrolytic conductivity	mS/cm	n/a	n/a	0.182	0.121	0.415	0.0736

Based on the results found exceeding of the limits of one or both mentioned standards in the ranges of pH and / or nickel for the samples slags S1 and S2 and A2 ash. Draws attention a very low pH and a very high content of nickel for slag S1, it is rather unusual things for Polish waste from coal combustion.

The content of radionuclides

The specific activities of analyzed material are assembled in Table 3. The study involved only gasification slags. Concentrations of natural radioactive isotopes are given in accordance with the instructions of Building Research Institute in Warsaw, No. 234 of 1995. According with the requirements of both backfilling standards, the specific activity of the radioactive isotope (isotopes 226Ra + 228Ra and / or 226Ra) in the backfilling material should not exceed 1×10^4 Bq/kg.

Analyzed slags from gasification meet these requirements. In addition, they also met a much tougher requirements for materials construction, concerning maximum content of natural radioactive isotope of potassium (40K), radium (226Ra) and thorium (228Th) „in raw materials and construction materials used in buildings designed to accommodate people and livestock, as well as in the construction of industrial waste“ referred to Council of Ministers Ordinance of January 2, 2007 (Journal of Laws No. 4, pos. 29). According to this regulation values of activity indicators f1 and f2 can not exceed by more than 20% of the value of f1 = 1 and f2 = 200 Bq / kg for raw materials used in buildings designed to accommodate people. Tested slags met the above inequality, so can be put into the production of construction materials used in buildings intended for human residence.

TABLE 3

Concentration of radionuclides in the slags from coal gasification

Type of material	**Specific activity**			**f1**	**f2**	**Specific activity**
	40K	**226Ra**	**232Th (228Ra)**			**226Ra+228Ra**
	[Bq/kg]	**[Bq/kg]**	**[Bq/kg]**	**[-]**	**[Bq/kg]**	**[Bq/kg]**
Slag from coal gasification in installations I	564 ± 27	132 ± 5	98 ± 5	1.12 ± 0.05	132 ± 5	230 ± 7
Slag from coal gasification in installation II	443 ± 23	84 ± 4	58 ± 3	0.72 ± 0.03	84 ± 4	142 ± 5
Slag from coal gasification in installation III	395 ± 21	72 ±34	78 ± 4	0.76 ± 0.03	72± 3	150 ± 5

5. Requirements for hydraulic backfill materials

PN-93/G-11010 standard that specifies requirements for hydraulic backfill materials defines three classes of backfill materials (Table 4). Requirements concerning density and grain size are met by all slags (Table 1 and Figure 1). The content of grain size less than 0.1 mm for all ot them corresponds to the class I of backfill materials. Gasification by-products do not contain the visible part of the plant, which is a natural consequence of the process, from which they originate. Among the remaining requirements summarized in Table 4 only grindability test were not realized. However, hardness of the slags, set at about 6.5 on the Mohs scale (Pomykała & Mazurkiewicz, 2011a), are only slightly less than the backfilling sand, so it can be assumed that grindability requirement can be met similar like for sand.

TABLE 4

Requirements for backfill materials according to Polish Standard PN-93/G-11010

Material class	**The content of particles of size less than 0.1 mm, at most:**	**Largest particle size**	**Compressibility at a pressure of 15 MPa, at most:**	**Permeability, at least**	**Grindability, at most:**	**Bulk density nasypowa at least**	**The content of the visible part of the plant**
	[%]	**[mm]**	**[%]**	**[cm/s]**	**[%]**	**[kg/dm^3]**	
I	10	60.0	5	0.007	20	1.3	should not contain
II	15		10	0.002			
III	20		15	0.0004			

Compressibility

Compressibility is one of the most important properties of the material used in the hydraulic backfill. This allow to determinate the possible reduction of the high and volume of backfill material under a load of the roof. Polish Standard PN-93/G-11010 indicates the maximum compressibility value at a load of 15 MPa, for each of the three classes of materials: 5% for class I, 10% for the second (II) and 15% for the third (III).

Compression tests were carried out for gasification slags, as well as their mixtures with backfilling sand class I (Fig. 3 to 5). Compressibility of the slags remains at level of 11÷14%, allowing them to qualify for class III of backfilling materials. For the second class of backfilling material, the compressibility of up to 10% is demanded. This condition is fulfilled for slag and sand mixtures. For the case of S2 and S3 slag minimum amount of sand in the mixture is 50%.

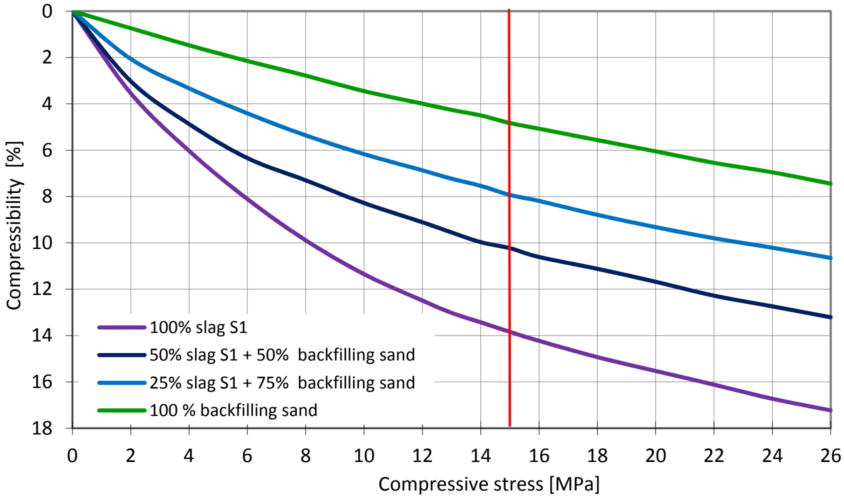

Fig. 3. Compressibility of coal gasification slag S1 and its mixtures with backfilling sand class I

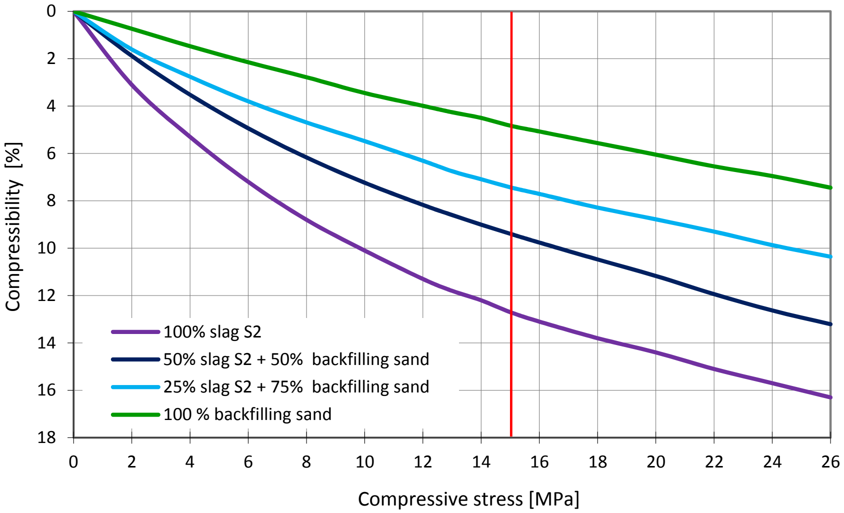

Fig. 4. Compressibility of coal gasification slag S2 and its mixtures with backfilling sand class I

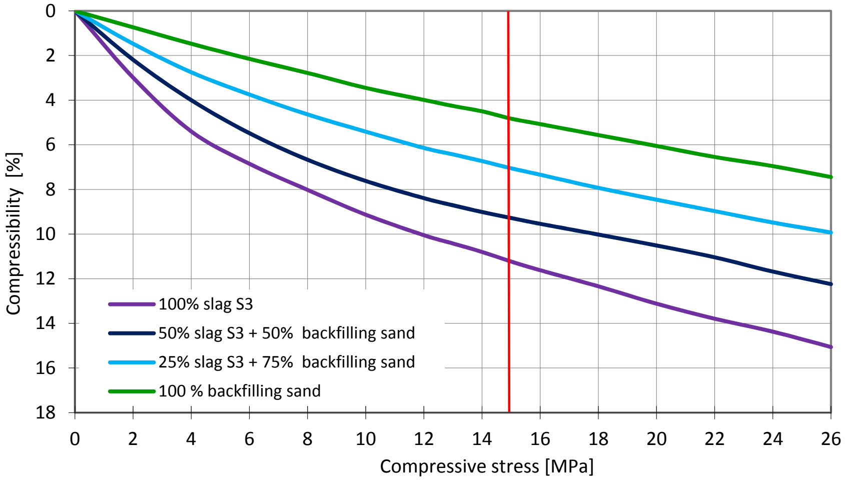

Fig. 5. Compressibility of coal gasification slag S3 and its mixtures with backfilling sand class I

However, this is not enough in the case of slag S1 (Fig. 3). Additional research conducted for this material indicated at least the 60-percent share of sand allows achieving compression rates below 10%.

Permeability

Permeability tests were carried out both for the slag and mixtures of sand backfilling. The results are summarized in Figure 6. Obtained permeability values allow to classification all analyzed materials and mixtures to the first class of backfilling materials.

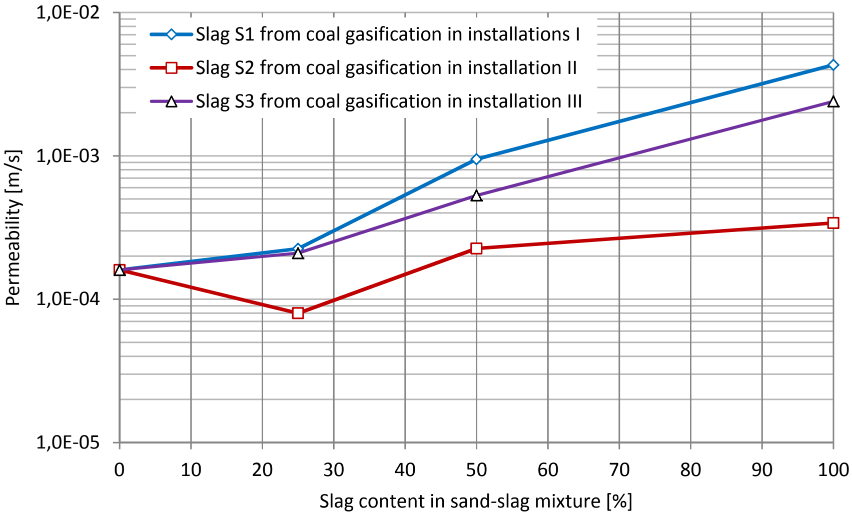

Fig. 6. Permeability of coal gasification slags and their mixtures with backfilling sand class I

6. Requirements for materials used in solidification backfill and mixture for gob caulking

Polish Standard PN-G-11011:1998 "Materials for solidification backfill and mixtures to caulking gob. Requirements and test methods" refers to both properties of materials, suspensions in a liquid state as well as suspension after solidification. Only for part of the defined properties, the specific quantitative requirements are indicated (Table 5). The results of the same material properties (density, grain composition, leachability of chemical contaminants, the content of radionuclides) have been discussed previously.

TABLE 5

The requirements for materials to solidification backfill and mixture for caulking gob

Lp.	Feature	Unit	Solidification backfill	Mixture for gob caulking
1.	Specific density of material	Mg/m^3	Over 1.0	
2.	Suspension density	Mg/m^3	At least 1.2	
3.	Largest particle size	mm	Conditioned by the ability to hydro transport; cannot exceed 1/3 the diameter of the pipeline	
4.	Leachability of chemical contaminants	mg/dm^3	According to table 2	
5.	Fluidity	mm	At least 90	
6.	Uniaxial compressive strength	MPa	At least 0.5	-
7.	Soakability (collapsing behaviour)	%	Up to 20	After soaking in water, the sample can not to disintegrate
8.	The content of the supernatant water	%	Up to 7 %	Max. 15%

In addition to the specific requirements for the properties of the ash and suspensions, the PN-G-11011 are also described other requirements which must be individualized to the local conditions of use. Belong to them viscosity (and more broadly, the rheological properties of suspensions), setting time, compressibility and water permeability. Among them the paper presents the results of the rheological properties and setting time. The results are shown in the form of rheological of flow curves of the Bingham model, which well reflects the characteristics of such mixtures, transported gravitationally by pipeline (Stryczek et al., 2009; Stryczek & Wiśniowski, 2001, 2004).

Properties of suspensions in a liquid state

To investigate the properties of the fine-grained suspensions in the liquid state, the water mixtures of gasification by-products were prepared in various proportions of solids to water. The proportions were titrated toward that, fluidity of suspensions was in the range from 180 to 300 mm, which ensures a stable flow in backfilling pipeline. The results of fluidity, the amount of supernatant water and setting time are summarized in Table 6 and shown in Figures 7, 8 and 9.

TABLE 6

Properties of suspensions based on based on fly ash and milled slags from coal gasification process

Lp.	Type of material	The weight ratio of solids to water s/w	Density [Mg/m3]	Fluidity [mm]	Amount of supernatant water [%]	Setting time	
						Beginning [day]	End [day]
1.	S1m	1,50	1,562	290	3,6	5	8
2.	S1m	1,70	1,619	220	2,9	3	5
3.	S1m	2,00	1,685	180	1,3	2	4
4.	S2m	1,50	1,568	300	5,3	5	8
5.	S2m	1,70	1,605	250	4,6	4	7
6.	S2m	2,00	1,698	180	1,7	3,5	6
7.	A2	0,70	1,345	300	8,3	13	16
8.	A2	0,80	1,345	250	4,5	10	12
9.	A2	0,90	1,369	220	2,4	9	11
10.	A2	1,00	1,411	200	1,8	8	10,5
11.	A2	1,25	1,460	160	0,3	7	9
12.	S3	1,50	1,547	320	18,2	12	14
13.	S3m	2,00	1,661	260	12,4	8	11
14.	S3m	2,50	1,743	200	3,1	7	9,5
15.	S3m	3,00	1,788	170	0,4	4	6

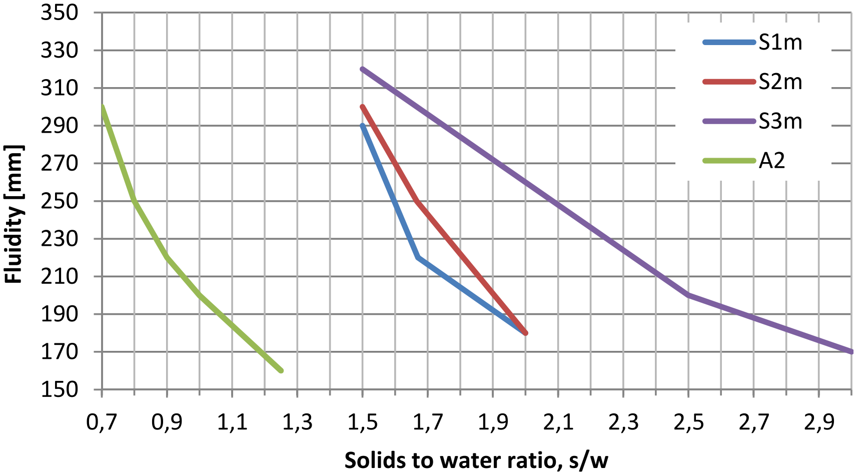

Fig. 7. Fluidity of suspension based on fly ash and milled slags from coal gasification process

Research results of suspensions in the liquid state allows for the indicate the three groups with slightly different behavior. To the first group includes suspensions prepared on the base of gasification ash A2, the second one – suspension of the milled slag S1 and S2, and the third – suspension on the base of milled slag S3. Water suspensions of ash the A2 already at small

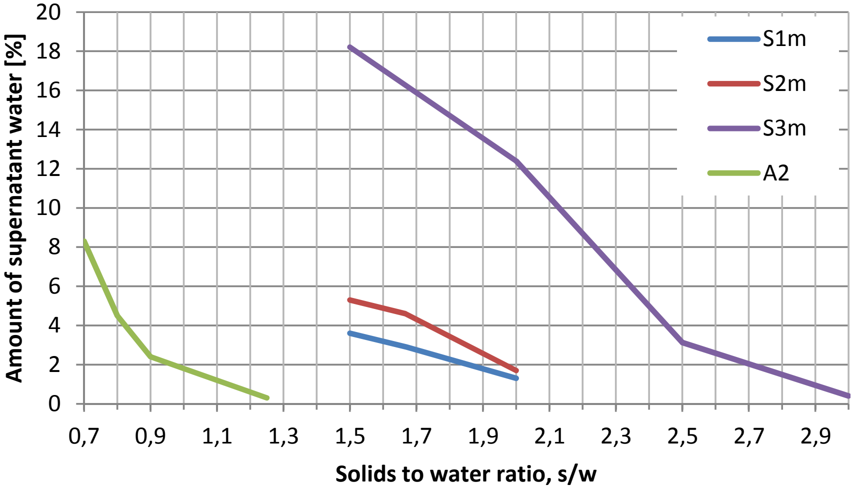

Fig. 8. Amount of supernatant water of suspensions based on fly ash and milled slags from coal gasification process

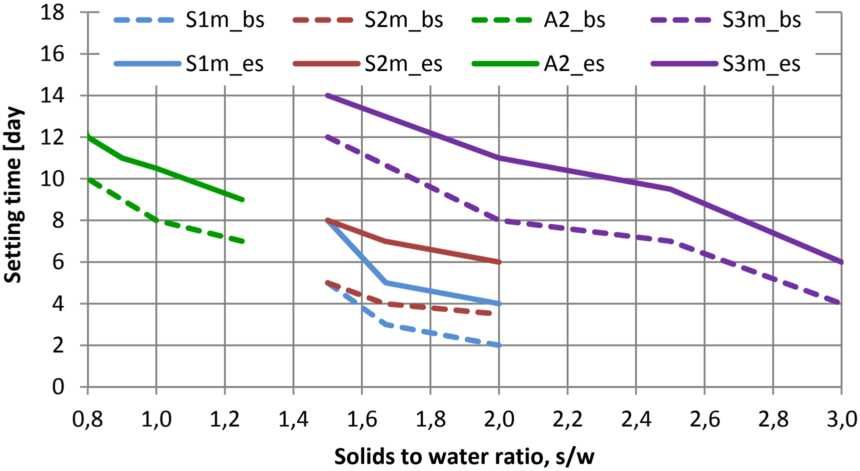

Fig. 9. Setting time of suspensions based on fly ash and milled slags from coal gasification process, “bs” index marks beginning of setting, and “es” – end of setting

values of the s/w ratio (solids to water ratio) had the consistency such as suspensions of milled slags with nearly double solids content (nearly twice bigger s/w). For example, to obtain a suspension with a fluidity of 250 mm, was enough to mix the A2 ash with water in the ratio with 0.8:1, but when the S1M was used – the s/w ratio was 1.6:1, for S2m – s/w = 1.7:1 and for S3M s/w had to increase even to 2.1:1. This had influenced clearly on the other properties – such as the amount of supernatant water.

From each of the analyzed material is possible to prepare suspensions that meet the standard requirements for the solidification backfill and mixture to caulking gobs, in the field of both the fluidity and amount of supernatant water.

Setting time of suspensions, calculated as the period between the begin of binding to the end, was practically independent of the type of material and the s/w ratio, and took about 2 days.

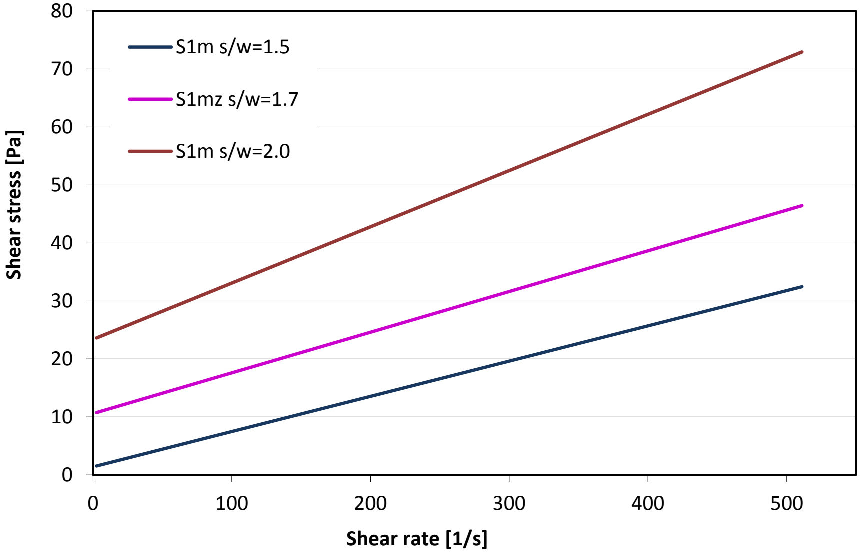

Fig. 10. Flow curves of rheological Bingham model of suspensions based on milled slag from coal gasification S1m

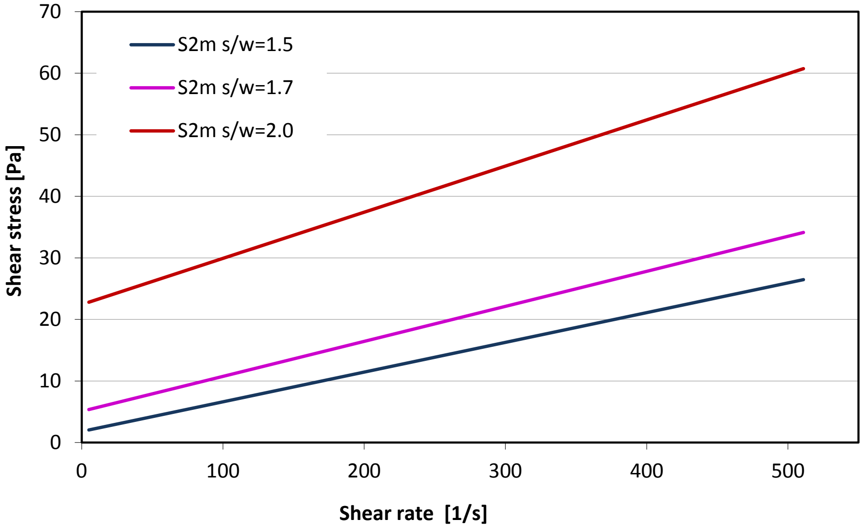

Fig. 12. Flow curves of rheological Bingham model of suspensions based on ash from coal gasification A2

Fastest the end of setting occurred at case of suspensions based on milled slag S1m and S2m with the s/w = 2.0:1. Latest: for the suspensions of ash A2 and milled slag S3m, with the s/w ratio of0.8:1 and 1.5:1, respectively.

The rheological properties of the suspensions in a liquid state was carried out using rotating viscometer of Rheotest. The results are presented in the form of the rheological parameters of the Bingham model: the plastic viscosity and yield stress. Flow curves of tested suspensions are presented in figures from 10 to the 13.

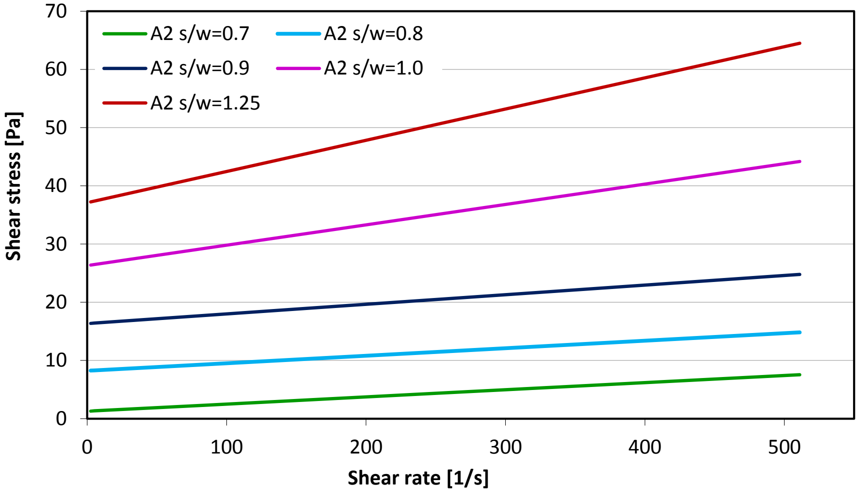

Fig. 12. Flow curves of rheological Bingham model of suspensions based on ash from coal gasification A2

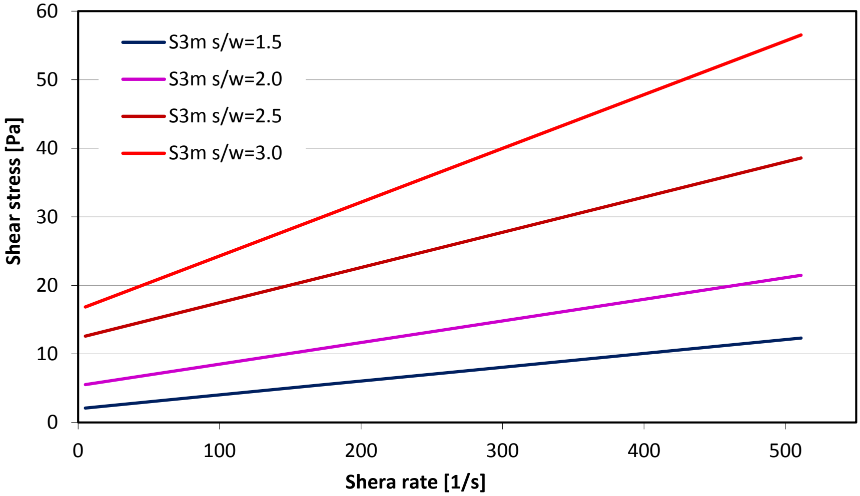

Fig. 13. Flow curves of rheological Bingham model of suspensions based on milled slag from coal gasification S3m

Properties of solidified suspensions

Research of solidified suspensions included determination of uniaxial compression and soakability. The results are presented in Figure 14 and 15.

Strength parameters of tested suspensions do not allow to qualify them as a solidification backfill according to PN-G-11011:1998. In any case, the compressive strength does not exceed

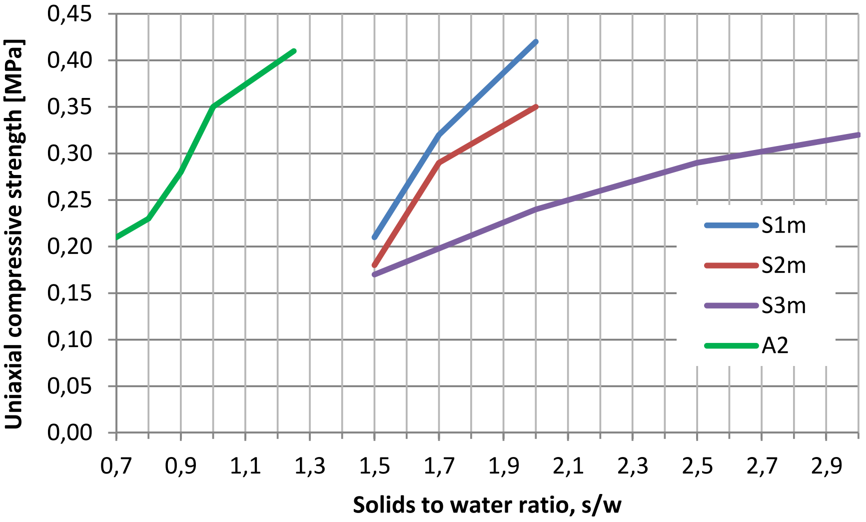

Fig. 14. Uniaxial compressive strength of suspensions based on fly ash and milled slags from coal gasification process

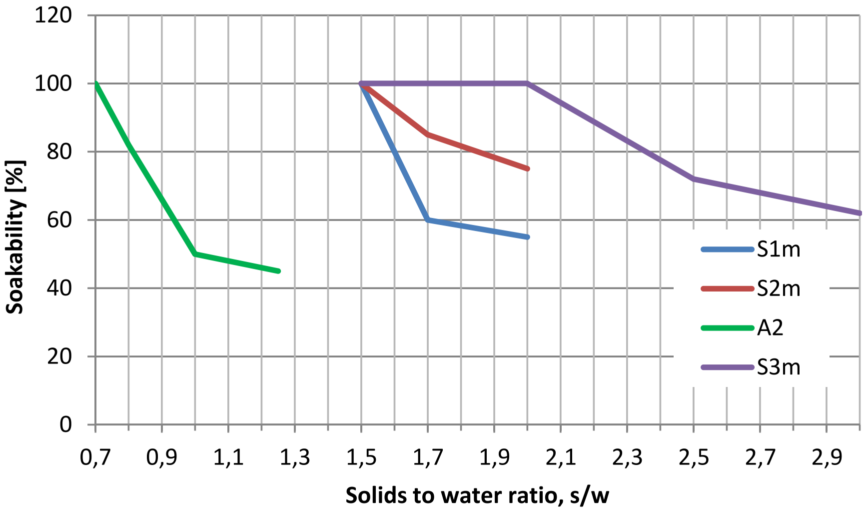

Fig. 15. Soakability of suspensions based on fly ash and milled slags from coal gasification process

the required minimum value of 0.5 MPa. Also, when testing soakability, part of the samples with the lowest values of ratio s/w – have completely disintegrated during the seasoning in water. This indicates practically lack of binding ability of these suspensions. This is also consistent with the results of the pozzolanic properties of such by-products of gasification (Mazurkiewicz et al., 2012). To use this type of materials to solidification backfill technology would be necessary to apply the binding materials such as cement.

Analyzed suspensions (except for one: prepared from milled slag S3m with ratio s/w = 3.0), meet the requirements in the range of mixtures for gob caulking. Depending on the local conditions and needs of the mining process, suspensions can be prepared in wide range of consistency.

7. Summary and Conclusions

The article discusses the possibility of using wastes from coal gasification processes in reactors dispersion as materials for: hydraulic backfill (according PN-93/G-11010) as well as solidification backfill and mixture to gob caulking (according to PN-G-11011:1998).

Research in this area has been taken knowing that the properties of wastes from thermal treatment of solid fuels depends not only on the parameters of the process itself, but also on the characteristics of the fuel used. Analyzed wastes were created from the gasification of coal and additives (bitumen and biomass) available in the local markets (specific to each installation). This is reflected, among others in the leaching test results – in two cases exceeded the maximum levels of nickel and pH of the effluent. These are not typical results for Polish energy waste, tested many times in this area (Mazurkiewicz et al., 1997; Piotrowski et al., 2009; Piotrowski, 2010). For this reason, at this stage of reflection, this should not be a cause for disqualification of the gasification wastes as a materials for use in mining technology.

The tests referred for the hydraulic backfill performed only for the slags. The obtained results allow to conclude that the slags from coal gasification can provide valuable backfilling material at least the third class (after eliminating objections to the leaching of chemical contaminants). There is also the possibility to achieve a higher class of backfill material, by mixing slags with good quality sand.

Fly ash and milled slags A2 were also tested for their suitability as backfill materials for and mixtures solidification to caulking gob. Studies have shown no binding properties of the suspension samples – in no case was achieved uniaxial compression required for the solidification backfill (0.5 MPa). Thus, analysed suspension cannot be used as solidified backfill. It is however possible to use them as a mixture to caulking gob, provided that the samples are not disintegrated during the test subject soakability (rozmakalność will be less than 100% – Figure 15).

Conducted research confirmed introductory the possibility of applying by-products from gasification installations based on dispersion reactors, to the mining technologies which are characteristic for the Polish underground coal mining. For the final acknowledgment are necessary, of course, thoroughly test of this waste that would be used in particular mines. Future applications of waste from gasification process as backfill material depends on many factors, among which include: further development of the technology of hydraulic backfill in mining Polish, as well as the properties and the availability of this type of material resulting from the gasification Polish coal and / or in systems in Polish.

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