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The effects of mineralogical changes that occur in artificial aggregates

Introduction

By-products of coal combustion as well as hard coal mining and metallurgical wastes constitute the largest source of industrial wastes generated in Poland. In 2013, the amount of wastes of that origin exceeded 124 mln Mg (Statistical Yearbook of the Republic of Poland 2014). For ecological and economic reasons, such wastes are being increasingly used as a binding component in road substructures (Dimter et al. 2011; Gawlicki and Wons 2012; Kołodziejczyk et al. 2012), or as a substitute for natural aggregates – they form the base of artificial aggregates (Borowski 2010; Barišić et al. 2010; Góralczyk and Kukielska 2011; Ebrahimi et al. 2012; Swamy and Das 2012; Vestin et al. 2012; Kolisetty and Chore 2013; Hainin et al. 2015; Uliasz-Bocheńczyk et al. 2015).

It is required that artificial aggregates meet standard parameters in terms of physical and chemical properties of natural aggregates, e.g. frost resistance, sulphate content, etc.: (PN-B-11115:1998; PN-S-96035: 1997; Sybilski and Kraszewski ed. 2004). In addition, this is required to determine additional characteristics, such as silicate dissolution and iron dissolution (PN-EN-1744-1:2010).

Wastes produced as a result of high temperatures (slag and power plants ashes, metallurgical wastes) are not as stable in terms of chemical and phase composition in the hyper-

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genic environment (Woolley et al. 2000; Adamczyk and Nowak 2012, 2013; Gawlicki and Małolepszy 2013; Nowak 2014; Akbarnejad et al. 2014). There are no studies on the potential transformations of artificial aggregate components caused by hypergenic influences. This could lead to a situation in which the material that is built-in as an embankment layer or the bedding layer of the road will be subject to uncontrolled changes in the chemical and/or phase composition, which may affect the design of the building structure.

This occurred on one of the roads where artificial aggregates produced on the basis of wastes: coal shale (hard coal mining waste) and fluidized ashes, among others, were used for construction. After completion of the construction works, but before making the road available for public use, local bumps of the surface appeared; the maximum height of which exceeded even 6 cm. It was excluded that this resulted from mining damage, design errors or performance mistakes, among others. A study of the materials that had been incorporated in the construction layers was undertaken in order to find the component and the mechanism responsible for the buckling of the road surface.

1. Sampling and research methodology

To achieve the above goal, mineralogical tests were conducted on the following samples (Fig. 1, Table 1):
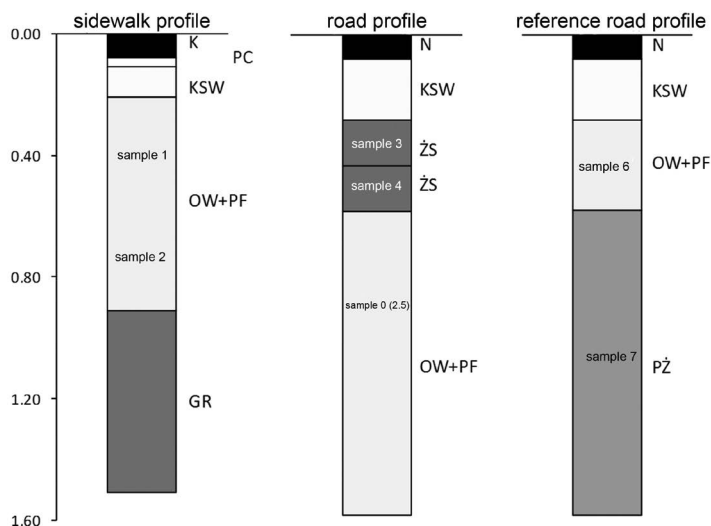

Fig. 1. Schematic profile of the pavement structure and sidewalk with separate bedding layers and the surface
GR – native soil, K – stones, KSW – carbonate rock aggregate, N – surface, OW+PF – coal shale with fluidized ash, OW+PL – coal shale with fly ash, PC – sand with cement, PŻ – improved slag sand, ŻS – steelmaking slag

Rys. 1. Schematyczny profil dróg i chodnika z wydzielonymi warstwami podbudowy i nawierzchni
GR – grunt rodzimy, K – kostka, KSW – kruszywo skał węglanowych, N – nawierzchnia,
OW+PF – łupek węglowy z popiołem fluidalnym, OW+PL – łupek węglowy z popiołem lotnym,
PC – piasek z cementem, PŻ – piasek żużlowy ulepszony, ŻS – żużel stalowniczy

Table 1.   Summary and characteristics of the artificial aggregates samples

Tabela 1.   Zestawienie i charakterystyka badanych próbek kruszyw sztucznych

Symbol of the sample	Characteristics of the sample	Macroscopic description
0	a reference sample for samples 1 and 2 collected during road construction	a mixture of hard coal mining wastes of dark gray to nearly black color (claystones, sandstones) and fluidized ash of light gray color, admixture of limestone aggregates
1	samples collected from the bump of the pavement surface	upper part of the bedding layer; a mixture of hard coal mining wastes (mainly claystones) and fluidized ash; gray in color with white grains of approximately 1 mm; the material makes hard agglomerates
2		lower part of the bedding layer; characteristics as in sample 1
3	a reference sample for sample 4; collected during road embankment construction	a mixture of wastes: porous steelmaking slags (including glaze) and burnt hard coal mining wastes of brick-red color
4	a sample collected from the bump of the road surface	heterogeneous material: porous steelmaking slags (including glaze and skulls) with admixture of hard coal mining wastes (mostly sandstones)
6	comparative samples for samples 1 and 2 from the surface without bumps	upper part of the bedding layer; dark gray mixture of hard coal mining wastes (with pyrite) with admixture of fly ashes
7		lower part of the bedding layer; improved slag sand; gray mixture of wastes: porous steelmaking slag (including glaze of olive color) with admixture of fly ashes

- ◆ samples collected from the profiles of building structures, bedding layers of the sidewalk (samples 1 and 2) and pavement structure (sample 4) where characteristic surface bumps were observed,
- ◆ reference samples (archive, collected during road construction (samples 0 and 3),
- ◆ comparative samples collected from the area where no bumps occurred (samples 6 and 7).

The following sample analysis techniques were applied:

- ◆ microscopic examination with transmitted and reflected light (Zeiss Axioskop and Axioplan microscopes),
- ◆ X-ray diffraction for phase identification (XRD, EMPIRIAN diffractometer from PANALITYCAL),
- ◆ X-ray fluorescence for chemical analysis (XRF, ZSX PRIMUS spectrometer from RIGAKU) as well as loss on ignition (in accordance with PN-EN 15169:2011 standard),
- ◆ differential-thermal analysis (Paulik, Paulik-Erdey derivatographs).

2. Study results

2.1. Mineral composition

The mineral composition of sample 0 consists of typical elements that constitute hard coal mining wastes (clay minerals – illite and kaolinite, quartz, siderite, organic matter) (Galos ed. 2009; Jonczy et al. 2012; Bzowski 2013). The presence of anhydrite and calcite, which are characteristic components of fluidized ashes, was also found (Giergiczny 2005, 2006; Brandt ed. 2010; Strzałkowska 2011; Gawlicki and Wons 2012; Stryczek ed. 2013).

In terms of mineral composition, samples 1 and 2 are very similar, because they have been identified to contain clay minerals (kaolinite), quartz and organic matter. Moreover, diffractograms of both samples (Fig. 2) showed mainly ettringite reflections (9,70; 5,60; 3,86 Å), while sample 2 also showed gypsum (reflections 7,60; 4,28; 3,06; 2,86 Å) (Fig. 2).
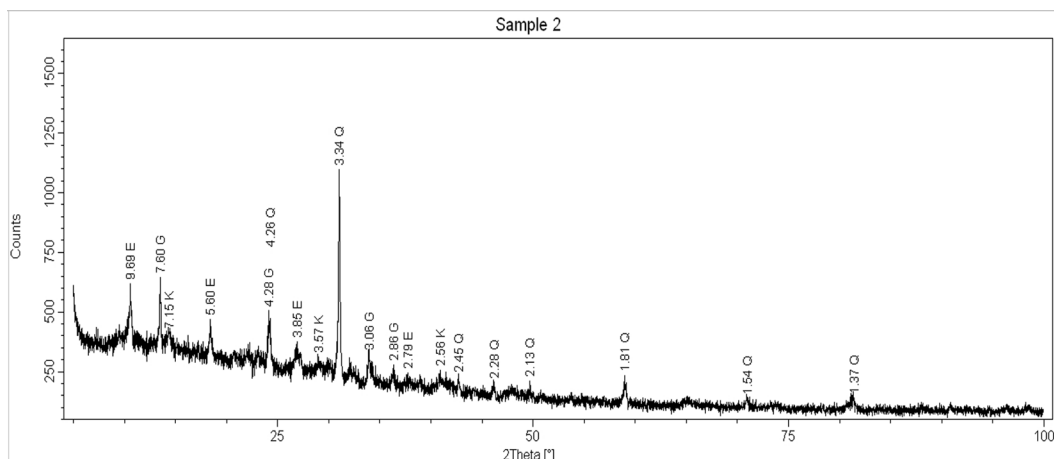

Fig. 2. Diffractogram of sample 2
Q – quartz, E – ettringite, K – kaolinite, G – gypsum

Rys. 2. Dyfraktogram próbki 2
Q – kwarc, E – ettringit, K – kaolinit, G – gips

Thermal analysis also indicated the presence of gypsum and ettringite, as the DTA curve in lower temperatures (100–200°C) showed a thermal effect associated with the hydration of these components (Fig. 3). Both gypsum and ettringite are not typical components of the material from which the aggregates were made, and therefore were most likely secondary components.
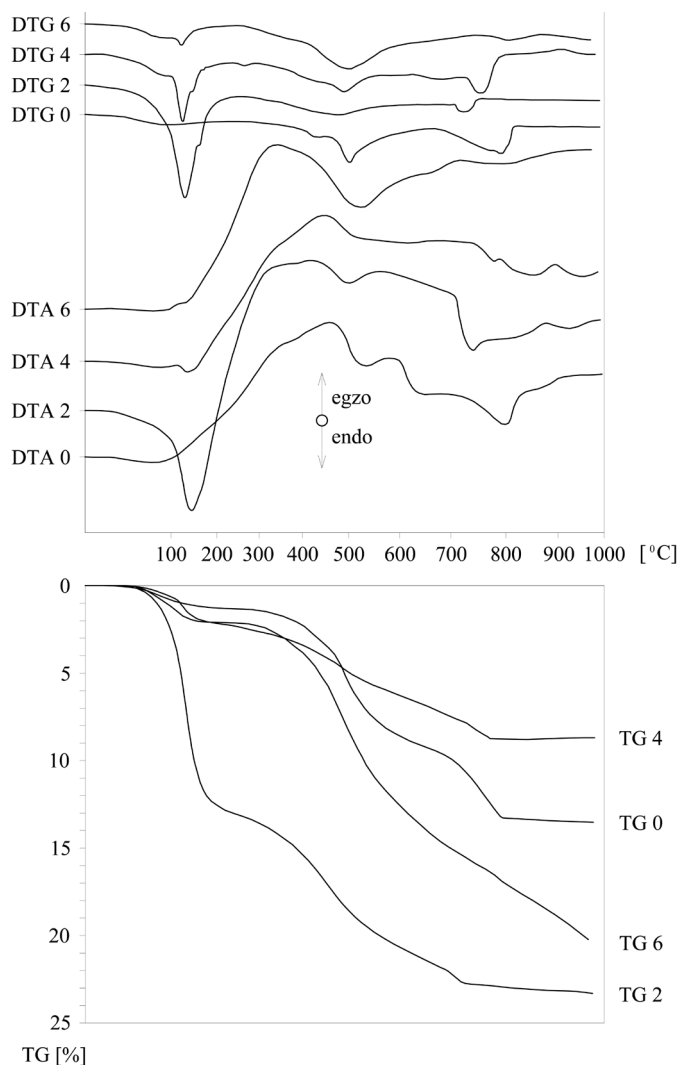
Fig. 3. Derivatograms of samples 0, 2, 4, 6

Rys. 3. Derywatogramy próbek 0, 2, 4, 6

Based on microscopic examination and XRD analysis of the mineral composition of sample 3, the presence of minerals typical for burnt hard coal mining wastes – quartz and hematite as well as minerals typical for steelmaking slag phases – monticellite, melilite, merwinite (Jonczy 2012, 2014) was revealed. In addition, a metallurgical component or an alteration of zinc and lead – sphalerite and willemite was identified (Fig. 4). Glaze constitutes an additional component of this material, which is showed on the diffractogram by an increased background angled at a range of 2 theta 10–35°.
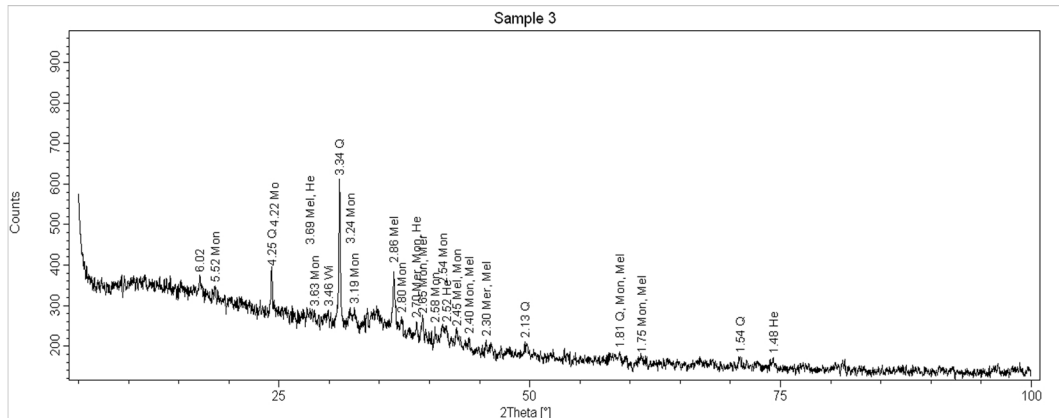
Fig. 4. Diffractogram of sample 3
Q – quartz, Mon – monticellite, Mel – melilite, Mer – merwinite, He – hematite, Wi – willemite

Rys. 4. Dyfraktogram próbki 3
Q – kwarc, Mon – monticellity, Mel – melility, Mer – merwinit, He – hematyt, Wi – willemit

Sample 4, due to its high heterogeneity, showed the presence of minerals such as: quartz, gypsum, hematite, clay minerals (kaolinite and Na-montmorillonite), feldspars (anorthite), monticellite, melilite, wustite, sphalerite, glaze and organic matter. Such a composition is characteristic of a mixture of materials of which the aggregate was formed – steelmaking slag and hard coal mining wastes. Only gypsum is not typical for such materials, but the presence of this mineral was documented by a microscopic examination, XRD method (Fig. 5) and with the results of thermal studies (Fig. 3). Gypsum is most likely a secondary component.
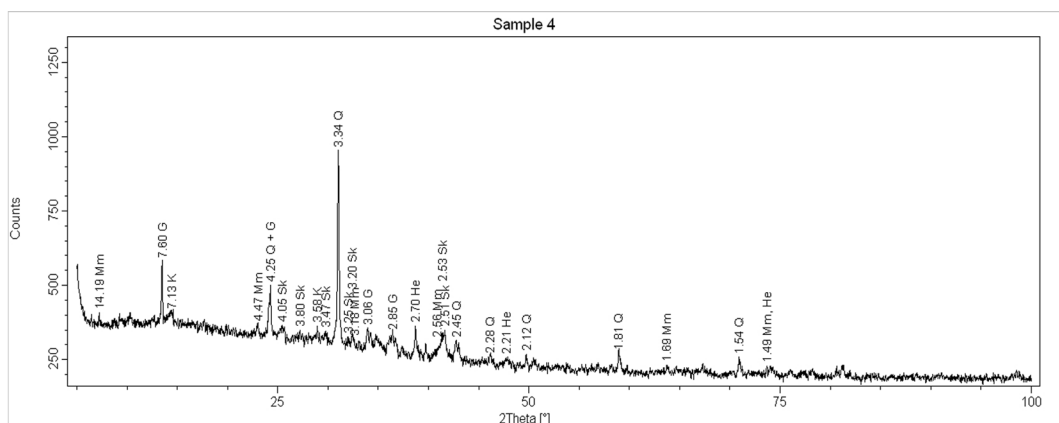

Fig. 5. Diffractogram of sample 4
Q – quartz, Sk – feldspars (anorthite), Mm – montmorillonite (Na), K – kaolinite, He – hematite, G – gypsum

Rys. 5. Dyfraktogram próbki 4
Q – kwarc, Sk – skalenie (anortyt), Mm – montmorillonit (Na), K – kaolinit, He – hematyt, G – gips

The mineral composition of sample 6 is similar to the composition of sample 0, as its main mineral components include: quartz, clay minerals (kaolinite and illite), feldspars, organic matter and a small amount of pyrite. These minerals are typical of hard coal mining wastes (Galos ed. 2009; Jonczy et al. 2012; Bzowski 2013). In addition, the aggregate contains glaze with optical and morphological characteristics (spherical shape) typical for glaze present in fly ashes, dolomite and gypsum. Dolomite is most probably a mechanical impurity from the carbonate rock aggregate layer located above the profile, and the gypsum is likely a secondary mineral (Figs 2 and 6).
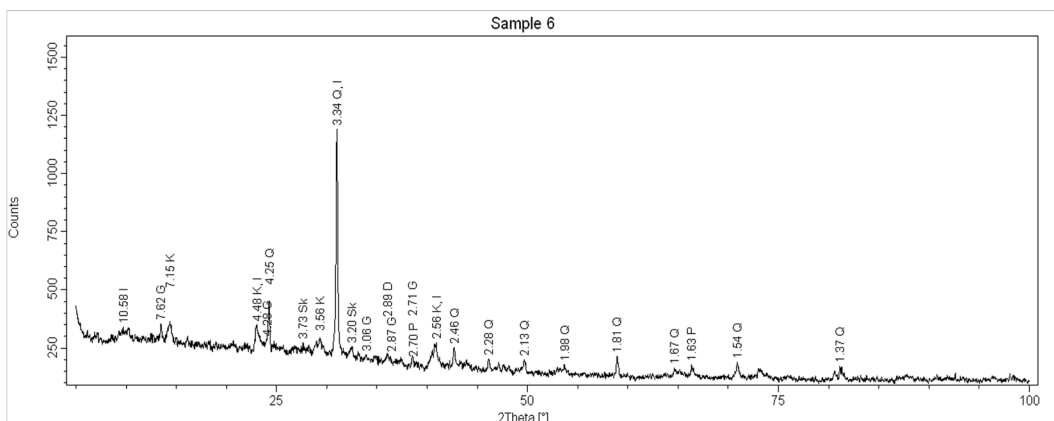

Fig. 6. Diffractogram of sample 6
Q – quartz, K – kaolinite, G – gypsum, I – illite, Sk – feldspars, d – dolomite, P – pyrite

Rys. 6. Dyfraktogram próbki 6
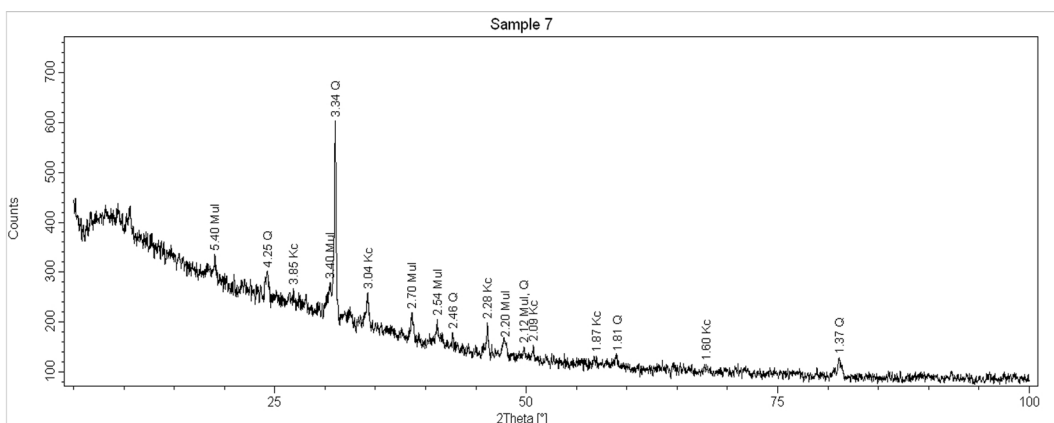Q – kwarc, K – kaolinit, G – gips, I – illit, Sk – skalenie, d – dolomit, P – piryt

Fig. 7. Diffractogram of sample 7
Q – quartz, Mul – mullite, Kc – calcite

Rys. 7. Dyfraktogram próbki 7
Q – kwarc, Mul – mullit, Kc – kalcyt

Sample 7 differed from all the others in terms of the development of mineral components. It comprised components typical of wastes from the combustion of hard coal, i.e. mainly glaze in a spherical form, quartz, mullite and spinels (Strzałkowska 2016). Additionally, calcite was present (Fig. 7).

2.2. Chemical composition

The chemical composition indicates (Table 2) that the dominant components in the samples collected from surface bumps and reference samples are: SiO_2, Al_2O_3 and CaO, which jointly comprised from 57 to 89wt%, with loss on ignition from 77 to 96wt%.

The chemical composition of comparative samples (6 and 7) is clearly different from the others, because the level of Al_2O_3 is much higher than in most of the samples, and the amount of CaO in sample 6 is significantly lower. The chemical composition of all the tested samples reflects the mineral composition identified in the analyzed aggregates.

Table 2.   The chemical composition of samples (in wt%)

Tabela 2.   Skład chemiczny badanych próbek (w % mas.)

| Chemical component	The symbol of the sample						
	0	1	2	3	4	6	7
SiO_2	45.38	40.90	26.01	34.70	37.77	42.14	39.08
Al_2O_3	19.74	18.82	13.83	9.75	13.17	20.04	21.08
TiO_2	0.90	0.79	0.61	0.47	0.60	0.71	0.93
Fe_2O_3	5.20	3.45	2.72	7.75	8.83	5.85	5.37
MnO	0.12	0.06	0.04	2.56	1.85	0.09	0.07
MgO	1.33	1.37	1.23	3.79	2.51	2.08	2.58
CaO	8.29	9.39	17.31	28.93	17.38	1.66	11.75
Na_2O	0.49	0.25	0.19	0.21	0.39	0.43	0.67
K_2O	2.81	2.51	1.57	1.06	1.46	3.09	2.38
P_2O_5	0.09	0.14	0.08	0.17	0.20	0.15	0.39
SO_3	2.08	6.56	12.70	4.35	3.82	2.43	4.80
ZnO	0.01	0.03	0.02	1.29	2.24	0.03	0.02
LOI	13.20	15.50	23.52	4.32	8.94	21.03	10.45
TOTAL	99.66	99.77	99.83	99.36	99.16	99.73	99.57

LOI – loss on ignition.

The chemical composition draws attention to a higher level of SO_3 in the analyzed aggregates collected from the bumps surface (samples 1 and 2) compared to the reference sample (0), as well as to the comparative samples (6 and 7). It is also noteworthy that there was a higher proportion of loss on ignition for samples from the surface bumps in comparison to the reference samples.

3. Discussion

The mineral composition of the samples is summarized in Table 3. Individual associations of mineral components are part of materials used for the production of aggregates, i.e. hard coal mining wastes (non-burnt and burnt), fluidized ashes, fly ashes, steelmaking slag, waste from the processing or smelting of zinc and lead as well as carbonate rock aggregates. However, with time secondary components are formed in the artificial aggregate that was used in the building structure.

The analyzed section of the pavement where the bumps occurred has a bedding layer (below the surface of the cobblestones, a thin layer of sand with cement and a carbonate rocks aggregate layer) consisting of a mixture of hard coal mining wastes and fluidized ash. The same section of the road has two additional layers of steelmaking slag between the carbonate rocks aggregate and the mixture. A comparison of mineral composition of reference sample 0 with the samples corresponding to embedded artificial aggregates (samples 1 and 2) after the bumps appeared showed (Table 4) that the material originally contained, among others, anhydrite – calcium sulphate, which is the main component of fluidized ashes (Brandt ed. 2010; Strzałkowska 2011; Rajczyk 2012; Stryczek ed. 2013). Meanwhile, this mineral was no longer present in the samples collected from aggregates where the bumps appeared.

It is significant that samples that were taken after the incorporation of the artificial aggregate and after a period of time contain different sulphates, namely ettringite in samples 1 and 2 and additionally gypsum in sample 2. Both of these sulphates were formed probably as a result of the transformation of anhydrite, according to the well-known hydration of anhydrite formula:

$$CaSO_4 + 2H_2O \rightarrow CaSO_4 \cdot 2H_2O \tag{1}$$
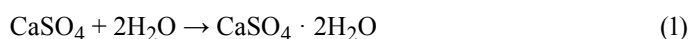
Thus a reaction occurs if water is present in the layer of hard coal mining wastes and fluidized ashes mixture. The product of this reaction is a secondary gypsum.

As a result of chemical weathering of sulfide minerals: pyrite FeS_2 (present in coal mining wastes) and sphalerite ZnS (present in wastes of metallurgy of zinc) (reaction 5) can lead to the creation of sulfuric acid.

An aqueous solution H_2SO_4 will be present in the material, which may further promote the degradation of other mineral components, e.g. kaolinite, derived from hard coal mining

Table 3. Mineral composition of tested samples (minerals are listed in the alphabetical order)

Tabela 3. Skład mineralny badanych próbek (minerały wymieniono w kolejności alfabetycznej)

Mineral component	The symbol of the sample						
	0	1	2	3	4	6	7
Anhydrite	+						
Calcite	++						+
Dolomite						tr.	
Ettringite		+	++				
Feldspars					++	+	
Glaze				++	++	++	++
Gypsum			++		++	+	
Hematite				+	+		
Illite	+					tr.	
Kaolinite	++	+	+		+	+	
Melilite				++			
Merwinite				+			
Metal alloys					+		
Monticellite				++			
Montmorillonite (Na)					tr.		
Mullite							++
Organic matter	+	+	+		+	+	+
Pyrite						tr.	
Quartz	+++	+++	+++	+++	+++	+++	++
Siderite	+						
Sphalerite					+		
Spinels							tr.
Willemite				+	+		
Wustite					+		

+++ – dominant component, ++ – high amount of component, + – component present in the sample in amounts lower than ++, Tr. – component present in the sample in trace amounts.

wastes or amorphous substance, anorthite from fly ashes. For example a reaction for kaolinite:

$$Al_2Si_2O_5(OH)_4 + 3H_2SO_4 \rightarrow Al_2(SO_4)_3 + 2SiO_2 + 5H_2O \qquad (2)$$
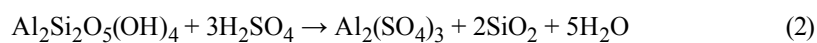
Table 4.   Comparison of mineral composition of reference sample 0 and samples 1 and 2

Tabela 4.   Porównanie składu mineralnego próbki referencyjnej 0 do składu próbek 1 i 2

Symbol of sample	Type of sample	Mineral composition
0	reference sample (to samples 1 and 2)	quartz, kaolinite, calcite, illite, anhydrite, organic matter, siderite
1	sample of material probably responsible for "bumping"	quartz, kaolinite, ettringite, organic matter
2	sample of material probably responsible for "bumping"	quartz, kaolinite, ettringite, gypsum, organic matter

However, $Al_2(SO_4)_3$ in an aqueous environment will undergo further reactions:

$$Al_2(SO_4)_3 + 6H_2O \rightarrow 2Al(OH)_3 + 3H_2SO_4 \qquad (3)$$
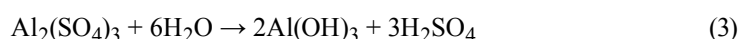
Therefore, the presence of $Al(OH)_3$ along with $CaSO_4 \cdot 2H_2O$ and $Ca(OH)_2$, can promote the formation of ettringite according to the reaction:

$$3CaSO_4 \cdot 2H_2O + 3Ca(OH)_2 + 2Al(OH)_3 + 20H_2O \rightarrow Ca_6Al_2(SO_4)_3(OH)_{12} \cdot 26H_2O \qquad (4)$$

The source of $Ca(OH)_2$ are probably fly ashes, in which CaO occurres (Gawlicki and Ro-szczynialski 2003; Kurdowski 2010). As a result of contact with water CaO easily changes into calcium hydroxide.

The crystallization of ettringite, similarly to $CaSO_4 \cdot 2H_2O$ and $Ca(OH)_2$, will be expansive (Glasser 1996; Tosun and Baradan 2010).

The above reactions are schematic, since in fact they occur between ions in aqueous solutions migrating through the material, and under favorable conditions (exceeding the solubility product) the crystallization of individual mineral components will follow.

The chemical and mineral composition of samples 1 and 2 confirms the relationship between the deformation of the surface and the occurrence of secondary minerals (hydrated sulphates) in them. These samples showed a considerable increase of the following:

◆ SO_3 (present in ettringite and gypsum) (6.56wt% in sample 1 and 12.70wt% in sample 2) compared to the reference sample (2.08wt% – present in anhydrite),

◆ CaO (present in ettringite, gypsum and $Ca(OH)_2$) (9.39wt% in sample 1 and 17.31wt% in sample 2) compared to the reference sample (8.29wt% – present in anhydrite).

This differentiation of SO_3 and CaO content could result from two reasons, i.e. differentiation of the content of fluidized ash, which is the carrier of anhydrite during the pro-

duction of aggregate or migration of aggregate components along with the infiltration of rainwater.

Taking the fact that the same material was used on the road beneath slag layers into account, very similar phenomena probably occurred, which resulted in the emergence of bumps.

Attention should also be paid to molar volumes of anhydrite and components resulting from its transformation – gypsum and ettringite, which are summarized below in Table 5.

Table 5.   A comparison of molar volumes of anhydrite, gypsum and ettringite

Tabela 5.   Zestawienie objętości molowych anhydrytu, gipsu i ettringitu

Mineral	Molar volume (cm^3/mol)	Theoretical increase in the volume resulting from the decomposition of anhydrite
Anhydrite	46.00	–
Gypsum	74.56	1.62
Ettringite	710.32	15.44

The above comparison clearly shows that:
- in the case of a total hydration of anhydrite and the formation of gypsum, anhydrite-occupied volume in the material will increase 1.62-fold relative to the original volume,
- in the case of a total reformation of anhydrite (with participation of aluminum oxide) and the formation of ettringite, anhydrite-occupied volume in the material (taking reaction 1 and 5 into account) will increase to a maximum ca. 5-fold relative to the original volume.

The increase in volume in the material will therefore occur only at the expense of anhydrite. The crystallization of gypsum and ettringite takes place initially in the intergranular spaces in the material, which results in filling the voids and consequently results in stiffening and bonding this part of the bedding layer of the road where crystallization occurs. This phenomenon should be regarded positively. However, in the case in which gypsum and//or ettringite fill in the intergranular voids, and their crystallization continues, tension occurs, which results in the mechanical destruction of the already stiffened bedding material. In such circumstances, some of the material may pile up, deforming the layers situated above, including the wearing course layer (also the cobblestones on the pavement).

A comparison of the mineral composition of reference sample 3 of slag with sample 4, collected after the bumps appeared (Tab. 6) showed that minerals of the melilite, monticellite and merwinite group – typical mineral components of steelmaking slag (Jonczy 2012, 2014), which represent the group of silicates, especially calcium were originally present, among others, in the tested material. Meanwhile, these minerals are no longer present in sample 4,

after the bumps appeared. Other mineral components are present, but the presence of feldspars is significant, which are represented in this case by anorthite, which is also calcium aluminosilicate.

Table 6.   Comparison of the mineral composition of reference sample 3 and sample 4

Tabela 6.   Porównanie składu mineralnego próbki referencyjnej 3 do składu próbki 4

Symbol of sample	Type of sample	Mineral composition
3	reference sample (to sample 4)	quartz, melilite, monticellite, merwinite, hematite, willemite, glaze
4	sample of material probably responsible for "bumping"	quartz, gypsum, feldspars, hematite, kaolinite, montmorillonite, sphalerite, willemite, wustite, metal alloys, glaze, organic matter

However, feldspars could not have formed as a result of the transformation of minerals of the melilite, monticellite and merwinite group, as anorthite crystallizes at high temperatures. Thus, samples 3 and 4 are difficult to compare. Sample 4 of slag was found to contain gypsum, which could have formed by the decomposition of sphalerite present in the material, according to the reaction:

$$ZnS + 2O_2 + H_2O \rightarrow ZnO + H_2SO_4 \qquad (5)$$
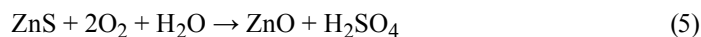
and then anorthite degraded in H_2SO_4 solution, according to the reaction:

$$Ca(Al_2Si_2O_8) + 3H_2O + H_2SO_4 = Al_2Si_2O_5(OH)_4 + CaSO_4 \cdot 2H_2O \qquad (6)$$

As a result, kaolinite $(Al_2Si_2O_5(OH)_4)$ and gypsum were formed.

At the same time, it cannot be ruled out that sample 4 of slag became mechanically contaminated with the material located directly beneath it – a mixture of hard coal mining wastes and fluidized ashes. Gypsum was present in this material, although in this case the gypsum should be accompanied with ettringite, present in the mixture.

On the neighboring section of the road, where samples for comparative purposes were collected, the bedding layer did not consist of the slag layer and a mixture of hard coal mining wastes and fluidized ashes. Instead, a mixture of hard coal mining wastes and fly ash as well as a material called "improved slag sand" (created on the basis of fly ashes) were used. On this stretch of the road, there were no bumps on the wearing course layer. The mineral composition of these samples is clearly different in comparison to the respective materials used for the bedding layer of the road on which the bumps occurred (Table 7). Samples 6 and 7 lack a component characteristic of fluidized ashes – anhydrite, responsible for the formation of ettringite.

Table 7.   Comparison of mineral composition of comparative samples 6 and 7

Tabela 7.   Porównanie składu mineralnego próbek porównawczych 6 i 7

Symbol of sample	Type of sample	Mineral composition
6	comparative sample (to samples 1 and 2)	quartz, kaolinite, illite, feldspars, dolomite, gypsum, pyrite, organic matter, glaze
7	comparative sample (to samples 1 and 2)	quartz, calcite, mullite, spinels, organic matter, glaze

It seems, therefore, that the material from the adjacent road section (despite the presence of gypsum in sample 6), obtained for comparative purposes, is stable in comparison to the section where the artificial aggregate with fluidized ash was used.

Rainwater infiltration probably occurred in each of the analyzed materials. Such waters flowing through the material resulted in a mechanical removal of ultrafine mineral particles (the phenomenon of suffosion), including anhydrite, and moving them to the areas located lower in the profile. The material in these areas became less porous, and the flow of water became difficult (the phenomenon of colmatage) (Hotloś et al. 1983; Piekarski 2009). Locally, there could be higher concentrations of anhydrite than originally.

Conclusions

Based on the mineralogical study, we draw the following conclusions:

1. Rainwater infiltration probably occurred in each of the analyzed materials. Such waters flowing through the material resulted in a mechanical removal of ultrafine mineral particles (the phenomenon of suffosion), including anhydrite, and infiltration to the lower lying areas of the profile. The material in these areas became less porous, and the flow of water became difficult (the phenomenon of colmatage). Anhydrite could become locally concentrated.

2. The material responsible for the occurrence of specific road bumps is a layer consisting of hard coal mining wastes and fluidized ash mixture. In particular, too large an amount of fluidized ash, which consists of anhydrite, is the essential component of the material. This component undergoes transformations which result in the crystallization of gypsum and ettringite, which contribute to the increase of its volume.

3. Slag could also be a material co-responsible for the occurrence of road bumps. The decomposition of anorthite, the result of which could lead to the crystallization of gypsum, may have contributed to the increase in volume of the material. However, this increase in volume would not be as significant as in the case of the crystallization of ettringite derived from anhydrite transformations, the latter being a component of fluidized ash.

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THE EFFECTS OF MINERALOGICAL CHANGES THAT OCCUR IN ARTIFICIAL AGGREGATES

Abstract

This article presents the results of the study of changes in mineral and chemical composition of artificial aggregates consisting of coal shale (a hard coal mining waste) and fluidized ashes. Such an aggregate was used for road construction. After completion of the construction works but before making the road available for public use, significant deformation of the surface in the form of irregular buckling of the asphalt layer occurred.

It was excluded that this resulted from mining damage, design errors or performance mistakes, among others. A study of the materials that had been incorporated in the construction layers was undertaken in order to find the component and the mechanism responsible for the buckling of the road surface.

A comparison of the mineral and chemical composition of aggregate samples collected from the embankment where the road buckled with the reference sample and samples from places without deformations showed that the bumps in the road embankment consisted of minerals that were not initially present in the aggregate.

Wastes produced as a result of high temperatures (slag and power plants ashes, metallurgical wastes) are not as stable in terms of chemical and phase composition in the hypergenic environment.

As a result of the processes occurring in the road embankment, anhydrite, which is the primary component of fluidized ashes, was transformed into gypsum and ettringite. As a result of contact with water CaO (present in fluidized ashes) easily changed into calcium hydroxide. As the crystallization of these minerals is expansive, it resulted in the filling of pores and, in extreme cases, in a substantial increase in the volume of the aggregate and, consequently, in the deformation of the road surface.

Keywords: aggregate, road materials, ettringite, anhydrite, fly ash

SKUTKI PRZEOBRAŻEŃ MINERALOGICZNYCH ZACHODZĄCYCH W KRUSZYWACH SZTUCZNYCH

Streszczenie

W artykule przedstawiono wyniki badań nad przeobrażeniami składu mineralnego i chemicznego, które zaszły w kruszywie sztucznym skomponowanym na bazie łupku węglowego (odpad pochodzący z górnictwa węgla kamiennego) i popiołów fluidalnych. Kruszywo to użyte zostało do budowy drogi. Po zakończeniu budowy, a jeszcze przed oddaniem jej do użytku stwierdzono znaczne deformacje nawierzchni w formie nieregularnych wybrzuszeń i wypiętrzeń warstwy asfaltowej.

Jako przyczyny wykluczono między innymi szkody górnicze, błędy projektowe czy błędy wykonawcze. Podjęto więc badania wbudowanych w warstwy konstrukcyjne materiałów w celu wskazania składnika i mechanizmu odpowiedzialnego za wypiętrzanie nawierzchni drogi.

Porównanie składu mineralnego i chemicznego próbek kruszywa pobranych z nasypu drogowego w miejscach deformacji z próbką referencyjną i próbkami z miejsc, gdzie deformacji nie stwierdzono

wykazało, że w nasypie drogowym w miejscu „wybrzuszeń" występują minerały, których pierwotnie nie było w kruszywie.

Odpady powstałe w wyniku oddziaływania wysokich temperatur (żużle i popioły elektrowniane, odpady hutnicze itp.) w środowisku hipergenicznym nie są stabilne tak pod względem składu chemicznego, jak i fazowego. Na skutek procesów zachodzących w nasypie drogowym anhydryt będący pierwotnym składnikiem popiołów fluidalnych uległ przeobrażeniu w gips oraz ettringit. W wyniku kontaktu z wodą CaO (obecny w popiołach fluidalnych) łatwo uległ przemianie w wodorotlenek wapnia. Krystalizacja tych minerałów jest ekspansywna, co doprowadziło do zapełnienia przestrzeni porowych, a w skrajnych przypadkach znacznego wzrostu objętości kruszywa i w konsekwencji do deformacji nawierzchni drogi.

Słowa kluczowe: kruszywo, materiały drogowe, ettringit, anhydryt, popiół lotny