Modification of fly ash produced in the process of burning fossil fuels - granulation method

To cite this article: P Gara and E Wisa-Walsh 2019 IOP Conf. Ser.: Earth Environ. Sci. 214 012059

View the article online for updates and enhancements.
Modification of fly ash produced in the process of burning fossil fuels - granulation method

P Gara¹*, E Wisła-Walsh¹
¹AGH University of Science and Technology, Faculty of Mechanical Engineering and Robotics, al. Mickiewicza 30, 30-059 Cracow, Poland

E-mail: pgara@agh.edu.pl

Abstract. The low grain size of fly ashes from the combustion of fossil fuels creates a number of ecological problems both during storage and transport, and often makes their re-use more difficult. One way to avoid this problem is to compact these materials in the granulation process. The granulation process generally requires the use of different binders, which are divided into matrix, film, and chemical type binders. Depending on the chemical composition of the fly ash and the type of the binder used, the obtained aggregate forms (granulates) find numerous applications, e.g. in the production of adhesives, zeolites and/or concrete, in manufacture of building materials, and in aggregates for road works or for ground leveling. In many applications, especially in road engineering works or in ground leveling, the basic requirements, next to the compressive strength of the granules obtained, are the leachability of sulfate ions and the pH-value of the eluates. The paper presents a research study investigating the granulation process of fly ashes produced by the combustion of hard and brown coals burned in both pulverized and fluidized furnaces, with the application of the following binders: water, calcium sulfate hemihydrate, and mixture of calcium sulfate hemihydrate and calcium hydroxide. For the resulting granulates, tests were conducted to determine compressive strength, SO₂ sorption capacity, the pH-value, and the content of sulfate ions in the eluate before and after sorption tests. The obtained results show that the granulation process mostly decreases leachability of sulfate ions and the pH-value of the eluates while simultaneously providing adequate compressive strength of the obtained compacted forms (granulates).

1 Introduction
Tighter environmental regulations in the world as well as in Poland [1] and broadly understood environmental awareness have led to the implementation of new combustion techniques [2] and a whole range of technologies aimed at reducing emission of oxides of nitrogen and sulfur, including the use of low-sulfur coal [2,3].

In power plants, reduction of sulfur dioxide emissions during combustion is carried out by FSI and LIFAC methods, and exhaust gas purification is conducted by using dry additives method (IDDS) or wet FGD processes. In the case of smaller power plants, FSI methods and their hybrids are an economical alternative to wet methods. However, their use is limited by the lack of solutions for the economic exploitation of the desulfurisation products which originate in these processes (mixtures of fly ash, calcium sulfate and unreacted calcium oxide) as well as by the lack of possibility of their storage [4].

While safe storage of conventional ashes is mainly associated with the protection of the landfill from secondary dusting [5], storage of the flue-gas desulfurisation products by dry and semi-dry
methods as well as solid waste resulting from the fluidized bed combustion process presents problems related primarily to greater leachability of sulphate and alkali ions [4,6-8].

With the storage and/or reuse in mind, one of the easiest ways to change the physico-chemical properties of conventional ashes and their mixtures with desulphurisation products is to subject them to the granulation process [9-12,13].

This process eliminates the secondary dusting of solid combustion products both in landfills and during transport, and facilitates all technological operations related to their further use. At the same time, it may provide a reduction in the leachability of many ions and a change in the pH-value of the eluate [4,5]. Moreover, depending on the chemical composition of the ash and the additives introduced during the process of their granulation, a product can be obtained that is a high-quality substitute of natural raw materials used in the production of cement and concrete [11,14-16]. Furthermore, due to the basic nature of the desulphurisation products present in many ashes and the possibility of introducing certain compounds into the granulation process, it is possible to reactivate and/or obtain a specific class of sorbents capable of removing acidic impurities from the waste gases [2,17].

The article presents the results of research on the granulation process of selected fly ashes, and evaluation of their development potential based on selected physicochemical and mechanical parameters of the obtained granulates. The process of granulation was investigated on fly ashes from lignite and hard coal, with and without desulphurisation products. The binders used were, respectively: water, calcium sulfate hemihydrate, and a mixture of calcium sulfate hemihydrate with calcium hydroxide. The individual samples were subjected to a seasoning process for (1, 4, 11, 18, 25) days, during which the compressive strength of the obtained granulates was measured. Basing on the results, the possibility of using the obtained materials as sorbent in industrial desulphurisation has been determined. Furthermore, after the batching process, for all samples of the obtained granules, the pH-value and the sulfate content of the eluates were measured.

2 Apparatus and Materials
Fly ash produced as a result of lignite coal and hard coal combustion was selected for research on the process of granulation. Fly ash obtained during the addition of calcium sorbent to the furnace (FSI method) and fly ash produced in the second desulphurisation step, i.e. ash mixed with the desulphurisation products of IDDS, were studied to determine the effect of the desulphurisation method.

To identify the role of the form of calcium in ash, and/or its mixture with desulphurisation products, the experiment also included fly ash from hard coal burned in a power plant without flue gas desulphurisation.

In this way, four samples of fly ashes were marked in the following order:
- B-1-lignite coal,
- R-1-hard coal without flue gas desulphurisation,
- R-2-hard coal with FSI flue gas desulphurisation,
- R-3-hard coal with flue gas desulphurisation by IDDS.

Table 1 shows the phase composition and Table 2 shows the chemical composition in the parent fly ashes.
Table 1. Phase composition of the parent ashes.

| PHASE/ASH | B-1 | R-1 | R-2 | R-3 |
|-----------|-----|-----|-----|-----|
| Glaze     | +   | +++ | ++  | +   |
| Mullite   | +   | ++  | ++  | ++  |
| Quartz    | +++ | ++  | +   | +   |
| Hematite  | +   | +   | +   | +   |
| CaO       | ND  | ND  | ++  | +++ |
| Ca(OH)₂   | ND  | –   | –   | +   |
| CaSO₄     | +   | ND  | ++  | ++  |
| CaCO₃     | –   | –   | +   | +   |
| Ettringite| +   | –   | –   | –   |

„ND“ - not detected.

Table 2. Chemical composition of the parent ashes.

| Component [% mass] | B-1 | R-1 | R-2 | R-3 |
|--------------------|-----|-----|-----|-----|
| SiO₂               | 40.98 | 49.35 | 43.73 | 35.53 |
| Al₂O₃              | 19.16 | 24.57 | 23.86 | 15.92 |
| Fe₂O₃              | 6.24  | 9.35  | 7.05  | 5.31  |
| MgO                | 4.36  | 7.24  | 3     | 2.93  |
| CaO                | 23.35 | 4.20  | 16.26 | 29.28 |
| CaO                | 2.38  | 0.97  | 6     | 13.92 |
| K₂O                | 0.64  | 1.08  | 0.35  | 0.28  |
| Na₂O               | 0.86  | 1.62  | 1.35  | 0.95  |
| SO₃                | 5.10  | 0.62  | 1.62  | 3.58  |
| C                  | 2.14  | 2.70  | 1.85  | 1.73  |
| Loss on ignition   | 4.72  | 5.75  | 7.73  | 5.59  |

*Analysis made from independent samples

As can be seen from the data presented in the above tables, only R-1 ash can be classified as a standard silica ash, whereas the remaining ashes, by virtue of the calcium oxide content, may be classified as calcium ash, with the sulfur trioxide content exceeding those indicated as the limit value of this component for this ash group [8,18].

The fly ash granulation experiment was carried out in a laboratory disc granulator with a plate diameter of 400 mm, varying the angle of inclination from 20° to 35°, and rotational speed in the range of 24-32 rpm. Based on these studies, it has been found that it is possible to obtain fresh granules of satisfactory strength parameters when using water as a binder. Prior to obtaining further batches of granulate for each of the ashes studied, specific parameters of the granulation process were determined, as well as the method and amount of water addition necessary for the proper course of the process. After initial testing, it was found that at a 25° slope angle and a rotational speed of 32 rpm it is possible to obtain granules from each ash examined. At the same time, it was found that, with the exception of R-1 ash, water granulation resulted in a granulate having a compressive strength of about 30N, measured after one day of seasoning.

In order to determine the possibility of increasing the strength and/or changing the chemical properties of the investigated ashes, granulation experiments were also carried out using calcium sulfate hemihydrate, calcium hydroxide, and their mixtures as additives. In this way, 12 granulates were obtained, the markings and composition of which are shown in Table 3. The granules were obtained from sieved ashes of 1 kg and/or 1.2 kg of mass if they were granulated with additives, and the amount of water necessary for the granulation process was determined by measuring its mass loss.
After producing each batch, two samples of the obtained granulate were taken. The first was placed in a drier to determine the amount of water collected by the material during the granulation process, while the second was seasoned in open containers along with the remaining material for further physicochemical studies.

### Table 3. Batch coding, water-to-bulk ratio of the feed, and the percentage composition of the granules.

| Batch code | Water/bulk ratio | additive | Content [% mass] |
|------------|------------------|----------|------------------|
| B-1G       | 0.30             | H₂O      | 25.97            |
| B-1G/I     | 0.25             | CaSO₄·0.5H₂O | 20               |
| B-1G/II    | 0.29             | CaSO₄·0.5H₂O+C₂(OH)₆ | 10+10          |
| R-1G       | 0.30             | H₂O      | 19.21            |
| R-1G/I     | 0.27             | CaSO₄·0.5H₂O | 20               |
| R-1G/II    | 0.25             | CaSO₄·0.5H₂O+C₂(OH)₆ | 10+10          |
| R-2G       | 0.28             | H₂O      | 17.77            |
| R-2G/I     | 0.25             | CaSO₄·0.5H₂O | 20               |
| R-2G/II    | 0.25             | CaSO₄·0.5H₂O+C₂(OH)₆ | 10+10          |
| R-3G       | 0.38             | H₂O      | 21.64            |
| R-3G/I     | 0.32             | CaSO₄·0.5H₂O | 20               |
| R-3G/II    | 0.28             | CaSO₄·0.5H₂O+C₂(OH)₆ | 10+10          |

The first study evaluating the effects of the granulation process and the impact of the chemical composition on the process was the compression strength test. Measurements were made on the ZWICK 1120 Universal Strength Machine by squeezing the granules between two parallel flat surfaces, (the full methodology is presented in the paper [19]).

For the selected samples, micrographs (SEM) were made on the JEOL 5500 LV scanning electron microscope (18×–3300000×), at the maximum resolution of 4 nm, and equipped with IXRF’s EDS (X-ray diffraction spectrometry) for X-ray microanalysis.

All the samples were also tested for sorption of SO₂ on sorption manostat apparatus [18]. These tests were carried out at a SO₂-pressure range from 0 to 150 mm Hg, at 120°C, after degassing the samples.

After 25 days of seasoning, SO₄²⁻ ions leachability from all the granules and ash was tested before and after the sulfurization. To do this, suspensions of 2 g of the sample in 200 ml of water were prepared and then shaken for 24 h. The slurries were then filtered, the pH of the eluates was measured, and the content of sulfate ions was determined by ion chromatography (IC) using the DX-100 DIONEX chromatograph.

## 3 Results and discussion

### 3.1 Compressive strength

Tables 4-5 show the results of the measured strengths of the tested granules at the time of seasoning for each added additive. As can be seen from the tables, the compressive strength of the test granules depends on both the type of ash and the additives added to the granulation process, as well as the seasoning time itself. Granulating the ashes with water allowed to obtain granules with a compressive strength of 70N for B-1 ash from lignite combustion, which is most likely related to the presence of anhydrous calcium sulfate, and of 3N for R-1 ash from hard coal combustion.
Table 4. Compressive strength of granules obtained from ash B-1 R-1.

| Time in days | Compressive strength [N] | B-1G | B-1G/I | B-1G/I+II | R-1G | R-1G/I | R-1G/I+II |
|--------------|--------------------------|------|--------|-----------|------|--------|-----------|
| 1            | 30                       | 66   | 40     | 3         | 67   | 44     |
| 4            | 71                       | 124  | 95     | 3         | 89   | 122    |
| 11           | 63                       | 199  | 77     | 3         | 159  | 87     |
| 18           | 75                       | 168  | 74     | 3         | 119  | 98     |
| 25           | 70                       | 196  | 72     | 3         | 129  | 101    |

Table 5. Compressive strength of granules obtained from ash R-2, R-3.

| Time in days | Compressive strength [N] | R-2G | R-2G/I | R-2G/I+II | R-3G | R-3G/I | R-3G/I+II |
|--------------|--------------------------|------|--------|-----------|------|--------|-----------|
| 1            | 32                       | 230  | 137    | 27        | 51   | 133    |
| 4            | 41                       | 308  | 309    | 73        | 196  | 160    |
| 11           | 35                       | 250  | 370    | 76        | 169  | 165    |
| 18           | 25                       | 260  | 292    | 87        | 127  | 153    |
| 25           | 21                       | 233  | 300    | 43        | 179  | 158    |

R-2 ash granulation with water, with its FSI desulfurisation product (unreacted CaO and calcium sulfate hemihydrate) yields an average compressive strength of 30 N, nearly half lower than for B-1 ash. Changing the composition of the desulfurisation product (FSI+IDDS) results in granules (with water) having an initial strength higher than the strength of B-1 ash and up to 90 N. This value quickly drops to a value of 43N after 25 days.

If it is assumed that in the case of R-3 ash, the second desulfurisation step, where the FSI products, after reactor humidification, re-contact the flue gases, leads to the change of a portion of free CaO into hydroxide and to the hydration of anhydrous calcium sulfate, then the initial compressive strength values would be expected to be lower than those measured due to the disappearance of the binder - calcium sulfate hemihydrate. However, it is not possible to account for such behavior in a relatively small number of experiments.

The increase in compressive strength of all the granules was obtained as a result of the 20% addition of calcium sulfate hemihydrate to the granulation process. For this additive, the greatest increase in strength was obtained for R-1, R-2 ashes. Also for this additive, relatively high fluctuations of this parameter were observed during the seasoning. For each ash, after the initial strength increase, a strong decrease occurred, followed by a slow increase in its value. After 25 days this parameter ranged from about 130N for ash granulate R-1 to about 230 N for ash granulate R-2. The maximum compressive strengths for conventional ash (B-1, R-1) granulated with 20% CaSO₄ 0.5H₂O were measured after 11 days of seasoning, while for the ash with flue gas desulfurisation products (R-2, R-3) already after 4 days.

The change in the amount of added calcium sulfate hemihydrate from 20% to 10%, with simultaneous 10% addition of calcium hydroxide, resulted in a slight decrease in compressive strength in the case of R-1 and R-3 ash granulates. Similarly, in the case of granules obtained from ash B-1, a decrease in this value was observed, but for this sample it was almost 50% greater. On the contrary, in the case of R-2 ash, the change in the composition of the additive in the granulation process resulted in an increase in compressive strength, which, after 25 days of seasoning, was 300N. Also for this ash there was a visible change in this parameter, where its maximum value was reached after 4 days and equaled 370N.

These data indicate that ash granulates (R-2G/I, R-2G/I+II) can be used commercially for road construction [4,15].
3.2 SO₂ sorption capacity

Figure 1 shows the SO₂ sorption isotherms for the parent ashes as well as the granules obtained therefrom, and Table 6 shows the SO₂ sorption capacity of ashes and the granules obtained therefrom at a pressure of SO₂=100 mmHg. For comparison, the sorption capacity of pure calcium hydroxide used in FSI [2] is shown.

From the above data, sorption of SO₂ is the lowest for the parent ash, and increases after the water-based granulation process except for B-1 and R-1 ashes, for which no adequate strength has been obtained (3N). In the case of R-2 and R-3 ashes, the increase in sorption of SO₂ after granulation with water is approximately 40% and 60%, respectively, which can be attributed to the presence of free calcium oxide in the material.

SO₂ sorption also increases both after the granulation of the ash with calcium sulfate hemihydrate and after the granulation of the ash with an additive (calcium sulfate hemihydrate + Ca(OH)₂), but more significantly in the case of the ash with the calcium sulfate hemihydrate alone.

![Figure 1. The SO₂ sorption isotherms of the parent material and the tested granules.](image)

| Sorbent | A SO₂ [mmol/g] at p SO₂=100 [mmHg] | Sorbent | A SO₂ [mmol/g] at p SO₂=100 [mmHg] |
|---------|----------------------------------|---------|----------------------------------|
| Ca(OH)₂ | 0.08                             | Ca(OH)₂ | 0.08                             |
| B-1     | 0.07                             | R-2     | 0.02                             |
| B-1G    | 0.07                             | R-2G    | 0.03                             |
| B-1G/I  | 0.10                             | R-2G/I  | 0.06                             |
| B-1G/I+II | 0.09                        | R-2G/I+II | 0.06                          |
| R-1     | 0.02                             | R-3     | 0.04                             |
| R-1G    | —                                | R-3G    | 0.06                             |
| R-1G/I  | 0.03                             | R-3G/I  | 0.08                             |
| R-1G/I+II | 0.03                        | R-3G/I+II | 0.08                         |
By analyzing in detail the highest sorption of SO$_2$ as shown by B-1 ash, and the effect of free lime present in the ash and of the added calcium sulfate and Ca(OH)$_2$, it can be stated that SO$_2$ sorption is more strongly dependent on $S_{BET}$ of ashes and granulates. Table 6 presents the value of this parameter. These data show that the surface of ash B-1 from lignite coal combustion is almost 5 times larger than of the other ashes from hard coal combustion.

Table 7. Surface area values of the tested ashes and granulates.

| Ash Parameter | B-1 120°C | B-1G/I 120°C | B-1G/I+II 120°C |
|---------------|-----------|---------------|-----------------|
| $S_{BET}$ [m$^2$/g] | 20.54 | 20.85 | 23.30 | 17.52 |

| Ash Parameter | R-1 120°C | R-1G/I 120°C | R-1G/I+II 120°C |
|---------------|-----------|---------------|-----------------|
| $S_{BET}$ [m$^2$/g] | 3.47 | – | 7.23 | 6.47 |

| Ash Parameter | R-2 120°C | R-2G/I 120°C | R-2G/I+II 120°C |
|---------------|-----------|---------------|-----------------|
| $S_{BET}$ [m$^2$/g] | 3.17 | 3.51 | 9.97 | 6.60 |

| Ash Parameter | R-3 120°C | R-3G/I 120°C | R-3G/I+II 120°C |
|---------------|-----------|---------------|-----------------|
| $S_{BET}$ [m$^2$/g] | 3.74 | 5.62 | 12.52 | 7.19 |

Addition of calcium sulfate hemihydrate and water as binders to all ash except B-1 ash increases the specific surface area 2 times, and the reduction of calcium sulfate hemihydrate to 10% and addition of Ca(OH)$_2$ reduces the value of this parameter as well as decreases the SO$_2$ sorption capacity, as indicated in Table 6.

Figure 2. SEM microstructure of B-1 and B-1G/I samples.

The relatively high value of the specific surface of ash B-1 is related to the presence of unburned porous material; in the case of the addition of calcium sulfate hemihydrate it is related to the formation, under the influence of water, of the expanded gypsum structure, as shown by SEM microstructure images in Figure 2.

In sum, from the presented data concerning SO$_2$ sorption on the obtained granules it can be concluded that, with the reduction of dusting, a material with sufficient compressive strength may be obtained, which may be used for roadwork purposes. Moreover, a sorbent can be obtained with a...
sorption capacity comparable to the sorption capacity of calcium hydroxide, which is used to reduce \( \text{SO}_2 \) in fluidized bed combustion, (Table 6, row 1).

### 3.3 pH-values and concentration of sulfate ions in eluates

Table 8 shows the pH-values for the eluates obtained for the parent ashes and their granulated forms before and after sorption of \( \text{SO}_2 \), and the concentration of sulfate ions in these eluates.

The pH changes of the eluates as well as the sulfate ions concentrations in the eluates obtained from them, as compared to the values of these parameters in the parent ash eluates, indicate that water granulation of all the ash samples produced a slight decrease in the pH value. The value of this parameter remains practically unchanged for granules obtained with 20% calcium sulfate hemihydrate. It is greater for granulation with 10% calcium sulfate hemihydrate and 10% \( \text{Ca(OH)}_2 \), but does not exceed the value of this parameter for the parent ash.

After \( \text{SO}_2 \) sorption, the pH of the eluates for the parent ashes is practically the same as for the granules obtained with water. In the case of calcium sulfate hemihydrate used as a binder for B-1 granules, this parameter is practically unchanged, while for the R-2 and R-3 ash granulates it increases slightly. It may be associated with a change in the degree of dissociation at the change of the hemihydrate sulfite into the dihydrate in the case of the R-3 sample. The observed pH drop for R-1 ash cannot be explained.

| Parameter | pH input gran. | pH gran. after \( \text{SO}_2 \) sorption | \( \text{SO}_4^{2-} \) concentration \([\text{mg/l}]\) | \( \text{SO}_4^{2-}-\text{SO}_2 \) concentration \([\text{mg/l}]\) |
|-----------|----------------|---------------------------------|---------------------------------|---------------------------------|
| B\(_0\)   | 11.48          | 11.80                           | 76.60                           | 91.30                           |
| B\(_G\)   | 10.75          | 10.34                           | 53.50                           | 308.79                          |
| B\(_G/I\) | 10.73          | 10.40                           | 203.80                          | 855                             |
| B\(_G/I+II\) | 11.23       | –                               | 190.80                          | –                               |
| R-1\(_0\) | 11.05          | 11.60                           | 22.60                           | 27.20                           |
| R-1\(_G\) | 9.01           | –                               | 17.90                           | –                               |
| R-1\(_G/I\) | 9.12          | 11.70                           | 206.80                          | 480                             |
| R-1\(_G/I+II\) | 11.13        | –                               | 191.50                          | –                               |
| R-2\(_0\) | 12.63          | 12.50                           | 227.30                          | 129                             |
| R-2\(_G\) | 11.93          | 12.01                           | 133.90                          | 196.01                          |
| R-2\(_G/I\) | 11.60         | 12.50                           | 126                             | 800                             |
| R-2\(_G/I+II\) | 12.01        | 12.60                           | 217.10                          | 459                             |
| R-3\(_0\) | 12.91          | 12.80                           | 198.90                          | 186                             |
| R-3\(_G\) | 12.05          | 12.12                           | 90.50                           | 331.30                          |
| R-3\(_G/I\) | 11.94         | 12.50                           | 207.10                          | 852                             |
| R-3\(_G/I+II\) | 12.31       | –                               | 143.20                          | –                               |

The granulation of the tested ashes with only water as a binder reduces \( \text{SO}_4^{2-} \) concentrations in the tested eluates. For conventional ashes (B-2 and R-1) this decrease is relatively small and is approximately 37% for ash B-1 and about 11% for ash R-1.

For R-2 and R-3 samples, the decrease is 40% and 61%, respectively. This phenomenon should be attributed to the change of anhydrous calcium sulfate present in B-1 and R-2 samples into lower solubility dihydrate sulfate, which occurs during granulation with water; in the case of R-3 ash, it is probably due to the change of both hemihydrate sulfate and sulfite to dihydrate forms.

Obtaining granules only with hemihydrate calcium sulfate (20%) results in approximately threefold increase in sulfate ion concentrations in the B-1 ash eluates, and about sevenfold increase for the R-1 ash.
For R-2 and R-3 granulates, the SO$_4^{2-}$ concentration in comparison to the parent ash increases by only about 3% and 4%.

Introducing equal amounts of calcium sulfate hemihydrate and calcium hydroxide (10%) into the granulation process increases the sulfate ions concentration in the eluate three times for sample B-2 and seven times for sample R-1. On the contrary, for the R-2 and R-3 ashes, the sulfate ions concentration in the eluates is lower than for the un-granulated samples by about 40% for R-2 and about 30% for R-3. For ash R-2, addition of the same amount of calcium sulfate hemihydrate and calcium hydroxide into the granulation process results in reduction of the sulfate ions in the eluate, as compared to the parent ash, nearly in the same degree as in the case of water granulation.

In turn, after sorption of SO$_2$, the concentration of sulfate ions increases with respect to the concentration of these ions in non-granulated ash eluates, but, except for the granules obtained with calcium sulfate hemihydrate, this increase does not exceed 500 ml SO$_4^{2-}$ per liter, which is the limit value required for storage of materials.

Considering the above mentioned standards, values of the pH parameters for the parent ashes, and their granulates both before and after the SO$_2$ sorption exceed the value of 12 or are close to it (with the exception of the ash R-3) that can be controlled by the granulation process.

**Conclusion**

The presented results of investigations of the granulation process in the case of conventional ash and ash with flue gas desulfurisation products were preliminary and were used to determine the influence of the basic parameters of the granulation process on the physicochemical properties of the obtained granules. Based on the results, it can be stated that:

- no matter the chemical composition of the parent ash, it is possible to obtain granules of relatively high strengths,
- obtaining relatively strong granules is associated with the presence of calcium in the fly ash, both in unbound form and in the form of sulfur compounds,
- depending on the proportion of the contents of these compounds, granulates with a distinctly different strength are obtained,
- achieving granules of strength comparable to that of light aggregates is associated with the use of small amounts of suitable additives,
- the granules obtained are characterized by a relatively good sorption of SO$_2$, so that after the granulation process and prior to storage and/or economic use they can serve as a sorbent to absorb acidic impurities present in the waste gas,
- after SO$_2$ sorption, the sulfate ion concentration exceeds the normalized values only in the case of granules obtained from R-2 ashes
- for all the tested ashes, the granulation process with the use of water alone leads to a reduction in both the amount of sulfate ions leached and the pH-value.

In conclusion, fly ash granulation, apart from the elimination of dusting of these materials both during transport and on landfills, may lead to changes in their chemical properties depending on the amount and type of additives introduced in the process. To investigate the mechanism in greater detail, further, more advanced research is required.

**Acknowledgements**

This article has been prepared within the scope of statutory activity, Contract No. 11.11.130.957.

**References**

[1] Badydaet K. al, *Selected Consequences of Adopting IED in Poland*, 2015, 41, 475-491
[2] Srivastava R K, et al, *J. of the Air & W-ste Mana-ment Association*, 2001, 51/12, 1676-1688
[3] Gara P, *Chemical Industry*, 2017, 96/8, 1669-1672
[4] Wisła-Walsh E, Mięso R, Sikora W S, *Mineralogical Society of Poland*, 1999, 13, 99-119
[5] Egemen E, Yurteri C, *Waste Management & Research*, 1996, 14, 43-50
[6] Gruchot A, Annals of Warsaw University of Life Sciences – SGGW, 2015, 47/2, 103-112
[7] Lecuyer I, et al, Waste Management & Research, 1996, 14, 15-28
[8] Wons W, Murzyn P, Klosek-Wawrzyn E, Ceramic Materials, 2015, 67/4, 407-412
[9] Baykal G, Döven A G, Resources, Conservation and Recycling, 2000, 30, 59-77
[10] Patel Tejas A, Patel Jignesh M, Patel Chirag B, Indian Journal Of Applied Research, 2015, 5(1), 8-10
[11] Obraniak A, Chemical Engineering and Equipment, 2013, 52(3), 213-215
[12] Feliks J, Kalukiewicz A, Drives and Controls, 2014, 7(8), 114-117
[13] Leszczuk T, Acta Mechanica et Automatica, 2014, 8(3), 141-145
[14] Gomathi P, et al, Research J. Applied Science Engineering Technology 2014, 7(6), 1101-1106
[15] Misra A, Draft Final Report, Combustion Byproducts Recycling Consortium, University of Missouri – Kansas City, 2005, 1-39
[16] Giergiczny Z, Construction Technology Architecture, 2009, 1(3), 40-43
[17] Lira-Zuñiga S, Saez-Navarrete C, Rodriguez-Córdova L, Herrera-Zeppelin L, Herrera-Urbina R, Ciencia y tecnología, 2016, 18(4), 607-616
[18] Wons W, Fluorescent properties of flanges of fly ash for the sintering process of ceramic masses, Ph D thesis, AGH Kraków, 2010
[19] Janewicz A, Kosturkiewicz B, Chemical Industry, 2015, 94/9, 1521-1523