

2022

## Carbonised fluidised fly ash (CFFA); A new product for mining engineering purposes (discussion of possible applications)

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### Recommended Citation

Łączny, Marian Jacek and Rompalski, Przemysław (2022) "Carbonised fluidised fly ash (CFFA); A new product for mining engineering purposes (discussion of possible applications)," *Journal of Sustainable Mining*: Vol. 21 : Iss. 3 , Article 2.

Available at: <https://doi.org/10.46873/2300-3960.1359>

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### Keywords

fluidised fly ash, carbonation, mining engineering

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# Carbonised Fluidised Fly Ash (CFFA); A New Product for Mining Engineering Purposes (Discussion of Possible Applications)

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## Abstract

The article presents and summarises the current state of research and laboratory results on the carbonation of fly ash with carbon dioxide in the context of its use in mining engineering. Based on previous publications and patent applications, the possibilities of using carbonated fly ash from fluidised bed boilers for the following applications were discussed: securing excavations particularly susceptible to fire hazards, shotcreting and securing longwalls and supports, constructing cases, securing decommissioned shafts, and others, which means wherever the use of cement is required. It was pointed out that the removal of excess free calcium oxide makes it possible to use carbonated fly ash in mining applications for placement in workings requiring increased tightness. It was also stated that carbonation allows the removal of hydrogen from fluidised fly ash (FFA) obtained during co-combustion. The research highlighted the potential and importance of granulating carbonised FFA in expanding the applications of this innovative product in mining engineering.

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## 1. Introduction

In fluidised bed coal combustion, limestone is added to eliminate sulphur dioxide emissions. A side effect of this process is an increase in the free calcium oxide content of the fluidised fly ash (FFA) and bottom ash (FBA). This increased free CaO content significantly limits the potential for FFA to be used in a wide range of mining techniques related to mine economics and safety. One way to avoid these limitations is to remove excess free calcium oxide from FFA.

Carbonation is the process in which carbon dioxide (CO<sub>2</sub>) reacts with various forms of calcium hydroxide to play an active role. It is a chemical process known in cement and concrete chemistry to influence the rheological properties of concretes, cement mortars and the final strength parameters of concretes.

This analogy was the inspiration for undertake research work which resulted in a number of experiments on the possibility of using this process to

increase the utilisation rate of FFA, taking into account possible future applications in mining techniques. This enables two objective types to be achieved: improving the efficiency and safety of mine operations and adapting the mine to operate in compliance with the postulate of a closed-cycle economy, combining coal extraction with its use in fluidised-bed combustion processes. The product obtained is a ternary micro-aggregate [1] containing the compounds carbonate, hydroxide and calcium sulphates in proportions that depend on the quality of the FFA used and the way the desulphurisation process is carried out. The previous experience of scientific units in the use of fly ash from coal combustion in the power industry allowed us to pose the following question: where and in which areas of mining engineering could this new product find application, taking into account its specific properties? Carbonisation of fluidised fly ash appears to be an opportunity to increase its use in mining engineering.

Received 8 December 2021; revised 5 April 2022; accepted 6 May 2022.  
Available online 24 October 2022

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<https://doi.org/10.46873/2300-3960.1359>

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From the analysis of existing knowledge, it can be assumed that the product obtained from the FFA carbonation process used in mining engineering, in particular, makes it possible to:

- reduce the free calcium oxide content of FFA, which reduces chemical hazards
- eliminate free hydrogen emissions from co-combustion ash used for goaf filling
- increase the efficiency of sealing mine goafs by improving the penetration capacity in the cave-in rubble
- improve the stability of the backfill setting processes and increase its resistance to saline mine water

Under the Regulation of the Minister of the Environment in Poland on the recovery of waste outside installations and equipment [2], *“recovery under underground mining techniques is the use of waste as, inter alia: an ingredient of hydraulic and self-solidifying backfill, for the liquidation of redundant workings, including shafts, and for the reinforcement and stabilisation of mine workings, on condition that this activity is carried out taking into account the properties of the waste and local conditions in such a way that this activity does not cause deterioration of underground water quality.”* Therefore, the location of wastes in underground mining technologies requires prior research to develop safe technology for their use, conditioned by formal and technical limitations [3,4].

In view of the above, considerations at this stage of knowledge of the carbonation process and the properties of the product obtained from FFA studied to date have been limited to the following applications:

- self-solidifying backfill
- shotcrete
- the construction of cases and dams

This paper also presents a formalised model for FFA carbonation based on the autocatalytic reaction of free CaO with CO<sub>2</sub>. It could be used in the future to design reactors to convert FFA into a useful product. It is worth noting that carbon dioxide may come from sequestration technology as the technology is developed and put into practice.

## 2. Management of FFA in mining

Fly ash from coal combustion in the 1980s was widely used in the mining industry, among other things, as an additive for hydraulic backfilling [5]. At that time, the Polish energy sector was based mainly on generating electricity and heat in power stations

and combined heat and power plants equipped with so-called pulverised fuel boilers. The combustion temperature of coal in this type of boiler varies around 1300°C. For this reason, a significant part of the mineral substance contained in the combusted coal (mineral substance bound in coal macerals and originating from the remains of the waste rock) undergoes transformation (melting, dehydration). The resulting ashes acquire pozzolanic properties due to the content, in appropriate proportions, of the following oxides: silicon, aluminium and calcium, as well as iron [6,7]. This is why they are widely used in the cement and concrete industry [8]. This resulted in their almost complete withdrawal from use as a raw material for backfill works.

Currently, fluidised bed boilers are widely used to combust coal for energy purposes. The main reason for the large-scale introduction of fluidised bed combustion was requirements related to the need to reduce emissions of sulphur dioxide and nitrogen oxides (NO<sub>x</sub> and SO<sub>2</sub>). In addition, interest in combustion in fluidised bed boilers, both atmospheric circulating and pressurised, is increasing due to the higher combustion efficiency, which is an important economic factor. This technique makes it possible to burn inferior types of coal as well as to co-fire biomass at a temperature of approximately 950°C, which reduces nitrogen oxide emissions. In order to reduce sulphur dioxide emissions, the addition of limestone (CaCO<sub>3</sub>) is required. Typically, its excess relative to the stoichiometric sulphur content of coal is between 2 and 3 if we expect to reduce SO<sub>2</sub> emissions above 90% [9,10]. Attention has also been drawn to the potential for CO<sub>2</sub> sequestration [11].

The FFA produced during coal combustion contains irregular amorphous minerals or poorly crystallised products of total or partial dehydroxylation of the clayey substance in the coal bed waste rock and anhydrite (CaSO<sub>4</sub>) as a desulphurisation product. Moreover, it contains: unreacted sorbent CaCO<sub>3</sub> – calcite and free CaO and its hydration product – Ca(OH)<sub>2</sub>, as well as unburned carbon [12].

As mentioned earlier, while the management of fly ash from ash-fired boilers is not a problem, a problem arises with FFA due to its high free calcium oxide content. This is usually a few or even several percent, due to the use of excess sorbent, as mentioned earlier. For example, its use in cement and concrete as a type II additive (understood as a granular inorganic material with pozzolanic or latent hydraulic properties) must comply with the standard and therefore should not contain more than 2.5% of free calcium oxide [13]. Furthermore, calcium oxide (CaO) is classified as a substance with irritant properties and is designated as H315 and

H318 [14]. The waste is hazardous due to its irritant properties if free calcium oxide ( $\text{CaO}_{\text{free}}$ ) content exceeds 1.0%. Waste from fluidised bed boilers containing more than 1.0% by weight of free calcium oxide  $\text{CaO}_{\text{free}}$  may be classified as hazardous waste. Its storage is also known to increase the temperature in contact with water, which occurs, for example, in landfill sites and threatens the environment [15]. This is due to the exothermic reaction of free calcium oxide with water. This phenomenon must be taken into account during FFA storage, transport and use in mining technologies.

As mentioned earlier, the presence of free calcium oxide in fluidised bed ash is one of the most significant features limiting the widespread use of fluidised bed ash as an additive in cement or concrete. The relatively high content of free calcium oxide ( $\text{CaO}_{\text{free}}$ ) and calcium sulphate ( $\text{CaSO}_4$ ) (two important constituents significantly affecting the properties of cement mortar) in the absence of silicon, aluminium, calcium, and iron oxides in adequate amounts is the reason that they are not classified, also as ASTM Class F or C additives [16,17].

One way to deplete fluidised bed ash of free calcium oxide is hydration to calcium hydroxide [18,19].

The papers also describes the use of fluidised bed ash for carbon sequestration both in the solid phase and in aqueous solutions [20–27]. The co-combustion of alternative fuels with coal has raised the issue of hydrogen release when dense ash slurry is prepared and then deposited in coal workings [28]. This phenomenon was first observed in the silting of FFA goafs originating from the co-combustion of coal and biomass. This was because it threatened to stop the mines receiving FFA for fear of it posing a threat to the working environment. This hazard was identified by measuring above-normal concentrations of free hydrogen in pits where combustion by-products were deposited when mixed with water during routine mining operations. Observations carried out during subsequent activities related to sealing collapsed goafs confirmed this fact, resulting in a temporary suspension of the collection of combustion by-products until this phenomenon is clarified. Literature reports confirm that this phenomenon is known for municipal waste incineration processes [29–32]. It has also been reported that this phenomenon was observed when such combustion by-products were used as an additive to concrete in the form of a partial cement replacement [33]. Thus, it can be considered that the phenomenon of free hydrogen release from FFA, under the conditions mentioned above, represents a

new research problem taking into account occupational safety in mining. It is also an engineering challenge, and its solution should guarantee the safe operation of mines in areas where FFA, originating from fluidised bed boilers from the co-combustion of coal and biomass, is and will be used.

The origin of free alumina is explained by the presence of packaging in municipal waste, e.g. from juices, dairy products, etc. It should be added that the release of hydrogen by the reaction of aluminium with water is favoured by the presence of sodium chloride and general salinity. Therefore, the preparation of a dense FFA suspension using saline mine water, intensifies this process [28].

### 3. FFA in mining engineering

Dense FFA suspensions are applied in mine workings. They are transported by gravity from the level of a mine shaft to mine workings or goafs in order to fill them. These suspensions may be used for sealing caving goafs, liquidating excavations, filling old voids in the rock mass, making backfill belts and plugs, liquidating shafts, and as a component of self-solidifying backfill and in technologies related to fire prevention [34].

The use of dense slurries based on combustion by-products has a number of advantages. The preparation is technically simple and uses, for example, tanks equipped with stirrers, barbotage or circulation pumps. However, it should be noted that their optimum technological parameters depend on the care taken in preparing such a mixture. The critical parameter is the amount of water used in their preparation. It is usually as high as 1 to 2, 1 to 3 by-products of combustion to water (in practice, the term “make-up water” is often used). The amount of water used depends in turn on the by-product characteristics. In addition to the grain size, the free calcium oxide content is the decisive factor here. The latter applies to by-products from fluidised bed boilers. Advantages include good penetration properties, good insulation properties in fire-prone areas, such as excavations and inactive workings, relatively low permeability in terms of water infiltration and associated low leaching of toxic metals. It should be added that the low permeability to water is due to the binding properties. The associated strength of the solidified material also prevents ground deformation to a large extent. In their place, FFA, without prior processing, began to be used on a massive scale. From the point of view of the application in mining engineering, however, it manifests certain disadvantages, which include:

- increased need for water to make a thick suspension due to the high content of free calcium oxide resulting from its hydration
- increased temperature in the installations for preparing and transporting the mixture to the excavations due to the exothermic nature of the hydration reaction, which promotes the overgrowth of the pipelines
- reduced spreadability of dense suspensions, which makes it necessary to increase injection pressure and to insert the pipelines deeply into the excavations to be protected
- increased risk of overgrowth of pipelines of slurry transport facilities
- increased drainage of water from suspensions due to the need to use excess water
- the risk of hydrogen release from FFA originating from co-combustion

The developed FFA carbonation process largely eliminates these disadvantages.

#### 4. Origin, nature and process mechanism of carbonation

For some time now, there has been growing interest, particularly in Europe, in the use of limestone as a filler for cement, which is advantageous both technically, economically and environmentally [35]. Calcium carbonate is an important and active ingredient that influences the setting process of cement mortar. Treated as a filler, calcite (above 5%) acts as an active reactant in cement. The mechanism of these reactions is described in detail in [36,37]. This, as well as the need to solve the many problems associated with FFA management (mentioned earlier), inspired the research in such a direction.

A new direction for the use of the carbonation process has been proposed, as described in [38]. In this case, carbonation was used to obtain a product with controlled free calcium oxide content. This resulted in a ternary micro-aggregate containing  $\text{CaO}_{\text{free}} - \text{CaCO}_3 - \text{CaSO}_4$ , which, as shown by research [39], can be used as an active ingredient in cement mortars. The beneficial effect of carbonated fluidised fly ash on the strength properties of cement mortar was demonstrated. It has also been shown that the compressive strength of mortar prepared from these ashes is improved compared to non-carbonated ashes, probably due to the beneficial effect of carbonate on ettringite transformation [40].

Mineral carbonation involves the exothermic reaction of carbon dioxide even at low  $\text{CO}_2$  concentrations in air and water. This process is very slow

under natural conditions. Its intensification is carried out in various types of reactors and water acts as a catalyst for the process.

Laboratory studies were carried out in the following reactors:

- a fluidised reactor
- a rotary reactor
- a ball mill-type reactor, and
- a non-pressurised closed granulator

The phenomenon of the occurrence of free calcium oxide in fluidised bed boiler ash is related to the mechanism of the calcination and desulphurisation process. It can occur as free grains or be incorporated into the grain structure in combination with calcium sulphate [41,42]. For this reason, the FFA carbonation process is slow due to the different grain structures and morphology of individual FFA grains.

The reaction scheme is as follows:



It was assumed that the model would be described by kinetic equations. It was proposed that the equation describing the change in CaO concentration over time would be described by first-order kinetics due to CaO. The presence of a factor responsible for taking into account the interfacial contact property is postulated in this equation. It was assumed that this relationship would be described by second-order kinetics. The introduced parameter  $y$  describing the interfacial contact properties is time-varying, and this variation is described by the first-order kinetic equation.

Ultimately, the model therefore takes the form of the following system of differential Equation (1 i 2):

$$\frac{dc_{\text{CaO}}}{dt} = -k_1 c_{\text{CaO}} y^2 \quad (1)$$

$$\frac{dy}{dt} = k_2 y \quad (2)$$

Where the  $y$  parameter can be interpreted as a linear measure of surface expansion. This assumption is justified by the fact that the grain size structures of the reaction products before and after the process maintain a similar normal distribution, as shown in Fig. 1. The observed change in grain size is related to the hydration reaction of calcium oxide to calcium hydroxide, which causes an increase in the volume of the FFA grains.

This interpretation justifies the adoption of second-order kinetics in the equation describing

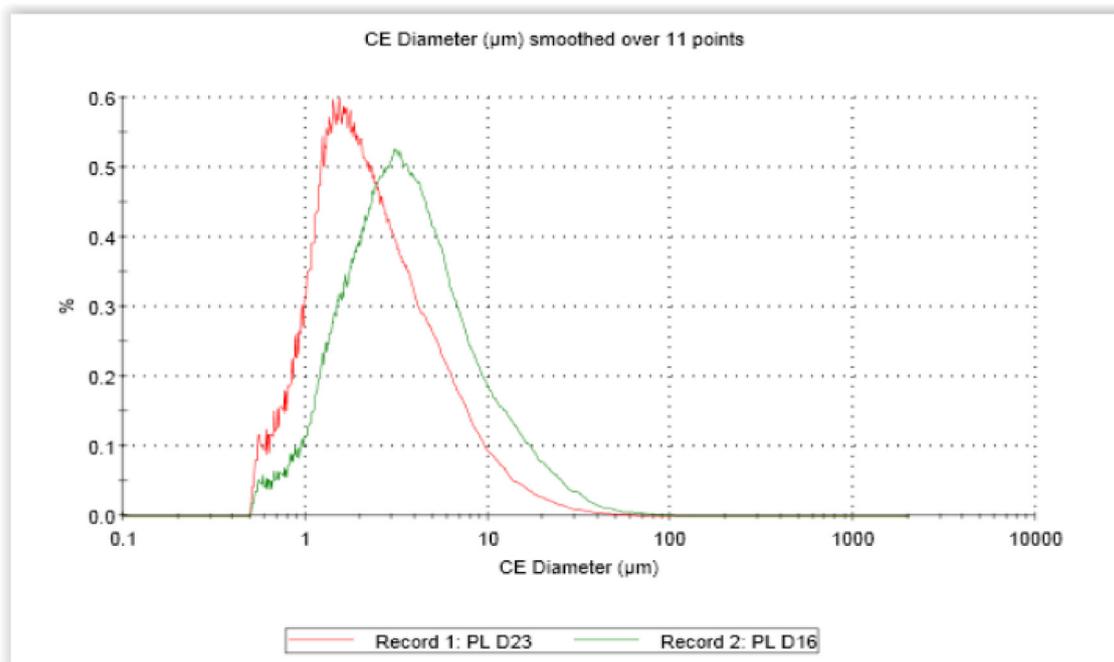


Fig. 1. Changes in grain size distribution before and after carbonation reaction (red – before reaction; green – after carbonation reaction). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article).

changes in the molar concentration of CaO. The parameters  $k_1$  and  $k_2$  in the equations are called process rate constants [43].

The process model presented here does not address the carbonation reaction in the granulating process because, as mentioned earlier, this process is influenced by additional factors, such as the presence of capillary water and pressure caused by the compression of the FFA grains during granulation. Nevertheless, granulation can be considered a future direction for using granulated carbonised FFA in underground mining techniques [44]. The product obtained in this way can be used as a supplementary aggregate for filling in cases, or in a suitable component structure for mine shaft decommissioning. It should be added that FFA granulation has already been proposed both in Poland [45] and worldwide [46]. Application research has focused on the use of different binder materials to improve product properties compatible with the expectations of different customers [47–49]. In the granulator, the carbonisation process takes place during the formation of the granules. The simultaneous chemical reaction promotes an increase in the strength of the product.

## 5. Use of deposits in hazardous excavations

The waste from the power industry (and others) has been used for many years [50]. Installations for

the transport of backfill material, including dense fly ash suspension, are complex systems with locations that are particularly sensitive to the possibility of failure. These critical sites can disrupt normal mine operations [51]. The transport of ash-water suspensions, and FFA in particular, is more complicated than that of traditional backfill materials [52]. This is due, among other things, to their characteristic properties affecting the specific properties of such mixtures. These mixtures change their properties during hydrotransport. The changes concern rheological properties, such as viscosity, flowability and flow limits. By reacting with the water used in hydrotransport, they change their density and structure. In addition, as mentioned earlier, the reaction with water is strongly exothermic, which, due to the initial temperature increase (at the time of suspension preparation) and subsequent cooling during transport, causes viscosity changes also due to changes in the density of the transport water. All these changes are caused by and depend on the mainly free calcium oxide and partly calcium sulphate content of FFA. For example, the dynamic viscosity index varies depending on the origin of the fly ash (and on the water-to-ash ratio). For ashes from pulverised coal boilers, it can vary from 0.1050 Pa to 0.6903 Pa, for FFA from 0.1107 to 0.6519 Pa, and for ashes from semi-dry desulphurisation from 0.0200 to 0.2419 [53]. Due to the stabilised content of free calcium oxide in carbonised fly

ash (approx. 1% – optimum value for cement and concrete applications), the viscosity factor is also relatively stable and close to that of fly ash from pulverised coal boilers. From the viscosity values quoted above, a cautious conclusion can be drawn regarding the influence of the free calcium oxide content on the viscosity of the ash-water suspension caused by fly ash from pulverised coal boilers.

Taking into account the specificity of hydrotransport of ash-water mixtures, the flow limit and the previously discussed viscosity coefficient and flow limit are important, as they determine the flowability and thus the efficiency of the injection process [53]. These parameters are the basis for the design of hydrotransport systems and the determination of critical locations in installations, especially when using specialised ANSIS software with the CFD package [52].

From the above considerations, it can be concluded that carbonised FFA should improve the operational safety of injection facilities as well as their working conditions, especially in situations where a high degree of leak-tightness of the protected product is required due to fire hazards. Carbonated FFA has a largely eliminated tendency to react with saline waters, limiting the formation of so-called “secondary ettringite” so that the formed dam does not unseal [40].

## 6. Use of carbonated FFA as a micro aggregate and cement replacement

In mining engineering, large quantities of cement are consumed mainly for the construction of cases, shotcreting, or reinforcing the support [52]. It is also used in mine shaft decommissioning regardless of the fly ash used [52].

Earlier, it was mentioned that previously conducted researches confirmed the possibility of using carbonated FFA as a cement substitute.

Shotcreting involves the pneumatic application of a pressurised cement-based mixture at high speed to the surfaces of carbon walls of supports, etc. The components of sprayed concrete are essentially a mixture of cement and fly ash mixed with sand, gravel and water. In the construction of cases, on the other hand, regardless of the method used, cement and its substitutes are also used, depending on the need for the effectiveness of the floor protection.

The PN-EN 450–1:2012 standard [54] sets out 16 chemical parameters that fly ash should meet in order to be used in the production of concrete, clinker and cement and for road foundations, as well as for building ceramics. The most important are: free calcium oxide, reactive calcium oxide,

sulphate content and the sum of silicon, aluminium and iron oxides.

Fly ash from fluidised coal combustion in fluidised bed boilers, despite its different chemical and mineral composition, compared to conventional fly ash and the many inconveniences and potential hazards of its use is a valuable material for the production of binders. In addition to its pozzolanic properties, fluidised ash exhibits binding properties. The durability of the product is required. In studies conducted [19] covering successively: hardening binders consisting only of fluidised ash, cement-ash binder, mortars and concretes containing fluidised ash, attention was drawn to the possibility of the formation of the so-called delayed ettringite, which may adversely affect the durability of the material containing fluidised ash, of the formation of ettringite called “cement bacillus” and the accompanying expansion phenomenon. Carbonation of fluidised bed fly ash using carbon dioxide may be one way of processing it into a product with a promising application as an additive for cement and concrete by preventing the occurrence of this adverse phenomenon [40].

It was mentioned earlier that, at present, due to its physical and chemical characteristics, especially its high free calcium oxide content, the applicability of FFA is severely limited and sometimes impossible. A significant reduction in free CaO or even its complete elimination is achieved at the expense of conversion to calcium carbonate. The FFA processed by carbonation contains two important components for cement mortar setting time and strength: calcium carbonate and calcium sulphate. Calcium carbonate, being hardly soluble, should not react with the other pore water components of the fluidised bed fly ash. The crystalline phases of calcium sulphates: anhydrite, gypsum and bassanite, which appear in bound volatile fluidised bed ash after carbonation, testify to the possibility of crystallisation of these phases in the presence of calcium carbonate. In particular, the change in bassanite content indicates that this phase, as a precursor of gypsum crystallisation, may play a decisive role in the binding processes of carbonated fly ash [40].

Many studies indicate that calcium carbonate is an active component of cement mortar, and there is an optimum ratio of sulphate to carbonate at which concrete achieves optimum strength [55]. The effect of carbonated fluidised fly ash observed in preliminary studies may additionally be related to the behaviour of sulphate forms present in fluidised fly ash, as in concrete [56]. Studies have also shown that carbonised FFA affects the spreading of cement mortar. Example results show that this spread can

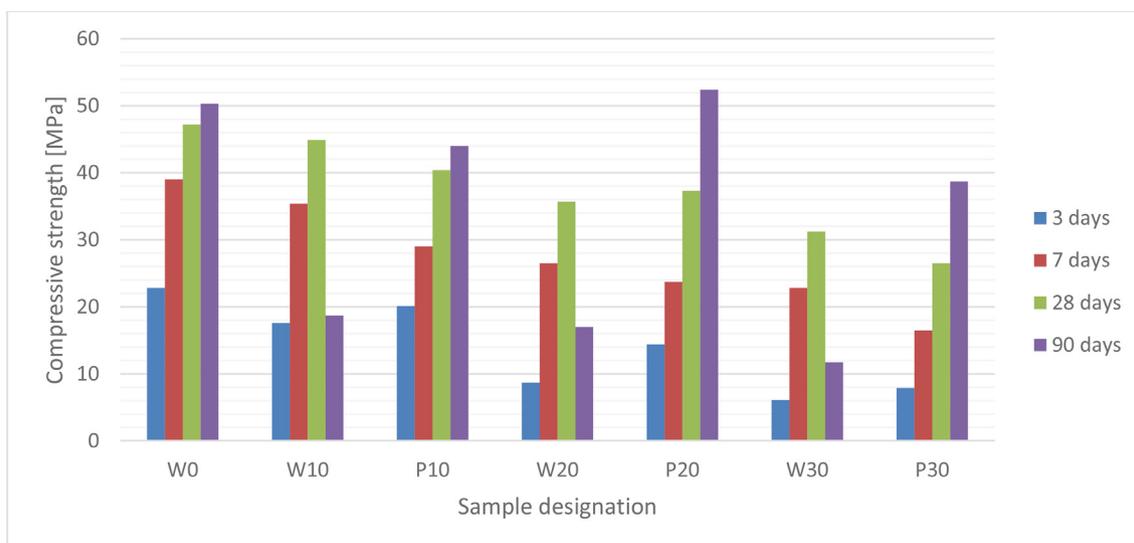


Fig. 2. Compressive strength of specimens in which cement was replaced with untreated FFA (W10, W20, W30) compared to carbonated FFA (P10, P20, P30) and a reference specimen (W0).

vary from about 160 mm with 10% addition of carbonated FFA to about 125 mm with around 30% addition. The spread for a standard sample is of the order of approximately 170 mm. The strength of cement mortar with carbonated FFA can be controlled by the amount of this micro-aggregate added. Fig. 2 shows the results of strength tests on cement mortar samples prepared with FFA before and after carbonation. Carbonated FFA contained 0.2% of free calcium oxide CaO. Comparative samples were prepared in compliance with the PN-EN 196-1 standard. Samples in which part of the cement was replaced by 10, 20, and 30%, respectively, were designated as P10, P20 and P30, whereas the non-carbonated FFA is designated, respectively, as: W10, W20 and W30. The determination of the compressive strength  $R_c$  after 3, 7, 28 and 90 days of maturation of the prepared bales was performed based on the PN-EN 196-1 standard.

The results of the cited studies indicate that even replacing 20% of the cement does not change its initial strength. As mentioned, appropriate amounts of micro filler obtained on the basis of carbonated FFA can be selected over a fairly wide range, depending on the engineering needs of the mining work in progress.

## 7. Conclusion

The aim of the analysis of the studies carried out at GIG was to show the new aspects in which the use of the properties of carbonised fly ash from the combustion or co-combustion of coal in fluidised bed boilers may be considered. The possibility of

a new innovative product coming onto the market from the treatment of combustion by-products (CBPs) would undoubtedly broaden the possibilities for using FFA by reducing the risk of use arising from excess free calcium oxide. It seems the mining industry should be particularly interested in this type of product, as it can be widely used to improve the quality and safety of the mining techniques and technologies used. Economic aspects are also important. Obtaining a new ternary micro-aggregate requires an FFA processing facility. The treatment of FFA as the currently dominant component of the total mass of CBPs produced is known and applied (for example, removal of unburned carbon – coke, ammonia, etc.). They all increase the cost of the products subsequently offered on the market. The situation will be similar with regard to FFA carbonation. However, economic issues remain to be resolved in a political, social and economic context. This is not a simple dilemma to resolve today. Nevertheless, it is worth pointing out another way in which CBPs can be managed in line with the postulate of a closed-cycle economy. An important factor in the possibility of realising this postulate will be the petrographic evaluation of coal resources intended for combustion in fluidised bed boilers in terms of obtaining FFA of a composition favourable for carbonation and processing into the product that is most optimal to the customer. The second important factor is the use for this purpose of CO<sub>2</sub>, which in future may come from sequestration processes. Finally, the third element is the replacement of some of the cement with carbonated FFA, which reduces its consumption in mines and may, at least

in part, offset the costs incurred in producing carbonated FFA.

The study showed that the bonding reactions between the constituents of carbonated FFA significantly depend on the presence and quantitative ratios of the three main components, i.e. CaO, CaCO<sub>3</sub> and CaSO<sub>4</sub> (hence the name tri-substituted micro-aggregate). The transformation is particularly affected by sulphur compounds when we subject FFA to a solidification process. It is also worth noting that other crystalline phases participate in this complex system of mutual reactions, especially those activated by dehydration in the combustion process [55]. At the same time, there are better conditions for the crystallisation of gypsum at the expense of the other sulphate phases: ettringite, anhydrite and bassanite. However, according to the literature cited earlier, it is likely that bassanite was converted to gypsum. In the FFA-Z sample, this process has not been observed. Anhydrite passes completely into hydrated forms in a strongly alkaline environment. The absence of anhydrite in the sample suggests that this is the explanation for the phenomenon of the increase in strength of cement mortar samples with the addition of fluidised bed fly ash after carbonation [38,55].

Carbonation of fluidised bed fly ash using carbon dioxide appears to be a promising treatment option for the recovery and utilisation of this waste. Due to the physico-chemical characteristics, especially the high content of free calcium, the application possibilities are very limited and sometimes even impossible. A significant reduction in CaO free or even its complete elimination is achieved by reactivating calcium carbonate (CaCO<sub>3</sub>). This opens up new perspectives with regard to the use of carbonated fluidised fly ash in various types of concrete. It can be hypothesised that this fact may also be significant in future directions of geotechnical applications of carbonated FFA, for example, in the process of regulating the hardening time or strength of mineral composites produced for degraded and revitalised post-mining areas. Finally, it is worth mentioning that the suggested application directions and application possibilities of carbonated FFA have not been tested in practice due to the current lack of this product on the CBP market. Its advantages can be expected to be quickly confirmed in practice once the technology is implemented.

### Ethical statement

The authors state that the research was conducted according to ethical standards.

### Founding body

This research received no external funding.

### Conflict of interest

The authors declare no conflict of interest.

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