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Using Agglomeration Techniques for Coal and Ash Waste Management in the Circular Economy

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ABSTRACT

This is a scoping review of agglomeration techniques to obtain of solid bodies from particle waste-materials for their utilization. For this purpose, the granulation and briquetting of fine coal and fly ash were presented in detail. Many successful works on solid fuels production, with coal only, and also with the addition of biomass, were presented. During the solid fuel combustion in power boilers, significant amounts of ash are generated. The properties of fly ashes were taken into consideration, and different methods of their utilization were proposed to obtain a wide range of useful products. Consequently, the waste resources of coal and ash were fully utilized. In final remarks, it was concluded, that the agglomeration techniques play an important role in waste management, but particularly in the circular economy.

Keywords: fine coal, fly ash, agglomeration, waste management, circular economy

INTRODUCTION

Fine-grained coal fractions are formed as by-products from the extraction and enrichment of hard coal and brown coal. These mainly include coal sludge and flotation waste. Depending on the energy properties, coal sludge is often used as independent fuel and as one of the components of the produced fuel mixtures. Fine coal can be enriched with physical and physicochemical methods, which allows obtaining high-energy carbon concentrates [1].

Fine coal sludge is a material with a grain size of up to 1 mm. It is often stored in settling tanks or in landfills – constituting fine-grained coal waste from settlers or landfills. Under the influence of gravity, grain sedimentation occurs, while the clarified water is returned to the processing plant. In the case of old mining dumps of waste, the mixtures of coal sludge and flotation waste with medium- and coarse-grained waste from coal enrichment can be found [2]. Fine coal sludge stored in earth settling tanks is characterized by high variability of the physical composition and water content. The use of filter presses in many cases results in more homogeneous mules in the form of filter cakes. They are suitable for making fuel mixtures [3].

The amount of deposited coal sludge and flotation waste in settlers in Poland varies, amounting from 11 million Mg to 20 million Mg [4]. Based on mining statistics, Kurus et al. [5] estimated that in the Upper Silesian Coal Basin there are up to 120 million Mg of coal sludge in settlers. In turn, the current production of coal sludge is about 5 million tons per year. The calorific value of fine coal sludge varies, and according to Hycnar et al. [4]: (i) coal with a calorific value >15 MJ/kg constitutes 9.3%, (ii) coal with a calorific value from 12 to 15 MJ/kg – 6.8%, (iii) coal with a calorific value from 10 to 12 MJ/kg – 22.3%, and coal with a calorific value <10 MJ/kg – 61.5%. It follows that the fine coal sludge with a calorific value below 10 MJ/kg was found in the largest amount.

Fine coal could be used as an independent fuel or as an additive to traditional fuels. However, they need processing for utilization [6]. Fine coal sludge has a high-water content of up to 48% [7]. The lowest water content is contained in the sludge that is subject to drying in atmospheric conditions. For drainage, coal sludge can be concentrated in settling tanks, in filtration devices, as well as sedimentation centrifuges. As a result of thickening, classification, and enrichment of suspensions, the dehydrated material with a calorific value above 14 MJ/kg is obtained. Flotation can increase the calorific value of coal sludge up to 25 MJ/kg [8].

In many cases, heavy dusting during transport and storage is a major obstacle in the utilization of fine coal. An effective way to eliminate dusting and reduce the volume of material is to use agglomeration (consolidation) with the addition of a binder. For fine coal, granulation and briquetting techniques are most often used for agglomeration. Fine coal is often mixed with other fine-grained fuels, together with calcium binders or starch, and after the consolidation is converted to solid fuels [9]. The obtained alternative fuels were used as sources of thermal energy as well for combustion in low-power household boilers [10].

Combustion of coal fuels produces more waste, namely fly ash and bottom ash, which must be disposed of. The present utilization of ashes from coal combustion varies widely from a minimum of 3% to a maximum of 57% of the total produced, with an average of 16% [11]. Large amounts of this waste are used by the cement industry and by the plants manufacturing building materials [12]. Some works on the use of ash as a backfill in the underground mine have been carried out [13]. There is the possibility of utilizing it in agriculture, for de-acidification of soils as well as in the process of composting and fertilization [14]. Ashes are also used as a material for the substructure of road pavement [15]. Querol et al. [16] described the process of synthesis from coal fly ash to obtain high cation exchange capacity zeolites used in the wastewater and flue gas treatment. The potassium-type zeolite was synthesized from coal fly ash with the microwave heating method that shortened the synthesis time compared to external heating [17]. Yang et al. [18] described a process involving the application of coal fly ash in the preparation of porcelain ceramic tiles with good mechanical properties. The results pertaining to substance flow, gas emission, and heavy metal leaching indicate that there was almost no hazardous waste emission in this process.

Merging was used to prevent dusting, reduce the leachability of soluble components, and obtain new types of materials in processing. The application of ash for the production of lightweight aggregate is useful in the construction industry [19].

In March, 2020, the European Commission adopted a new Circular Economy Action Plan – one of the main blocks of the European Green Deal, Europe's agenda for sustainable growth. The Action Plan announces initiatives along the entire life cycle of products, targeting for example promoting circular economy processes, and aiming to ensure that the resources used are kept in the EU economy for as long as possible. This plan introduces a closed circuit of materials and products into the everyday life of the population [20].

The purpose of this scoping review is to verify whether the agglomeration techniques of fine coal and fly ash meet the objectives of the circular economy. The produced solid bodies are possibly for be using it entirely – as a product or material.

PRODUCTION OF SOLID FUEL FROM THE FINE COAL

The granulation method

Granulation (pelleting) is a method of non-pressure agglomeration of a material to obtain a product with increased mechanical strength. This method is also implemented by applying increased pressure at an ambient or higher temperature, in a pouring or mixed layer of material [21]. The binder increases the strength of the product. The most useful additives in the coal mix include binders such as calcium hydroxide, cement, water glass, asphalts, polymers, and organic adhesives [22].

As a result of granulation, regular granules with a porous structure, similar to a spherical shape, with dimensions of several millimeters are obtained. They have a much higher bulk density than the raw material [23,24]. For the processing of fine-grained materials, consolidation on a granulation plate is the most often used solution. Individual grains form a stable agglomerate only when there are sufficiently high forces connecting these grains. This requires a large fragmentation of the bulk medium and maintaining its humidity at a constant level [25,26].

Typical water content in the granular material ranges from 11% to 20%, depending on the type of material, and is higher in porous materials [27]. The granules usually have a diameter of 10–20 mm. According to Herting and Kleinebudde [28], the pelleting efficiency decreases rapidly with the increasing size of pellet diameter. The scheme of producing the coal fuel with the granulation method is shown in Figure 1.

The mechanical strength of the granulate is relatively small. This is due to both the conditions for forming the granules and the degree of homogeneity of the mixture [30]. The final mechanical strength of the coal granules is obtained during the seasoning process within a few hours to several dozen days [31]. The method of dispensing the binder into the material has a significant impact on the process of formation and properties of granules. Frequently, binders are added during the material transport to the mixer or granulator. Powdering by cement is also used to accelerate the hardening process of the granule surface [32].

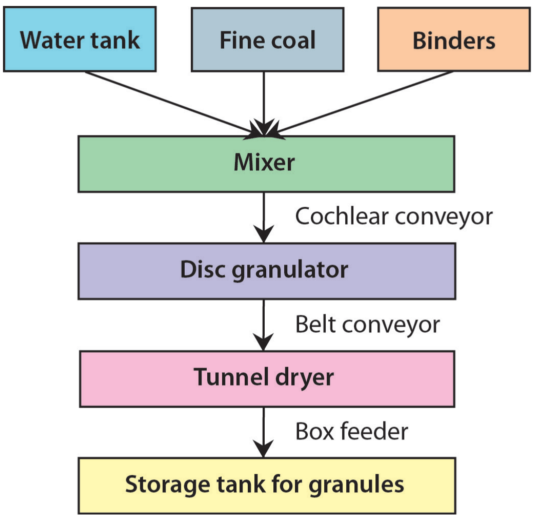

Figure 1. Blok scheme of the technology for granulation the fine coal (based on [29])

Fine coal sludges and dust are most often processed to produce alternative solid fuels. The basic criterion is calorific value. The calorific value of the fuel obtained as a result of the processing of fine coal with the granulation method reaches 19 MJ/kg [33]. The estimated amount of coal waste in Poland reaches 0.5 billion tons. The content of pure coal in this waste should exceed 8%, if it is used for energy recovery. The method of producing coal fuel was developed by Borowski and Hycnar [34]. The pellets with a grain size of over 5 mm were obtained, with a calorific value of 26–29 MJ/kg and sulfur content of about 0.6%, and ash below 15%. Fine coal granulation was used to produce alternative fuel for combustion in fluidized bed furnaces. The addition of these fuels to the stationary fluidized bed resulted in an increased combustion efficiency [35].

The laboratory work to date confirms that the fine-grained coals are preferably converted into granulates in disc granulators [36]. As a binder, quicklime was used in a proportion from 1% to 1.5% of mass share. The granules between 5 and 10 mm were obtained. The sizes of the different fractions of granulated coal are shown in Figure 2.

Under industrial conditions, intensive heating of the coal-lime mixture should be taken into account to evaporate water before the granulation process. The addition of lime (CaO) is often used to produce granules from fine coal. Calcium oxide, due to its sorption properties, reduces the moisture content, and also the SO_2 emissions in the flue gas during the combustion process. Lime and coal granulate have good mechanical toughness and energy efficiency [37,38].

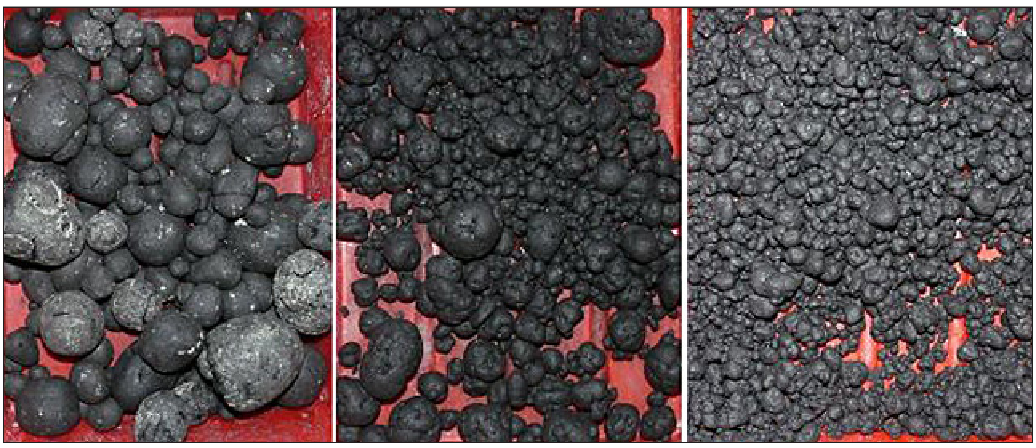

Figure 2. The different fractions of granulated coal [36]

Figure 3 shows a schematic of the fine coal processing using a disk granulator with a diameter of 1.5 m at a speed of 15–20 rpm and a plate angle of 40–45°. The sizes of the granules formed were from 15 mm to 20 mm [33].

A binder was used in the form of an aqueous solution of lignosulfonate (wood industry waste) in an amount of 2–3% by weight. The granulation process was preceded by heating fine-grained material in a specially constructed vortex chamber at a temperature of 430 °C. It was found that the mechanical strength of the granules obtained from fine coal is comparable to the strength of carbon nuggets. The agglomerates produced are suitable for combustion in domestic heating furnaces, where an efficiency increase by 63–64%, and reduction of losses caused by incomplete combustion has been achieved [33].

It is possible to use granulated fine coal as a substitute for artificial aggregates. The mechanical properties of granules with a small addition of ash, cement, and water were tested [39]. He found that the compressive strength of the obtained granules is slightly dependent on the type and size of coal grains with ash. In turn, the value of internal stress in granules significantly depends on the type and grain size of the material.

Solovei et al. [40] presented a method of granulating coal dust to obtain mechanically strong spherical granules with a diameter of 1 to 6 mm, with a dominant size of 3 mm. They showed that the composition of the granular material fraction can be significantly changed by introducing surfactants during the consolidation process. Due to the favorable parameters and high mechanical strength of the carbon granules, it was possible to use them as bed filler in adsorption processes.

Despite good research results, pelleting is not widespread in Poland for processing large amounts of fine coal due to, among others, the limited capacity of granulators. For this reason, coal pelleting using drum and disc pelletizers is carried out only in small enterprises. Coal sludge is most often agglomerated to reduce dusting and produce solid fuels for combustion in power boilers.

The briquetting method

Briquetting is a pressure agglomeration that allows obtaining a high degree of concentration of matter. This requires an increase in energy expenditure. Briquetting enables to obtain homogeneous nuggets of many shapes (barrel, cushion, saddle, etc.) and dimensions usually

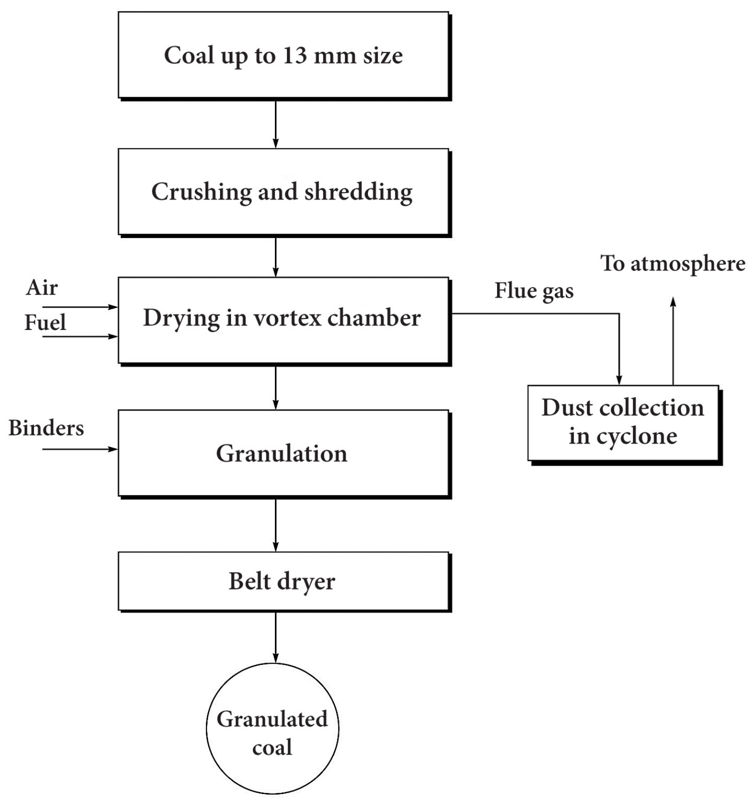

Figure 3. Scheme of fine coal processing to obtain pellets for use in domestic heating furnaces [33]

larger than 20 mm. The essence of briquetting is that as a result of exerting pressure on the granular material, the grains get closer together. Close direct contact of the grains helps adhesion, which has a significant impact on the surface joining of these grains [41]. Stamp, screw, and cylindrical presses are the most commonly used for briquetting [42]. The stamp presses allow achieving high pressures. Due to their low efficiency, they are used in low volume production and in laboratory tests. The roller presses have high performance. Most often, the fine-grained mineral materials and post-production waste are briquetted [43].

Briquetting is often used to merge bulk materials with binding additives (binders) [44]. The addition of a binder significantly increases the mechanical strength of briquettes. Further improvement of the mechanical properties is obtained by using curing (seasoning) briquettes [45]. Owing to this property, briquettes can be loaded, transported, and stored until development, without fear of losing their consistency.

Briquetting is purposeful to merge fine-grained coals. The currently produced briquettes contain fine coal, lignite, and coke, often with the addition of sawdust, peat, straw, or other raw materials [46]. Fine-grained coal fractions are often used as stand-alone fuels or as an ingredient in alternative solid fuels [47]. Fine coal is the hardly-compressive material, as the only component of the briquette, and it is advisable to mix it with other fuels, e.g., crumbled biomass. The calorific value of coal is twice higher as biomass; however, when coal is burned, more ash is generated and there is a greater emission of sulfur compounds into the atmosphere [49].

The production of smokeless briquettes for individual households and district heating has been developed by Wang and Wang [50]. This technology involves briquetting a mixture of coal with the addition of biologic binders. The prepared material was fed to a two-roll press and fuel bodies were obtained. Zhong and Cao [51] described the technology for producing the coal and biomass briquettes with biomass of share 20% by weight. A mixture of fine coal with the carboxylmethyl starch binder was added, which increased the mechanical strength of the briquettes. This solid fuel was characterized by high waterproofness, as well. The calorific value of fuel ranged from 19 to 25 MJ/kg.

The fine coal sludge from Polish coal mines was investigated to produce energy solid fuel. It was found that the briquettes made of coal alone did not meet the minimum strength requirements, while the addition of biomass improved their toughness. The hard bodies were obtained by adding about 8% of starch. The curing time increased the hardness of bodies, and the greatest toughness was obtained after about 28 days of curing [48]. The results of laboratory tests showed that the grade of material, water content, and binders affected the briquetting process to the greatest degree. Moreover, important factors of body quality were: binder content, the mixing time of material, hydration, size of compaction, as well as drying time.

More authors have shown that good briquettes are largely influenced by the selection of the correct binder with adequate material moisture [52–54]. In addition to material preparation, the consolidation parameters also affect to briquette body. The mechanical properties of a body depend on its size and shape resulting from the geometry of the compactor. However, it was found that the type of material and the method of preparation have a greater impact on obtaining the proper goods than the configuration and parameters of the compactor [55]. The briquetting of the coal in a roller press required the addition of potato starch or hydrated lime, but the water content had to be increased to 24% of dry mass [48]. Highly hydrated briquettes should be dried and then cured in containers or bags, owing to which they acquired high mechanical strength. The results of tests of two types of coal briquettes (starch or biomass added – Table 1) allowed producing an alternative solid fuel with excellent parameters.

Many researchers have stated that the addition of biomass to fine coal enables to reduce the dust emissions to the atmosphere, as well as to reduce the content of volatiles, ash, and sulfur during briquette combustion compared to the combustion of coal alone [56,57]. Therefore, for ecological reasons, burning coal briquettes with biomass are more advantageous than combustion coal alone [58]. It was shown that the addition of biomass as a binder did not significantly decrease the mechanical strength of the briquettes. Biomass coal briquettes have a sufficient calorific value to be used as an alternative fuel for low power boilers.

Table 1. Comparative characteristics of two type of solid fuels [48]

Parameter	Units	Biomass and coal fuel	Starch and coal fuel
Specific density	kg/m³	1 120	1 200
Calorific value	kJ/kg	18 520	23 675
Heat of combustion	kJ/kg	20 372	25 095
Water content	%	4.3	3.8
Volatile matter content	%	42.5	26.6
Ash content	%	2.1	12.2
Sulfur content	%	0.05	0.9
Gravity discharge resistance	%	98.1	94.7
Compressive strength	MPa	2.30	2.14
Waterproof	min	13.0	12.0

ENERGY USE OF GREEN SOLID FUELS

In comparison with coal combustion, the use of coal and biomass mixtures results in a reduction of sulfur dioxide emissions into the atmosphere, thanks to which flue gas desulphurization is not required. One of the advantages of biomass with coal is the possibility of using it in high-power boilers. In this mixture, coal plays the role of a stabilizer of the combustion process. However, not all boilers are adapted to co-firing coal with biomass, which is associated with their modernization and decommissioning for some time. On the basis of the co-firing tests, the mass share of biomass in the mixture with hard coal was determined at the level of about 8%. The results of combustion tests confirmed a small impact of biomass on the chemical composition of the ash obtained. It is caused by a much lower content of ash in biomass in relation to coal. The slight difference in composition, however, had a significant impact on lowering the softening temperature of the ash components. The ashes from biomass combustion were characterized by lower softening temperatures (in the range from 750 °C to 1000 °C) compared to the ashes from coal (approx. 1000 °C and more) [59].

Due to the lower softening temperature of ash during combustion of the coal and biomass mixture, the speed of sediment accumulation on the heating surfaces of boilers increases. The ash layer lying on the pipes is more susceptible to the deposition of subsequent particles, which in consequence causes a rapid increase of the sludge and enlargement of its size in relation to the sludge resulting from the combustion of coal alone. The tests carried out so far at the Polish Energy Concern (the group of power plants) have indicated that the co-combustion of biomass (up to 5%) with fine coal is practically possible in a non-investment way [60]. In the case of co-firing biomass in a proportion greater than 5%, it is necessary to build technological lines ensuring that this fuel is fed to the boiler in a coal-independent manner. In this way, the share of the co-fired biomass increases to 10–15% of the energy value of the fuel stream. Fluidized bed boilers provided very good biomass and coal co-firing. It should be noted that during the combustion process in these boilers neither briquetting nor granulating the mixture is necessary.

The calorific value of green bodies decreases as the biomass content increases. For the briquettes with a 20% biomass share, the calorific value is about 12% less than for the briquettes made of coal only. The calorific value of fuel recommended by many manufacturers of central heating boilers should be at least 24 MJ/kg; therefore, it is justified that the maximum share of biomass in the mixture with fine coal should not exceed 20% [48]. The emission of gases and dust to the atmosphere was determined (Table 2) during the combustion of two types of coal fuel in a chamber furnace.

It was noted that the addition of small amounts of additives to coal does not significantly change the indicators of flue gas pollution. The content of nitrogen oxides and sulfur dioxide decreased with the increase of biomass share. The changes in the content of carbon monoxide, carbon dioxide, and hydrogen sulfide indicate an insufficient amount of air introduced to the furnace. A larger amount of air is required to burn a mixture of coal and biomass than coal alone [61].

Table 2. Dust emissions to the atmosphere during the combustion of two types of solid fuel [48]

Compound	Units	Dust emissions of coal fuel combustion, with addition of:	
		Starch (8% share)	Biomass (20% share)
NO_x	mg/m^3	420	400
SO_2	mg/m^3	1320	1224
CO	mg/m^3	12	19.2
CO_2	%	5.1	4.6
H_2S	mg/m^3	13.1	18.3

Borowski and Hycnar [34] investigated the briquetting of fine coal with the addition of biocomponents as a fuel used in the energy facilities with thermal power. The mechanical strength of the briquettes was examined taking into account the share of binder and cure time. Other research results [62] indicate the possibility of coal and biomass briquette production with an energy value in the range of 19–24 MJ/kg with 15–28% of ash content and 4–8% of water. These briquettes can be used for combustion in stoker-fired boilers and low- and medium-power furnaces. The biomass briquettes are suitable as an alternative solid fuel for combustion in low-power central heating boilers in households, as well, they were recommended for grilling meat in gastronomy.

UTILISATION OF RESIDUES FROM COAL FUEL COMBUSTION

Combustion of coal and coal briquettes results in the formation of large amounts of slag and fly ash [63]. During the year, around 24 million Mg of ash and slag is generated in Poland. Only about 15% of this amount is used economically [64]. The cement industry is a large recipient of fly ash. They act as aggregates and partly binders in the production of cellular concrete [65]. The products with good technical properties are obtained with reduced production costs. In the production of aggregate concrete, ashes play the role of fine fillers as a cement substitute [66]. They improve workability and reduce the heat of hydration of concrete, as well as increase tightness and resistance to sulphates.

Fly ash is used as an active additive [67]. Mixed with Portland clinker, they participate in chemical reactions, changing the functional properties of the binder and leading to the formation of pozzolanic cement. Ash is also used as a component of the raw material from which Portland clinker is fired. Ash increases the mass of cement and improves its frost resistance and resistance to aggressive factors [68]. The addition of ash also reduces the concrete shrinkage. Fly ash and microspheres were used to produce some types of concrete and mortar, including concrete composites. The ash-microsphere additives have proved to be a favorable factor in protecting concrete composites against corrosion. It is also possible to exchange up to 30% of cement by ash in a high-quality concrete mix [69].

In mining, fly ash is used to fill the underground excavations. It consists of the hydraulic injection of ash at a pressure of 0.05–0.2 MPa. They were also used to “screen” the coal mining landfills. The surface of the landfill is covered with a sealing layer formed of ash and water pulp, where the ash content was 70% [37]. Fly ash is also used for ceramic products, such as: solid bricks, checker bricks, holes, and cavity blocks. These materials can be produced from raw materials containing up to 90% ash [70]. The cement-ash mixture is used to build the body of flood embankments. A mixture of ash with a small amount of cement improves the strength properties, and, in addition, when used in the shaft body, it contributes to the occurrence of aggregates, i.e., large lumps that stiffen the structure and give it very good stability [71].

The works on the use of ashes for the construction of transport embankments and the foundation of local roads have been carried out for many years [72]. The use of ash allows a significant reduction in cost while achieving the same stabilization parameters that are obtained when using pure lime or cement. This use of ash is the simplest way to dispose of this waste, without requiring additional refining processes and with the use of typical earthmoving machinery. The cost of constructing a road made of concrete proved to be comparable to the cost of constructing an asphalt road. On the other hand, the durability of the concrete road is greater and the operating costs are lower [73]. Ashes and slags are most often used to form road bodies, soil stabilization, and for improving the bottom layer and foundation of low-traffic local roads. However, storing and transporting ash is burdensome due to dusting and large volumes. Therefore, ashes are increasingly subjected to agglomeration processes [31].

The granulation technology was developed in disk granulator of coal scrubber waste and power plant ash, enabling the production of lightweight aggregates for concrete mortars and building materials [74]. Briquetting of the power plant waste was undertaken as well. The starting material was a mixture of dust and ashes with binders. Cellulose derivatives (methylcellulose, hydroethyl cellulose) were used as binders, in addition to the substances accelerating hardening (calcium and magnesium oxide) and graphitizing substances (graphite and aluminum) [75]. The use of ashes from the combustion of coal-biomass briquettes is an increasing problem due to the systematic increase in the demand for heat energy. Some types of ash can be used directly for fertilizing or improving soil [61]. However, most ashes can be used after appropriate modifications.

The ash from coal fuel combustion was in the form of fine mineral dust in light to dark gray and light brown colors. The ashes were in the form of glassy, usually spherical particles with a diameter usually between 100 and 50 µm [76]. Their melting point was below 900 °C and bulk density above 600 kg/m^3. The moisture content of the ashes did not exceed two percent. Ashes have high pozzolanic activity, i.e., the ability to bind with calcium compounds in combination with water, which allows their use in the production of cement mixtures [69]. The results pertaining to the physical properties and chemical analysis of two different types of fly ashes taken from coal incineration and lignite from the power plant of Silesia (Poland) were shown in Tables 3 and 4.

Table 3. Physical properties of fly ashes from lignite and hard coal combustion [36]

Physical parameters	Units	Value	
		Lignite fly ash	Coal fly ash
Specific surface – Blaine method	cm^2·g	1925	2780
Bulk density	kg/m^3	900	750
Tapped density	kg/m^3	1125	1120
Content of fraction with grain size:			
<0.063 mm	%	36.7	58.8
0.063–0.075 mm	%	5.4	6.8
0.075–0.125 mm	%	3.7	6.0
0.125–0.25 mm	%	38.2	25.5
0.25–0.50 mm	%	14.1	2.0
>0.50 mm	%	1.9	0.9

Table 4. Chemical analysis of fly ashes [36]

Chemical parameters	Content, %	
	Lignite fly ash	Coal fly ash
SiO_2	56.72	45.27
Al_2O_3	19.61	23.45
Fe_2O_3	6.41	11.99
CaO	7.73	6.34
MgO	2.80	2.24
Na_2O	0.30	0.60
K_2O	1.31	3.15
P_2O_5	0.13	0.52
SO_3	1.90	1.79
Loss on ignition	1.09	4.65

The chemical composition of ashes, however, is variable and depends not only on the type of coal used, but also on the method of combustion and the type of power boiler [77]. Silicates are the main component of ashes from the combustion of coal. They also contained oxides of calcium, iron, cadmium, manganese, and potassium. No dangerous substances were found in the ash samples taken. The agglomeration of ash is the right way to treat this waste. Granulation is a common method of agglomeration, but good results have not always been obtained with fluidized ashes. The fly ash from the fluidized bed did not form solid lumps, although they met the theoretical requirements of the granulation material. Similarly, silicate ashes did not form solid granules. Ground slag from a fluidized bed (from 5% to 30%) was added to the ashes. The impact and compressive strength of the obtained granules increased along with the slag content [78].

The briquetting method, due to the application of pressure in presses, enabled to obtain durable fittings from the bottom and fly ash. Durable briquettes were obtained, in particular with a two-component binder (hydrated lime with cement) in a total proportion of 8% to 10% and using mixture irrigation up to 6% humidity. The optimal unit pressure of the punch press of 4.25 MPa was also determined. The briquettes of high mechanical strength were achieved after 28 days of curing [48]. The ash briquettes were characterized by good weather tolerance including frost resistance and waterproofness. These parameters met the requirements set for mineral and artificial building aggregates [79]. Briquetting of the analyzed ashes also resulted in a significant reduction in the leaching of water-soluble substances compared with the leaching of components from loose ashes.

THE CYCLE OF WASTE MANAGEMENT

In a circular economy, the value of products and substances is maintained as long as possible, minimizing waste and the use of resources [80]. The circular economy has two main components: (i) a ban on waste landfilling, and (ii) total waste-free management [81]. The production of fuels from fine coal is part of the waste-free economy, mainly because the by-products resulting from the combustion of these fuels can be used in many industries. In addition, solid fuels can be supplemented with bio-materials, and combustion by-products also find practical applications [82].

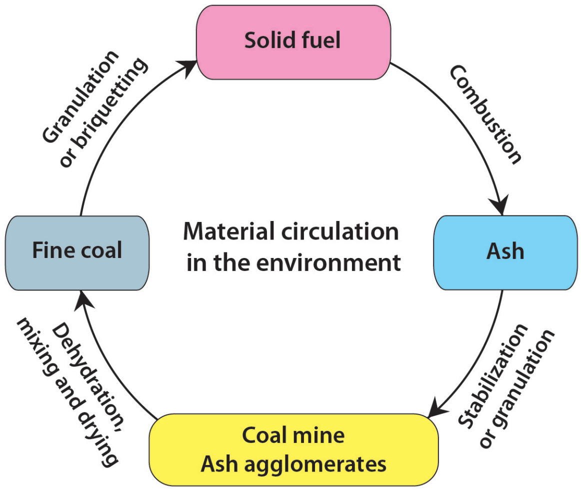

Figure 4. Coal and ash management in the circular economy [29]

Figure 4 schematically illustrates the concept of material circulation with waste management of fine coal and fly ash.

The presented concept of waste management consists of four basic stages [29]:

1) Coal sludge is generated in the mining during raw-material processing, which is fine-grained waste directed to landfills or to settlers. This waste can be transformed into high-calorific material after dehydration, mixing, and drying.
2) Fine coal can be mixed with other shredded energy materials (e.g., biomass in a share of 20% by dry mass) and added binders as well. After mixing and assuming the moisture, this material is directed to a granulator or briquetting machine.
3) The agglomeration process produces solid fuel with a calorific value of up to 24 MJ/kg. The mechanical strength of this fuel increases further when cured. Next, it can be directed for combustion in low- and medium-power power furnaces.
4) Combustion residues (fly ash) are utilized in loose form (e.g., for road foundations), or by the use of cement stabilization (e.g., for safe storage, for strengthening levees), as well as using agglomeration processes (e.g., for drainage, for building structures). Ashes can also be used as a backfill in the underground excavation. In that case, they return without processing to the coal mine.

Thus, the management of fine coal is in line with a waste circulation – it starts in the coal mine and can also finishing there, as well in diverse deposits – as a land stabilizer or the soil fertilizer and many others [83]. It is important that implementing the above-mentioned concept of material circulation with the management of coal and ash, the raw materials are fully utilized and there is no waste left that may threaten the natural environment. More scientists also arrived at similar conclusions [84,85]. They stated that energy materials play an important role in the circular economy due to the high efficiency of their utilization – in the scope of sustainable management of raw materials, for the preservation of the Energy Union, as well improvement of the natural environment.

CONCLUSIONS

Studies have shown that it is possible to produce a solid fuel of good quality from waste-coal resources. The fuel required a binder addition and achieving the specific moisture content as well as devising the appropriate granulation or briquetting parameters. The fuel characterized by high hydration needs to be dried and then cured to attain high strength. The addition of biomass up to 20% by total mass produces an alternative green body. It was found that biomass addition improves the combustion process of fuel, particularly by reducing the sulfur and ash content. Thus, it is acceptable as a commercial product for the power industry and for individual consumers. Using the granulation method, the solid coal fuel with a calorific value of about 19 MJ/kg was obtained; however, in the case of the briquetting method, the calorific value increased to about 24 MJ/kg. The utilization of fly ashes from the combustion of coal bodies is relevant in many applications, starting from road building and ceramic products. Importantly, the ashes can be fully used to minimize waste in material management. Therefore, the coal or ash agglomeration techniques were highly proven for waste management, under the circular economy.

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REFERENCES

1. Boruk, S.; Winkler, I. Ecologically friendly utilization of coal processing waste as a secondary energy source. In: Energy and Environmental Challenges to Security; Stec, S., Baraj, B., Eds.; Springer Publishers, Dordrecht, The Netherlands, 2009, pp. 251–259.
2. Lazaro, M.J.; Boyano, A.; Galvez, M.E.; Izquierdo, M.T.; Moliner, R. Low-cost carbon-based briquettes for the reduction of NO emissions from medium-small stationary sources. Catalysis Today 2007, 119, 175–180. [https://doi.org/10.1016/j.cattod.2006.08.038]
3. Aghazadeh, S.; Gharabaghi, M.; Azadmehr, A. Increasing the useful heating value of coal using a physico-chemical process. International Journal of Coal Preparation and Utilization 2016, 36, 175–191. [https://doi.org/10.1080/19392699.2015.1069280]
4. Hycnar, J.J.; Fraś, A.; Przystaś, R.; Foltyn, R. Current state and perspectives of quality improvement of coal slimes for power generation. In: The issues of energy resources and energy in the national economy; Proceedings of the 27th Conference; Zakopane, Poland, 13–16 Oct., 2013, pp. 61–74.
5. Kurus, K.; Bialecka, B.; Foitová-Dernerová, P. Model of coal mining waste management system in Upper Silesian Coal Basin. Systemy Wspomagania w Inżynierii Produkcji 2014, 3, 131–142.
6. Merkus, H.G.; Meesters, G.M.H., Eds. Production, handling and characterization of particulate materials. Springer Int. Publ., Switzerland, 2016, p. 548.
7. Zaostrovskii, A.N.; Sarychev, V.D.; Umanskii, A.A.; Murko, V.I. Thermal analysis of coal and water-coal suspensions. Coke and Chemistry 2012, 55, 10–14. [https://doi.org/10.3103/S1068364X12010085]
8. Kuczyńska, I. Alternative fuels prepared from coal mud. In: International Coal Preparation Congress: Conference Proceedings; Honaker, R.Q., Ed.; Littleton, Colorado, USA, 2010, pp. 811–816.
9. Temmerman, M.; Rabier, F.; Jensen, P.D.; Hartmann, H.; Bohm, T., Comparative study of durability test methods for pellets and briquettes. Biomass and Bioenergy 2006, 30, 964–972. [https://doi.org/10.1016/j.biombioe.2006.06.008]
10. Purohit, P.; Tripathi, A.K.; Kandpal, T.C. Energetics of coal substitution by briquettes of agricultural residues. Energy 2006, 31, 1321–1331. [https://doi.org/10.1016/j.energy.2005.06.004]
11. Shuming, W.; Caixing, Z.; Jundan C. Utilization of coal fly ash for the production of glass-ceramics with unique performances, A brief review. Journal of Materials Science & Technology 2014, 30, 1208–1212. [https://doi.org/10.1016/j.jmst.2014.10.005]
12. Safiuddin, Md.; Jumaat, M.Z.; Salam, M.A.; Islam, M.S.; Hashim, R. Utilization of solid wastes in construction materials. International Journal of Physical Sciences 2010, 5, 1952–1963. [https://doi.org/10.5897/IJPS.9000617]
13. Blissett, R.S.; Rowson, N.A. A review of the multi-component utilisation of coal fly ash. Fuel 2012, 97, 1–23. [https://doi.org/10.1016/j.fuel.2012.03.024]
14. Basu, M.; Pande, M.; Bhadoria, P.B.S.; Mahapatra, S.C. Potential fly-ash utilization in agricul-

ture, A global review. Progress in Natural Science 2009, 19, 1173–1186. [https://doi.org/10.1016/j.pnsc.2008.12.006]

15. Toraldo, E.; Saponaro, S. A road pavement full-scale test track containing stabilized bottom ashes. Environmental Technology 2015, 36, 1114–1122. [https://doi.org/10.1080/09593330.2014.982714]
16. Querol, X.; Moreno, N.; Umaña, J.C.; Alastuey, A.; Hernández, E.; López-Soler, A.; Plana, F. Synthesis of zeolites from coal fly ash, An overview. International Journal of Coal Geology 2002, 50, 413–423. [https://doi.org/10.1016/S0166-5162(02)00124-6]
17. Fukasawa, T.; Horigome, A.; Karisma, A.D.; Maeda, N.; An-Ni Huang; Fukui, K. Utilization of incineration fly ash from biomass power plants for zeolite synthesis from coal fly ash by microwave hydrothermal treatment. Advanced Powder Technology 2018, 29, 450–456. [https://doi.org/10.1016/j.apt.2017.10.022]
18. Yang, L.; Ying-hong, W.; Shu-hua, M.; Shi-li, Z.; Chu, P.K. An eco-friendly and cleaner process for preparing architectural ceramics from coal fly ash. Pre-activation of coal fly ash by a mechanochemical method. Journal of Cleaner Production 2019, 214, 419–428. [https://doi.org/10.1016/j.jclepro.2018.12.292]
19. Johnson, O.A.; Napiah, M.; Kamaruddin, I. Potential uses of waste sludge in construction industry, A review. Research Journal of Applied Sciences, Engineering and Technology 2014, 8, 565–570.
20. COM(2020) 98 final. A new Circular Economy Action Plan for a cleaner and more competitive Europe. [https://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1583933814386&uri=COM:2020:98:FIN]
21. Pietsch, W.B. Agglomeration processes: Phenomena, technologies, equipment. John Wiley & Sons, 2008, p. 622.
22. Altun, N.E.; Hicyilmaz, C.; Kök, M.V. Effect of different binders on the combustion properties of lignite, Part I. Effect on thermal properties. Journal of Thermal Analysis and Calorimetry 2001, *65*, 787–795. [https://doi.org/10.1023/A:1011915829632]
23. Reynolds, G.K.; Fu, J.S.; Cheong, Y.S.; Hounslow, M.J.; Salman, A.D. Breakage in granulation: A review. Chemical Engineering Science, 2005, 60, 3969–3992. [https://doi.org/10.1016/j.ces.2005.02.029]
24. Shanmugam, S. Granulation techniques and technologies: Recent progresses. Bioimpacts 2015, 5, 55–63. [https://doi.org/10.15171/bi.2015.04]
25. Iveson, S.M.; Litster, J.D.; Hapgood, K.; Ennis, B.J. Nucleation, growth and breakage phenomena in agitated wet granulation processes: A review. Powder Technology 2001, 117, 3–39. [https://doi.org/10.1016/S0032-5910(01)00313-8]
26. Zainuddin, M.I.; Tanakaa, S.; Furushimaa, R.; Uematsu, K. Correlation between slurry properties and structures and properties of granules. Journal of the European Ceramic Society 2010, 30, 3291–3296. [https://doi.org/10.1016/j.jeurceramsoc.2010.07.004]
27. Gurses, A.; Doymus, K.; Dogar, C.; Yalcin, M. Investigation of agglomeration rates of two Turkish lignites. Energy Conversion and Management 2003, 44, 1247–1257. [https://doi.org/10.1016/S0196-8904(02)00142-5]
28. Herting, M.G.; Kleinebudde, P. Roll compaction/dry granulation: Effect of raw material particle size on granule and tablet properties. International Journal of Pharmaceutics 2007, 338, 110–118. [https://doi.org/10.1016/j.ijpharm.2007.01.035]
29. Borowski, G. Agglomeration processes for waste utilization in a circular economy. Published by Polish Academy of Science, Warsaw, 2020, p. 160.
30. Mangwandi, C.; Adams, M.J.; Hounslow, M.J.; Salman, A.D. Effect of batch size on mechanical properties of granules in high shear granulation. Powder Technology 2011, 206, 44–52. [https://doi.org/10.1016/j.powtec.2010.05.025]
31. Flore, K.; Schoenherr, M.; Feise, H. Aspects of granulation in the chemical industry. Powder Technology 2009, 189, 327–331. [https://doi.org/10.1016/j.powtec.2008.04.010]
32. Feliks, J. Laboratory testing of coal sludge granulation. Chemik 2012, 66, 388–395.
33. Naumov, K.I.; Maloletnev, A.S.; Mazneva, O.A. Advanced processes for manufacturing agglomerated fuel from fine coals. Solid Fuel Chemistry 2013, 47, 47–55. [https://doi.org/10.3103/S0361521912060080]
34. Borowski, G.; Hycnar, J.J. Utilization of fine coal waste as a fuel briquettes. International Journal of Coal Preparation and Utilization 2013, 33, 194–204. [https://doi.org/10.1080/19392699.2013.787993]
35. Obraniak, A.; Gluba, T.; Ławińska, K.; Derbiszewski, B. Minimisation of environmental effects related with storing fly ash from combustion of hard coal. Environment Protection Engineering 2018, 44, 177–189. [https://doi.org/10.5277/epe180412]
36. Borowski, G.; Ozga, M. Comparison of the processing conditions and the properties of granules made from fly ash of lignite and coal. Waste Management 2020, 104C, 192–197. [https://doi.org/10.1016/j.wasman.2020.01.024]
37. Pyssa, J. Extractive waste from hard coal mining in Poland – balance, status of management and environmental aspects. In: Energy and Fuels 2016; Proceedings of the E3S Web of Conferences, 2017. [https://doi.org/10.1051 /e3sconf/20171402024]
38. Łączny, J.M.; Iwaszenko, S.; Gogola, K.; Bajerski, A.; Janoszek, T.; Klupa, A. Cempa-Balewicz M.:

Study on the possibilities of treatment of combustion by-products from fluidized bed boilers into a product devoid of free calcium oxide. Journal of Sustainable Mining, 2015, 14, 164–172. [https://doi.org/10.1016/j.jsm.2015.12.002]

39. Yoshimoto, N.; Hyodo, M.; Nakata, Y.; Orense, R.P.; Hongo, T.; Ohnaka, A. Evaluation of shear strength and mechanical properties of granulated coal ash based on single particle strength. Soils and Foundations 2012, 52, 321–334. [https://doi.org/10.1016/j.sandf.2012.02.009]
40. Solovei, V.N.; Spiridonova, E.A.; Samonin, V.V.; Khrylova, E.D.; Podvyaznikov M.L. Synthesis of spherically shaped granulated carbon sorbent. Russian Journal of Applied Chemistry 2016, 89, 1102–1108. [https://doi.org/10.1134/S1070427216070090]
41. Zhao, Y.; Chang, H.; Ji, D.; Liu, Y. The research progress on the briquetting mechanism of fine coal. Journal of Coastal Conservation 2001, 24, 12–14.
42. Taulbee, D.; Patil, D.P.; Honaker, R.Q.; Parekh, B.K. Briquetting of coal fines and sawdust. Part I: Binder and briquetting-parameters evaluations. International Journal of Coal Preparation and Utilization 2009, 29, 1–22. [https://doi.org/10.1080/19392690802628705]
43. Yilmaz, E. Advances in reducing large volumes of environmentally harmful mine waste rocks and tailings. Gospodarka Surowcami Mineralnymi – Mineral Resources Management 2011, 27, 89–112.
44. Galos, K.; Szluga, J. Management of hard coal mining and processing wastes in Poland. Gospodarka Surowcami Mineralnymi – Mineral Resources Management 2014, 30, 51–64. [https://doi.org/10.2478/gospo-2014-0039]
45. Blesa, M.J.; Miranda, J.L.; Izquierdo, M.T.; Moliner, R. Curing time effect on mechanical strength of smokeless fuel briquettes. Fuel Processing Technology 2003, 80, 155–167. [https://doi.org/10.1016/S0378-3820(02)00243-6]
46. Honaker, R.Q.; Patil, D. P.; Sirkeci, A.; Patwardhan, A. Production of premium fuels from coal refuse pond material. Mining, Metallurgy & Exploration 2001, 18, 177–183. [https://doi.org/10.1007/BF03403246]
47. Zakari, I.Y.; Ismaila, A.; Sadiq, U.; Nasiru, R. Investigation on the effects of addition of binder and particle size on the high calorific value of solid biofuel briquettes. Journal of Natural Sciences Research 2013, 3, 30–34.
48. Borowski, G. 2013. Methods of fine-grained waste processing into useful products. Published by Lublin University of Technology, Lublin, Poland, p. 112.
49. Iacovidou, E.; Hahladakis, J.; Deans, I.; Velis, C.; Purnell, P. Technical properties of biomass and solid recovered fuel (SRF) co-fired with coal: impact on multi-dimensional resource recovery value. Waste Management 2018, 73, 535–545. [https://doi.org/10.1016/j.wasman.2017.07.001]
50. Wang, J.C.; Wang, J.Q. Study on biologic briquette binder. Applied Energy Technology 2004, 4, 15–16.
51. Zhong, H.; Cao, Z. A study on carboxylmethyl starch as the binder in coal briquets. Hunan Chemical Industry 2000, 30, 23–25.
52. Zhu, S.K.; Wu, X.X. Study on coking waste to prepare the binder for briquette coal. Guangzhou Chemical Industry 2011, 39, 106–108.
53. Zhang, G.; Sun, Y.; Xu, Y. Review of briquette binders and briquetting mechanism. Renewable and Sustainable Energy Reviews 2018, 82, 477–487. [https://doi.org/10.1016/j.rser.2017.09.072]
54. Leokaoke, N.T.; Bunt, J.R.; Neomagus, H.W.J.P.; Waanders, F.B.; Strydom, C.A.; Mthombo, T.S. Manufacturing and testing of briquettes from inertinite-rich low-grade coal fines using various binders. Journal of the Southern African, Institute of Mining and Metallurgy 2018, 118, 83–88. [http://dx.doi.org/10.17159/2411-9717/2018/v118n1a10]
55. Wang, Ch.; Harbottle, D.; Liu, Q.; Xu, Z. Current state of fine mineral tailings treatment, A critical review on theory and practice. Minerals Engineering 2014, 58, 113–131. [https://doi.org/10.1016/j.mineng.2014.01.018]
56. Kubica, K.; Ściążko, M.; Rainczak, J. Co-firing of coal and biomass. Polityka Energetyczna – Energy Policy Journal 2003, 6, 297–308.
57. Faizal, M. Utilization biomass and coal mixture to produce alternative solid fuel for reducing emission of greenhouse gas. International Journal on Advanced Science Engineering Information Technology 2017, 7, 950–956. [https://doi.org/10.18517/ijaseit.7.3.2474]
58. Kalembkiewicz, J.; Chmielarz, U. Ashes from co-combustion of coal and biomass: new industrial wastes. Resources, Conservation and Recycling 2012, 69, 109–121. [https://doi.org/10.1016/j.resconrec.2012.09.010]
59. Ozga, M.; Borowski, G. The use of granulation to reduce dusting and manage of fine coal. Journal of Ecological Engineering 2018, 19, 218–224. [https://doi.org/10.12911/22998993/89794]
60. Hycnar, J.J.; Pasiowiec, P.; Tora, B. Methods of increasing the calorific value of fine coal waste. In: Proceedings of the XVIII International Coal Preparation Congress, Litvinenko, V., Ed.; Springer, Cham, 2016. [https://doi.org/10.1007/978-3-319-40943-6_61]
61. Isobe, Y.; Wang, Q.; Sakamoto, K. 2004. Utilization of coal-biomass briquette combustion ash for soil improvement. Environmental Science 17(6), 431–438. [https://doi.org/10.11353/sesj1988.17.431]
62. Giemza, H.; Gruszka, G.; Hycnar, J.J.; Józefiak, T.; Kiermaszek, K. Optimization of coal sediment

management – sediment briquetting technology. Polityka Energetyczna – Energy Policy Journal 2007, 10, 417–429.

63. Fecko, P.; Tora, B.; Tod, M. Coal waste, handling, pollution. impacts and utilization. In: The Coal Handbook, Towards Cleaner Production. Coal Utilisation. Volume 2 in Woodhead Publishing Series in Energy, 2013, pp. 63–84. [https://doi.org/10.1533/9781782421177.1.63]
64. Kijo-Kleczkowska, A. Combustion of coal-mule briquettes. Archives of Mining Sciences 2013, 58, 617–628. [https://doi.org/10.2478/amsc-2013-0043]
65. Fu, X.; Wang, Z.; Tao, W.; Yang C.; Hou, W.; Dong, Y.; Wu, X. Studies on blended cement with a large amount of fly ash. Cement and Concrete Research 2002, 32, 1153–1159. [https://doi.org/10.1016/S0008-8846(02)00757-3]
66. Yao, Z.T.; Ji, X.S.; Sarker, P.K.; Tang, J.H.; Ge, L.Q.; Xia, M.S.; Xi, Y.Q. A comprehensive review on the applications of coal fly ash. Earth-Science Reviews 2015, 141, 105–121. [https://doi.org/10.1016/j.earscirev.2014.11.016]
67. Arslan, H.; Baykal, G. Utilization of fly ash as engineering pellet aggregates. Environmental Geology 2006, 50, 761–770.
68. Huang, S-C.; Chang, F-C.; Lo, S-L.; Lee, M-Y.; Wang, C-F.; Lin, J-D. Production of lightweight aggregates from mining residues, heavy metal sludge, and incinerator fly ash. Journal of Hazardous Materials 2007, 144, 52–58. [https://doi.org/10.1016/j.jhazmat.2006.09.094]
69. Mäkelä, M.; Paananen, T.; Kokkonen, T.; Makkonen, H.; Heino, J.; Dahl, O. Preliminary evaluation of fly ash and lime for use as supplementary cementing materials in cold-agglomerated blast furnace briquetting. International Science and Investigation Journal 2011, 51, 776–781. [https://doi.org/10.2355/isijinternational.51.776]
70. Lin, K.L. Feasibility study of using brick made from municipal solid waste incinerator fly ash slag. Journal of Hazardous Materials 2006, 137, 1810–1816. [https://doi.org/10.1016/j.jhazmat.2006.05.027]
71. Gesoglu, M.; Güneyisi, E.; Öz, H.Ö. Properties of lightweight aggregates produced with cold-bonding pelletization of fly ash and ground granulated blast furnace slag. Materials and Structures 2012, 45, 1535–1546. [https://doi.org/10.1617/s11527-012-9855-9]
72. Senol, A.; Edil, T.B.; Bin-Shafique, Md.S.; Acosta, H.A.; Benson, C.H. Soft subgrades' stabilization by using various fly ashes. Resources, Conservation and Recycling 2006, 46, 365–376. [https://doi.org/10.1016/j.resconrec.2005.08.005]
73. Toraldo, E.; Saponaro, S. A road pavement full-scale test track containing stabilized bottom ashes. Environmental Technology 2015, 36, 1114–1122. [https://doi.org/10.1080/09593330.2014.982714]
74. Kępys, W. Manufacture of artificial aggregates using fine-grained hazardous wastes. Inżynieria Ekologiczna 2010, 23, 70–76.
75. Bultmann, J.M. Multiple compaction of microcrystalline cellulose in a roller compactor. European Journal of Pharmaceutics and Biopharmaceutics 2002, 54, 59–64. [https://doi.org/10.1016/S0939-6411(02)00047-4]
76. Trivedi, A.; Sud, V.K. Grain characteristics and engineering properties of coal ash. Granular Matter 2002, 4, 93–101. [https://doi.org/10.1007/s10035-002-0114-6]
77. Werther, J.; Ogada, T. Sewage sludge combustion. Progress in Energy and Combustion Science 1999, 25, 55–116. [https://doi.org/10.1016/S0360-1285(98)00020-3]
78. Rahman, M.M.; Nor, S.S.M.; Rahman, H.Y.; Sopyan, I. Effects of forming parameters and sintering schedules to the mechanical properties and microstructures of final components. Materials and Design 2012, 33, 153–157. [https://doi.org/10.1016/j.matdes.2011.07.019]
79. Mueller, A.; Sokolova, S.N.; Vereshagin, V.I. Characteristics of lightweight aggregates from primary and recycled raw materials. Construction and Building Materials 2008, 22, 703–712. [https://doi.org/10.1016/j.conbuildmat.2007.06.009]
80. Rogowska, D. Biofuel production as part of a circular economy. Nafta-Gaz 2018, LXXIV, 156–163.
81. Kalmykova, Y.; Sadagopan, M.; Rosado, L. Circular economy – from review of theories and practices to development of implementation tools. Resources, Conservation and Recycling 2018, 135, 190–201. [https://doi.org/10.1016/j.resconrec.2017.10.034]
82. Malinauskaite, J.; Jouhara, H.; Czajczyńnska, D.; Stanchev, P.; Katsou, E.; Rostkowski, P.; Thorne, R.J.; Colon, J.; Ponsa, S.; Al-Mansour, F.; Anguilano, L.; Krzyżyńska, R.; Lopez, I.C.; Vlasopoulos, A.; Spencer, N. Municipal solid waste management and waste-to-energy in the context of a circular economy and energy recycling in Europe. Energy 2017, 141, 2013–2044. [https://doi.org/10.1016/j.energy.2017.11.128]
83. Heshmati, A. A review of the circular economy and its implementation. In: IZA Discussion Paper Series, Paper No. 9611, Bonn, Germany, 2015, p. 61. [https://doi.org/10.1504/IJGE.2017.089856]
84. Rada, E.C.; Cioca, L. Optimizing the methodology of characterization of municipal solid waste in EU under a circular economy perspective. Energy Procedia 2017, 119, 72–85. [https://doi.org/10.1016/j.egypro.2017.07.050]
85. Millward-Hopkins, J.; Purnell, P. Circulating blame in the circular economy, The case of wood-waste biofuels and coal ash. Energy Policy 2019, 129, 168–172. [https://doi.org/10.1016/j.enpol.2019.02.019]