Possibilities of Management of Fly Ash from Municipal Solid Waste Incineration Plant in Building Industry in the Circular Economy

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Abstract. To improve the condition of the environment and prevent its degradation, global trends have moved from linear to the circular economy. Closing the loop is to protect natural resources, minimize waste, emissions, and pollution. The circular economy assumptions are based mainly on the 3-R: Reduce (minimum use of raw materials); Reuse (maximum reuse of products and components); Recycle (high-quality reuse of raw materials). In the waste management hierarchy, the last place in the circular economy is energy recovery. In the process of incinerating municipal waste, secondary waste is generated. Some of them, like fly ash, are hazardous waste. It includes, among others heavy metals, chlorine, sulphur, and other pollutants, hence it is currently not used as a raw material. The management of fly ash from municipal solid waste incineration plant in the construction industry is a part of sustainable development and the circular economy. Fly ash is a hazardous and heterogeneous waste, therefore it is important to know its physicochemical and construction properties, which are presented in the article. Fly ash has pozzolanic properties, therefore it can be a good binding and building material. For fly ash to be a component of the construction mixture, it is necessary to immobilize pollutants, heavy metals, and some elements so that they do not leach into the environment. For this purpose, the concrete structure and the C-S-H matrix should be compacted. Currently, fly ash is stabilized and stored in underground landfills. They are storage in closed salt, manganese, and potassium mines. However, the volume of post-mining voids is limited, and storage is not part of the circular economy. In addition, some countries do not have their fly ash storage facilities and it has to be exported across borders. This increases the carbon footprint and shortens the product life cycle.

1. Introduction

Average municipal waste production in European Union has been growing since 2013 [1]–[3]. There has been a 5% increase by 2019. Figure 1 shows the European Union trend of municipal waste production and its amount per capita [1-3].
Management of municipal waste is a complex problem. Its stream depends on the season, regulations, wealth of society, city’s character (touristic, industrial, multi-family housing, single-family housing), etc. The most important part of waste management is selective collection. However, even correct waste hierarchy, not every waste is possible to recycling. Residual waste needs an incineration plan to not be landfill. Heat or/and electrical energy is recovered in the municipal solid waste incineration plant. Unfortunately, over 30% of secondary waste is generated. Mainly fly ash (approx. 4%) and slag (30%). Slag is non-hazardous waste and is used as road priming. The problem of management is hazardous fly ash. Currently, it is stabilized and stored. Not every country has a special place as old, underground, disused salt, manganese, and potassium mines or an appropriate landfill for hazardous waste. For example, Poland takes out fly ash to Germany. Storage is not a part of a circular economy, while transport produces CO2 emission [4].

To close the loop and reduce greenhouse gases, it must find a management solution for fly ash. Figure 2 shows the ideal circular economy (CE) [5].

New Circular Economy Action Plan (CEAP) is adapted by The European Commission. CEAP is one of the building blocks of the Green Deal [6]. The main concept of CE is 3-R (Reduce-Reuse-Recycle). Reduce (minimum use of raw materials); Reuse (maximum reuse of products and components); Recycle (high-quality reuse of raw materials). Figure 3 shows the material cycle and three phases of the building industry and fly ash as a substitute for raw material [7].

**Figure 1.** Municipal waste production in UE per capita, 1995-2019 (own study) [1-3].

**Figure 2.** Ideal circular economy with fly ash management (own study) [5].
Waste is a common material use in the building industry. Blast furnace slag can be a substitute for a natural aggregate. The final product with blast furnace slag has better physical and chemical properties than with natural aggregate. Another example is the X-type zeolite material, which is produced from fly ash from a coal-fired heat and/or power plant [9].

Zeolite material from municipal solid waste incineration plant fly ash will not be a good material for the synthesis of zeolite due to the problem of obtaining the zeolite phase. The problem is caused by the physicochemical characteristics and the variability of parameters.

Fly ash from waste incineration plants can be a substitute for cement. Cement production is an energy-intensive process. To produce 1 Mg of cement, more than 1 Mg of raw minerals is used and over 1 Mg of carbon dioxide is produced. Fly ash as a cement substitute will be an environmentally friendly solution.

Another way to manage fly ash is to use it in the production of geopolymers. Geopolymer in its composition does not contain any or only small amounts of cement. In addition, the activator used in the production of geopolymer during the reaction shows properties that immobilize heavy metals. Concentrated NaOH or water glass is used to produce the geopolymer [10].

2. Current waste recycling in building industry from different industries

The construction industry is one of the best end-users of municipal solid incineration secondary waste. Geopolymer and concrete are a good environments for the immobilization of pollutants. Various industries use construction as a recipient of waste. Figure 4 shows waste materials used in construction depending on the industry sector [11].

Slag is produced by the non-ferrous metal industry, iron and steel industry, and municipal solid waste incineration plans. Fly ash is produced by power engineering, construction, recycling, and ceramics industry, and a municipal solid waste incineration plant. Bottom ash is produced by power engineering, construction, recycling, and ceramics industry, and a municipal solid waste incineration plant. Secondary waste from different industries have different properties and some of them are value product on the market. Sustainability technology development can cause change the value of waste. From unnecessary material into a valuable product, as was the case with blast furnace slag. Currently, fly ash is a by-product because of the lack of pollution immobilization technology. However, its development is not impossible [12, 13].
Fly ash from municipal waste incineration plants is a hazardous and heterogeneous waste. Its composition depends on the season, legal regulations, combustion process, etc. Its dangerous characteristics are related to the number of heavy metals, chlorine, and sulfur. These parameters are directly related to the processed municipal waste. The content of organic carbon that affects the color of the waste is related to the combustion process. Fly ash is light gray. Thanks to its light color, it can be used for external surfaces, because it will not disturb the aesthetics of the appearance [14, 15].

Table 1 shows fly ash physicochemical properties from municipal solid waste incineration plants in Poland.

| Property                        | Standard Reference                              |
|--------------------------------|------------------------------------------------|
| Content of carbon (C)          | EN 15407:2011 and organic carbon (TOC)-EN-Z-15011-3:2001 [16], |
| Content of sulfur (S)          | EN-ISO 334:1997                                  |
| Content of chloride (Cl)       | EN-ISO 587:2000                                  |
| Content of nitrogen (N)        | PN-G-04523:1992                                  |
| Content of sodium (Na), calcium (Ca), potassium (K), lithium (Li), barium (Ba) | PN-ISO 994-3:1994 [20, 21], |
| Content of moisture            | PN-Z-15008-02:1993 [22],                        |
| Determination of bulk density  | EN 1097-3:2000                                  |
| Determination of caloric value (CV) | PN-EN ISO 1716:2010 [24], |
| Content of phosphorus          | EN-Z-15011-3:2001[16],                          |

Fly ash is a dusty material. The specific volume of fly ash is approximately 480 kg / m³.

Fly ash has a high silica content, therefore it can be used in the production of geopolymer. Geopolymer is a material without the addition of cement. It can be also met as a hybrid with a small amount of cement. The activator in the geopolymer formation process is NaOH or water glass [25].

Fly ash with NaOH reagent forms a liquid consistency with sediment. After evaporation, it forms a dense and hard material. If excess NaOH is added, it forms white bubbles on the surface of the material. Fly ash does not change color when NaOH or distilled water is added. He reacts strongly during the reaction. Figure 5a shows fly ash. Figure 5b shows the reaction with NaOH. Figure 5c shows fly ash with concentrated NaOH after drying at 105 °C. Figure 5d shows fly ash with concentrated NaOH after drying at 105 °C [26].
Table 1. Fly ash physicochemical properties from municipal solid waste incineration plant in Poland.

| Properties/Element         | Symbol | Unit   | Fly ash |
|----------------------------|--------|--------|---------|
| Moisture                   | M      | %      | 1,45    |
| Density                    | ρ      | kg/m³  | 469,03  |
| Caloric value              | CV     | J/g    | <100    |
| Total Carbon               | TC     | %      | 2,1031  |
| Total Organic Carbon       | TOC    | %      | 1,98    |
| Nitrogen                   | N      | %      | 0,26    |
| Orthophosphate(V)          | P2O5   | %      | 1,19    |
| Phosphorus                 | P      | %      | 0,52    |
| Sodium                     | Na     | %      | 2,07    |
| Potassium                  | K      | %      | 2,29    |
| Lithium                    | Li     | %      | 0,025   |
| Calcium                    | Ca     | %      | 13,49   |
| Bar                        | Ba     | %      | 1,23    |
| Chloride                   | Cl     | %      | 7,23    |
| Sulphur                    | S      | %      | 1,98    |
| Sulfur trioxide            | SO₃    | %      | 4,95    |
| Magnesium oxide            | MgO    | %      | 2,58    |

Figure 5. a. Municipal solid waste incineration plant fly ash (own study), b. NaOH reaction with municipal solid waste incineration plant fly ash (own study), c. NaOH white bubble on municipal solid waste incineration fly ash (own study), 5d. Municipal solid waste incineration plant after NaOH reaction (own study).
Fly ash is hygroscopic. It has pozzolanic and binding properties. Hence, it can be a substitute for cement. The problem is the leachability of pollutants and compliance with regulations. The low proportion of fly ash in mixed concrete has no economic justification. A mixture with a small addition of fly ash will be a much cheaper product. The problem will be the receipt of the product, due to the content of hazardous waste, and the use of cement and natural resources will not change much. Moreover, its hygroscopicity makes it necessary to add more water or plasticizers. Figure 6 shows a mortar with a cement substitute in an amount of 30% of fly ash. Mortar composition: 135g fly ash, 315g cement, 225g water, 1350g sand according to PN-196. The mortars were made in accordance with the PN-EN 480-1 standard [27, 28].

![Figure 6. Mortar with fly ash (30% of cement).](image)

Table 2 shows strength tests for mortars. Fly ash accounts for 30% by weight of cement.

| Type of Cement in Mortar       | 28 Days Bending | 28 Days Compressing |
|-------------------------------|-----------------|---------------------|
| 30% fly ash, 70% cement       | 1,80            | 44,31               |
| 100% cement                   | 2,93            | 116,63              |

Fly ash as a cement substitute affects negatively bending and compressing. Mortar with fly ash has 1,80 kN 28 days bending and 44,31kN 28 days compressing, while reference mortar has 2,93 kN 28 days bending and 116 kN 28 days compressing. In order to improve the quality of mortar, plasticizers and aerators should be added. It can also reduce w/c.

The reduction in w/c will also affect the C-S-H concentration and the reduction of the leaching of pollutants. Additives and admixtures will improve the quality of the mixture in terms of e.g. frost resistance, durability, negative environmental impact, etc [12, 29].

4. Results and discussions

Secondary waste from municipal solid incineration plants can be used in the building industry in many ways. The most common application is the use of slag as a priming road. Slag can be used as a substitute for aggregate, but it needs to be improved in the valorization process [4].

The biggest problem is with hazardous fly ash management because of high content of heavy metals, chlorine, sulfur, heterogeneous composition, and other pollution. In order to use fly ash in concrete, the matrix should be sealed by lowering the w/c. For this purpose, the appropriate number of plasticizers and aerators should be selected. Then the strength of the material will increase and the leaching of pollutants into the environment will decrease [14, 15].

Another solution for manage fly ash is to create a geopolymer. The geopolymer mix does not contain cement or contains a small amount of it, therefore the carbon dioxide equivalent will be the lowest in this solution. However, geopolymer is fairly new material on the market and is not widely used [10].

The main goal of research on secondary waste is to recycle it. First of all, it is necessary to reduce the leaching of pollutants by immobilizing them. The next tests should concern the strength and quality of the final product. Then the idea of CE and sustainable development will be fulfilled [5, 6, 30].
5. Conclusions
Municipal solid waste incineration secondary waste is a growing global problem because of a growing amount of municipal waste, and abandonment of landfilling. In order to create and promote a circular economy, secondary waste management technology should be researched and developed. It should be looked for the least environmentally burdensome solutions. One of the tools for assessing the environmental impact is the Life Cycle Assessment. The management of residual waste will be the last step in the waste management chain [31].

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