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Industrial Waste Management: Economical Benefits of the Resource Utilization of Phosphogypsum

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Abstract

There are many publications in the literature on the reuse of waste gypsum in material production. In this study, in which the analysis of these existing publications is made through the determinations, the data examined are limited to the article and these are not included. However, to understand the general framework of the research in this field better, a few of these in the related literature are given below as examples. It is seen that industrial waste gypsum, which is a type of waste gypsum, has been examined more. Phosphogypsum, which is included in this waste group, reduces the water requirement for adjusting the cement consistency by adding phosphogypsum in cement production. As a result of the addition of phosphogypsum in wall element production, it was determined that the addition of phosphogypsum caused a decrease in mechanical strength, a decrease in unit weight and an increase in water requirement. It has been concluded that the addition of 15% phosphogypsum in soil stabilization of phosphogypsum, which is in the chemical waste class, causes an increase in water demand and pressure strength. In addition, 5.4% gypsum board waste with recycling potential is generated in the production of building elements made with waste gypsum boards formed at a construction site.

Keywords: Waste Management, Phosphogypsum, Circular economy, Resource Utilization

1. Introduction

1.1 From Linear to Circular Flow in Economy Strategies

Regarding to the “produce, use and dispose” motto, conventional linear flow-based economy strategy enables a continuous consumption of the limited global resources. This one-direction point of view results the generation of municipal, industrial, or agricultural wastes due population growth, economic growth, and urbanization causes, which significantly affect the environment in case of inefficient management (Fiksel & Lal, 2018; Johansen et al., 2022). Wastes can be classified according to their sources and their effects on the environment in terms of air, water and soil pollution can be predicted, however the resulting impact on the environment faces a challenge for quantification.

Emerging terms such as “sustainability” and “circular economy” has introduced into our lives as efficient alternative to linear flow strategy. Sustainability approach requires interdisciplinary considerations including waste management together with communities, economic and natural processes, and environmental resources. Circular economy term, designed as a cyclic flow of raw materials and energy consumption, considers the systems defined in sustainability, and enabling a cost-effective improvement and resilience. Cyclic flow in the circular economy focuses on economic development by resource utilization, sustainable consumption of resources, re-manufacturing, and environmental protection (Chojnacka et al., 2021; Silva et al., 2022). Circular economy can be an alternative solution to the ever-increasing demand to fixed quantity natural resources due rapid growth in population, urbanization and industrialization by providing a continuous flow of recycled raw materials. Economic, environmental and social benefits of the circular economy have triggered an increase in the awareness to sustainability (Rathore & Sarmah, 2020; Malinauskaite et al., 2017).

1.2 Economic, Environmental and Societal Advantages in Circular Economy Strategy

Resource preservation and increasing the utilization rate of renewable resources and increasing the re-use capacity of wastes as secondary resources are the basis of circular economy and sustainable development concepts. Waste management has a strategic role in circular economy by promoting the circularity of a material through recycling. Waste management can be defined as the collection, transportation, recovery, treatment and disposal of waste, however the term requires diversifications i.e. providing industrial-specific solutions and efficient implementation of the circular economy goals (Tulebayeva et al., 2020; Salmenperä et al., 2021; Palafox-Alcantar et al., 2020). Recent studies aim to develop a circular economy and improve resource efficiency; however further research are recommended the impact of technologies for waste minimization and the direct impact of sustainability rating tools in various areas (Shooshtarian et al., 2022).

Design of new models to reduce the waste treatment-related process costs and optimize both economic and environment perspectives are of importance (Hidalgo et al., 2019). Resource utilization provides benefits to both approaches by preserving wastes as low-cost raw material and minimizing the quantity of waste materials.

1.3 Phosphogypsum as a Challenge for Phosphate Fertilizer Industry

Phosphate fertilizers are basically phosphoric-acid derived salts, thus the main raw material in the phosphate fertilizer industry is phosphoric acid. Most economically feasible fertilizer grade industrial scale phosphoric acid production is conducted through wet process. However, wet process results a huge quantity of waste product, phosphogypsum (PG). Although the main structure is gypsum ($CaSO_4.2H_2O$), PG has a complex and changeable structure with phosphate rock-based radionuclides, rare earth elements, process residues such as phosphorus, sulfate, fluoride, and heavy metals. According to the stoichiometry, 5 tons of PG is generated per ton of phosphoric acid, and the annual accumulation rate has reached up to 300 Mtons (Feng et al., 2021; Yang et al., 2016; Wang et al., 2021).

One of the current hottest environmental topics is PG in terms of environmental solid waste treatment. However, the main challenge is the impurities fixed in the structure of PG, hindering the direct resource utilization rate (Wu et al., 2022; Silva et al., 2022). Additionally, waste classification code for PG also hinders its utilization rates, since PG can only be labeled as non-hazardous waste if it meets the specific requirements of hazard property codes for a specific application area (Rosales et al., 2021, Cao et al., 2022).

PG is >95% $CaSO_4.2H_2O$ by weight, having a high potential as an alternative to gypsum as a high-content gypsum source. According to the resource utilization related studies, PG can mostly be used as a raw material in the preparation of finer aggregates, supplementary cementitious material, mine backfill, cement, mortar, bricks and whisker or rare earth element extraction (Liu et al., 2019; Wei et al., 2022). Another alternative direct utilization area of PG is in agriculture as $CaSO_4$ fertilizer or soil modifier (Değirmenci et al., 2007).

2. Results and Discussion

2.1 Economıcal Benefits of the Resource Utilization of Phosphogypsum

Gypsum has been a preferred material in many areas with different functions and purposes since ancient times. The Egyptians used plaster to slide large stones in the construction of the pyramids. In the Greek period, plaster found its place in areas such as sculpture and decoration. Today, PG, a type of gypsum; is used in many independent sectors such as agriculture, medicine, food, and construction. On the other hand, although the reserve amount of gypsum is high, the fact that it is not a renewable resource makes it important to protect the existing gypsum resources. For this reason, the reuse of waste plasters is an important requirement that can be applied to protect the existing reserve, both to ensure the protection of raw materials and to prevent the deterioration of the environmental balance. The reuse of waste plasters in the production of building materials is one of these reuse methods. In this study, an examination was carried out on domestic and foreign sources related to the subject in order to determine the evaluation methods during the reuse of waste plasters and to determine which sub-headings these evaluations were made.

The storage or abandonment of various products obtained as waste creates great problems and causes significant problems, including environmental pollution. Today, it is important to recycle the by-products or wastes obtained during the production of various products to the economy in order to protect the ecological balance and prevent pollution. With the recycling of wastes, environmental pollution is prevented, some properties of the materials used in the construction sector can be improved and contribution to the economy can be made. One of the product wastes that cause environmental pollution is PG.

PG, a by-product of the phosphoric acid fertilizer factory, is a by-product resulting from the reaction of phosphate rock and sulfuric acid in the production of phosphoric acid. This production method is called wet method. In wet method production, phosphoric acid and by-product formed as a result of the reaction are separated from each other by filtration. The resulting by-product is called PG. PG, a by-product of the phosphoric acid fertilizer factory, which contains acidic properties, reaches the sea with the dam waters. In addition, the creation of waste storage areas suitable for PG increases production costs. In order to reduce the cost and serve the purpose of sustainable life, the efforts for the recovery of PG into the economy should be accelerated. PG, whose chemical composition is the same as natural gypsum, cannot be used instead of natural gypsum due to the impurities it contains. In the construction industry, when purified from its impurities; it can be used effectively as a set retarder and clinker raw material in cement production, as a secondary binder with cement and lime, in artificial aggregate production and road stabilization. It needs to undergo a series of pre-treatments to be free of impurities. Chemical analyzes showed that approximately 93% of the waste material was gypsum and the remaining 7% was phosphate, fluoride and organic materials. The amount of these impurities in phosphogypsum depends on the production method and the phosphate rock used as raw material. It is effective to wash the water-soluble impurities with water or lime milk several times, and to calcine at 140 $^{\circ}$C – 150 $^{\circ}$C to remove the impurities settled in the crystal lattice. Numerous studies have been carried out on purification, and various results have been achieved with the calcination processes carried out. Phosphogypsum, which is the waste material of phosphoric acid factories and causes environmental pollution because it is not stored properly, has been investigated as a building material for the purpose of recycling it to the economy. Experimental studies were completed by mixing phosphogypsum, which was calcined at 230 $^{\circ}$C, with natural base gypsum due to its pH level, which prevents it from being used as a building material. In addition, the same experimental studies were repeated separately for natural base plaster and phosphogypsum for reference. As a result of the experiments, the pH levels, setting (freezing) times, axial compressive strength and bending tensile strength of the materials were determined. Considering the strength values, the tensile strength in bending at normal speed is 40-50% higher than the base plaster used in the experiments. The same tensile strength increase continued in 2 hours of loading. Again, compared to the base plaster, the axial compressive strength is 70 - 80% higher at normal speed loading. It was observed that the increase in axial compressive strength was the same at 2 hours of loading. 85% base gypsum-15% phosphogypsum mixture; It has been obtained as a gypsum product with a pH level suitable for usability, a fast-setting time, and a high tensile and compressive strength. Accordingly, it has been determined that the mixture sets faster and has higher strength compared to the base plaster. Due to these properties, it is possible to use the product obtained from the said mixture in places where fast socket is needed, and high strength is required. With these features, it can also be used in gypsum panel production. The increase in the price of the new product obtained will provide a significant economic gain per ton. Considering the damage caused to the landfill and its environment, the storage cost, and the sale price of the new product, it is thought that it will be a reasonable price for the waste PG to be recycled to the economy. As a result of the analyzes made, the use of the mixture obtained as a building material will be very useful in preventing environmental pollution. Waste material stored in the open will be used, the damage to the environment will be minimized and economic benefit will be provided by the evaluation of PG.

Waste means "anything that the producer or owner will no longer use and is thrown into the environment or abandoned". In recent years, it is seen that the amount of waste generated has increased with the increase in the needs of the consumers and the production to meet these needs. When we look at the data of all wastes evaluated through different variables such as food waste, health waste, construction, and demolition waste in the world, 2.01 billion tons of waste was generated in 2016, while this value is expected to be 2.59 billion tons in 2030 and 3.40 billion tons in 2050. It is possible to say that the waste group that fits the definition of construction and demolition waste has a rate of 38% in the total amount of waste. This rate is the second group after the food group, which is the highest waste group. In this respect, the reuse of construction waste, which has a large proportion, is important in terms of protecting the environmental balance that is gradually deteriorating. Construction & demolition waste is briefly referred to as C&D. The definition of this type of waste is expressed as "debris generated during the construction, renovation and demolition of buildings, roads and bridges". One of the materials with the highest recyclability potential among construction wastes is gypsum. Considering the usage rates of gypsum, which is the raw material of gypsum, it is seen that 5% is for agricultural purposes, 15% is for industrial purposes, and the remaining use belongs to the construction sector. Although plaster is used in different sectors such as medicine, food, ceramics and agriculture, it is possible to say that its most intensive use is in the construction sector. The recyclability potential of gypsum, which has superior properties such as easy workability, resistance to fire, maintenance-free, flexible design, is defined as a closed loop recycling system (close loop recycling), which is expressed as the "recycling of waste product into the same product". The fact that the waste plasters have a closed loop system, that is, there is no deterioration in their chemical structure during the recycling process, which ensures that they can be used in the same product. The high use of gypsum in the construction sector causes an increase in the production need and therefore the amount of waste gypsum generated as a result of production. These wastes are grouped under three headings:

1. Production Wastes: Wastes generated during the production of the material

2. Construction Wastes: Wastes generated at the construction site during the construction of a new building

3. Demolition Wastes: The wastes generated during the demolition or renewal phase of structures that have completed their life or function.

The common feature of waste plasters classified under different variables is the necessity of disposal. The systematic approach used for the disposal of waste is referred to as waste management in the literature. Waste management is defined as "management method that includes reduction of waste at its source, separation according to its characteristics, collection, temporary storage, interim storage, recovery, transportation, disposal and control after disposal and similar processes". As it can be understood from the definition, there are many methods used in the evaluation of wastes. In this study, the storage and recycling headings, which are more preferred in the reuse of waste plasters, are emphasized.

Storage, which is one of the methods used in the disposal of waste plaster, has different types as temporary or regular. However, in general, landfilling can be defined as keeping the wastes in the facility where they are generated before they are processed. As a result of the application of this method for the disposal of waste plaster, some environmental damage may occur. Although waste gypsum is not harmful to the environment under normal conditions, the hydrogen sulfide gas (H_2S) it contains has a life-threatening role when mixed with water or soil. Penetration of this gas into water and soil more than certain rates causes fatal effects. For this reason, it is possible to say that it is not appropriate to store waste plasters.

3. Conclusion

In this study, in which academic articles were examined in order to determine the evaluation methods during the reuse of PG waste and to determine which sub-headings these evaluations were made, determinations such as waste gypsum type, material type and waste number were reached. The results obtained from the evaluation made on these determinations are as follows:

In the examination made according to the PG formation stage, it was concluded that the waste plasters formed during the construction process (56%) were used the most in the articles. Based on this situation, it is possible to say that waste gypsum formation is more in the fertilizer production phase. It is thought that the waste generated during the fertilizer production phase depends on various variables such as workmanship, application, and analysis of the dimensions of the material, which is effective in achieving this result. When the articles containing production wastes are examined in terms of material, it has been concluded that the wastes generated in the production of PG (57%) are more preferred than the wastes generated in the production of ceramics (43%). In this case, it can be deduced that more waste is generated in the production of PG than in the production of ceramics. It is thought that there are reasons such as the possibility of using PG, which is used in different sectors, more than once and not being evaluated as waste immediately. Another factor is that PG, which is used in different sectors, has the potential to occur as waste only during the production phase. In the evaluation made according to the PG type, it was seen that waste PG (56%) was more common than waste gypsum (30%) and waste gypsum plaster (7%). The fact that PG is in the first place is thought to be an important material for the construction industry and its potential to generate waste at different stages such as production, construction and demolition. The reason why waste PG is in the second place can be shown as the reason why PG, which is used in the production of materials in different industries, turns into waste when it completes its function. In the examination of the articles using waste PG, it was determined that 73% of the waste obtained from PG was used. In other articles

(27%), it was seen that PG, which is referred to as recycled basanite, was used. Recycled basanite is obtained by heating waste gypsum. The additional processing required in the recovery process may be related to the less preference of recycled basanite. When an evaluation is made according to the type of waste, it is seen that a single type of waste is used with a high rate of 96%. The labor and time required for the supply of waste and the preparation of the waste for the article used may be the reason for the tendency to use one type of waste. Although there is a tendency to use only one type of waste in the articles examined, it is possible to compare waste plasters by conducting research examining the use of different types of waste. This will be beneficial in determining the most suitable PG in terms of building material production. In the evaluation made according to the subject headings, it is seen that the material property (78%) is examined the most, followed by the material property and environmental impact (8%), environmental impact (7%) and recycling potential (7%). In this case, it can be said that the effects of PG on the material were examined in the majority of the articles examined. With the evaluation of waste PG, positive effects such as prevention of air pollution, waste disposal, reduction of toxic gas emission are observed. This situation is effective in taking the second place in the environmental impact topic. In the evaluation made in terms of material type, it is seen that gypsum ranks first with 22%. The fact that PG has a closed-loop recycling system can be shown as the reason for this situation. Cement and soil come second with 18%. This situation may be caused by the fact that one of the main raw materials of Portland cement is gypsum. In the articles under the title of soil, the subject of soil improvement has been examined. Improvement with cement additive, which is one of the soil improvement methods, is the part where the use of waste plaster is examined. With the increasing housing need, the unsuitable grounds need to be improved as the land is not sufficient. In this evaluation, the reason why the soil is in the second place (15%) is the excess of soil improvement applications. Concrete, which has a share of 15%, is in the third place. It can be interpreted that the fact that one of the main raw materials of concrete is cement is the reason for this situation. It can be said that the use of waste gypsum should be investigated further in order to keep PG in the 11% slice. Increasing the researches on ceramics, bricks and gypsum remaining in the 4% slice will contribute to the expansion of the waste PG utilization areas. The fact that the article on the subject could not be reached within the scope and limits of the study shows that more studies should be done in this area. Increasing the number of studies to be conducted in this area will contribute to a better understanding of waste PG reuse methods. In this case, it is thought that PG, which is one of the important resources, will also contribute to the circular economy by providing resource conservation. Since waste phosphorus does not only occur in the fertilizer sector, it is thought that the reuse of waste gypsum generated in different areas, in terms of material, may be the subject of future studies.

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