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ANALYSIS OF SHORT-TERM LEACHING BEHAVIOR OF PYROLYZED PLASTIC ASH

ПИРОЛИЗДЕНГЕН ПЛАСТМАССА КҮЛІНІҢ ҚЫСҚА МЕРЗІМДІ ШАЙЫЛУ ҚАСИЕТІН ТАЛДАУ

АНАЛИЗ КРАТКОВРЕМЕННОГО ВЫЩЕЛАЧИВАНИЯ ПИРОЛИЗОВАННОЙ ПЛАСТИКОВОЙ ЗОЛЫ

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анализ, ICP-MS, ICP-AES,
элемент, полимер,
выщелачивание

АННОТАЦИЯ

Анализ краткосрочного выщелачивания пиролизированных пластиковых отходов является необходимым условием для использования пиролизной золы в качестве строительного материала. В данной статье представлены экологические характеристики пиролизной золы. Химические и минералогические характеристики пиролизованного образца определялись с помощью рентгеновской дифракции (XRD). Концентрации выщелачивания Al, Mn, Fe, Ni, Cu, Zn, As, Sr, Cd, Ba, Pb анализировались с использованием японского метода испытания на выщелачивание (уведомление Агентства по охране окружающей среды Японии № 13: JLT-13). Подвижность микроэлементов была объяснена результатами XRF и XRD, которые показали преобладание SiO₂ в золе. Кроме того, результаты экспериментов по выщелачиванию показали, что алюминий и железо эффективно стабилизируются в структуре. В целом, концентрации выбранных элементов в конечных выщелачиваемых продуктах были ниже нормативных пределов для захоронения на полигонах. Эти результаты имеют важное значение для изучения потенциального использования отходов в геотехнических инженерных применений.

Түйінді сөздер:

Пластикалық қалдықтар,
пиролиз, рентгендік
талдау, ICP-MS, ICP-AES,
элемент, полимер,
шаймалау.

ТҮЙІНДЕМЕ

Пиролизденген пластмасса қалдықтарының қысқа мерзімді шаймалау әрекетін талдау пиролиз күлін құрылыс материалы ретінде пайдаланудың міндетті шарты болып табылады. Пиролиз күлінің экологиялық сипаттамалары осы мақалада баяндалған. Пиролизденген үлгінің химиялық және минералогиялық сипаттамасы рентгендік дифракция (XRD) талдауын қолдану арқылы анықталды. Al, Mn, Fe, Ni, Cu, Zn, As, Sr, Cd, Ba, Pb шайылу концентрациясы жапондық шаю сынағы әдісімен (Жапонияның қоршаған ортаны қорғау агенттігінің № 13 хабарламасы: JLT-13) талданған. Микроэлементтердің қозғалғыштығы күлде SiO₂ үстемдігін көрсететін XRF және XRD нәтижелерімен түсіндірілді. Сонымен қатар, қысқа мер-



зімді шаю эксперименттерінің нәтижелері алюминий мен темірдің құрылымда тиімді тұрақтандырылғанын көрсетті. Тұтастай алғанда, соңғы шайма сулардағы таңдалған элементтердің концентрациясы полигонға арналған нормативтік шектен төмен болды. Бұл тұжырымдар геотехникалық инженерия қолданбаларында қалдық материалдарды пайдалану мүмкіндігін зерттеу үшін маңызды.

Keywords:

Plastic waste, pyrolysis, X-ray analysis, ICP-MS, ICP-AES, element, polymer, leaching.

ABSTRACT

Analyzing short term leaching behavior of pyrolyzed plastic waste is the prerequisite to utilize pyrolysis ash as a construction material. Environmental characteristics of pyrolysis ash were reported in this paper. Chemical and mineralogical characterizations of the pyrolyzed sample were determined using X-ray diffraction (XRD) analysis. Leaching concentrations of Al, Mn, Fe, Ni, Cu, Zn, As, Sr, Cd, Ba, Pb were analyzed using Japanese leaching test method (Japan environment agency notification no.13: JLT-13).

The mobility of trace elements was explained by XRF and XRD results that showed SiO₂ domination in the ash. Furthermore, the results of the leaching experiments indicated that aluminum and iron were effectively stabilized within the structure. Overall, the concentrations of the selected elements in the final leachates were below the regulatory limits for landfilling. These findings are significant for exploring the potential use of waste materials in geotechnical engineering applications.

INTRODUCTION

Rapidly increasing global plastic production and consumption lead to a massive plastic waste accumulation and posing severe environmental and socioeconomic problems. The combination of low cost, ease of production, light weight and high corrosion resistance has made plastics a preferred alternative material to wood and metal. (PWTMI 2019, Syamsiro et al. 2014; Kawai et al., 2015; Kumar and Samadder, 2016; Nanda et al., 2020). Therefore waste stream contains significant amount of plastic disposals that requires long time to be fully decomposed (UNEP 2009). Traditional waste management methods such as landfilling and high-temperature incineration, come with several serious disadvantages, including long plastic decomposition times, huge amount of storage requirement, greenhouse gas emissions, and the toxic substance formation (Powrie and Dacombe, 2006; Syamsiro et al. 2014; Geyer et al. 2017,). Recently, thermal treatment technologies, particularly pyrolysis, have been viewed as a promising and more sustainable approach to plastic waste management (Geyer et al. 2017). Pyrolysis process produces valuable treated products such ash liquid and gaseous products that are widely known in scientific studies, while a solid residue, pyrolysis ash, has not attracted the attention of researchers. This pyrolyzed ash material has huge potential to be used as a construction material, therefore its composition, stability, and environmental safety require detailed study before further utilization or disposal.

Original plastic material, additive and mineral filler types and thermal treatment conditions determine the mineralogical and elemental composition of pyrolyzed ash. During the thermal treatment, additives such as pigments, stabilizers, fillers and flame retardants that are contained in the plastic are retained or transformed. Therefore, it determines the chemical characteristics of the pyrolyzed plastic ash, such as amorphous and crystalline phases, as well as trace metal impurities. There is a risk of environmental issues such as groundwater and soil contamination due to the leaching of these impurities. Therefore, studying leaching characteristics of the pyrolyzed ash is required in order to utilize it as a man-made material or safely dispose (Funatsuki et al. 2017, Zhang et al. 2016). Standardized leaching procedures, such as JLT-13, provide a validated tool for determining the extent of release of potentially harmful



components under given laboratory conditions. Leachate parameters must comply with established environmental standards governing permissible levels of soil contamination. Furthermore, the analysis results should serve as the basis for assessing potential environmental risks. Generally, ash materials dominated by crystalline phases of quartz, mullite, and stable iron oxides demonstrates low leachability characteristics. However, amorphous or alkali-rich constituents may mobilize certain metals or promote solubility of the pyrolyzed ash.

Although pyrolysis of plastic waste is gaining increased attention day by day, data on the detailed composition and properties of the resulting pyrolysis ash remains insufficient, particularly for its practical applications in the construction industry and geotechnical engineering. Therefore, a thorough assessment of its mineralogy, chemical stability, and environmental safety is required to guarantee proper material management.

The aim of this study is to provide a comprehensive characterization of pyrolyzed plastic-waste ash by the integrated X-ray diffraction (XRD), X-ray fluorescence (XRF), and batch leaching analyses.

This study, based on the comprehensive study of the material's mineralogical phase, elemental composition, and leaching behavior, evaluates its stability, environmental safety, and suitability for use in cement and geopolymer systems, as well as refractory and other structural materials. The data presented expands our understanding of solid pyrolysis products and forms the basis for developing sustainable strategies for the management and recycling of such waste.

MATERIALS AND METHODS

Catalyst Co., Ltd prepared man-made pyrolyzed ash by shredding plastic waste into 8 mm pieces and pyrolyzing it at 400°C. At the Environmental Engineering Department laboratory of Kyoto University mineralogical composition of the sample was analyzed qualitatively and quantitatively using XRD RINT-UltimaPC and Shimadzu XRF-1700 spectrometer, respectively. The sample was meticulously ground into a uniform powder prior to analysis since proper sample preparation is very important in order to conduct x-ray analysis. Concentration of the elements were determined in terms of oxide concentrations by compressing 5 grams of pyrolyzed ash under 30 tons of loading.

X-ray analysis were followed by Japanese standard batch leaching tests (JLT-13, 1973). Batch leaching tests were conducted to assess the release of constituents from the man-made pyrolyzed ash material under controlled liquid–solid contact conditions. Therefore, 5 grams of sample was taken and mixed with 50 ml distilled water to get 1:10 of solid-to-liquid ratio. This mixture was shaken and liquid separated from ash by centrifuge for six hours at 200 rpm and 20 minutes at 3000 rpm, respectively. Leachates were subsequently analyzed to evaluate contaminant mobility and potential environmental impacts.

Inductively coupled plasma mass spectrometry was used in order to determine concentrations of Sr, Ba, Mn, Zn, Cu, Ni, Pb, As, and Cd while inductively coupled plasma atomic emission spectrometry determined Si, Al, and Fe concentrations. For that liquid was separated from ash by filtering through a 0.45-micrometer membrane filter. The results were evaluated against the established JLT-13 leaching limits for the industrial waste disposal.

RESULTS AND DISCUSSIONS

Mineralogical composition of the man-made pyrolysis ash sample was examined using XRD method. X-ray diffraction analysis results revealed that the pyrolyzed plastic waste ash is predominantly crystalline with the presence of quartz defined as primary component of the sample. Sample contains silicate minerals alongside primary and secondary iron minerals, including quartz (SiO_2), mullite ($3\text{Al}_2\text{O}_3 \cdot 2\text{SiO}_2$), maghemite ($\gamma\text{-Fe}_2\text{O}_3$), hematite (Fe_2O_3), and magnetite (Fe_3O_4). A strong and sharp quartz peak at $\sim 26.6^\circ 2\theta$ confirms its high abundance and

high crystallinity. Additional to quartz, high amount of mullite ($3\text{Al}_2\text{O}_3 \cdot 2\text{SiO}_2$) was detected based on characteristic reflections at $\sim 16^\circ$, 26° , 33° , and $40\text{--}42^\circ$ 2θ . Non-uniform redox environment during pyrolysis treatment, typical to heterogeneous mixed plastic waste, was indicated by the coexistence of quartz and mullite. Minor iron oxides appear with well-defined phases which confirms the presence of Fe-bearing pigments, fillers and metal contaminants in the plastic waste. Even though trace amorphous calcium–magnesium–sodium–potassium silicates are expected, an overall low and uniform background signal pattern confirms that the expectations were not validated.

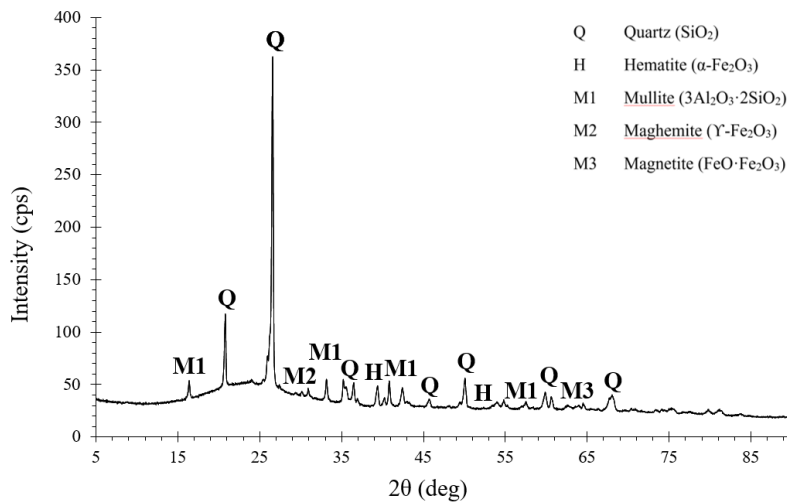


Figure 1. Mineralogical composition results of pyrolyzed ash

Note – compiled by the authors

Moreover, XRF results also validated that SiO_2 (60.64 wt%) and Al_2O_3 (15.48 wt%) were the dominant element oxides in the sample, consistent with the dominant crystalline phases of quartz and mullite observed in XRD. Results of mineralogical composition and elemental oxide concentrations of the man-made pyrolyzed ash were demonstrated in the Figure 1 and Table 1, respectively. The $\text{SiO}_2\text{--Al}_2\text{O}_3$ ratio is in good agreement with the mullite stoichiometry, confirming its formation during high-temperature processing.

Moderate concentrations of CaO (3.30 wt%), MgO (1.82 wt%), Na_2O (0.68 wt%), and K_2O (1.15 wt%) probably influenced an amorphous silicate matrix which were not detected by XRD. The presence of alkali and alkaline earth oxides lowers the melting point of the man-made pyrolysis ash and can alter its reactivity.

Minor oxides, such as TiO_2 (0.91 wt%), SO_3 (0.86 wt%), and trace amounts of SrO , BaO , ZnO , MnO , and P_2O_5 , were also observed. These components may have originated from pigments, stabilizers, and inorganic additives which are typical of mixed plastic waste.

Table 1. Elemental oxide concentration results of pyrolyzed ash

Oxides	Elemental oxide concentration (wt%)
SiO_2	60.640
Al_2O_3	15.480
Fe_2O_3	3.730
CaO	3.300
MgO	1.820
K_2O	1.150
TiO_2	0.911



End of table 1

Oxides	Elemental oxide concentration (wt%)
SO ₃	0.859
Na ₂ O	0.683
P ₂ O ₅	0.602
SrO	0.079
BaO	0.057
ZnO	0.030
MnO	0.029

Note – compiled by the authors

Japan Leaching Test Method #13 (JLT-13, 1973) was used in order to conduct and analyze batch leaching behavior of man-made pyrolyzed ash. Short term batch leaching test results are demonstrated in the Table 3 and further confirm the stability of the material.

Table 3. Short-term leaching test results

Elements	Leached element concentrations (mg/L)	JLT-13 Disposal of industrial wastes (mg/L)
Al	not detected	-
Fe	not detected	-
Sr	1.159	-
Ba	0.086	-
Mn	0.004	-
Zn	0.002	5.000
Cu	0.005	3.000
Ni	not detected	-
Pb	not detected	0.300
As	0.018	0.300
Cd	not detected	0.300

Note – compiled by the authors

All selected environmentally regulated metals such as Zn, Pb, Cu, As and Cd were determined to be below the respective JLT-13 limits.

According to previous studies, Ca, Cr and Mg tend to concentrate on the particle surface, while Al, Si, K, Pb and other trace elements are more uniformly present inside fly ash particles. (Akar et al., 2012). In this study the undetected levels of Al, Fe, Ni, Pb, and Cd in the leachate demonstrate their effective immobilization within the silicate and iron-oxide matrix. Low concentrations of both Sr (1.159 mg/L) and Ba (0.086 mg/L) were leached out below the JLT-13 thresholds that indicates low solubility of alkaline earth components. The very low leaching is explained by the high degree of crystallinity of the ash and the dominance of chemically inert phases such as quartz, mullite and stable iron oxide minerals.

CONCLUSIONS

The comprehensive set of mineralogical component, concentration and their leaching analysis indicate that the man-made pyrolyzed plastic-waste ash shows highly crystalline and environmentally stable silica-rich material behavior. The key findings of this study are as follows:

The mineralogical composition is dominated by quartz and mullite, which is consistent with the high SiO₂ and Al₂O₃ contents determined by XRD, while the presence of iron oxide phases reflects the complex redox conditions of the pyrolysis process. The transformation of



inorganic constituents into heat-resistant crystalline phases can be seen by the contained trace amounts of amorphous phase of Ca, Mg, Na, K silicates in the pyrolysis ash.

Stability of pyrolyzed ash material was further confirmed by the batch leaching test results demonstrated that all selected metals leaching concentrations (Si, Al, Fe, Sr, Ba, Mn, Zn, Cu, Ni, Pb, As, and Cd) were below the JLT-13 limits or undetected. Effective immobilization of potentially toxic elements in the silicate and iron oxide structure indicates the high chemical stability of the ash. Trace concentrations of leached Sr and Ba were detected below the standard thresholds, consistent with limited dissolution of alkaline-earth constituents.

Taken together, the man-made pyrolyzed plastic waste ash exhibits characteristics typical of inert aluminosilicates, including high crystallinity, limited amorphous content and minimal metal mobility. Indicated properties of pyrolyzed ash poses low environmental risk and it is safe to dispose as a non-hazardous waste. Moreover, its composition and stability highlight potential possibilities of beneficial utilization in following applications of supplementary cementitious materials, geopolymer production, refractory or ceramic composites, and filler materials

To ensure the safe use of pyrolysis ash in geotechnical applications and reduce environmental risks, future research is recommended to focus on its incorporation into concrete and long-term leaching tests to assess the release of elements over time. Given that a catalyst was used in the pyrolysis process, it is likely to influence the mineralogy of the final product. Therefore, elemental analysis of the catalyst is planned to determine the extent of its impact on the ash characteristics and clarify its functional role in the pyrolysis process.

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All intellectual contributions, interpretations, conclusions, and final decisions presented in this work are solely those of the authors. The authors take full responsibility for the content and affirm that AI technologies were used in accordance with ethical guidelines and did not replace original research or critical thinking.

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