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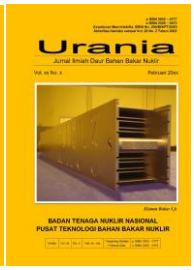

DEVELOPMENT OF MATERIALS FOR IMMOBILIZATION OF CESIUM AND CERIUM BASED ON A COMBINATION OF NOCHAR SUPER ADSORBENT AND UNSATURATED POLYESTER FOR PRODUCTION WASTE RADIOISOTOPE ^{99}Mo

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ABSTRACT

DEVELOPMENT OF MATERIALS FOR IMMOBILIZATION OF CESIUM AND CERIUM BASED ON A COMBINATION OF NOCHAR SUPER ADSORBENT AND UNSATURATED POLYESTER FOR PRODUCTION WASTE RADIOISOTOPE 99Mo. This research aims to develop unsaturated polyester-based materials combined with Nochar superabsorbent as radioactive waste immobilization materials. The focus is to lock up radioactive elements such as cesium (Cs) and cerium (Ce), which are used as surrogates for ^{99}Moradioisotope waste. This study evaluates the performance of immobilized materials in adsorbing and stabilizing radioactive elements using various waste loading percentages of 10%, 15%, 20%, and 25%. The characterization results showed that the combination of unsaturated polyester and Nochar was able to absorb the waste effectively without any migration of radioactive elements to the environment, according to the leaching test results. However, based on the compressive strength test, a high increase in waste loading resulted in a decrease in the mechanical strength of the composite. Thus, an optimal waste loading of 20% provides a balance between absorption capacity and mechanical strength. This study demonstrates the potential of using unsaturated polyester and Nochar as safe and effective immobilization materials for radioactive waste, especially in the context of long-term radioactive waste management.

Keywords: Unsaturated polyester, Nochar, waste loading.

INTRODUCTION

Science and technology (science and technology) are continuously developed and utilized in an effort to meet basic human needs, extend life expectancy and stimulate improvements in the quality of life. One of them is the utilization of nuclear technology which is currently used in various fields such as energy, agriculture, industry, food preservation, and health. The world of medicine has utilized nuclear technology for diagnosis of bone, brain, thyroid, lung, liver, and kidney disorders with the use of radioisotope Technetium-99m (^{99m}Tc) [1]. ^{99m}Tc is produced from the production of radioisotope Molybdenum-99 (^{99}Mo) as its decay child which has a half-life of 6 hours and decays into ^{99m}Tc by emitting gamma energy (Eγ = 140 keV) [2]. The short half-life of Tc^{99m} is expected to be used upimmediately after the diagnosis process is completed so that the impact can be minimized Indonesia produces radioisotopes ^{99}Mo through PT INUKI from uranium targets both High Enrich Uranium (HEU) and Low Enrich Uranium (LEU) irradiated in the G.A. Siwabessy Multipurpose Reactor (RSG-GAS) [3]. Oneof the wastes generated from this production is radioactive liquid waste called Radioactive Fission Waste (RFW). RFW contains residual non-fission ^{235}U, activation products, several actinides including plutonium, and fission products [3]. In addition, RFW includes waste with a radioactive activity of more than 100 GBq/g, which is classified as High Level Waste (HLW) based on Government regulation No. 45 of 2023 concerning Radioactive Waste Management.

High of activity RFW waste with the main composition of actinides, namely ^{238}U and ^{137}Cs fission products has a lung time of 4.468 billion years so that it requires good and proper management so that it is safe for workers, does not pollute the environment, and does not have an impact that disturb public health. The potential hazards of radioactive waste for the human body arise from radiation emission that can directly or indirectly ionize organic molecules of the human body, radiation exposure from radioactive waste can cause the development of cancer in humans, and long- term radiation exposure can cause serious diseases such as leukemia, organ damage, and reproductive disorders [3].

Radioactive waste immobilization is one of the biggest challenges in nuclear waste management, given its potential hazards to the environment and human health. The materials used for this immobilization must have high chemical and physical stability, the ability to withstand radiation, and ensure no release of radionuclides to the environment. Cement and glass materials have been widely used for radioactive waste immobilization. Cement is readily available and relatively cheap compared to other materials, and the process of mixing and hardening cement is relatively simple and does not require specialized equipment[4]. However, cement has a lower resistance to radiation, and it is porous, which can allow permeation. Water and potential *leaching of* radioactive isotopes. Glass materials use a vitrification process that involves melting radioactive waste together with glass-forming materials at high temperatures to produce a homogeneous glass matrix. The vitrification process requires specialized equipment and high energy, so the cost is relatively high. In addition, glass can crack under mechanical or thermal stress conditions, which can affect its effectiveness in the long term [5].

Polymers are emerging as a potential alternative for radioactive waste immobilization materials. Polymeric materials offer several significant advantages in radioactive waste immobilization compared to glass and cement materials. One of the main advantages of polymers is their flexibility and adaptability. Polymers can be formulated and modified according to specific needs, enabling their use in various types of radioactive waste with varying characteristics. This makes polymers more flexible than glass, which has a fixed composition and is difficult to modify. This flexibility in design and application allows polymers to provide better performance in effectively locking up radioactive waste [6]. In addition, polymers have the ability to fill gaps and empty spaces in the waste, ensuring all parts of the waste are well encapsulated. This is important to prevent the spread of radioactive isotopes into the environment. These advantages make polymers more effective in sealing waste than cement, which tends to be more porous and allows water permeation that can lead to leaching of radioactive isotopes. This superior sealing

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ability of polymers enhances the long-term safety of radioactive waste storage [7]

This type of waste immobilization technique has been developed in several previous studies with composite materials such as epoxy polymers [8], Synroc Titanat matrix [9], polyurethane [10], epoxy acrylate [11], styrene divinyl benzene [12]. These polymers have certain advantages and disadvantages depending on the nature of the waste to be immobilized and the required storage conditions. Based on previous research, there is a need for renewal and development of polymeric materials that are more effective in immobilizing waste and have durability in maintaining the safety of consolidated waste. The novelty of this research is the development of Unsaturated polyester polymer- based materials combined with superabsorbents that have good strength and stiffness, making them suitable for use in making strong and durable composites, and have good tolerance to radiation exposure, especially in the form of gamma rays or particle radiation. The superabsorbent used is Nochar which has high chemical resistance and has the ability to absorb waste up to one hundred times the volume of the absorbent under low pH condition [13] This study aims to determine the effectiveness of polymer composites of nochar and unsaturated polyester for surrogate immobilisation of liquid radioactive waste from the production of radioisotope ^{99}Mo.

METHODOLOGY

The tools used are analytical digital scales, watch glasses, cups, ice cream sticks, plastic bottles, 5 cm × 2 cm paralon, blades, chopsticks, thread, 2000 ml beaker glass, 1000 ml beaker glass, origen 2.1 software, ICP-OES Optima 8300 Perkin Eimer, and Bruker-Tensor II Raman Spectrometer. The materials used are $CsNO_3$, $CeNO_3$, N960 acid bond nochar, waste nochar pH 1, waste nochar pH 3, polyester, cesium (Cs), cerium (Ce), HNO_3 20%, distilled water, catalyst, stone, and plastic.

1. Viscosity Characterization

Measurement of viscosity of unsaturated polyester with a volume of 50 ml was carried out using a viscometer and rotational rheometer using a systematic method. Set the rotational speed (RPM) according to the expected viscosity range. After the spindle is inserted into the sample, turn on the viscometer and record the stable viscosity result. This process is done three times to obtain consistent data. The data from the device is then analyzed, with averages calculated and, if required, statistical analysis to evaluate variations. Cleaning the device before and after measurement is essential to ensure accurate results. With this method, the viscosity of unsaturated polyester can be measured precisely and reliably.

2. Sewage Sorption Using Nochar and Immobilized Super Absorbent

Uranium waste is very dangerous to be processed directly, therefore simulated waste is made from cesium as a fission product and cerium as a substitute for actinide because it has the same chemical properties. SAP Nochar is a Co-Polymer of Acrylamide. Cerium as much as 44.014 g and cesium as much as 7.216 mg were mixed into 1000 mL distilled water, then added 20% HNO_3 to pH 1 and pH 3. Weigh SAP Nochar as much as 49.59 g twice and 26.1 g. Nochar powder with a weight of 49.59 g was put into a bottle and added 190 mL of distilled water, then shaken until it evenly formed a gel, as well as for the second repeat. SAP Nochar powder with a weight of 26.1 g is put into a bottle and 100 mL of distilled water is added, then shaken until it evenly forms a gel.

Nochar and Unsaturated polyester polymer were weighed according to their respective waste loading requirements as in Table 1. The catalyst was added to the polyacrylic as much as 5 drops and stirred until slightly brassy, then the polymer was added to the container containing nochar and stirred until homogeneous. The mixture is put into a paralon that has been coated with vaseline and allowed to harden.

Table 1. Weight of waste nochar and Unsaturated polyester polymer for immobilization

Waste Loading	Total weight (g)	Nochar-Waste (g)	Unsaturated polyester
0.10	31.00	3.10	27.89
0.15	30.70	4.61	26.12
0.20	30.50	6.09	24.38
0.25	30.20	7.55	22.66

3. Characterization Using a Raman Spectrometer

Irradiated and non-irradiated samples were characterized using the Micro Confocal Hyperspectral 3D Imaging Raman Spectrometer LabRAM HR Evolution instrument (HORIBA, Kyoto, Japan) with a wavelength of 785 nm. The resulting spectra were then processed using Origin software with smoothing treatment. The spectra were then identified by looking at the raman shift curve against the intensity seen in the raman spectra.

4. Determination of Leaching Rate

The leaching rate was carried out according to ASTM C-1308 which is an accelerated leaching rate in aqueous medium. Distilled water was poured into 1200 ml glass goblets in the amount of 8 cups. One consolidated sample each was hung on a glass goblet containing distilled water. The sample was tied with thread in the glass cup. At certain time intervals the sample was lifted, then a 10 mL sample of used leach water (water was stirred first) was taken for characterization of Ce and Cs elements with ICP-OES. The sample is put back into the glass cup that has contained new distilled water with the same volume.

Table 2. Accelerated leaching test interval

Interval	Time	Cumulative Time
1	2 hours	2 hours
2	5 hours	7 hours
3	17 hours	1 day
4	1 day	2 days
5	1 day	3 days
6	1 day	4 days
7	1 day	5 days
8	1 day	6 days
9	1 day	7 days
10	1 day	8 days
11	1 day	9 days
12	1 day	10 days
13	1 day	11 days

5. Characterization Using Inductively Coupled Plasma-Optical Emission Spectrometry (ICP OES)

The standard series was made with a concentration variation of 0.1; 0.5; 0.75; 1; 2.5; 5; 10; 25; 50; and 100 ppm with 25 ml each using 100 ppm cerium and cesium mother liquor in a 25 ml volumetric flask using distilled water solvent. The standard and sample series were then tested using ICP-OES so that the results obtained in the form of intensity and absorbance data are then processed as a result of the leaching rate.

6. Compressive Strength Testing

To obtain the mechanical properties of the polymer-waste blocks that have been made, a compressive strength test was conducted. The compressive strength test followed the ASTM D-695 standard at a speed of 3 mm/minute (Appendix 7). The compressive strength test was carried out using a Universal Testing Machine (UTM) which is a testing tool to determine the stress of a material using tensile or compressive modes.

7. Characterization Using SEM

SEM (Scanning Electron Microscopy) combined with EDS (Energy Dispersive X-ray Spectroscopy) is a powerful technique for morphological and chemical characterization of samples. EDS provides information on the chemical composition of the sample by detecting the X-rays produced when the sample is exposed to the SEM electron beam. The steps in using SEM (Scanning Electron Microscopy) combined with EDS (Energy Dispersive X-ray Spectroscopy) for the characterization of waste immobilization samples involve sample preparation, such as cutting and drying, followed by possible conducting coating. Afterwards, the sample is placed in an SEM chamber, and SEM images are taken to observe the morphological structure of the sample surface. Next, the EDS system is activated to obtain X-ray spectra representing the chemical composition of the sample.

RESULT AND DISCUSSION

Measuring the viscosity and determining the molecular weight of unsaturated polyester polymers are very important in the radioactive waste immobilization process, as they affect the mechanical properties and chemical strength of the polymer [14]. Viscosity, which is a measure of a liquid's resistance to flow, gives an indication of the polymer's chain length and molecular mass distribution. Polymers with high molecular weights usually have higher viscosities because their longer polymer chains experience greater internal friction. In the context of radioactive waste

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immobilization, an appropriate viscosity is essential for the polymer to be processed properly; too high a viscosity can make mixing or casting difficult, while too low a viscosity may not adequately protect against diffusion of radioactive substances [14].

In addition, the molecular weight of the polymer affects many physical and chemical properties of the material. Polymers with higher molecular weights generally have better mechanical strength and chemical resistance. Longer polymer chains increase the interactions between chains, giving the material additional strength as well as better resistance to aggressive chemicals. In radioactive waste immobilization, high molecular weights can potentially provide better protection against chemical decay and radioactive material release. However, polymers with high molecular weights also have higher viscosity, which can complicate the process [15]. In contrast, low molecular weight polymers have a lower viscosity, making them easier to process, but with lower mechanical strength and chemical resistance. Therefore, in radioactive waste immobilization, it is important to balance the viscosity and molecular weight of the polymer to ensure an efficient process and optimal protection of the radioactive material.

Based on a viscosity value of 1320 mPa^{-s} and using the Mark-Houwink equation to relate viscosity to polymer molecular weight, a molecular weight of 1.25×10^{10} g/mol was obtained, as shown in Figure 1. This very large molecular weight contributes significantly to the mechanical strength and durability of the material, resulting in better performance in mechanical tests such as tensile strength and elasticity. In addition, the increased chemical stability makes the polyester more resistant to chemical degradation and reactions, making it a highly suitable material for radioactive waste immobilization applications. In this context, the high molecular weight allows the polyester to efficiently absorb and lock in radioactive ions, preventing harmful leakage into the environment and ensuring resistance to extreme environmental conditions[16].

In this study, Raman spectroscopy was used to characterize polyacrylamide that has adsorbed radioactive cesium simulation waste and consolidated with unsaturated polyester. Raman spectroscopy plays an important role in several aspects. Firstly, this method allows the identification of chemical structures, i.e. verifying the presence and interaction between polyacrylamide, unsaturated polyester and cesium ions. In addition, Raman spectrum analysis is used to detect chemical changes that may occur due to cesium absorption, as well as provide insight into specific molecular interactions. Furthermore, Raman spectroscopy is used to detect interactions between polymers and absorbed cesium ions through changes in specific vibrational modes. This technique also serves in material characterization at the micro level, which is useful for understanding how the sorption and solidification processes take place in the polymer matrix [17].

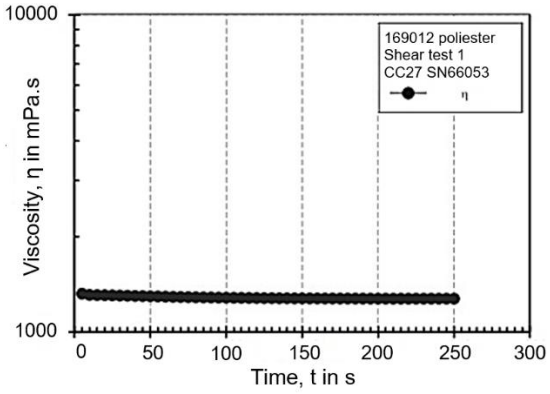

Figure 1. Viscosity of unsaturated polyester

The change in chemical structure between polyester and various levels of waste loading (10%, 15%, 20%, and 25%) occurs through the interaction between the polyester polymer chains and the added cerium a n d cesium waste. In pure polyester, the Raman spectra show characteristic peaks related to vibrations of chemical bonds such as carbonyl groups (C=O) around 1700 cm^{-1}, ether groups (C-O-C) between 1000-1300 cm^{-1}, and C-H bonds in methyl or methylene groups around 2900 cm^{-1}. The Raman spectrum of the polyacrylamide-based super absorbent shows peaks of compared to polyester, mainly related to amide groups (N-H) and carbonyl groups (C=O). These peaks are located in the 1000-1700 cm^{-1} region, indicating strong hydrogen bonding interactions as well as the ability of the SAP to absorb waste. At 10% waste loading, cerium and cesium begin to interact with the polyester, although their effect is still limited. This interaction causes changes in the Raman spectrum, such as a small shift or decrease in the intensity of the

carbonyl peak due to the bonding of the waste metals with oxygen in the polyester carbonyl group. However, due to the low effluent concentration, the structure and characteristic peaks of the polyester remain dominant.

At a waste loading level of 15%, the chemical interaction between polyester and waste is more pronounced. The addition of cerium and cesium caused a decrease in the intensity of the C=O peak, indicating the bonding of the waste metal with the carbonyl group. In addition, changes in the C-O groups in the ester structure occurred, characterized by a peak shift or intensity change in the Raman spectrum. The basic structure of the polyester is maintained, but begins to show significant modifications. By increasing the waste loading to 20%, the effect of waste on the polyester structure becomes stronger. The interaction between cerium and cesium with oxygen in the carbonyl group around 1700 cm^{-1} and ether between 1000-1300 cm^{-1} causes a larger shift in the Raman spectrum can be seen in Figure 2. The formation of complexes or coordination bonds between the waste metals and the polyester occurs, reflected by the appearance of new peaks or changes in the intensity of existing peaks. At this point, the polyester structure is significantly disrupted by the presence of waste.

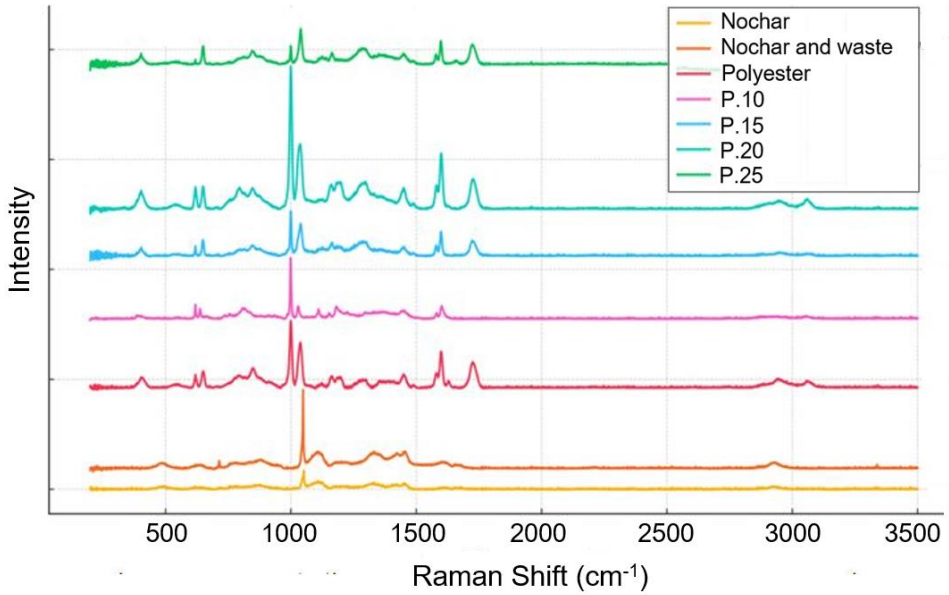

Figure 2. Comparison of Raman Spectum of solidified samples of Unsaturated polyester, SAP Nochar, waste loading 10%, 15%, 20%, and 25%.

At 25% waste loading, the structural changes in the polyester are very obvious. The Raman spectrum shows a large shift in peak intensity and position, indicating that the interaction between waste and polyester has caused significant structural modifications. The formation of new phases or complex compounds between cerium, cesium, and polyester may occur, resulting in a decrease in the stability and mechanical properties of the polyester as the polymer matrix undergoes structural damage. The presence of cerium and cesium is detected through changes in the polyester spectrum. The interaction of cerium with carbonyl or ether groups causes a distinctive shift or change in peak intensity. Cesium, although more ionic in nature and having weaker interactions, also affects the intensity of certain peaks if it forms bonds with the polyester.

The increase in waste loading from 10 to 25% shows that cerium and cesium waste further affects the chemical structure of the polyester. At lower loadings, changes in the properties and structure of the polyester are minimal, so the original properties of the material are retained. However, at higher loadings, strong chemical interactions cause significant modifications in the structure and properties of the material, including the formation of new phases. Therefore, the selection of the optimal waste loading level

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should consider the balance between waste utilization and preservation of the essential properties of the polyester. The literature generally suggests waste loading of about 10%-15% is effective for improving certain properties without significantly disturbing the basic structure of the polyester.

The leaching process was carried out by dipping the solidified solid sample into distilled water as much as 1200 ml according to the time interval in Table 2. The samples tested were variations of several waste loadings, namely 10%, 15%, 20%, and 25%. The different percentage of waste loading in the samples shows the difference in cerium and cesium contained in the samples. The greater the percentage of waste loading will have greater concentrations of cerium and cesium but less weight of vinyl ester polymer. The initial concentrations of cerium and cesium of each sample before the leaching process are shown in Table 3.

Table 3. Cerium and Cesium concentrations before leaching test

Waste Loading (%)	Concentration (g/cm^3)	
	Cerium	Cesium
10	1.80×10^{-3}	6.30×10^{-7}
15	2.68×10^{-3}	9.37×10^{-7}
20	3.53×10^{-3}	1.23×10^{-6}
25	4.37×10^{-3}	1.52×10^{-6}

Each sample was then subjected to leaching tests to determine the amount of Ce and Cs that could migrate out of the sample and escape into the environment. The leaching process water samples were then subjected to rare earth metal characterization, namely Ce and Cs using ICP-OES. Based on the results of ICP-OES, the concentration of each sample is obtained which is then processed so as to obtain the results of the leaching rate of each sample with a certain time variation. Based on the results of the Cesium and cerium leaching test, none of them migrated into the water medium as shown in Figure 3, these results are because polyacrylamide has a polymer chain containing amide groups (-$CONH_2$) which can form hydrogen bonds and ionic bonds with metal cations such as Ce^{3+} and Cs^{+}. When these metals interact with polyacrylamide, the metal cations are trapped inside the hydrophilic network of the polymer through ionic or coordination bonds, making them immobile. Furthermore, the solidification process with unsaturated polyester produces a strong three-dimensional structure, trapping the metals physically and chemically within the matrix. As a result, metal migration to the environment is minimal, even under leaching test conditions, as the bonds formed are stable and durable. This process is highly effective in controlling the release of harmful metals into the surrounding environment.

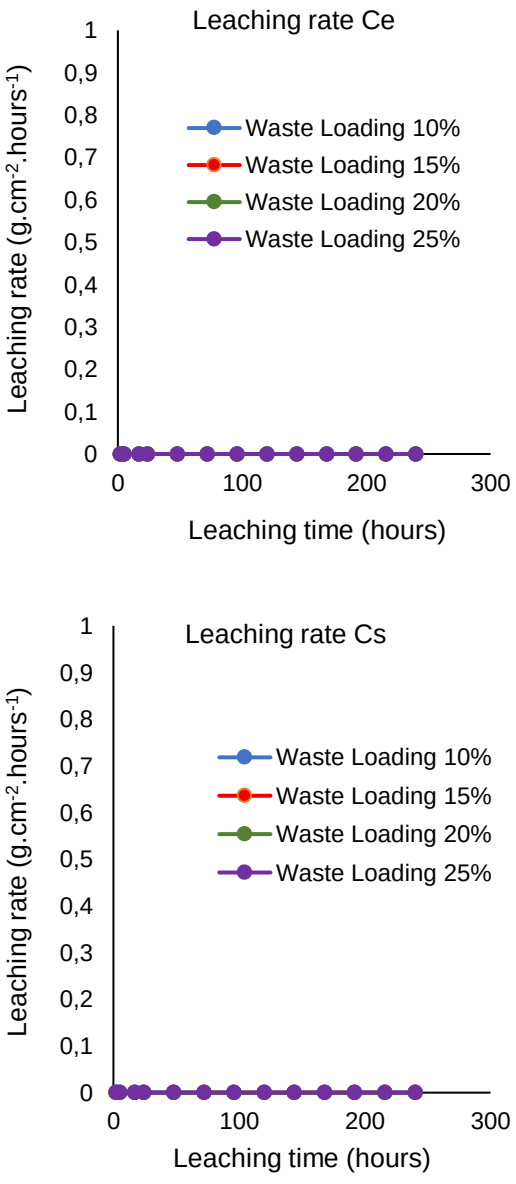

Figure 3. Leaching rate of Cs and Ce in solidification samples with waste loading of 10% (blue), 15% (red), 20% (green), and 25% (purple).

Testing the compressive strength of polyacrylamide absorbent composites with waste loading variations of 10%, 15%, 20%, and 25% showed a significant decrease as the percentage of waste loading increased (Figure 4). At 10% waste loading, the composite reached the highest compressive strength of 18.79 N/mm², while at 25%, the compressive strength decreased drastically to 11.06 N/mm². This decrease was due to the increased porosity and decreased density of the composite, which resulted in the material becoming more brittle and less able to withstand loads. Unsaturated polyester was used as a matrix to provide structural support to the polyacrylamide, improving the mechanical strength and stability of the composite. The effectiveness of waste absorption remains high at lower waste loading (10-15%), but at higher waste loading (20-25%), the composites tend to become too weak to maintain the same absorption efficiency. Although the waste absorption capacity increases with higher waste loading, the decrease in mechanical strength limits the practical application of these composites.

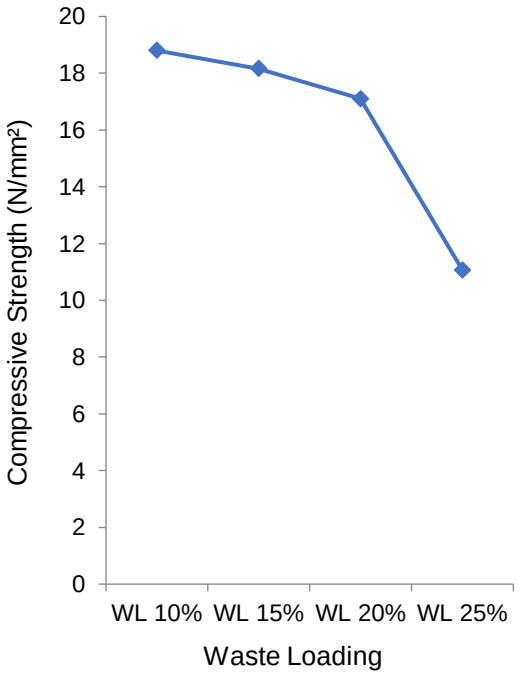

Figure 4. Comparison of compressive strength values of unsaturated polyester composites and SAP with waste loading 10, 15, 20, and 25%.

The significant decrease in compressive strength with 25% waste loading indicates a possible decrease in the density of the composite. Materials with lower densities generally have more pores, reducing their ability to withstand loads. Conversely, materials with higher density (lower waste loading) tend to have stronger bonds between the polymer components, resulting in better mechanical strength. Based on the literature, the limit for polymer waste immobilization blocks is 10 to 20 N/mm²[15]. so that from an economic point of view, 20% waste loading canbe said to have good resilience and can load more waste.

In the SEM characterization results of unsaturated polyester composites with polyacrylamide as super absorbent as shown in Figure 5, the surface morphology shows changes along with the increase of waste loading. At 10% waste loading, the SEM characterization results show a relatively smooth surface morphology, indicating that the interaction between unsaturated polyester and polyacrylamide is still minimal. This indicates that the waste absorption capacity has not been maximized, with the formation of small pores that are still limited. When the waste loading increased to 15%, the morphology began to show more lumps on the composite surface. This indicates an increase in the interaction between polyester and polyacrylamide, which starts to be more effective in absorbing waste. As a result, the surface becomes rougher, reflecting the increased contribution of both materials in the composite structure.

At 20% waste loading, the surface morphology starts to show larger voids and pores. This indicates a more dominant role of polyacrylamide in absorbing the waste, which causes expansion of the composite matrix and gives a more open and irregular morphological appearance. This structure increases the immobilization capacity of the waste by the composite. At 25% waste loading, the morphology becomes highly porous with many large voids, indicating that the waste absorption capacity has reached its maximum limit. The interaction between unsaturated polyester and polyacrylamide resulted in a highly irregular structure, indicating the material had reached its optimum limit in absorbing and retaining waste.

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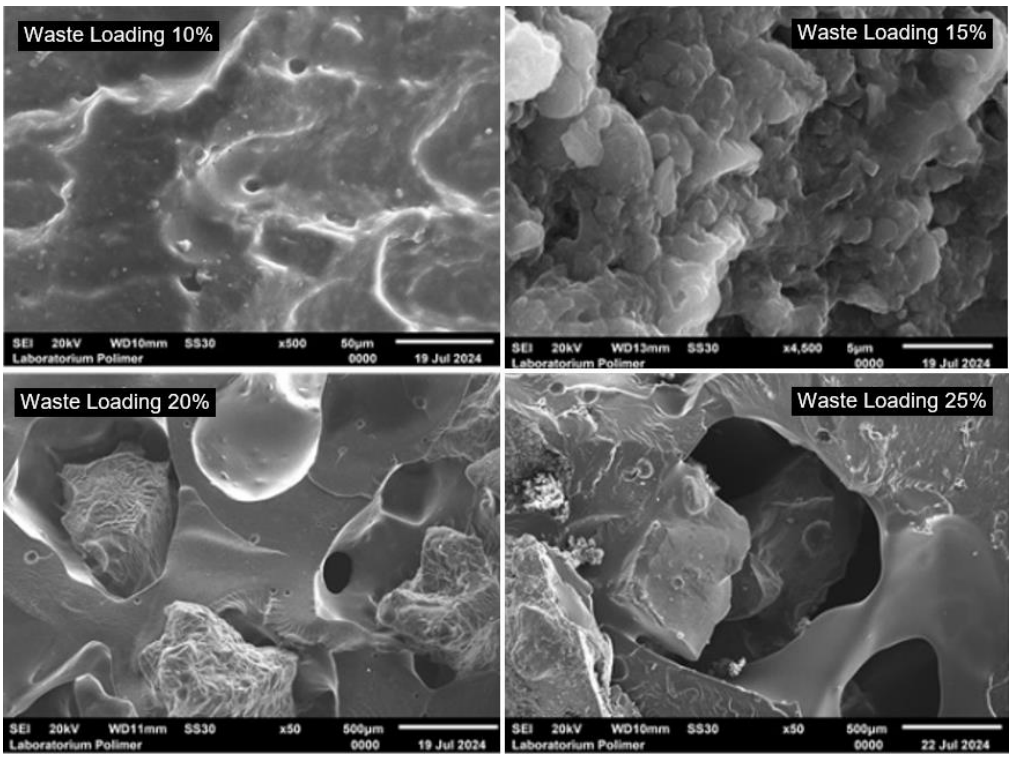

Figure 5. Microstructure and morphology of unsaturated polyester before and SAP with waste loading of 10, 15, 20 and 25%.

Based on the SEM image showing the elemental distribution map (by EDX analysis) of the immobilization of cesium and cerium waste adsorbed by polyacrylamide and consolidated by unsaturated polyester. Figure 6 is an interpretation of the distribution of cesium and cerium metals and the bonding between unsaturated polyester and polyacrylamide to the waste: The distribution of cesium is shown in Figure 6. It can be seen that the cesium dots are spread quite evenly on the surface of the material. The green color represents the presence of Cs metal in the structure. This indicates that cesium is successfully distributed and immobilized in the polyacrylamide and polyester matrix. The uniform degree of distribution may indicate that the cesium is well absorbed by the polymer. Figure 6 shows that the distribution of cerium has a similar distribution pattern to cesium. The green color indicates that cerium is also evenly distributed within the structure. This distribution indicates that cerium is well immobilized by polyacrylamide and consolidated by unsaturated polyester, similar to cesium.

Polyacrylamide has amide groups that are able to interact with metals through electrostatic bonds or ionic interactions with metal cations such as cesium (Cs^{+}) and cerium (Ce^{3+}). When polyacrylamide adsorbs metals, the metals bind to the active groups on the polyacrylamide. The unsaturated polyester then acts as a solidification material that surrounds and stabilizes the mixture of polyacrylamide and absorbed metal. The bond between the unsaturated polyester and polyacrylamide is likely to be physical, where the polyester envelops the polyacrylamide that has bound the metal, as well as playing a role in the solidification process to produce a material that is more stable and resistant to dissolution. The unsaturated polyester used acts as a binder polymer, and its unsaturated nature allows for copolymerization reactions with other active groups present in the polyacrylamide. This solidification process locks heavy metals (such as Cs and Ce) inside the matrix, so the results are relevant to the leaching test results of both metals, none of which migrated in aqueous media.

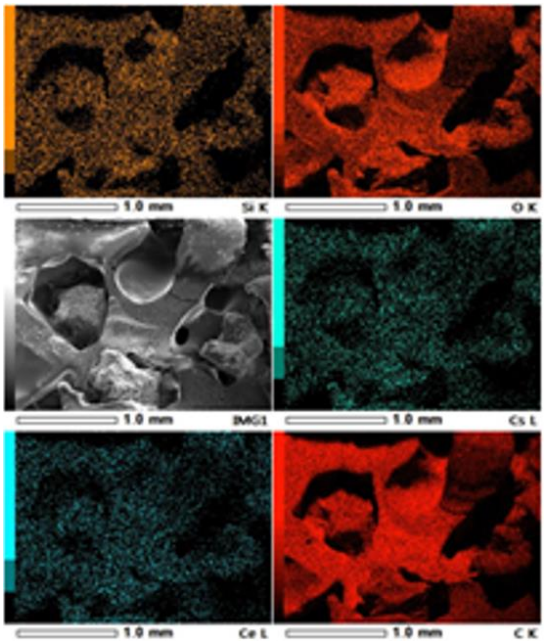

Figure 6. Element distribution map (by EDX analysis) of waste cesium (Cs) and cerium (Ce) immobilization adsorbed by polyacrylamide and consolidated by unsaturated polyester

CONCLUSION

Research on radioactive waste immobilization using unsaturated polyester shows that it has great potential as a solidification material and Nochar as an effective radioactive waste absorbent. By combining unsaturated polyester and polyacrylamide as a superabsorbent, this process is able to effectively lock radioactive elements such as cesium (Cs) and cerium (Ce), preventing the release of radionuclides into the environment. Leaching test results showed that there was no migration of radioactive elements into the aqueous medium, indicating the stability of the polymer matrix in resisting environmental contamination. Although increasing the capacity of the absorbed waste (waste loading) can improve the absorption capability, it also reduces the mechanical strength of the composite. Our result shows that the optimal waste loading that gives best both mechanical strenght and stabilization of radioactive waste is 20% waste loading.

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REFERENCES

[1] W. C. Eckelman, A. G. Jones, A. Duatti, and R. C. Reba, “Progress using Tc-99m radiopharmaceuticals for measuring high capacity sites and low density sites,” *Drug Discovery Today*. 2013. doi: 10.1016/j.drudis.2013.06.008.

[2] M. Marlina, S. Sriyono, E. Lestari, A. Abidin, H. Setiawan, and K. Kadarisman, “Desain dan performa prototipe generator 99Mo/99mTc dengan kolom material berbasis zirkonium dan kolom alumina,” *J. Kim. dan Kemasan*, 2016, doi: 10.24817/jkk.v38i2.2703.

[3] Aisyah *et al.*, “Radioactive fission waste of the conversion of high-enriched uranium to low-enriched uranium target on 99Mo production,” in *IOP Conference Series: Earth and Environmental Science*, 2023. doi: 10.1088/1755-1315/1201/1/012003.

[4] I. Luhar *et al.*, “Solidification/stabilization technology for radioactive wastes using cement: an appraisal,” *Materials*. 2023. doi: 10.3390/ma16030954.

[5] M. I. Martín, F. A. López, F. J. Alguacil, and M. Romero, “Technical Characterization of sintered-glass ceramics derived from glass fibers recovered by pyrolysis,” *J. Mater. Civ. Eng.*, 2015, doi: 10.1061/(asce)mt.1943-5533.0001090.

[6] A. V. Obruchikov, E. P. Magomedbekov, and A. O. Merkushkin, “Removal of radioactive methyliodide from the gas stream with a composite sorbent based on polyurethane foam,” *Nucl. Eng. Technol.*, 2020, doi: 10.1016/j.net.2019.10.019.

[7] S. V. S. Rao, K. B. Lal, S. V. Narasimhan, and J. Ahmed, “Copper ferrocyanide - polyurethane foam as a composite ion exchanger for removal of radioactive cesium,” *J. Radioanal. Nucl. Chem.*, vol. 240, no. 1, pp. 269–276, 1999, doi: 10.1007/BF02349164.

[8] Y. D. Jati and H. Martono, "H-Zeolit serta solidifikasi dengan polimer epoksi," *J. Tek. Lingkung.*, vol. 2, no. 2, pp. 1–8, 2013.

[9] Gunandjar, T. Sundari, and Y. Purwanto, "Imobilisasi limbah radioaktif dari produksi radioisotop molibdenum-99 (99 Mo) menggunakan bahan matriks synroc titanat," in *Prosiding Seminar Nasional Teknik Kimia "Kejuangan,"* 2016.

[10] E. Mossini *et al.*, "Pre-impregnation approach to encapsulate radioactive liquid organic waste in geopolymer," *J. Nucl. Mater.*, vol. 585, no. March, p. 154608, 2023. doi: 10.1016/j.jnucmat.2023.154608.

[11] L. Jiao *et al.*, "Effect of gamma and neutron irradiation on properties of boron nitride/epoxy resin composites," *Polym. Degrad. Stab.*, 2021. doi:10.1016/j.polymdegradstab.2021.109643.

[12] A. T. Naikwadi, B. K. Sharma, K. D. Bhatt, and P. A. Mahanwar, "gamma radiation processed polymeric materials for high performance applications: A review," *Frontiers in Chemistry*. 2022. doi: 10.3389/fchem.2022.837111.

[13] L. S. Relleve *et al.*, "Radiation-synthesized polysaccharides/ polyacrylate super water absorbents and their biodegradabilities," *Radiat. Phys. Chem.*, 2020, doi: 10.1016/j.radphyschem.2019.108618.

[14] C. He *et al.*, "Development of a Purity Certified Reference Material for Vinyl Acetate," *Molecules*, 2023. doi: 10.3390/molecules28176245.

[15] A. Bedar *et al.*, "Nanodiamonds as a state-of-the-art material for enhancing the gamma radiation resistance properties of polymeric membranes," *Nanoscale Adv.*, 2020. doi: 10.1039/c9na00372j.

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