DETERMINATION OF FLASH POINT, FIRE POINT, AND PENETRATION VALUE ON IMMOBILIZATION $^{88}SR(NO_3)_2$ WITH ZEOLITE AS ION EXCHANGER USING POLYETHYLENE TEREPHTHALATE MATRIX AND POLYSTYRENE ADDITIVE

F.S.B. PERKASA
Gadjah Mada University
Yogyakarta, Indonesia
Email: fadjris@gmail.com

Abstract

The immobilization of ^{90}Sr liquid waste simulated by $^{88}Sr(NO_3)_2$ solution with polyethylene terephthalate matrix mixed with a polystyrene additive had been carried out. These materials were selected due to its properties that is suitable for immobilization of radioactive waste. In addition, the usage of polyethylene terephthalate and polystyrene are able to reduce plastic waste. Zeolite was used to adsorp ^{88}Sr. Polystyrene additive was varied to 10%, 20%, and 30%. Polyethylene terephthalate and polystyrene were heated at 250°C for 20 minutes to melt. Zeolite which has adsorbed $^{88}Sr(NO_3)_2$ was added into the mixture and stirred to homogenous mixture. Then, the mixture was molded and cooled. Flash-fire point testing was performed with the Cleveland Open Cup whereas the penetration testing was carried out with a penetrometer. Results of the flash and fire point testing shown that there is an effect of adding polystyrene additive on the waste-polymer block. The highest thermal resistance is on the 30% polystyrene additive. The highest flash and fire point are 340.67 (± 0.58)°C and 356.33(± 0.58)°C, respectively. In a penetration testing, there isn't the effect of polystyrene additive because the test results 0 mm value for all variations. All of the above test results meet the specified standard (GOST/Russian's ANSI) or better than the average value of the previous product.

1. INTRODUCTION

Radioactive waste is a material that cannot be utilized and contains or is contaminated with radioactive substances (radionuclides). There are various types of radioactive waste depending on activity, half-life, and phase. Waste treatment, especially solid and liquid waste, is carried out by reducing volume and solidification or immobilizing waste. The process of waste immobilization can be done in four ways, namely cementation, bituminization, polymerization, and vitrification. Waste immobilization using polymers can be classified into bituminization. This process is a waste treatment process that has not been widely used because of many limitations for now. But, it is one of the waste treatment techniques that are projected to be superior in the future because it has several advantages, such as relatively inexpensive, waterproof, long life, able to withstand waste in large number, lighter, and faster process. Some things that must be considered in carrying out the immobilization process with polymers for low level radioactive waste are hardness (penetration value), softening point, flash point, fire point, leaching rate, moisture content, and radiation resistance [1].

Research on ^{90}Sr waste immobilization simulated with $^{88}Sr(NO_3)_2$ waste with polyethylene terephthalate (PET) matrix mixed with styrene-butadiene rubber (SBR) additive was carried out. The properties of the waste-polymer block can be determined by testing the moisture content, hardness (penetration value), softening point, flash point, leaching rate, and radiation resistance. The results of previous studies showed that samples were damaged, and the methods of testing polymer-waste blocks did not meet the standards [2].

This study uses polyethylene terephthalate as a matrix and polystyrene as additive. Polyethylene terephthalate is chosen because this polymer can crosslink if it is exposed to radiation, has good chemical resistance, and has good thermal resistance (softening point of 250°C and flash point ± 341°C). Polystyrene is chosen as additive because it is hard (has a hardness of 125 on the Rockwell R. scale), radiation resistant (crosslinking if exposed to radiation), has a high flash point (345–360°C), and has a long lifespan. Both materials can crosslink because they have $[-CH_2-CH-R-]_n$ chemical structure. In addition, the two materials were chosen because they were cheap and easily obtained in the form of waste [3].

This study uses $^{88}Sr(NO_3)_2$ crystals as simulated waste. ^{88}Sr nuclide contained in these crystals are non-radioactive. $^{88}Sr(NO_3)_2$ crystals have the same chemical properties as $^{90}Sr(NO_3)_2$, so they can be used as simulated waste in the process of immobilizing low level radioactive waste using polymers [4]. Radionuclide ^{90}Sr was chosen as a representation of low-level radioactive waste because this radionuclide has a fairly long

half-life compared to other radionuclides included in low level radioactive waste and has a high yield of ^{235}U fission products [5].

The choice of these two materials as matrix and additive in this study is to reduce the diversity of waste on this earth, especially plastic waste. Plastic waste is one of the most dangerous types of waste. The diversity of plastic waste is also a problem in plastic waste handling. Production of plastic bottle waste annually is 300 million tons worldwide and only 10% is recycled [6]. Styrofoam waste is produced at 14 million tons annually [7]. Based on these data, these two types of waste have serious problems and potential problems for the environment.

The process of radioactive waste immobilization with polymers can improve safety aspects and reduce economic aspects. If viewed in terms of volume reduction and weight reduction, this process is not as good as the vitrification process. However, the advantage of polymerization is that the process is simple, so the cost of construction and process is cheap. The safety aspect is higher than the cementation process [8].

This study aims to make improvements from the research that has been done before. Improvements are made to the method, specifically the polymer-waste block testing method. The matrix used in this study remains a polyethylene terephthalate (PET) matrix. The difference lies in the additive added, namely polystyrene (PS) and the absorbent used, namely zeolite. This research was conducted to determine flash point, fire point, and penetration value by knowing the factors that could influence it, namely the weight percentage (wt.%) of polystyrene so that the influence of polystyrene weight percentage can be determined on the characteristics needed in the process of radioactive waste immobilization.

2. RESEARCH METHODOLOGY

The research was conducted from February to April 2018 at the Process Technology and Nuclear Chemistry Laboratory, Department of Nuclear Engineering and Engineering Physics, Faculty of Engineering, Gadjah Mada University for the manufacturing polymer-waste blocks. Penetration testing was carried out at the Transportation Laboratory, Department of Civil and Environmental Engineering, Faculty of Engineering, Gadjah Mada University. Flash point and fire point testing was carried out at the Heat and Mass Transfer Laboratory, PAU, Postgraduate School, Gadjah Mada University.

This study was designed with independent variables, control variables, variables that were kept constant, and dependent variables. The independent variables in this study are variations in weight percentage (wt.%) of polystyrene as additive which are varied to 10%, 20%, and 30%. Determination of these variations based on previous research which showed additive additions of 20% of the total weight produced the best results so the researchers chose the number 20% and deviation ± 10% [1]. The control variable is a sample of polymer-waste block with a polyethylene terephthalate (PET) matrix without polystyrene (PS) additive. In this study, there are variables that were kept constant, namely weight percentage (wt.%) of ^{88}Sr which was absorbed by natural zeolite and mould size. The response of this study (dependent variable) is the results of flash point, fire point, and penetration value of the polymer-waste blocks with polystyrene additive compared to the standard immobilization using bitumen and polymer-waste blocks without polystyrene additive.

This research was conducted in three stages, namely:

(a) Making simulated waste.
(b) Making polymer-waste blocks.
(c) Sample testing and data analysis.

2.1. Making Simulated Waste

$^{88}Sr(NO_3)_2$ crystals with a purity of 99.99% are weighed using an Ohaus balance of 10 g. Then, Aquadest is poured into 1 L beaker glass. Then, 10 g of $^{88}Sr(NO_3)_2$ crystals is dissolved with Aquadest and stirred with spatula until homogeneous so that it becomes 1 L of simulation waste solution. Adsorption is done by put 300 g of zeolite in 1 L of $^{88}Sr(NO_3)_2$ solution and it is stirred together in a container for 5 minutes and left to reach equilibrium [9]. Then, zeolite which has absorbed ^{88}Sr is filtered to separate the solid residue from the filtrate. Finally, the solid residue from the zeolite is then dried in the oven for 10 minutes and 250ºC.

2.2. Making Polymer-Waste Blocks

PET plastic bottle with a maximum size of 1.5 L without the neck, base, and bottle cap is cut into squares measuring about 2 × 2 cm. Polystyrene from cork waste is cut into squares measuring about 2 × 2 cm. PET, polystyrene, and zeolite with ^{88}Sr are weighed using an Ohaus balance with sizes according to the needs of the polymer-waste blocks in each additive variation. Weighted PET and polystyrene are then melted together in one container using the oven. The weighted zeolite with ^{88}Sr is then mixed into the same container with PET and polystyrene, then stirred until homogeneous. The homogeneous polymer-waste block is inserted into the mould for cooling. Finally, the hard polymer-waste blocks are taken out from the mould.

2.3. Sample Testing and Data Analysis

Polymer-waste blocks or samples are tagged according to the type of test and its variations. The tests are carried out according to the tags previously given. Data from the test results are recorded and data analysis is performed using the Analysis of Variance (ANOVA) method.

Data analysis and initial hypothesis examination are carried out using Analysis of Variance (ANOVA) which is processed in Microsoft Excel 2013 and Multiple Correlation with SPSS 23. The number of variations is four and there are three samples in each variation.

The calculated F value (F-count) is compared with F-table value. The F-table value must consider the values of alpha, k-1, and k(n-1). There are two types of hypotheses in this analysis, namely null hypothesis (H0) and working hypothesis (H1). The null hypothesis is a hypothesis which states there is no relationship between the addition of PS additive and the value of flash points, fire points, and penetration value, which means that the average treatment or variation is not different. The working hypothesis is a hypothesis that states the relationship between the addition of PS additive and the value of flash points, fire points, and penetration value, which means that at least one average treatment or variation differs significantly. If F-count is less than F-table or sig. (2-tailed) value less than alpha value, then H0 is accepted or H1 is rejected and if F-count is more than F-table or sig. (2-tailed) value more than alpha value, then H0 is rejected or H1 is accepted. If H0 is rejected, then the analysis is followed by the Pearson multiple correlation test. The alpha value used is 0.05 [10]. This ANOVA can determine the effect of the addition of PS with variations in weight percentage (wt.%) to flash point, fire point, and penetration value of PET and PS polymers which are low-level radioactive waste immobilization materials.

3. RESULTS AND DISCUSSION

The tests carried out in this study were thermal resistance testing and penetration testing. The thermal resistance tested is flash point and fire point. Both tests were conducted to determine the effect of the addition percentage of polystyrene additive on the polymer-waste blocks made and to find out the best polymer-waste block composition. The hypothesis formed in this study is that the polymer-waste blocks made from PET matrix differs from the polymer-waste blocks made from PET matrix and PS additive on thermal resistance and penetration value. The difference is expected to lead to a positive direction, which means that with the addition of PS additive, the quality of the polymer-waste block based on thermal resistance and strong penetration is better.

3.1. Flash Point Research Results and Analysis

Based on the tests that have been carried out on the polymer-waste block, the flash point values for each variation of the addition of the polystyrene additive are shown in Table 1. The table also shows the average and standard deviation of each polymer-waste block sample. The results of the flash point testing in the table are then processed using the ANOVA method as shown in Table 2.

The ANOVA results in Table 2 show whether there are significant differences between the four polymer-waste block samples. Calculations are performed on all four samples at once. The F value obtained in this ANOVA is 62.90909091. This value is far greater than the F-critical value of 4.066181. The P-value obtained is 6.62×10^{-6}. The P-value is much smaller than the alpha value used, which is 0.05. Based on these two

evidences, H0 is rejected or H1 is accepted, so there is a significant difference between the four flash point values of the polymer-waste block sample.

TABLE 1. FLASH POINT TESTING RESULTS

	Variation				
Sample	A PET 70% PS 0% (ºC)	B PET 60% PS 10% (ºC)	C PET 50% PS 20% (ºC)	D PET 40% PS 30% (ºC)	
1	328	331	337	341	
2	325	332	336	340	
3	326	329	334	341	
Total	979	992	1007	1022	4000
Mean	326,33	330,67	335,67	340,67	333,33
Std	1,53	1,53	1,53	0,58	

TABLE 2. ANOVA FOR FLASH POINT RESULTS

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
0% PS additive	3	979	326.3333	2.333333333
10% PS additive	3	992	330.6667	2.333333333
20% PS additive	3	1007	335.6667	2.333333333
30% PS additive	3	1022	340.6667	0.333333333

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	346	3	115.3333	62.90909091	6.61939E-06	4.066181
Within Groups	14.66667	8	1.833333			
Total	360.6667	11				

Multiple correlation is performed to see if there are significant differences between each polymer-waste block sample. The results of multiple correlations are shown in Table 3. Sig. (2-tailed) value for 0% additive and 10% additive is 0.909. This value is greater than the alpha value used, which is 0.05. This shows that H0 is rejected, so there is a significant difference for the flash point value between 0% sample and 10% PS additive.

Sig. (2-tailed) value for 0% additive and 20% additive is 0.667. This value is greater than the alpha value used. This shows that H0 is rejected or H1 is accepted, that is, there is difference in the flash point value between 0% and 20% PS additive samples.

Sig. (2-tailed) value for 0% additive and 30% additive is 0.454. This value is greater than the alpha value used. This shows that H0 is rejected or H1 is accepted, so there is difference in the flash point value between 0% and 30% PS additive samples.

Sig. (2-tailed) value for 10% additive and 20% additive is 0.425. This value is greater than the alpha value used. Based on this evidence shows that H0 is rejected or H1 is accepted, that is, there is difference in the flash point value between 10% and 20% PS additive samples.

Sig. (2-tailed) value for 10% additive and 30% additive is 0.454. This value is greater than the alpha value used. The proof shows that H0 is rejected or H1 is accepted, that is, there is difference in the flash point value between 10% and 30% PS additive samples.

Sig. (2-tailed) value for additive 20% and additive 30% is 0.879. This value is greater than the alpha value used. The proof shows that H0 is rejected or H1 is accepted, that is, there is difference in the flash point value between 20% and 30% PS additive samples.

TABLE 3. MULTIPLE CORRELATION FOR FLASH POINT RESULTS

		0% PS Adv.	10% PS Adv.	20% PS Adv.	30% PS Adv.
0% PS Adv.	Pearson Correlation	1	-.143	.500	.756
	Sig. (2-tailed)		.909	.667	.454
	N	3	3	3	3
10% PS Adv.	Pearson Correlation	-.143	1	.786	-.756
	Sig. (2-tailed)	.909		.425	.454
	N	3	3	3	3
20% PS Adv.	Pearson Correlation	.500	.786	1	-.189
	Sig. (2-tailed)	.667	.425		.879
	N	3	3	3	3
30% PS Adv.	Pearson Correlation	.756	-.756	-.189	1
	Sig. (2-tailed)	.454	.454	.879	
	N	3	3	3	3

Based on the results of sample testing and data analysis, it has been determined that the sample with the highest flash point value is the polymer-waste block with PS additive of 30%, that is 340.67 (± 0.58)°C. This is because the PS (flash point: 345 to 360ºC) has a higher flash point value than PET (flash point: ± 341ºC) so that along with the addition of PS additive, the flash point value of polymer-waste block increases until PS 30% additive. The flash point value of polymer-waste block has met the minimum flash point standard for bituminization of radioactive waste valued at 200°C (GOST 12.1.044). When compared with the literature review, based on Sadewo's research results, the flash point value of Sadewo's research results was only found on the 0% SBR additive with a value of 280ºC. Based on this data, the lowest flash point value in this study is better than the flash point value in Sadewo's study. In addition, the completeness of the flash point data presented in this study is also more complete than Sadewo's research. This shows that the results of this study are better than previous study.

3.2. Fire Point Research Results and Analysis

Fire point value testing is done simultaneously with flash point testing. The results are shown in Table 4. The table also shows the average and standard deviation of each polymer-waste block sample. The ANOVA results for all samples are shown in Table 5. The F and F-critical values in the table are 91.222 and 4.066181. This result shows that the F value is greater than the F-critical value. The P-value in Table 5 is 1.58 × 10-6. This value is lower than the alpha value used, which is equal to 0.05. Both evidences indicate that H0 is rejected or H1 is accepted. This H0 rejection indicates that there is a difference in the value of the fire point between the four polymer-waste blocks.

TABLE 4. FIRE POINT TESTING RESULTS

	Variation				
Sample	A PET 70% PS 0% (ºC)	B PET 60% PS 10% (ºC)	C PET 50% PS 20% (ºC)	D PET 40% PS 30% (ºC)	
1	345	349	352	357	
2	343	348	352	356	
3	342	347	351	356	
Total	1030	1044	1055	1069	4198
Mean	343.33	348	351.67	356.33	349.83
Std	1.53	1	0.58	0.58	

TABLE 5. ANOVA FOR FIRE POINT RESULTS

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
0% PS additive	3	1030	343.3333	2.333333333
10% PS additive	3	1044	348	1
20% PS additive	3	1055	351.6667	0.333333333
30% PS additive	3	1069	356.3333	0.333333333

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	273.6667	3	91.22222	91.22222222	1.58E-06	4.066181
Within Groups	8	8	1			
Total	281.6667	11				

The multiple correlation method is carried out to ascertain whether there are differences in the fire point values between each polymer-waste block sample. The results of multiple correlation are shown in Table 6. Sig (2-tailed) value for 0% additive and 10% additive is 0.121. This value is greater than the value of alpha used, which is 0.05. This indicates that H0 is rejected or H1 is accepted. This H0 rejection shows that there is a fire point difference between the polymer-waste block samples with 0% and 10% PS additive.

TABLE 6. MULTIPLE CORRELATION FOR FIRE POINT RESULTS

		0% PS Adv.	10% PS Adv.	20% PS Adv.	30% PS Adv.
0% PS Adv.	Pearson Correlation	1	.982	.756	.945
	Sig. (2-tailed)		.121	.454	.212
	N	3	3	3	3
10% PS Adv.	Pearson Correlation	.982	1	.866	.866
	Sig. (2-tailed)	.121		.333	.333
	N	3	3	3	3
20% PS Adv.	Pearson Correlation	.756	.866	1	.500
	Sig. (2-tailed)	.454	.333		.667
	N	3	3	3	3
30% PS Adv.	Pearson Correlation	.945	.866	.500	1
	Sig. (2-tailed)	.212	.333	.667	
	N	3	3	3	3

Sig (2-tailed) value for 0% additive and 20% additive is 0.454. This value is greater than the value of alpha used. The proof shows that H0 is rejected or H1 is accepted, that is, there is difference in the value of fire points between 0% and 20% PS additive samples.

Sig (2-tailed) value for 0% additive and 30% additive is 0.212. This value is greater than the value of alpha used. The proof shows that H0 is rejected or H1 is accepted, that is, there is difference in the value of fire points between 0% and 30% PS additive samples.

Sig (2-tailed) value for 10% additive and 20% additive is 0.333. This value is greater than the value of alpha used. Based on this evidence shows that H0 is rejected or H1 is accepted, so there is difference in the value of fire points between 10% and 20% PS additive samples.

Sig (2-tailed) value for 10% additive and 30% additive is 0.333. This value is greater than the value of alpha used. The proof shows that H0 is rejected or H1 is accepted, so there is difference in the value of fire points between 10% and 30% PS additive samples.

Sig (2-tailed) value for 20% additive and 30% additive is 0.667. This value is greater than the value of alpha used. The proof shows that H0 is rejected or H1 is accepted, that is, there is difference in the value of fire points between 20% and 30% PS additive samples.

Based on the results and data analysis of sample testing, it is known that the sample with the highest fire point value is the polymer-waste block sample with 30% PS additive, which is equal to 356.33 (± 0.58)°C. The value of the fire point is much higher than the minimum standard value of the fire point for radioactive waste bituminization, which is equal to 250°C (GOST 12.1,044). When compared with the literature review, based on Sadewo's research results, the value of the fire point from Sadewo's research results was only found on SBR additive of 20% and 40% with values of 320ºC and 270ºC. Based on these data, the lowest fire point value in this study is better than the highest fire point value in Sadewo's study. In addition, the completeness of the fire point data presented in this study is also more complete than Sadewo's study. This shows that the results of this study are better than previous study.

The results of the flash and fire point tests showed very high numbers and increased for each variation in the addition of PS additive. This is because the flash and fire point values for PET and PS materials are very high so that the combination of the two materials can produce a mixture with high flash and fire point values. In addition, there is an increase in the flash and fire point values in each addition of PS additive caused by the flash and fire point values from the PS (flash point: 345 to 360°C) which is higher than PET (flash point: ± 341 ° C), so that the more PS is added to the mixture, the higher value of the flash and fire point.

The flash and fire point value obtained continue to increase along with the addition of PS additive. This shows that when additive is added more than 30%, the value of the flash and fire point produced are even higher. However, PS additions of more than 30% are not permitted because the addition of PS for more than 30% causes the PS to no longer be an additive because the amount is greater than PET. Based on the results of

flash point, fire point, and density, it is known that the higher of flash and fire point value, the density has a value that tends to increase. Although the polymer-waste blocks with 20% and 30% PS additive have decreased density values, but the density values of the two samples are still higher than 0% additive.

3.3. Penetration Value Research Results and Analysis

The last test is a penetration test. This test produces 0 mm for all values. The smaller of penetration value, the harder of material is. The value of 0 mm is because all samples very hard so that the test needle in the penetration test cannot penetrate the sample surface. This means that all polymer-waste block samples have very high hardness levels. A very high level of hardness is advantageous for the immobilization of radioactive waste because this containment material makes radioactive waste not released into nature. Unprocessed PET and PS materials have a structure that is not as strong as after being a polymer-waste block. This is because PET and PS have flat shapes. This reason makes the structure of each material not strong. After melting, PET and PS are stirred together until homogeneous with zeolite which has absorbed ^{88}Sr. The mixture is poured into mold and cooled. The polymer-waste block formed has a very high level of hardness because the mixture fills the mold space and solidifies. Based on the results of the tests above, it cannot be concluded whether the addition of PS additive affects the penetration value of the polymer-waste block because all the results are zero. In addition, there is another proof, that in the absence of PS additive, the polymer-waste blocks made have a high level of hardness. The addition of PS additive is intended to increase the penetration value of the polymer-waste block, but in the absence of PS additive, the sample is still very hard. Previous tests have been carried out to determine whether the addition of zeolite enhances the quality of polymer-waste blocks. This test is carried out by simply compacting PET without PS and zeolite additive. The results show that compacted PET has a high hardness level and PS also has a very high level of hardness because its specification shows that PS is much harder than PET. All results of penetration testing on polymer-waste blocks indicate that with or without PS additive, the polymer-waste blocks made have a very low penetration value that is far better than the average value of radioactive waste bituminization penetration values, which are 21 to 40 mm (lower, better). When compared with the literature review, based on the results of a study by Guzella and Silva (2001), the best value of the penetration test was 0.6 mm at a 49.5% waste load rate. Based on these data, the strong penetration value of these four polymer-waste block samples is higher than the best value of the penetration test in the study of Guzella and Silva (2001). This shows that the results of this study are better than previous study.

4. CONCLUSIONS

Determination of the flash point, fire point, and penetration value on the immobilization of 88Sr(NO3)2 with zeolite as ion exchanger using polyethylene terephthalate matrix and polystyrene additive concluded that the addition of polystyrene additive on polymer-waste blocks has an effect on the flash and fire point values, but it cannot be proven to affect the penetration value.

- The lowest flash point value is 326.33 (± 1.53)°C in the polymer-waste block with 0% PS additive and the highest flash point value is 340.67 (± 0.58)°C in the polymer-waste block with 30% PS additive. All values meet the flash point standard for radioactive waste bituminization, which is 200°C (GOST 12.1.044 / Russia State Standard).
- The lowest fire point value is 343.33 (± 1.53)°C in the polymer-waste block with 0% PS additive and the highest fire point value is 356.33 (± 0.58)°C in the polymer-waste block with 30% PS additive. All values meet the fire point standard for radioactive waste bituminization, which is equal to 250°C (GOST 12.1.044 / Russia State Standard).
- Penetration value for all types of polymer-waste block samples has the same value, which is 0 mm. All values are far better than the average value of radioactive waste bituminization penetration test, which is 21 to 40 mm (parameters from Russian trademark bitumen).

ACKNOWLEDGEMENTS

Thank you to the family, all lecturers in Nuclear Engineering and Engineering Physics Department especially to Mr. Susetyo and Ms. Nunung as supervisors, and all friends in Nuclear Engineering and Engineering Physics Department who have helped the author to complete this research and writing.

REFERENCES

[1] OJOVAN, M. I., LEE, W. E., An Introduction to Nuclear Waste Immobilization, Elsevier, Oxford (2005).

[2] SADEWO, PRASETYO HARYO., Studi Polyethylene Terephtalate dengan Aditif Styrene-Butadiene Rubber sebagai Matriks Immobilisasi Strontium Klorida Hexahidrat [Study of Polyethylene Terephthalate with Styrene-butadiene Rubber Additive as An Immobilization Matrix of Strontium Chloride Hexahydrate] (Bachelor's Thesis), Gadjah Mada University, Yogyakarta (2015).

[3] KREVELEN, D. W., NIJENHUIS, K., Properties of Polymers. Elsevier. Slovenia (2009).

[4] OXTOBY, DAVID W., GILLIS H. P., NACHTRIEB, NORMAN H., Principles of Modern Chemistry, 4th Edition., Saunders College Pub, United States (1986).

[5] C-3, Cumulative Fission Yields 90-Th-232 92-U-233 92-U-235 92-U-238 94-Pu-239 94-Pu-241 (no year), https://www-nds.iaea.org/sgnucdat/c3.htm

[6] WASSENER, B., Raising Awareness of Plastic Waste (2011), https://www.nytimes.com/2011/08/15/business/energy-environment/raising-awareness-of-plastic-waste.html

[7] CHANDRA, M., KOHN, C., PAWLITZ, J., POWELL, G., Real Cost of Styrofoam, St. Louis Earth Day, Saint Louis University, Missouri, 2016.

[8] LEE, SE YUP, "Performance Test on Polymer Waste Form" - 12137, WM2012: Waste Management 2012 conference on improving the future in waste management, United States, 2012.

[9] McCabe, W., Unit Operation of Chemical Engineering, Journal Adsorption Zeolite of Applied Toxicology. 8. 19. (1999) 277.

[10] HARINALDI, Prinsip-Prinsip Statistik untuk Teknik dan Sains [Principles of Statistics for Engineering and Science], Penerbit Erlangga, Jakarta (2005).

BIBLIOGRAPHY

"An Introduction to PET (Polyethylene Terephthalate)", Publication of PET Resin Association, New York (2015).

"EPA Facts About Strontium-90", Publication of Environmental Protection Agency, Washington DC (no year).

"Radioactive Material Safety Data Sheet (Strontium-90)", Publication of Stuart Hunt & Associates Ltd, St Albert (no year).

"Standard Test Method for Flash and Fire Point by Cleveland Open Cup Tester". Publication of ASTM International, Pennsylvania (2003).

Asphalt Testing Laboratory Manual, Department of Civil & Architectural Engineering, Qatar University, Doha (no year).

Kusnadi, Ajeng Sartika, Resin Poliester Tak Jenuh Untuk Imobilisasi Resin Bekas Pengolah Simulasi Limbah Radioaktif Cair [Unsaturated Polyester Resin for Immobilization of Former Resin of Simulated Liquid Radioactive Waste Processor] (Bachelor's Thesis), UIN Syarif Hidayatullah, Jakarta, 2010.

Martono, Herlan, "Glass Frit dan Polimer Untuk Solidifikasi Limbah Cair Aktivitas Rendah Skala Industri [Glass Frit and Polymers for Solidification of Low-Level Liquid Waste at Industrial Scale]", National Seminar on Waste Processing Technology IX (Proc. Tangerang, 2011), BATAN, Tangerang (2011).

Moriyama, N., Dojiri, S., Emura, S., Sugo, T., Machi, S., Incorporation of Radioactive Spent Ion Exchange Resins in Plastics, J. Nucl. Sci. Technol. 12 (1975) 362-369.

Moriyama, N., Dojiri, S., Honda, T., Solidification of Powdered Ion Exchange Resins with Polyethylene, J. Nuclear and Chemical Waste Management Vol. 3 Issue 2 (1982) 131-137.

Mujiarto, Iman, Sifat dan Karakteristik Material Plastik dan Bahan Aditif, Vol. 3 No. 2 [Properties and Characteristics of Plastic Materials and Additives, Vol. 2 No. 2], AMNI, Semarang (2005).

Penetration Value of Bitumen – Determination for Road Construction (no year), https://theconstructor.org/building/building-material/penetration-value-of-bitumen/1403/

Ronodirdjo, S., Pengelolaan Sampah Radioaktif [Radioactive Waste Management], BATAN, Yogyakarta (1982).

Shon, J. K., Lee, S. H., Park, H. S., Kim, K. J., Min, D. K., The Improvement of the Mechanical Stability and Leachability of Bituminized Waste Form of Radioactive Ash by Addition of Reused Polyethylene, Korean J. Chem. Eng. 18 (2001) 668-672.

Testing of Fuels: Flash and Fire Point, Department of Mechanical Engineering, Indian Institute of Technology New Delhi, New Delhi (2017).

Virta, Robert L., "Zeolites", Publication of US Bureau of Mines, Washington DC (no year).

Wati, "Imobilisasi Limbah Cair Transuranium Simulasi dari Instalasi Radiometalurgi Dengan Polimer Poliester Tak Jenuh [Immobilization of Simulated Transuranium Liquid Waste from Radiometallurgical Installations with Unsaturated Polyester Polymers]", National Seminar on Nuclear Technology HR V (Proc. Tangerang, 2009), BATAN, Tangerang (2009).