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Base Course Stabilization Performance Using Fly Ash-Based Geopolymers and Their Effect on Water Quality Standards

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A B S T R A C T

The road is the main gateway to human life and links essential access points. Some structure pavement failures happened due to the base layer's instability. Fly ash has been used in several parts of pavement structures to increase stability. One significant concern with using fly ash in base course stabilization is its proportion and potential impact on water quality standards. This research aimed to evaluate base course stabilization performance using fly ash-based geopolymers, as well as assess their impact on water quality standards. Materials in this study consisted of aggregate, fly ash, water, and alkaline reagent solutions. The variation of mix considered with a variety of alkaline reagents, namely without alkaline reagents, 3 mol, 6 mol, 9 mol, and 12 mol of NaOH. The ratio between NaOH and Na2SiO3 is 1:2. The use of fly ash in the class A aggregate base course layer has not been able to meet specifications. However, by providing 9 mol of alkaline reagent, the strength of the mixture increases so that the CBR value meets the specifications due to geopolymer bonding. When the alkaline reagent solution becomes more concentrated, the optimum water content decreases, and the bond between aggregates strengthens. The effect of alkaline reagents on water quality standards increases the acidity (pH) value, while other parameters such as BOD, COD, and TSS still meet the standards. This research point to another practical approach that is effective in the field to increase the stability of the base course layer and is environmentally friendly.

1. Introduction

The road is the main gateway to human life and links essential access points. Adequate road infrastructure can open up new opportunities for investment and boost economic growth. In its construction, this road pavement structure must provide a durable and reliable surface for vehicles to travel. Flexural pavement is a widely used type of road pavement, especially for urban roads with moderate to heavy traffic. The flexibility that can adjust to changes in

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temperature and soil conditions, so it is more resistant to cracking and deformation, is an advantage of this type of pavement. Flexural pavement structures require multiple layers of material as they are not rigid enough to distribute wheel loads over a large area [1]. Flexible road pavements generally consist of 3 layers: the asphalt layer, the base course layer, and the sub-base layer. The base layer of pavement is a critical component of any road or structure, providing the necessary support and stability to the upper layers. The instability of the base layer can lead to significant damage and failure of the pavement. This instability can be caused by various factors, including poor soil conditions [2], water infiltration [3], and inadequate base material.

There is an urgent need to address the instability of the base layer, as it can lead to safety hazards, increased maintenance costs, and decreased pavement lifespan. Traditionally, natural materials such as gravel and crushed stone combined with cement, lime, or other chemical stabilizers have been used for base course stabilization. However, the natural materials caused problems such as material scarcity that meet specifications, fluctuations in the soaking CBR value, and high plasticity index are becoming a significant threat to structures built on the base layer due to swelling characteristics [4]. Besides that, producing these stabilizers requires considerable energy and generates high carbon emissions, leading to environmental concerns.

Base course stabilization using fly ash-based geopolymers has addressed the problem of instability of the base layer pavement, limited use of natural materials, and compaction with standard effort considered less effective. It has emerged as a promising alternative to conventional cement-based materials for base course stabilization in road construction. Alternative materials, such as industrial or organic waste, as a significant environmental problem, can be used in pavement material [5] [6] [7]. However, fly ash is an industrial waste material most popularly selected for pavements due to mass production. [8] The Indonesian government has also supported using fly ash as an alternative material for construction. The fly ash can turn into geopolymer cement.

Geopolymer cement is a fastening system that hardens at room temperature. It comprises alumina silicate, alkaline reagents, and water as solvents. Surface and interfacial deformation of pavements under different loading conditions showed that these optimized alkali-treated fly ash acted as a better base layer than granular materials [9]. In addition, fly ash found in base course layer materials can reduce the plasticity index value [10]. One significant concern with using fly ash-based geopolymers in base course stabilization is their potential impact on water quality standards. Geopolymers have been reported to leach metals and metalloids such as arsenic, chromium, and lead, which can pose a risk to human health and the

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environment. [11] Pavement damage, such as potholes, often penetrates the base course layer. The use of chemicals in the base course layer is expected to influence environmental changes, mainly when pothole damage occurs. Therefore, in the event of rainfall, the runoff water and chemicals in the base course layer will be included in the wastewater category. The runoff water will enter the environment or river, resulting in pollution. Direct testing should be carried out to see how far the effect is. [12] Hence, it is essential to assess the leaching behavior of fly ash-based geopolymers and their impact on water quality standards.

This research aims to evaluate base course stabilization performance using fly ash-based geopolymers and assess their impact on water quality standards. So, it is expected that fly ash-based geopolymers will increase the strength and stability of the base course and meet applicable standards and regulations related to water quality and the environment. Moreover, it is to inform and guide decision-making in another method approach to see its effectiveness in increasing the stability of the base course layer using fly ash-based geopolymers, which is considering the environmental effect.

2. Research Method

The research will be carried out using quantitative methods, using numerical analysis through a laboratory test. Research begins with preparing equipment and materials that comprise the aggregate base course layer mixture for testing. The constituent materials of the aggregate base course layer mixture are previously tested for feasibility against specification standards. Suppose the material has met the specification standard. In that case, the material is mixed according to the gradation plan, and prepared several test specimens needed for density and CBR testing. In the remaining water-soaking CBR testing, water quality testing is carried out. The results of all tests in this study become material for researchers to analyze and draw conclusions and suggestions. The method of implementation is described in more detail as follows.

2.1 Materials

The aggregate materials used in this research are from Clereng Andesite Stone, Kulon Progo Regency. Fly ash from PT Pembangkit Jawa Bali Paiton and chemicals as alkaline reagents, namely NaOH and Na2SiO3 from PT Asahimas Chemical, with a ratio of 1:2. NaOH is in the form of flakes, while Na2SiO3 is in the form of a viscous liquid as seen in **Figure 1.**

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Source: Research Documentation (2022).

Figure 1. The Materials Used.

After the material has passed the feasibility testing standard, a class A aggregate base course layer mixture is prepared with the specified gradation, as shown in **Table 1**. It is divided into a coarse aggregate (retained in sieve no. 4) and a fine aggregate (passed sieve no.4). [13] The fly ash replaces 100% of rock ash or 8% of the Weight of the mixture on conventional mixtures.

Table 1. Mix Design of Class A Aggregate Base Course Layer.

Sieve Size		Percent of Weight Passed (%)			Type of Materials
inch	mm	Min	Max	Determined	
1 ½	37,5	100		100	Coarse aggregate
1	25,0	79	85	82	
3/4	19,0			70	
3/8	9,50	44	58	51	Fine aggregate
No. 4	4,75	29	44	36	
No. 10	2,0	17	30	23	
No. 40	0,425	7	17	12	
No. 200	0,075	2	8	8	Fly ash

Source: Research Method (2022).

2.2 Methods of Data Collection and Analysis

The research began with identifying the characteristics of the material. The characteristics of materials and mixtures of grade A aggregate base course layers must meet the testing standards and provisions used by almost all road construction practitioners in Indonesia, namely the general specifications of the 2018 highways**.**

Fly ash consists of minerals in crystalline and amorphous form. Crystals are solids of atoms, ions, or solid molecules arranged regularly and repeatedly in three dimensions. Amorphous is solid with atoms or particles arranged randomly and irregularly. The amorphous fraction determines the reactivity of fly ash to alkaline reagents, and Class F has a high amorphous fraction and is more reactive. In contrast, class C is less amorphous and has lower reactivity [14]. It is essential to know what fly ash class was used in this research to predict their reactivity. According to SNI 2460:2014, the standard specification for coal fly ash, the classification of fly ash is determined from the chemical requirement in **Table 2**.

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Table 2. Fly Ash Classification

Description	Class N	Class F	Class C
Silicone dioxide (SiO2) + Aluminum oxide (Al2O3) + Iron oxide (Fe2O3), min, %	70	70	50
Sulfur trioxide (SO3), max, %	4	5	5
Moisture content, max,%	3	3	3
Loss on ignition, max,%	10	6	6

Source: SNI 2460:2014.

SiO2, Al2O3, and Fe2O3 are minerals found in fly ash. However, because these minerals cannot be seen with the human eye, it is assisted by testing mineral diffraction with X-rays (X-Ray Diffraction / XRD) to see the composition of the constituent minerals[15]. In addition to mineral composition, the XRD test results can also determine the ratio of the number of minerals in the form of crystals and amorphs.

The Class A aggregate base course mix was tested with laboratory compaction using standard effort according to SNI 1742:2008, and the test object was prepared according to the D way. That is the laboratory method of experimentally determining the optimum moisture content (OMC) at which a given soil type achieves its maximum dry density (MDD). MDD and OMC are calculated from the relationship curve of dry density with moisture content. Data analysis obtained from test results is assisted by using predetermined equations, including:
The equation for calculating water content (1)

$$W = \frac{(A - B)}{(B - C)}\ x\ 100\% \qquad (1)$$

Where w is the water content, expressed as %; A is the mass of the cup and wet specimen, expressed in grams; B is the mass of the cup and dry specimen, expressed in grams; C is the mass of the cup, expressed in grams.
The equation for calculating dry density (2),

$$\rho d = \frac{(\rho)}{(100 + w)}\ x\ 100\% \qquad (2)$$

Where ρd is the dry density, expressed in grams/cm^3; ρ is the wet density or the mass of the wet specimen divided by volume, expressed in grams/cm^3; w is the water content, expressed as %.

After MDD and OMC values were obtained for every variation from the laboratory compaction test, the CBR-soaked test was conducted according to SNI 1744:2012. In the variation mixed with an alkaline reagent solution, the specimens were aged in a closed condition for one day after compaction, soaked for four days, and then tested. It aims to have a chemical reaction between the alumina silicate in the fly ash and the alkaline reagent solution before being soaked. In addition, the sample maintains its moisture content, as shown in **Figure 2**. In

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variation 1, the test object without alkaline reagent solution was soaked immediately after compaction for four days.

Source: Research Documentation (2022).

Figure 2. Curing Conditions Before Soaked.

The CBR value is expressed in percent, obtained by dividing the value of the load on the piston for each test object at the penetration of 2.54 mm (0.10 inches) and 5.08 mm (0.20 inches) with a standard load of 3000 lbs and 4500 lbs. CBR design is determined at the percentage of the maximum dry density. According to specifications, namely 100% density, the CBR design must reach a value minimum of 90%. The percentage change in the test sample height is calculated as swelling/shrinkage value. The last test was carried out on the remaining water from the CBR test sample. Tests for these cases include the following **Table 3.**

Table 3. Water Quality Test Standard Requirements.

Water Quality Test	Standard	Parameter
Acidity (pH)	SNI 6989.11:2019	6-9
Total Suspended Solid (TSS)	SNI 06-6989.3-2004	Max 100
Biochemical Oxygen Demand (BOD)	SNI 6989.72:2009	Max 6
Chemical Oxygen Demand (COD)	SNI 6989.73:2009	Max 40

Source: Research Method (2022).

An acidity test is a way to measure the acidity or alkalinity of a substance, typically a liquid. Indicators such as pH paper or a pH meter can also be used, which measures and provides a numerical value for its acidity level. The acidity level of a substance is typically expressed using the pH scale, which ranges from 0 to 14.

A Total Suspended Solids (TSS) test is a way to measure the number of solid particles that are suspended in a liquid sample. The test involves collecting and filtering a liquid sample through a pre-weighed filter paper. The filter paper is then dried in an oven to remove any moisture then weighed again to determine the Weight of the suspended solids. A high TSS concentration can indicate poor water quality, as suspended solids can cause cloudiness or turbidity in the water. BOD and COD tests measure the oxygen required to degrade organic matter in water or wastewater. BOD measures the amount of oxygen microorganisms consume in the water during the breakdown of organic matter. In contrast, COD measures the amount of oxygen required to oxidize all the organic and inorganic substances in the water. Both tests are

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necessary for determining water and wastewater quality and identifying potential sources of pollution or contamination.

2.3 Samples

The number of test samples needed is in **Table 4.**

Table 4. Recapitulation of Test Sample Requirements.

Variation	Alkaline Content (Mol)	Laboratory Compaction Test Using Standard Effort	CBR-soaked Test Using Standard Effort
1	0	5	3
2	3	5	3
3	6	5	3
4	9	5	3
5	12	5	3
Sum		25	15
Total			40

Source: Research Method (2022).

3. Results and Discussions

3.1 Characteristic material test result

The material must meet the requirements specified in the 2018 General Highways Specifications for Road and Bridge Construction Works (Revision 2). Based on the tests, the materials met the class A aggregate base course layer specification, as shown in **Table 5.**

Table 5. Recapitulation of Feasibility Material Testing Results.

Physical Properties	Standard	Parameters	Result
Abrasion of coarse aggregate	(SNI 2417:2008)	0-40%	24%
Percentage of fractured particles in coarse aggregate	(SNI 7619:2012)	95/90	96/93
Liquid limits	(SNI 1967:2008)	0-25	0
Plasticity index	(SNI 1967:2008)	0-6	0
Plasticity index multiplied by percent passing sieve No.200		Max.25	0
Clay lumps and friable particles in aggregates	(SNI 4141:2015)	0-5%	1,6%
The ratio of percent passing sieve No.200 and No. 40		Max. 2/3	2/3

Source: Author's Analysis (2022).

In addition, specific gravity and absorption testing is also carried out for each type of aggregate. In this research, the coarse aggregate had a specific gravity of 2.69 with water absorption of 0.93%; the fine aggregate had a specific gravity of 2.72 with water absorption of 2,02% and a specific gravity of fly ash 2,58.

Fly ash class is determined by XRD testing and analysis of its mineral content. The XRD test result, a collection of mineral structure patterns, was analyzed using Software Match. The principle is to match the pattern of mineral structure in the database with the results of the XRD test, as shown in **Figure 3**. Structural patterns referenced in the matching of mineral structures refer to the XRF test results from previous studies [15]. The analysis result is shown in **Table 6**.

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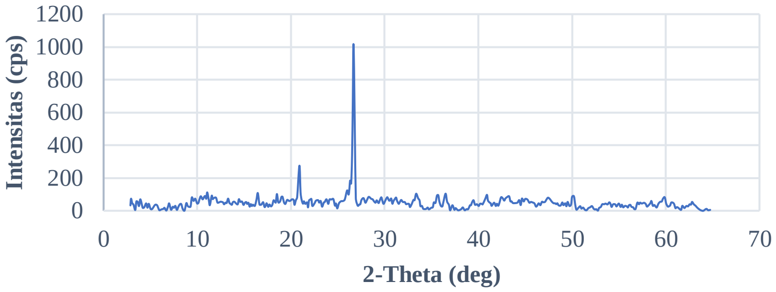

Source: XRD test result (2022).

Figure 3. Mineral Structure Patterns of Fly Ash Used in Research.

Table 6. Percentage of Fly Ash Mineral Composition in The Form of Crystals.

SiO2	Al2O3	Fe2O3	Fe3O4	CaO	TiO2	MgO	MnO	BaO
59,76	12,11	7,23	5,55	5,16	3,27	2,87	2,72	1,33

Source: Author's Analysis (2022).

The ratio between the number of crystal structures in this fly ash is 18.16% crystalline and 81.84% amorphous. In the XRD results, no reading angle matches the mineral pattern SO3. Previous studies with the same resources indicate a value range from 0,40 to 1,88 % and a loss of ignition range of 0,44 to 0,80 % [16]. Class N differs from the source material; class N is from volcanic ashes or pumicites, calcined or uncalcined, while class F is from ground or powdered coal combustion processes. The conclusion from **Table 7**, the fly ash material used in this research is included in class F based on the chemical requirement, which is reactive to alkaline reagents. The test process is in **Figure 4.**

Table 7. Determining Fly Ash Classification.

Description	Class N	Class F	Class C	Sample
Silicone dioxide (SiO2) + Aluminum oxide (Al2O3) + Iron oxide (Fe2O3), min, %	70	70	50	79,10
Sulfur trioxide (SO3), max, %	4	5	5	0,40
Moisture content, max,%	3	3	3	0,72
Loss on ignition, max,%	10	6	6	0,44

Source: Author's Analysis (2022).

Source: Research Documentation (2022).

Figure 4. XRD Mineral Testing and Analysis Process.

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3.2 Compaction test result

At the initial stage, the addition of water is regulated to obtain optimum moisture content by adding water. Previous research shows that the MDD value for the base courses layer is between 2,23 to 2,32 gr/cm3, while the OMC value is between 5% and 7%. [17] [18] [19]. The MDD values where no unique patterns were observed. Dry density values are affected by the wet mixture's weight and moisture content. However, both values are difficult to obtain accurately because there are heterogenous in specific gravity, water absorption ability, and surface area of aggregate particles. The value of MDD ranges between 2.10 to 2.12 gr/cm^3, and OMC is from 6,80% to 5,90%, as shown in **Table 8**.

Table 8. Compaction Test Results.

Variation NaOH (mol)	MDD (gr/cm^3)	OMC (%)
0M	2,115	6,80
3M	2,107	6,60
6M	2,111	6,30
9M	2,122	6,00
12M	2,117	5,90

Source: Author's Analysis (2020).

The MDD value from this research is below the reference because compaction energy is different. This research's compaction energy is lower than the reference, which used a modified method. The compaction test results also show that the OMC value tends to decrease as the concentration of the alkaline reagent solution increases. Alkaline reagent solutions are increased based on molarity values. Molarity is a solubility measure expressing the number of moles of a substance per volume of solution or water. The more moles of a solution, the volume of water in the solution decreases. That is why the value of OMC decreases with the increase of alkaline reagents. However, due to the low water absorption of the mixed material, there is no significant difference in OMC values between the standard and the modified effort methods.

3.3 CBR test result

The result of the CBR-soaked testing on variations 1 and 2 showed no significant change in the CBR-soaked value. Nevertheless, in variations 3, 4, and 5, there was a significant increase in the CBR-soaked value. The CBR-soaked value increases with the increasing volume concentration of the alkaline reagent solution. Adding an alkaline reagent solution that reacts with alumina silicate to the fly ash increases the bond strength between the aggregate particles. At the same time, the water only helps the particles form a tighter mixture with each other. So the increased volume of alkaline reagents positively affects the mixed material of class A aggregate base course layer in strengthening CBR-soaked value. The value of CBR-soaked is shown in **Table 9.**

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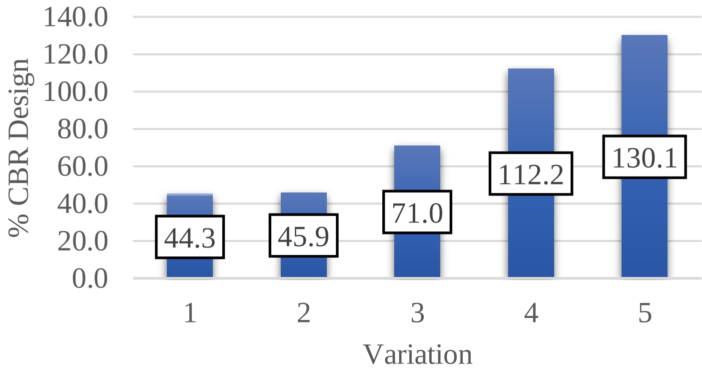
Table 9. CBR-soaked Test Results.

Variation	MDD (gr/cm^3)			CBR-soaked (%)		
	10 blow	30 blow	65 blow	10 blow	30 blow	65 blow
1	1,93	2,04	2,12	15,1	28,8	46,4
2	1,92	2,04	2,12	11,6	31,3	48,5
3	1,94	2,05	2,12	19,7	42,4	74,7
4	1,94	2,05	2,13	46,9	88,3	113,6
5	1,95	2,05	2,13	88,3	98,9	135,8

Source: Author Analysis (2022).

From **Table 9**, CBR-soaked values, and MDD values from **Table 8**, the CBR design value of each variation is obtained. The values of the CBR design for each variation are shown in **Figure 5.** CBR design values in variation 1 or without alkaline reagents up to variation 3 cannot reach a value of 90% as the minimum specifications SNI 1744:2012. However, in variations 4 and 5, the CBR design value has met the minimum specifications set. With a concentration of 9 mol NaOH, it is enough to get CBR design values that meet the minimum specifications by laboratory compaction method using standard effort.



Source: Author's Analysis (2022).

Figure 5. Graph of the CBR Design Value of Each Design Variation.

Swelling or shrinkage conditions in the class A aggregate base course layer mixture tend not to change significantly. The dial reading for changes in the height of the test object does not exceed two divisions shown in **Figure 6.** Even though there are readings on the dial, all numbers show negative values; in this case, the test object is experiencing shrinkage. The shrinkage happens because this aggregate base course layer mixture consists of non-plastic or granular material and does not have a clay content with a high water absorption ability and plasticity index. Based on this, the characteristics of the mixed aggregate base course layer materials only undergo deformation in the form of shrinkage due to load and no swelling condition due to water.

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Source: Research Documentation (2022).

Figure 6. Dial Reading for Changes in the Height of the Test Object at Variation 4 with 10 Blow.

However, the reading value is relatively low, so the mixture of class A aggregate base layer with fly ash is stable against changes due to load and water. Previous studies stated that the characteristics of fly ash do not have swelling potential because it is considered non-plastic [20]. The values of the dial reading are shown in **Table 10.**

Table 10. Recapitulation of Changes in The Height of The Test Object.

Variation	Changes in The Height of The Test Object (%)		
	10 blow	30 blow	65 blow
1	0,004272	0,001709	0
2	0,008545	0,004272	0
3	0,008545	0,012817	0,004272
4	0	0	0
5	0,008544	0,008544	0,001708

Source: Author Analysis (2022).

3.4 Water quality test results

Based on the observations made, it was found that the remaining chemicals that did not react with the test specimen were dissolved in the bath water. The condition of the bath water looks a little cloudy. If it is allowed to stand for a while, we can see the dissolved chemical particles, as shown in **Figure 7.**

The residual water of the test object with a concentration of 9 mol NaOH was tested to see the wastewater parameters. The test parameters are acidity (pH), Total Suspended Solid (TSS), Biochemical Oxygen Demand (BOD), and Chemical Oxygen Demand (COD), with quality parameters values referring to Government Regulation Number 22 of 2021 concerning Guidelines for Environmental Protection and Management. [21]

Source: Research Documentation (2022).

Figure 7. Condition of Soaked Water for CBR Test Specimens after 4 days.

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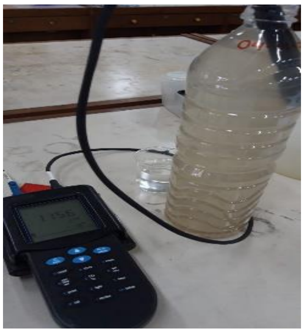
As an assumption, the water quality standard as the benchmark parameter is class 3. Class 3 is a category of water that can be used for freshwater fish farming, animal husbandry, agriculture, and other purposes that require the same water quality as these uses. The sample test results against the standard quality values are as follows in **Table 11.**

Table 11. Test Results for Water Quality Standards.

Parameter	Unit	Standard	Sample	Remarks
Degree of acidity (Ph)		6-9	11,56	Unacceptable
Total Suspended Solid (TSS)	mg/L	Max 100	42,67	Acceptable
Biochemical Oxygen Demand (BOD5)	mg/L	Max 6	0,13	Acceptable
Chemical Oxygen Demand (COD)	mg/L	Max 40	7,78	Acceptable

Source: Author Analysis (2022).

Based on testing, as seen in **Figure 8**, the value of the degree of acidity (pH) does not meet the water quality standards. It can affect the condition of the aquatic environment, such as fish growth. The degree of acidity that is too acidic inhibits fish growth, while if it is too alkaline, it is not suitable for the fish's living environment [22]. The value of the test results shows that the water is included in highly alkaline conditions. The degree of acidity for natural soil is 4,37 to 8,50, but materials with alkaline reagent solutions are between 11,05 to 12,65 [23]. However, after experiencing several cycles of washing with rainwater, the degree of acidity will tend to decrease. In addition, prevention can also be done by providing good drainage to drain rainwater so as not to erode the aggregate base course layer.



Source: Research Documentation (2022).

Figure 8. The Process of Testing the Degree of Acidity.

The bath water has a total suspended solids (TSS) value of 42.67 mg/L from the test, as shown in **Figure 9**. This value is below the established quality standard, 100 mg/L. However, the value of total suspended solids in the field may increase as construction activities continue or decrease as a high volume of precipitation rainfall. In addition to construction activities, the value of total suspended solids on road pavement is also influenced by the area of the watershed or rain catchment area and land use. [24] Furthermore, The load on the surrounding water body is highly dependent on wind, traffic volume, road material, road angle, road embankment design and filter capacity, gutter design, type of soil runoff, flow, and distance to receive water [25].

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Source: Research Documentation (2022).

Figure 9. Total Suspended Solids (TSS) Testing Process.

The BOD and COD testing process is seen in **Figure 10** and **Figure 11.** From the result of the test, BOD and COD values that meet quality standards are due to the presence of sodium hydroxide (NaOH) and polymer reactions. Using sodium hydroxide (NaOH) reduces the BOD and COD values as a coagulant. [26]

Source: Research Documentation (2022).

Figure 10. BOD Testing Process.

Source: Research Documentation (2022).

Figure 11. COD Testing Process.

4. Conclusion

Based on the research results, the use of fly ash in the class A aggregate base course layer has not been able to meet specifications. However, by providing 9 mol of alkaline reagent, the strength of the mixture increases so that the CBR value meets the specifications due to geopolymer bonding. The value of the change in the height of the test specimen does not experience significant changes due to non-plastic materials. With this value, the class A

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aggregate base course layer with fly ash mixture is relatively stable due to load and water changes. With this mixed design, implementing the class, A aggregate base course layer is more effective even though it is carried out with light compaction equipment. However, the results obtained by the base course layer are stable and meet the specifications.

The effect of chemicals in alkaline reagents increases the pH level of runoff water. The impact is that runoff water that is too alkaline or basic will pollute the life of the aquatic environment, both in animals and plants. At the same time, the other water quality standard parameters do not show pollution. Based on the results of water quality testing, it also recommends using fly ash-based geopolymer in the base course layer in the field must have sufficient spatial drainage infrastructure to reduce environmental pollution, and it needs environmental study.

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