Paper DAK-Revision

by Dewa Alit Karyawan

Journal of Engineering Science and Technology
Vol. XX, No. Y (Year) PPP - QQQ

THE EFFECT OF VARIOUS NA_2SIO_3/NAOH RATIOS ON THE PHYSICAL PROPERTIES AND MICROSTRUCTURE OF ARTIFICIAL AGGREGATES

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Abstract

Aggregates are the main material components used in most infrastructure construction works. Therefore, an alternative is needed to meet the needs by making aggregates. In this advanced study, the aggregate was made with geopolymerization of fly ash and alkaline activators with granulation systems. Aggregates are planned for road and airfield pavement material. This research is about the alkaline activator to the aggregate produced by sodium silicate (Na2SiO3) and sodium hydroxide (NaOH). The ratio of Na2SiO3 to NaOH that is tried is 1.5, 2.0, 2.5, and 3.0. Statistical tests show that there is a significant effect between the ratio of Na2SiO3 to NaOH on all artificial aggregate properties. The test results for properties of hardness, strength and durability indicate that for all alkali ratios, the aggregate meets the requirements for use as road and airport pavement materials. Except at ratio 3.0 only suitable for pavement materials. While the absorption value of all Na 2 SiO 3 to NaOH ratios was not met the requirements (> 3%). The scanning electron microscope (SEM) observation results indicated the similarity of the geopolymerization reaction for all ratios, but the best reaction occurred at a ratio of 1.5.

Keywords: artificial aggregate, geopolymer, alkaline ratio, physical properties, microstructure

1. Introduction

The growth of infrastructure development has resulted in an increase in material requirements. Aggregate is the main material components used in most infrastructure construction works. Alternatives have been explored to meet aggregate supply requirements in Indonesia. The demand for aggregate increases in line with the increase in infrastructure construction works. There are only limited sources for good quality natural aggregates. Therefore, there is a need to find alternative aggregate supplies to fulfil the increasing demand. On the other hand, artificial aggregates can be manufactured from by-product materials. Their properties can be designed to meet the construction requirements [1], [2].

Artificial aggregates become an interesting topic to discus. The property of light weight artificial aggregates is produced from mining and industrial waste with tubular rotary [3]. It is observed that 1.5 and 3 minutes of pre-firing and firing dwell periods, respectively, are more sufficient than 5 and 4 minute-processes to produce artificial aggregates with lesser density. [4] investigated the effect of the artificial lightweight aggregate and the water to binder ratio on the initial and final setting times of self-compacting mortars and found that that the timing of the initial and final mortar compaction, the flow diameter down and the funnel flow time were significantly influenced by the water to binder ratio. In addition, Shi *at al.* (2019) attempted to deal with recycled concrete waste powder effectively using granulation technology by making artificial aggregates with 5-20 mm in diameter. The material used in the research was carbonated powder waste.

Fly ash is a by-product of a power plant that uses coal [6]. The use of fly ash as a hot mix asphalt material, can improve the mechanical property and reduce the use of asphalt [7]. Fly ash which is used as a mixture for the base layer can improve the performance and age of the asphalt pavement plan compared to the use of natural aggregates [8]. This coal waste is proven to be a good material to increase the stability of asphalt concrete after being solidified as geopolymer material [9]. A fly ash-based geopolymers have the potential to be utilized as artificial aggregate materials and as natural aggregate substitutes [10]. In addition, it is suitable for making geopolymer paste because it contains aluminosilicate [11]. Several methods have been employed to produce fly ash paste geopolymers such as the pelletization process [12], cold bonding [13], sintered fly ash aggregates [14] and sintered pellets [15]. In the cold bonding method,the geopolymerization process occured by mixing fly ash with alkaline activators [16]. The alkaline activators used in these studies were a blend of sodium silicate (Na_2SiO_3) and sodium hydroxide (NaOH). The alkaline activators worked as the inducers of pozzolanic properties in raw materials [17], [18]. This process produces an aluminosilicate gel which acts as a binder [19].

The geopolymer aggregate strength is influenced by the ratio of fly ash to alkaline activators. Fly ash with sodium (Na) and aluminum (Al) content reacts instantly when mixed with the alkaline activators. The reactivity level of fly ash is indicated by the amount of aluminum in the aluminosilicate gel [17], [18]. The addition of an alkaline activator to the raw material resulted in hardening due to the geopolymerization process. The hardening process takes place, when there is a reaction of aluminum and oxide silicate in raw materials with alkaline polysilicate [6], [20] The geopolymer quality of fly ash can be improved by modifying the alkaline activators during the mixing process. One option is by varying the ratio of Na_2SiO_3 to NaOH [10]. The ratio of 1.5 of Na_2SiO_3 to NaOH presents the maximum compressive strength as stated in two separated studies. This was based on testing at either three [10] or four [19] different Na_2SiO_3 to NaOH ratios between 1 and 2.5. The compressive strength is lower as the ratio of Na_2SiO_3 to NaOH increases [10]. This was due to an increase in the number of non-reacting fly ash particles as the Na_2SiO_3 to NaOH ratio increases. However, it was found that the resulting geopolymer hardening of mortar was more influenced by the type of fly ash, specifically by their fineness and mineralogical composition than by the increasing proportion of sodium silicate solution in the mixture [21]

The results of several studies indicate that the properties of geopolymers are suitable for use as building materials. These properties include high compressive strength, low shrinkage, and acid and fire resistance [22]. This property causes the geopolymer aggregate to be an option for use as a construction material. The aggregate properties are influenced by the slope of the granulator and the ratio of Na2SiO3 to NaOH. Therefore a series of studies were conducted to obtain the effect of the slope of the granulator and the ratio of Na2SiO3 to NaOH on the aggregate properties. In the previous paper, the results of a study of the effects of the slope of the granulator on the properties of artificial aggregates have been described. Meanwhile, this paper reviews the effect of the ratio of Na2SiO3 to NaOH on microstructure and physical properties of artificial aggregates, which is a series of previous studies. In this study, the slope of the granulator was 50 °, referring to a previous study which stated this was the best slope for the process of making artificial aggregates and their absorption value [23]. This paper describes the results of research that can complement the previous results, which are the latest findings from the manufacture of artificial aggregates produced by the geopolymerization process, using fly ash collected from the Suralaya plant in West Java, Indonesia. The resulting aggregate is used for asphalt concrete mixtures, both for road pavement and airfield.

2. Experimental Procedure

This study is a series of studies on the manufacture of aggregates with geopolymer fly ash. Previous research recommended 50o as the best granulator slope because it obtained better properties compared to 45o and 55o slopes (23). Therefore, in this study, aggregates were made by locking the slope of the granulator at an angle of 50o. As in the previous study [23], as an activator also used an alkaline solution consisting of a mixture of Na2SiO3 and NaOH. In this study, variations in the ratio of Na2SiO3 and NaOH were carried out, so that the ratio that gave the best properties was found. The production process uses the same method, namely fly ash based geopolymerization. The resulting aggregate has to be used in asphalt concrete mixtures.

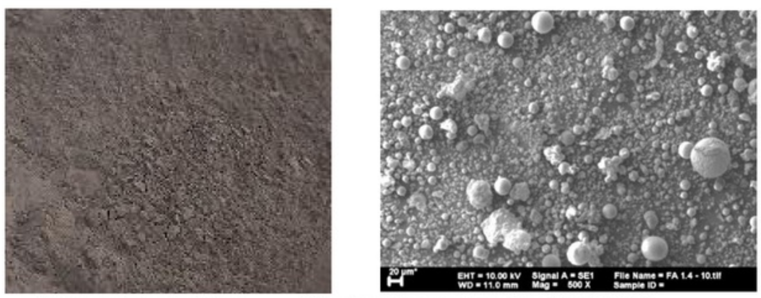
2.1. Fly Ash

Table 1 presents the chemical composition of the fly ash from Suralaya power plant, determined by X-Ray Fluorescence (XRF). The data in Table 1 indicate that the combined chemical composition of Al_2O_3, SiO_2 and Fe_2O_3 reached more than 70% to fall within the characteristics of Class F in accordance with ASTM C618-12a [24]. The apparent condition and microstructure characteristics (under a

Scanning Electron Microscopy (SEM)) of the fly ash are presented in Fig. 1. The morphology of fly ash particles as illustrated in Fig. 1 shows that the distribution of fly ash particles is heterogeneous and not uniformed. The forms of round particles vary in size. These irregular grain sizes can appear as a result of incomplete combustion during the production process [25].

Table 1. Chemical composition of fly ash

No	Compound	Content (%)	No	Compound	Content (%)
1	SiO_2	45.00	9	BaO	0.27
2	Fe_2O_3	18.45	10	Re_2O_7	0.25
3	Al_2O_3	18.05	11	MgO	0.20
4	CaO	10.85	12	V_2O_5	0.07
5	MoO_3	3.29	13	ZnO	0.05
6	TiO_2	1.70	14	CuO	0.04
7	K_2O	1.47	15	Cr_2O_3	0.03
8	MnO	0.35	16	Na_2O	0.00



(a) apparent condition **(b) microstructure under SEM 500X**

Fig. 1. Suralaya Fly Ash

2.2. Alkaline Activator

The alkaline activators utilized in this study were sodium silicate (Na_2SiO_3) and sodium hydroxide (NaOH). Na_2SiO_3 was the solution while NaOH was in the form of flakes. The NaOH concentration in this study was 8 molar. One liter of solution was made by dissolving 320 grams of NaOH with distilled water. The amount of 320 grams was obtained from the period of NaOH atom = 40 gram/mol and 8 molar concentration. Na_2SiO_3 was added to improve the geopolymerization process. The molar ratio influenced increase in the bond strength between the aggregate and the paste [26]. The alkaline solution was prepared a day before making the aggregates.

2.3. Mix Design

The ratio of fly ash to alkaline activator was 75% to 25%. The ratios of Na_2SiO_3 to NaOH solution were 1.5, 2.0, 2.5 and 3.0. Based on the mix design, the materials were prepared as required. Table 2 shows the amount of material required for the granulation process for each Na_2SiO_3/ NaOH ratio.

Table 2. Amount of material requirements based on mixed design details for one mixing.

Alkaline (Na_2SiO_3/ NaOH)	Fly ash (grams)	Alkaline (grams)	Na_2SiO_3 (grams)	NaOH (grams)
1.5	1,500	500	300	200
2.0	1,500	500	333	167
2.5	1,500	500	357	143
3.0	1,500	500	375	125

2.4. Production

The artificial aggregate production used a granulator with a diameter of 1.2 meters, with a pan slope of 50° angle. The equipment used is shown in Fig. 2.

Fig. 2. Granulator for aggregate manufacture

The aggregate production began with adding 1,500 grams of fly ash into the granulator pan, which was running at 26 rotations per minute. This step was followed by the next step, i.e. the formation of aggregate granules through the geopolymerization process. The geopolymerization process took place after adding alkaline activators to the fly ash. This was done by continuously spraying a total of 500 grams of alkaline activator solution until it ran out and granules were formed. The formation of granules would indicate that the geopolymerization process started to occur. The resulting aggregate granules were subsequently removed from the granulator pan and stored away for further use. The same process was repeated for different ratios of Na_2SiO_3 to NaOH, as detailed in Table 2.

For each set of granulated aggregates, a curing process at room temperature was applied. The tests to determine the aggregate properties of fly ash geopolymers was carried out after the 28 day curing period.

2.5. Laboratory Test Program

2.5.1. Determination of Aggregate Properties

This section presents the raw material, the procedure to manufacture the artificial aggregates and the test methods. A suite of laboratory tests was carried out to assess the main properties required for the pavement aggregates. The selected properties included: a) Absorption, b) Hardness, c) Durability, and d) Strength.

The standards, descriptions or significance, designs, and formulas used in the process of analyzing data from the test results to obtain properties values are as follows:

a) *Absorption*. Absorption value is the weight ratio of water absorbed in the aggregate pore by weight in dry conditions. Absorption testing uses SNI 1969: 2008 [27] which refers to ASTM: C 127-07 [28]. The laboratory standards to determine the amount of water absorbed by the pore aggregate are obtained after immersing dry aggregates for a specified period of time [27][28] where the weight of water is the aggregate weight in the state of saturated surface dry (W_{SSD}) after immersion which is then reduced by oven dry weight aggregate (W_{Dry}). The absorption value is the weight percentage of water to oven dry weight. The technical specification values for absorption as road pavement materials and airfields are <3% [29] [30]. The formula used to determine the absorption value is as follows:

$$\text{Absoption} = \frac{W_{SSD}-W_{Dry}}{W_{Dry}} x\ 100\% \quad (4)$$

b) *Hardness*. The aggregate must be hard enough to resist abrasive action due to constant friction from traffic movements. Obtained with the Los-Angeles Test, referring to SNI 2417: 2008 [31]. The hardness specification to be road pavement material, based on Indonesian standards, is generally <30% [29]. Meanwhile, the hardness for airfield pavement is <25% [30]. If the amount of aggregate sample held by the sieve is expressed as "Wt" and the weight of the original sample is expressed as "Wo", the aggregate crushed is Wo-Wt. Therefore, the formula used to find the hardness value is as follows:

$$\text{Hardness} = \frac{W_t-W_o}{W_t} \text{x } 100\% \qquad (1)$$

c) *Durability* is the aggregate properties to resist weathering due to adverse weather. Durability is obtained by soundness test referring to SNI 3407: 2008 [32]. Soundness test is intended to study the resistance of aggregates to weathering action, by conducting accelerated weathering test cycles. Aggregates of the specified size are subjected to five cycles of alternate wetting in a saturated solution of either sodium sulphate or magnesium sulphate. The loss in weight of aggregates is determined by sieving out all undersized particles and weighing them. The durability value is the percentage of weight crushed to the weight of the original sample. The specification of durability value as road pavement material, based on Indonesian standards, is typically <12% [27]. Meanwhile, the airfield pavement is set at <10% [30]. If the number of aggregate samples held by the sieve is expressed as "Wt" and the weight of the original sample is expressed as "Wo", the aggregate crushed is Wo-Wt. Therefore, the formula used to find the durability value is as follows:

$$\text{Durability} = \frac{W_t-W_o}{W_t} \text{x } 100\% \qquad (2)$$

c) *Strength*. The aggregate used for high-quality pavement surface layers, should possess high resistance to crush, and withstand stresses due to traffic wheel loads. This ability depends on the aggregate strength as measured by the impact test, referring to BS 812-112: 1990 [33]. The strength of aggregate value depends on the resistance to impact. Impact value is the aggregate percentage that passes sieve No.8 (2.36 mm) to the aggregate amount before the impact is given. The specification value for the aggregate impact value or strength is <30%. If the aggregate impact value (AIV) is greater than 30%, the results obtained must be treated with care [33]. If the number of aggregate samples held by the sieve is expressed as "M_3" and the weight of the original sample is expressed as "M_1", the aggregate crushed is $M_2=M_1-M_3$. Therefore, the formula used to find the aggregate impact value or strength is as follows [33]:

$$\text{Strength} = \frac{M_2}{M_1} \text{x } 100\% \qquad (3)$$

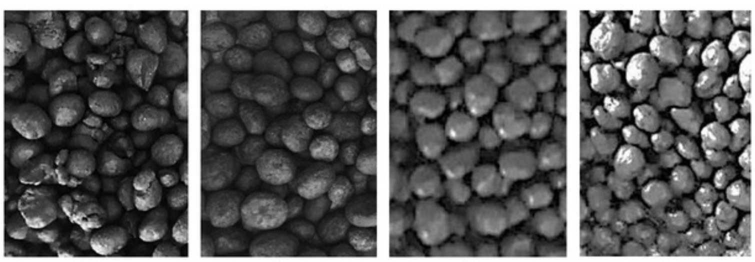
Analysis of the effect of the ratio of Na2SiO3 to NaOH using an analysis of variance (ANOVA). Univariate One Way ANOVA is chosen because there are one independent variable and the dependent variable [34]. As the free variable (X) is the ratio of Na2SiO3 / NaOH (1.5, 2, 2.5 and 3) while as the dependent variable (Y) is the aggregate properties (water absorption, hardness, durability and strength).

2.5.2. The Method of Determining the Aggregate Microstructure

The microstructure of the aggregate formed from the geopolymer process was analyzed based on the scanning electron microscope (SEM). The SEM analysis was carried out to discover the variation in the microstructure formed in the geopolymer artificial aggregates. The SEM was carried out on aggregates formed from fly ash with the addition of alkaline (Na_2SiO_3/NaOH) at four ratios, i.e. 1.5, 2, 2.5, and 3.

3. Results and Discussion

The apparent condition of the artificial aggregates at different composition of alkaline activators are shown in Fig. 3. Furthermore, Table 3 presents the test result summary for artificial aggregates incorporating Na_2SiO_3/ NaOH ratios of 1.5, 2.0, 2.5 and 3.0.



(a) (b) (c) (d)

Fig. 3 Artificial aggregate at Na_2SiO_3/NaOH ratios of: 1.5 (a), 2.0 (b), 2.5 (c) dan 3.0 (d)

Table 3. Summary of aggregate test results and specifications for pavement

No	Aggregate Properties	Ratio of Na2SiO3 to NaOH				Requirement	
		1.5	2.0	2.5	3.0		
1	Water Absorption	9.5	9.5	6.1	8.6	3.0*)	3.0**)
2	Aggregate Hardness	22.8	24.3	22.8	29.1	30*)	25**)
3	Aggregate Durability	3.4	8.1	5.2	2.8	12*)	10**)
4	Aggregate Strength	11.9	12.9	15.8	15.7	30***)	30***)

Note: *)[29]; **)[30]; ***)[33]

3.1. Physical Properties Artificial Aggregate

3.1.1. Water Absorption

Porosity allows absorption moisture and/or asphalt binder into aggregates where the latter can facilitate the formation of bonds between aggregates and binder. Low level porosity is often desirable, and highly absorbing aggregates are generally avoided [35] [36]. Based on the specifications and the value of the absorption properties test results in Fig. 4 (left), all mixtures did not meet the typical specifications for pavement materials. The maximum allowable absorption for pavement materials is typically either 2% or 3%. Meanwhile, the best results water absorption found in this study were 6.1% for the aggregates produced at the Na_2SiO_3/ NaOH ratio of 2.5. The high water absorption can reduce aggregate durability, particularly when they are exposed to the severe environment (such as freeze and thaw, high saturation and/or marine condition). Furthermore, water absorption also affects the aggregate capability to absorb asphalt binder in hot mix asphalt [37]. Therefore, it is necessary to find another formula or method that can produce artificial aggregates with water absorption <3%. Alternatively, the aggregates can only be considered acceptable for use in asphalt mixture if the results from the durability or soundness test meet the specification.

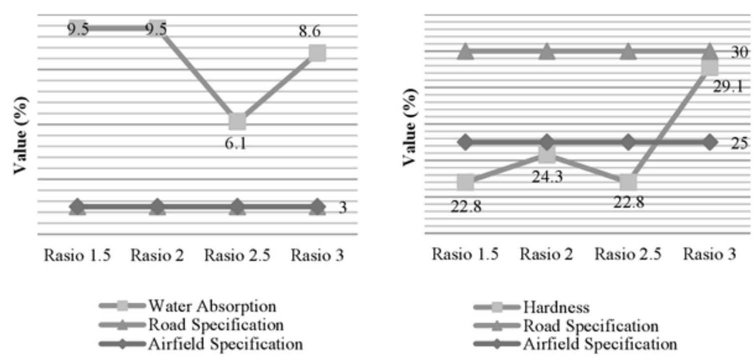


Fig. 4. Value of water absorption and hardness to specifications

3.1.2. Aggregate Hardness

Fig. 4 (right) suggests that there was a decrease in aggregate hardness value if the Na_2SiO_3/ NaOH ratio was increased. This could be seen from the increase in the percentage of crushed aggregate if the Na_2SiO_3/NaOH ratio was increased.

The more aggregates crushed in the test, the lower the hardness (the higher the hardness value). These results indicate that an increase in the $Na_2SiO_3/NaOH$ ratio reduces aggregate hardness. The best value for hardness came from the aggregate made with a ratio of $Na_2SiO_3/NaOH$ of 1.5. The aggregates that do not meet the requirements of hardness if used as pavement material can risk disintegration during mixing, placement and compaction when receiving enduring traffic loads.

The test results showed that artificial aggregates made from fly ash, with four ratios of $Na_2SiO_3/NaOH$ tested, met the requirements as road pavement material, because the value was below 30%. However, for airfield pavement, artificial aggregates made from fly ash which is activated with a Na_2SiO_3/ NaOH ratio of 3.0, do not meet the requirements, because the value is above 25%. Thus, aggregate with the ratio Na_2SiO_3/ NaOH of: 1.5, 2.0 and 2.5, which can be used as an airfield pavement material.

3.1.3. Aggregate Durability

The durability of artificial aggregates for all Na_2SiO_3/ NaOH ratios fulfills the requirements as road and airfield pavement materials, as shown in Fig. 5 (left). The aggregate could withstand weathering due to environmental conditions if used as pavement material. The worst durability artificial aggregate with a value of 7.8% was produced when the $Na_2SiO_3/NaOH$ ratio is 2.0. The aggregate properties with the best durability were those made with a mixture of fly ash and alkaline with the $Na_2SiO_3/NaOH$ ratio of 3.0.

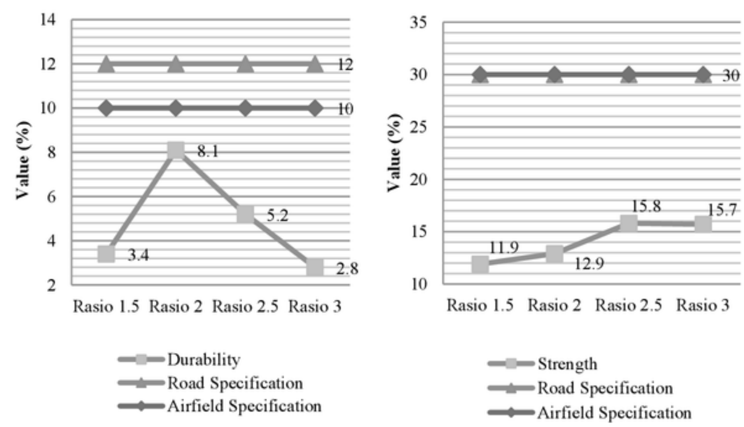


Fig. 5. Value of durability and strength to specifications

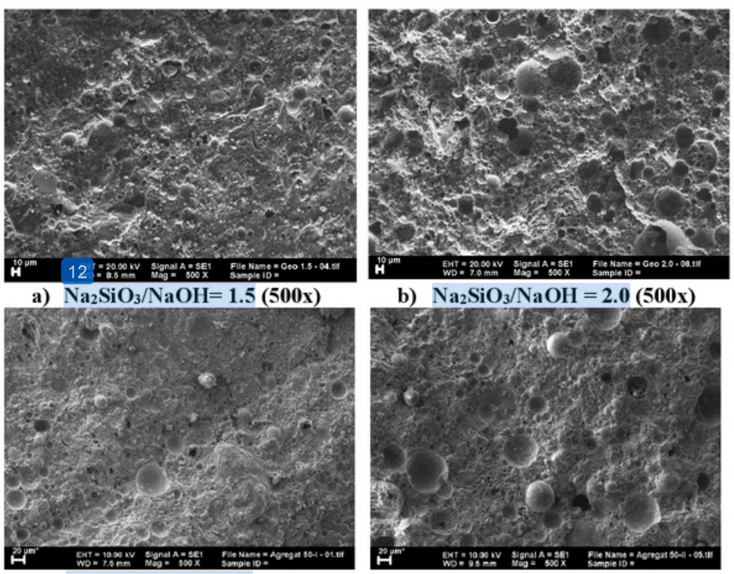
3.1.4. Aggregate Strength

Fig. 5 (right) shows the $Na_2SiO_3/NaOH$ ratio of 1.5 with the aggregate strength properties reaching 11.9%. This was the best value over all ranges of $Na_2SiO_3/NaOH$ ratios. The higher the Na_2SiO_3/ NaOH ratio, the more the amount of aggregate is crushed. This means that there is a decrease in aggregate performance as pavement materials.

3.2. Artificial Aggregate Microstructure

The geopolymerization reaction process can be observed from the changes in fly ash particles, which are spherical in nature and are precipitators of fly ash type, as seen in Fig. 1. There is a change in the microstructure of the fly ash system as a consequence of the dissolution of caustic particles and spheres by the alkaline activator. This process depends on the level of local reactivity. The geopolymerization process begins with the dissolution of the ball shell by an alkaline activator to expose smaller particles. During this reaction, sodium silicoaluminate is formed. Subsequently, a gel in the form of colloids is varied. The formed gel finally fills the fly ash particles and forms aluminosilicate masses [38].

The matrix formation reaction in various Na_2SiO_3/NaOH ratios is indicated by the SEM image in Fig. 6. SEM image at Fig. 6 (a) is artificial aggregate samples with a Na2SiO3/NaOH ratio of 1.5, indicating a better reaction than ratios of 2.0, 2.5, and 3. This is evident from the highest reduction in the spherical of fly ash on the aggregate microscopic surface artificial with the Na_2SiO_3/NaOH ratio of 1.5. In the SEM image it also appears that the matrix had formed well but there were still fly ash particles that had not reacted. This finding is consistent with the optimum aggregate properties.



a) Na_2SiO_3/NaOH= 1.5 (500x) **b) Na_2SiO_3/NaOH = 2.0 (500x)**

c) Na_2SiO_3/NaOH=2.5 (500x) **d) Na_2SiO_3/NaOH=3.0 (500x)**

Fig. 6. SEM images of artificial aggregates made from fly ash with variations in the ratio of Na_2SiO_3 / NaOH

Fig. 6 (b,c), display SEM images for artificial aggregate samples with Na_2SiO_3/NaOH ratios of 2.0 and 2.5. In those ratios, a matrix was well-formed but there were fly ash particles that had not reacted. The diameter size of unreacted fly ash in the image ranged from 10 µm to 21 µm.

The microscopic surface of the SEM image in Fig. 6 (d) indicates the reaction of fly ash with alkaline activator on Na_2SiO_3/NaOH ratio of 3.0. The aluminosilicate reaction that occured is indicated by the changes in spherical fly ash. The more perfect the reaction was, the more dissolution of spherical fly ash particles occured. In the Na_2SiO_3/NaOH ratio of 3.0, there were bigger spherical of fly ash that had not reacted with diameter size between 25 µm to 57 µm. At SEM image, cracks appeared to be greater than other Na2SiO3/NaOH ratios. It could be seen that the mixtures were denser and lack of liquid. In this case, shrinkage occured and created more pores in the geopolymer product. The increase in alkaline ratio made the ratio of liquid to solid decreased.

Based on the visible morphology on the SEM images of the experiment result, a good reaction between particles of fly ash and alkaline activators occured. In round fly ash particles called cenospheres, destruction occured, forming aluminosilicate [17][18] 41]. In the aggregate surface, cenospheres fly ash were visible, together in the paste. Increasing the Na_2SiO_3/NaOH ratio resulted in the reduced reaction of fly ash particles. This was due to the reduced amount of NaOH in the activating solution, causing insufficiency to dissolve the compounds in fly ash. Silicate solutions help in geopolymer polycondensation. Nonetheless, it could only occur if silicates and aluminate in the raw material were dissolved by NaOH. It really depended on the adequacy of the NaOH amount. On the other hand, excessive NaOH caused the hardening process to become fast, resulting in a decrease in strength [19].

4. Effect of Various Na_2SiO_3/NaOH Ratios

The effect of various Na_2SiO_3 to NaOH ratios can be seen from the results of ANOVA analysis in Table 4. Table 4 shows that for all properties with variations in the ratio of Na_2SiO_3 to NaOH the value of the calculated F is greater than F critical. This states that the ratio of Na_2SiO_3 to NaOH has a significant effect on all properties tested [34].

The results of the experimental data analysis showed that the aggregates made with all variations in the ratio of Na_2SiO_3 to NaOH met the specifications for properties of hardness, durability and strength as road pavement and airfield materials. Only from absorption properties, the aggregate does not meet the requirements for pavement material. Absorption has an effect on the performance of concrete asphalt, therefore a maximum limit of 3% is given (reference). From the results of the experiment, the lowest absorption value (6.1%) in the ratio of Na2SiO3 to NaOH = 2.5. So that the aggregate made with this ratio will have the best performance of other ratios if used as a pavement material.

Table 4. The ANOVA results to determine the effect of the ratio Na_2SiO_3 to NaOH on aggregate properties

Source of Variation	Sum of Squares	Degree of Freedom	Mean Squares	F_0	P-value	$F_{critical}$
Water Absorption						
Between Groups	15.49	3	5.16	17.18	0.01	6.59
Within Groups	1.20	4	0.30			
Total	16.69	7				
Aggregate Hardness						
Between Groups	54.39	3	18.13	10.29	0.02	6.59
Within Groups	7.05	4	1.76			
Total	61.44	7				
Aggregate Durability						
Between Groups	33.85	3	11.28	7.86	0.04	6.59
Within Groups	5.74	4	1.44			
Total	39.59	7				
Aggregate Strength						
Between Groups	23.64	3	7.88	11.08	0.02	6.59
Within Groups	2.85	4	0.71			
Total	26.49	7				

5. Conclusion

The results of the discussion based on research data analysis using ANOVA showed that variations in the ratio of Na_2SiO_3 / NaOH influenced the aggregate properties and microstructure made with Suralaya fly ash, with the following details:

1) The aggregate absorption value was > 3% for all Na2SiO3 to NaOH ratios, so it did not match the specifications. But the 2.5 ratio is worth considering because it has the lowest absorption value.
2) Based on aggregate hardness, all Na2SiO3 to NaOH ratios meet the requirements for road pavement material. But for airfield pavement material, only the ratio of Na2SiO3 to NaOH = 3.0 does not meet the requirements, because the value is above 25%. While the other 3 Na2SiO3 to NaOH ratios, 1.5, 2.0 and 2.5, meet the requirements.
3) Based on the durability and strength properties, the aggregate with four Na2SiO3 / NaOH ratios fulfilled the requirements as road pavement and airfield materials.
4) From the SEM analysis, the reaction of fly ash to alkaline activators reflected the properties of artificial aggregates. Visual observations showed the similarity of the geopolymerization reaction for all ratios, but the best reaction occurred at a ratio of 1.5.
5) Further research is required to optimize the design, to produce artificial aggregate products that meet all the requirements.

Acknowledgments

The authors thank and acknowledge those who contributed directly to carrying out this research, especially the Education Fund Management Agency (LPDP) of the Ministry of Finance of the Republic of Indonesia for their support through the Indonesian scholarship program.

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