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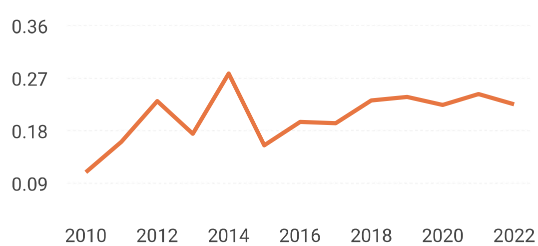

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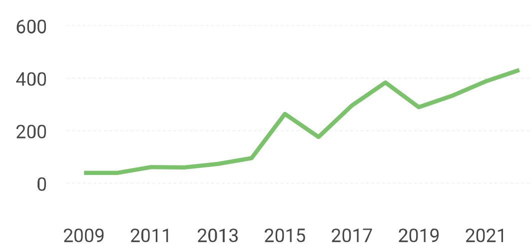

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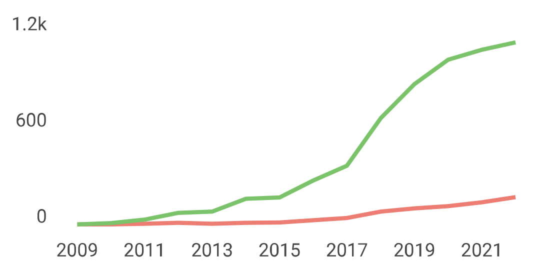

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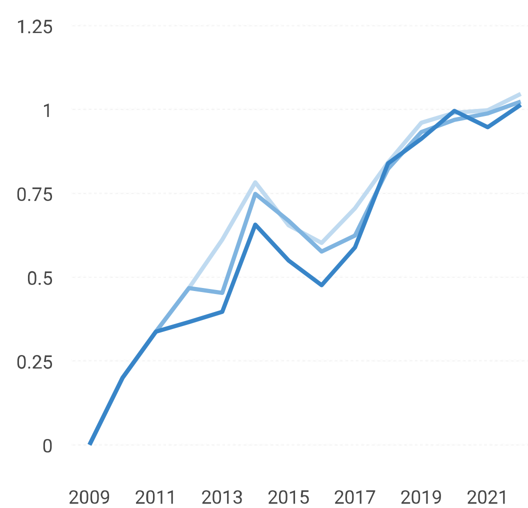

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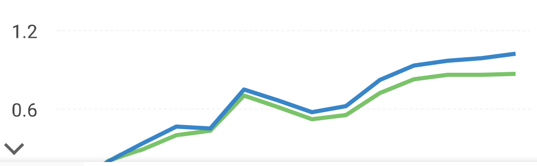

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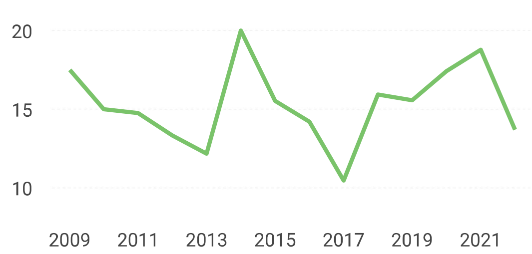

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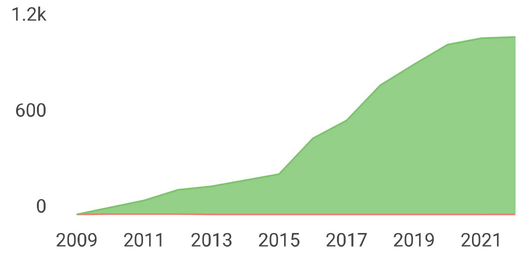

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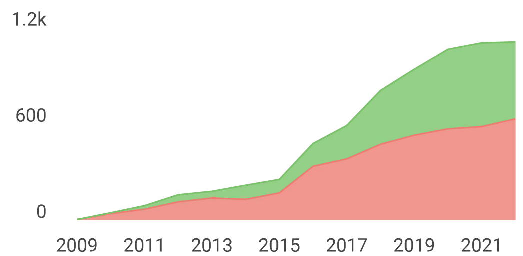

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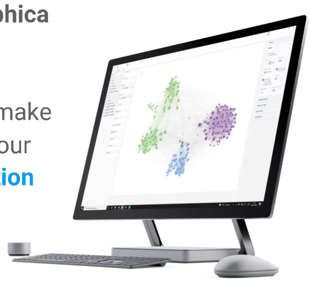

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THE EFFECT OF VARIOUS NA_2SiO_3/NAOH RATIOS ON THE PHYSICAL PROPERTIES AND MICROSTRUCTURE OF ARTIFICIAL AGGREGATES

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Abstract

Artificial aggregate was manufactured by using geopolymerization of fly ash, with alkaline activators using granulation systems. The activators comprised a mixture of sodium silicate (Na_2SiO_3) and sodium hydroxide (NaOH). The geopolymerization process formed different microstructure and physical properties. This study aimed to determine the effect of alkaline activators ratios on the artificial aggregate properties for use as road and airfield pavement materials. The laboratory trials explored the impact from Na_2SiO_3 to NaOH ratios, from 1.5 to 3.0, on the properties of the artificial aggregate. Statistical tests demonstrated that there was a significant effect between different ratios of Na_2SiO_3 to NaOH on artificial aggregate properties. The absorption value of all Na_2SiO_3 to NaOH ratios (>3%) did not meet the specification requirements. However, the test results for artificial aggregates with alkaline activator ratios less than 3.0, met the requirements for the properties of hardness, strength and durability, therefore the aggregates were deemed suitable for use as road and airfield pavement materials. The scanning electron microscope results indicated similarity of the geopolymerization reaction for all alkali activator ratios. Overall an activator ratio of 2.5 was recommended to provide the best balance in aggregate properties.

Keywords: Alkaline ratio, Artificial aggregate, Geopolymer, Microstructure, Physical properties.

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 discuss. The property of lightweight artificial aggregates can be produced from mining and industrial waste with tubular rotary [3]. It was reported 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. In addition, Shi et al. [4] 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.

Nor et al. [5] mentioned that fly ash is a by-product of a power plant that uses coal. The use of fly ash as a hot mix asphalt material was found improving the mechanical property and reduce the use of asphalt [6]. Fly ash, which was used as a mixture for the base layer was reported to have improved the performance and life time of the asphalt pavement compared to the use of natural aggregates [7]. After being solidified as geopolymer material, coal waste was proven to be a good material to increase the stability of asphalt concrete [8].

Based on studies by Karyawan et al. [9], a fly ash-based geopolymers have the potential to be utilized as artificial aggregate materials and as natural aggregate substitutes. In addition, it is suitable for making geopolymer paste because it contains aluminosilicate [10]. Several methods have been employed to produce fly ash paste geopolymers such as the pelletization process [11], cold bonding [12], sintered fly ash aggregates [13] and sintered pellets [14]. In the cold bonding method, the geopolymerization process occurred by mixing fly ash with alkaline activators [15]. The alkaline activators used in these studies were a blend of Na_2SiO_3 and NaOH. The alkaline activators worked as the inducers of pozzolanic properties in raw materials [16, 17]. This process produced an aluminosilicate gel, which acts as a binder [18].

The geopolymer aggregate strength can be influenced by the ratio of fly ash to alkaline activators. Fly ash with sodium (Na) and aluminium (Al) content is known to react instantly when being mixed with the alkaline activators. The reactivity level of fly ash is often indicated by the amount of aluminium in the aluminosilicate gel [16, 17]. The addition of an alkaline activator to the raw material can result in hardening due to geopolymerization process. The hardening process often took place, when there was a reaction between aluminium and oxide silicate in raw materials with alkaline polysialate [5, 19]

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 [9]. The ratio of 1.5 of Na_2SiO_3 to NaOH often presents the maximum compressive strength as stated in two studies, which was based on testing at either three [9] or four [18] different Na_2SiO_3 to NaOH ratios between 1.0 and 2.5. The compressive strength was found to be lower as the ratio of Na_2SiO_3 to NaOH increases [9]. This was due to an increase in the number of non-reacting fly ash particles as the Na_2SiO_3 to NaOH ratio increased. However, it was found that physical and petrological properties of fly ash, especially fineness and mineralogical composition, had more influence on the hardening of geopolymer mortar than by increasing the proportion of sodium silicate solution in the mixture [20].

The results of several studies indicated 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 [21]. This property causes the geopolymer aggregate to become an option for use as a construction material. The above-mentioned studies reported that geopolymer aggregate properties were influenced by the slope of the granulator and the ratio of Na_2SiO_3 to NaOH.

Therefore, a series of studies were conducted to obtain the effect of the slope of the granulator and the ratio of Na_2SiO_3 to NaOH on the aggregate properties. In the previous paper [22], 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 Na_2SiO_3 to NaOH on microstructure and physical properties of artificial aggregates, which is a series of previous studies. This study found that the slope of the granulator of 50°, was the best slope for the process of making artificial aggregates and their absorption value [22]. This paper describes the results of research that can complement the previous results, highlighting the latest findings from the manufacture of artificial aggregates produced by the geopolymerization process, using fly ash for use in asphalt concrete mixtures, both for road and airfield pavement.

Whilst previous studies [9, 20, 18] presented the influence of the ratio of Na_2SiO_3/ NaOH as an alkali to fly ash in the geopolymerization process, however, there was a lack of detailed review of its effects on the physical properties and microstructure as an aggregate for asphalt pavement material. Therefore, this research was aimed to address the following question: "What is the effect of the Na_2SiO_3/NaOH ratio on physical properties and aggregate microstructure as an asphalt pavement material?". The key novelty from this research was to determine the ratio of alkali (Na_2SiO_3/NaOH), which produces aggregates with the best physical and microstructural properties to be used as road or airfield asphalt pavement materials. It is expected that positive findings from this study will allow wider utilisation of fly ash from Suralaya power plant, promoting its use as a viable alternative construction material, which is friendlier to the environment.

2. Material

2.1. Fly ash

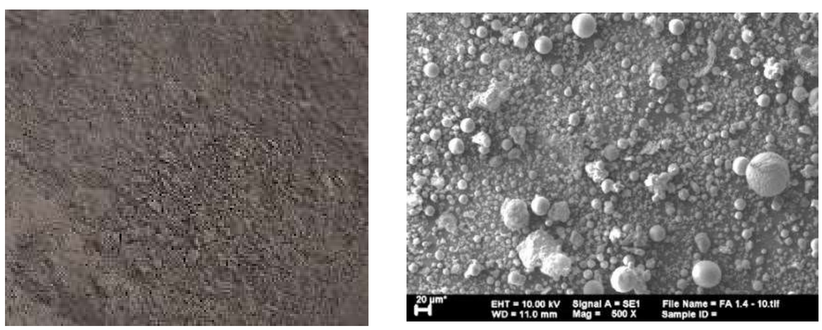
Table 1 presents the chemical composition of the fly ash from Suralaya power plant, determined by X-Ray Fluorescence (XRF). The data in Table 1 indicate that the combined chemical composition of Al_2O_3, SiO_2 and Fe_2O_3 reached more than 70% to fall within the characteristics of Class F in accordance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

[23]. 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 it is not uniform. Particles shapes are rounded, with varying sizes. These irregular grain sizes can appear as a result of incomplete combustion during the production process [24].

Table 1. Chemical composition of fly ash.

Compound	Content (%)	Compound	Content (%)
SiO_2	45.00	**BaO**	0.27
Fe_2O_3	18.45	**Re_2O_7**	0.25
Al_2O_3	18.05	**MgO**	0.20
CaO	10.85	**V_2O_5**	0.07
MoO_3	3.29	**ZnO**	0.05
TiO_2	1.70	**CuO**	0.04
K_2O	1.47	**Cr_2O_3**	0.03
MnO	0.35	**Na_2O**	0.00



(a) Apparent condition. **(b) Microstructure under SEM 500X.**

Fig. 1. Suralaya fly ash.

2.2. Alkaline activator

Alkali activator in this study used sodium silicate (Na_2SiO_3) mixed with sodium hydroxide (NaOH). Chemical contents of Na_2SiO_3 solution is silicate oxide (30%), sodium oxide (15%), and water (55%). The NaOH concentration in this study was 8 molar. One litre of the 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 an increase in the bond strength between the aggregate and the paste [25]. 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. This value is used referring to previous studies, which get Na_2SiO_3 / NaOH ratio has optimal values at 2 and 2.5, for concentrations of eight and ten molars NaOH [26]. 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 for one mixing.

Alkaline (Na_2SiO_3/NaOH)	Fly ash (grams)	Alkaline (grams)	Na_2SiO_3 (grams)	NaOH (grams)
1.5	1500	500	300	200
2.0	1500	500	333	167
2.5	1500	500	357	143
3.0	1500	500	375	125

3. Experimental Procedure

This study is a series of studies on the manufacture of aggregates with geopolymer fly ash. Previous research by Yuliana et al. [22] recommended 50° as the best granulator slope because it obtained better properties compared to 45° and 55° slopes. Therefore, in this study, aggregates were made by locking the slope of the granulator at an angle of 50°. As in the previous study by Yuliana et al. [22], as an activator also used an alkaline solution consisting of a mixture of Na_2SiO_3 and NaOH. In this study, different ratios of Na_2SiO_3 and NaOH were assessed to find the ratio that gave the best overall properties for the geopolymer aggregate.

3.1. Production process

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.

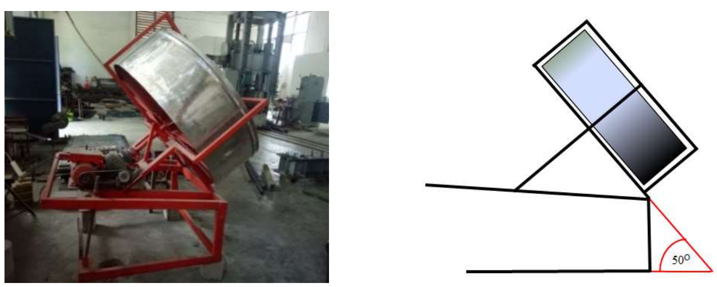


Fig. 2. Granulator for aggregate manufacture.

Figure 3 illustrates the process of making artificial aggregates, from the ingredients used (fly ash and the alkali activator), granulation (geopolymerization) process, to the end-product artificial aggregates ready for further testing. The aggregate production began by 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.

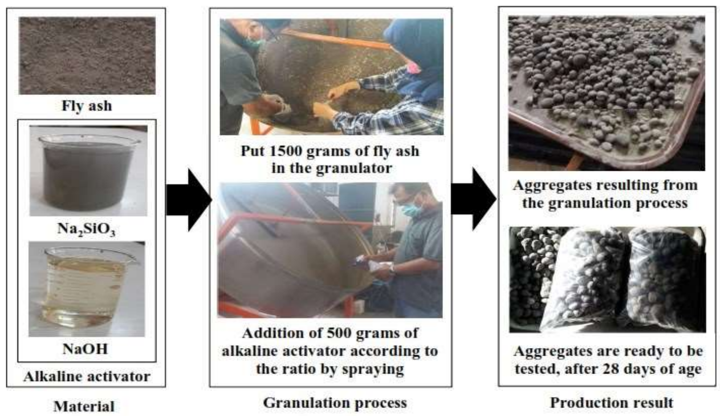


Fig. 3. Aggregate production process.

3.2. Laboratory test program

3.2.1. 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: Absorption, Hardness, Durability, and Strength. The standards, descriptions or significance, designs, and formulas used in the process of analysing data from the test results to obtain properties values are as follows:

- **Absorption**. Absorption testing to SNI 1969: 2008 [27], which refers to ASTM: C 128-04a [28], was adopted. Absorption value represents the weight ratio of water absorbed in the aggregate pore by weight in dry conditions. The technical specification values for absorption as road pavement materials and airfields are <3% [28, 29].
- **Hardness**. The aggregate must be hard enough to resist abrasive action due to constant friction from traffic movements. Hardness value was determined from the Los-Angeles Test, referring to SNI 2417: 2008 [30]. The hardness specification for road pavement material, based on Indonesian standards, is generally <30% [29]. Meanwhile, the hardness for airfield pavement aggregates is <25% [31].
- **Durability.** Durability is the aggregate properties associated with resistance to weathering in service. Durability was obtained by soundness test to SNI 3407: 2008 [32]. The durability value is the percentage of weight crushed to the weight of the original sample. The specification for durability value of road

pavement material, based on Indonesian standards, is typically <12% [29]. Meanwhile, the airfield pavement's specification is set at <10% [31].

- **Strength**. The aggregate used for high-performance pavement surface layers should possess high resistance to crush and withstand stresses induced by wheel loads. This ability depends on the aggregate strength as measured by the impact test, referring to BS 812-112: 1990 [33]. 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].

The effect of ratios of Na_2SiO_3 to NaOH was assessed using an analysis of variance (ANOVA). Univariate One Way ANOVA was chosen because there were one independent variable and the dependent variable [34]. As the free variable (*X*) is the ratio of Na_2SiO_3/NaOH (1.5, 2, 2.5 and 3) while as the dependent variable (*Y*) is the aggregate properties (water absorption, hardness, durability and strength).

3.2.2. The method of determining the aggregate microstructure

Variations in the microstructure of the artificial aggregate made from the geopolymerization process were analysed under a scanning electron microscope (SEM). The SEM analysis was performed at the alkaline activator ratios of 1.5, 2.0, 2.5, and 3.0.

4. Results and Discussion

Discussions on research results include: visual assessment of artificial aggregates, results from laboratory test on aggregate physical properties and the SEM analyses on aggregate microstructure.

4.1. Visual assessment of artificial aggregates

The apparent conditions of the artificial aggregates made at alkaline activator ratios from 1.5 to 3.0 are illustrated in Fig. 4. This figure demonstrates the speed of granulation due to influence from different ratios of Na_2SiO_3/NaOH to the shape of the artificial aggregate. At a ratio of 1.5, the aggregate was not perfectly round, due to slow granulation. At a ratio of 2.0, the geopolymerization process was faster resulting in a more spherical shape. The 2.5 ratios provided relatively more uniform shapes and sizes, with small pores. Whereas, at the 3.0 ratio, the granulation process was very fast resulting in larger, and somewhat oval, granules.

(a) Ratio of 1.5. **(b) Ratio of 2.0.** **(c) Ratio of 2.5.** **(d) Ratio of 3.0.**

Fig. 4. Artificial aggregate at Na_2SiO_3/NaOH ratios.

4.2. Physical properties artificial aggregate

4.2.1. Water absorption

Porosity allows absorption of moisture and/or asphalt binder into aggregates. The latter is known to facilitate the formation of bonds between aggregates and binder and between the aggregate coated binders. Very 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. 5, all mixture combinations did not meet typical specifications for pavement materials. Homogeneity of the results occurs in samples with a ratio of 1.5 and 2.

Meanwhile, the best results on water absorption found in this study were 6.1% for the aggregates produced at the $Na_2SiO_3/NaOH$ ratio of 2.5. Risdanareni et al. [37] found that the smallest pore was obtained at an alkaline ratio of 2.5.

Pore enhancement is proportional to the ratio of alkaline activators. This is consistent with the results of this research, namely the smallest pore or lowest absorption is obtained at an alkaline 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 [38].

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 prevailing specification.

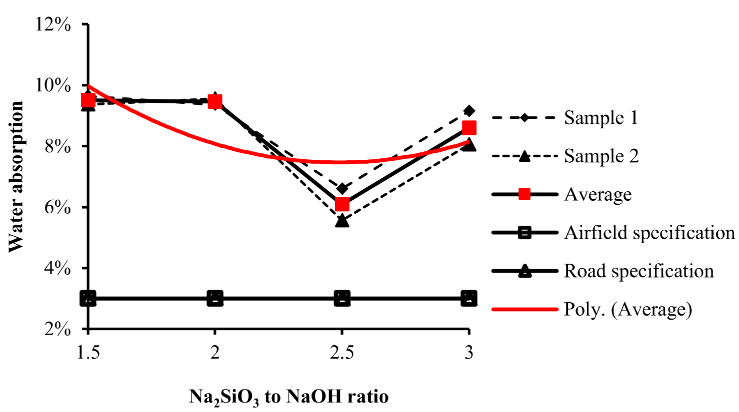


Fig. 5. Value of water absorption to specifications.

4.2.2. Aggregate hardness

Figure 6 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 values below 30%, suggesting that artificial aggregates made from fly ash, with four ratios of Na_2SiO_3/NaOH tested, met the requirements as a road pavement material.

However, for airfield pavement, artificial aggregates made from fly ash, which is activated with a Na_2SiO_3/ NaOH ratio of 3.0, did not meet the requirements, because the hardness value was higher than 25%.

Indeed, airfield pavement materials tend to have more rigorous specification than those for road pavements. This was because the risk associated with materials degradation (disintegration under traffic loading) on airfield pavements will be much higher than that for road pavements.

These results suggest that only artificial aggregate produced with the ratio Na_2SiO_3/NaOH of 1.5, 2.0 and 2.5, which can be used as an airfield pavement material.

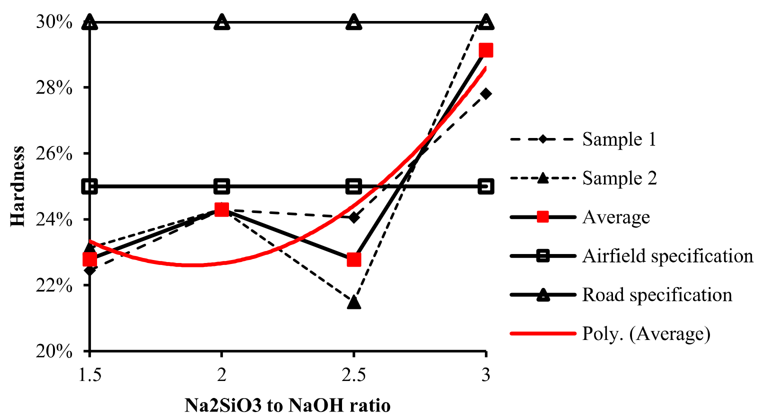


Fig. 6. Value of hardness to specifications

4.2.3. Aggregate durability

The durability of artificial aggregates for all Na_2SiO_3/NaOH ratios fulfils the requirements as road and airfield pavement materials, as shown in Fig. 7. This means that the aggregates are considered to have good resistance to weathering due when used as a pavement material.

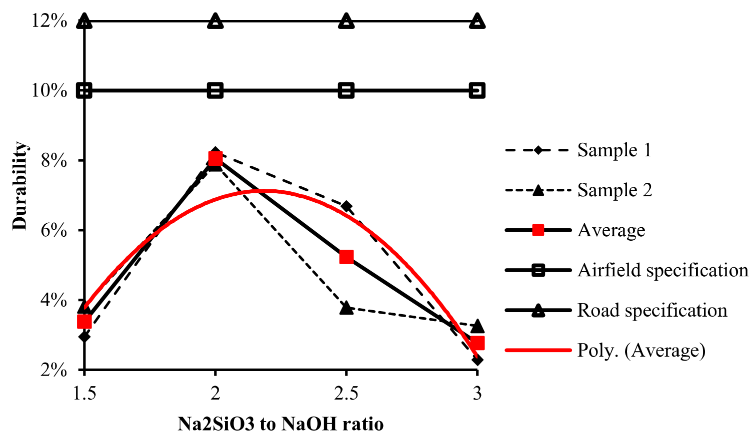


Fig. 7. Value of durability to specifications.

4.2.4. Aggregate strength

Figure 8 shows the Na_2SiO_3/NaOH ratio of 1.5 with the aggregate strength properties reaching 11.9%. This was the best value overall 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. Nevertheless, all results were lower than 30% suggesting that the artificial aggregate would meet the specification requirements for use in airfield pavement.

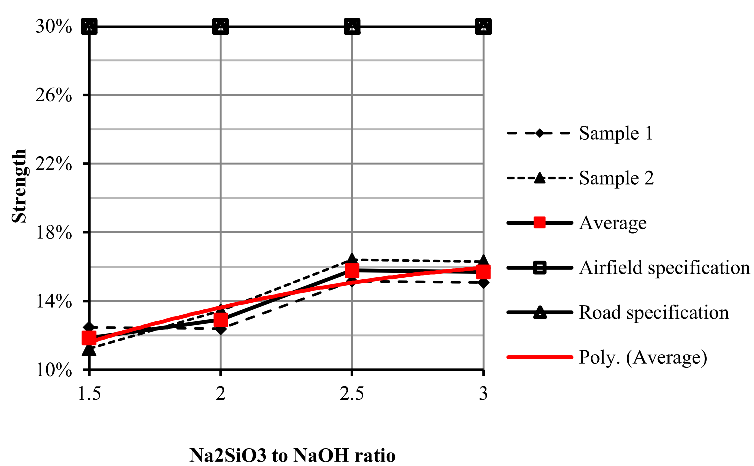


Fig. 8. Value of strength to specifications.

4.3. Artificial aggregate microstructure

The geopolymerization reaction process can be observed from the changes in the shape and apparent condition of fly ash particles. They are often 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 because 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 [39].

The matrix formation reaction in various $Na_2SiO_3/NaOH$ ratios is indicated by the SEM image in Fig. 9. The image is shown in Fig. 9(a) is artificial aggregate samples with a $Na_2SiO_3/NaOH$ 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.

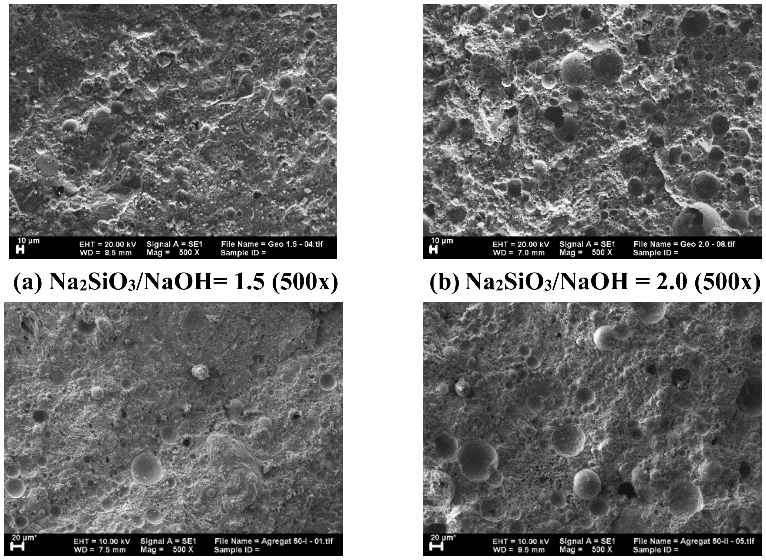
Figures 9(b) and (c), display SEM images for artificial aggregate samples with $Na_2SiO_3/NaOH$ ratios of 2.0 and 2.5. In these ratios, a matrix was well-formed but there were fly ash particles that had not reacted. The diameter size of unreacted fly ash in the image ranged from 10 μm to 21 μm.

The microscopic surface of the SEM image in Fig. 9(d) indicates the reaction of fly ash with alkaline activator on $Na_2SiO_3/NaOH$ ratio of 3.0. The aluminosilicate reaction that occurred is indicated by the changes in spherical fly ash. The more perfect the reaction was, the more dissolution of spherical fly ash particles occurred. 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.

In this SEM image, cracks appeared to be greater than other $Na_2SiO_3/NaOH$ ratios. It could be seen that the mixtures were denser and lack of liquid. In this case, shrinkage occurred 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 in the SEM images of the experiment result, a good reaction between particles of fly ash and alkaline activators occurred. In round fly ash particles called cenospheres, destruction occurred, forming aluminosilicate [16, 17, 40]. 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 [18].



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

5. Effect of Alkaline Activator Ratio on Artificial Aggregate Properties

The results of ANOVA analysis in Table 3, show the effect of various alkaline ratios (Na_2SiO_3/ NaOH) on the properties of artificial aggregate geopolymer fly ash. Table 3 shows that for all properties with a variation of the Na_2SiO_3 / NaOH ratio, the F critical value is smaller than the calculated F. This means that based on the results of testing all aggregate properties are significantly affected by the Na_2SiO_3/NaOH ratio [34].

Table 3. 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				

6. 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. The results of the experimental data analysis show that the aggregate properties made with four variations ratio activators alkaline met specifications as road and airfield pavement materials, except their absorption properties. The latter, however, have been compensated by good results on durability and resistance to weathering (soundness test), therefore the artificial aggregate was deemed suitable for use as road and airfield pavement materials. Further technical details are reproduced below:

- The aggregate absorption value was > 3% for all Na_2SiO_3 to NaOH ratios. The recommended optimal ratio of Na_2SiO_3 and NaOH is 2.5 because it has the smallest absorption value. In practice, these high-water absorption values can be acceptable where the aggerates passed the criteria for durability and resistance to weathering.
- The artificial aggregates met the criteria for durability and resistance to weathering (soundness test) for use as road and airfield pavement materials.
- The aggregates made with the Na_2SiO_3 to NaOH ratios of less than 3.0 met the requirements of hardness properties for road and airfield pavement materials. A ratio above 3.0, the aggregate is only suitable for road pavement.
- The fly ash reaction to the alkaline activator seen from the SEM analysis results shows the similarity of the geopolymerization reaction for all ratios, but the best reaction occurs at a ratio of 1.5, which gives the best properties for strength and hardness.
- Further research is required to optimize and validate the design such as by installation of a larger-scale field trial, to produce artificial aggregate products that meet all the requirements for construction works.

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Abbreviations

ANOVA	Analysis One Variance
ASTM	American Standard Testing and Materials
Na_2SiO_3	Sodium Silicate
NaOH	Sodium Hydroxide
SNI	Standard Nasional Indonesia

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