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Potential utilization of natural zeolite, fly ash and rice husk ash for geopolymer concrete production

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Abstract

Purpose. The experimental research purpose is to study the potential use of natural zeolite, fly ash, and rice husk ash for geopolymer concrete production based on the effect of the Al/Si ratio on microstructure properties and compressive strength.

Methods. The formulation process is based on the ratio of Al/Si contained in the raw material, the selection of raw material grain size, mixing and molding of the geopolymer concrete. The geopolymer concrete properties are analyzed in terms of compressive strength and microstructure properties.

Findings. Fly ash, natural zeolite and rice husk ash can be used to produce new functional materials in the form of geopolymer concrete with a compressive strength of up to 16.74 MPa. The mixing formula is based on the ratio of Al/Si contained in the raw materials, and their ratio is 1:2; 1:2.5; 1:3; 1:3.5 and 1:4. Geopolymer concrete specimens showed the required physical and mechanical properties.

Originality. The originality of this research lies in the utilization of natural zeolite, fly ash, and rice husk ash as raw materials for geopolymer concrete production. This approach offers a practical solution by utilizing these common and readily available materials, rich in silica and alumina, to produce functional and environmentally friendly building materials.

Practical implications. This research can provide a practical solution to the problem of natural zeolite, fly ash, and rice husk ash rich in silica and alumina, which can be utilized for geopolymer concrete production. Thus, geopolymer concrete can mainly be utilized as a building material for laying walls and floors in pedestrian areas and parks or for other purposes.

Keywords: *concrete, fly ash, geopolymer, rice husk ash (RHA), natural zeolite*

1. Introduction

One of the main components in construction throughout the world is heavily dependent on Portland cement products. The production of Portland cement requires very high temperatures and releases large amounts of carbon dioxide, which leads to air pollution. Structural members, walls and panels are usually made of Portland cement [1]. Portland cement production requires a significant amount of energy, while generating about 5% of greenhouse gases annually [2]. Each production of one ton of Portland cement releases one ton of CO_2 into the air [3]. An alternative technology is needed to reduce the use of Portland cement concrete. Various studies have been conducted on the manufacture of concrete by utilizing geopolymer properties. Silica and alumina mixed in high activator solutions are new cement materials to be developed in the Portland cement production. Geopolymer is an environmentally friendly concrete that may become an alternative to conventional concrete in the future.

According to Davidovits [4], geopolymers can be defined as "materials produced from polymeric aluminosilicate and alkali-silicate which produce a polymer framework of SiO_4 and AlO_4 tetrahedral bound". Fly ash is a potential raw material for geopolymers, thanks to the presence of SiO_2 and Al_2O_3 as the main components [5]. New materials needed as an alternative in the world of construction, geopolymer based on fly ash, can use as a new cement alternative [6]. In addition, to fly ash, other materials used in the manufacture of geopolymers are zeolites, rice husk ash, and alkaline-activator solution. The geopolymerization reaction can be classified as an inorganic polycondensation reaction as the reaction of zeolite formation. Most of the zeolite synthesis is also carried out under alkaline conditions using OH – as a mineralizing agent [7]. According to van Jaarsveld et al. [8], alkali metal salts and/or hydroxides must dissolve the silica and alumina as catalysis reactions in the condensation reaction. Geopolymer material with lower Ca content has better acid resistance than the material from portland cement [9]. Geopolymers have attracted much attention for good mechanical properties, good chemical resistance, low shrinkage, eco-friendly and long endurance [10].

RHA can use in the appropriate amount as an additive in the manufacture of geopolymers [11]. Zeolite can remove Formaldehyde, benzene, and n-hexane from the air contained in the room [12]. The addition of 5A zeolite to geopolymers can apply in building materials with the advantage of being able to purify indoor air [13]. Sodium hydroxide (NaOH) and

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potassium hydroxide (KOH) are the most commonly used alkali-activators [14]. Fly ash (Class F) is a good source of raw materials in geopolymer production, and from some FA activators, NaOH is the best in geopolymer production [15]. Additionally, the use of NaOH and sodium silicate (Na_2SiO_3) together will result in higher geopolymer compressive strength compared to only the use of NaOH [16]. According to Zhuang et al. [17], the basic principle of forming geopolymers based on fly ash is the decomposition of aluminosilicate due to the presence of alkali in fly ash, which then occurs polycondensation. This process is a clean technology that saves energy and resources because reactions can occur under mild temperatures. However, the real reactions that happened in the process are very complicated and remain elusive. A reaction between fly ash and alkali produces condensation between Si^{4+} and Al^{3+} types; this process is followed by complicated nucleation, oligomerization, and polymerization. It then provides a polymer with a new aluminosilicate-based amorphous three-dimensional network structure. For testing or use, geopolymer paste cast into the mold, then oven at a predetermined temperature as needed or placed at room temperature to be cured for a specific time.

The Si/Al ratio significantly determines the structure of the geopolymer material [18]. For example, the critical parameter that determines the geopolymer product's compressive strength is the porosity (size and quantity) of the amorphous geopolymer, which is greatly influenced by the Si/Al ratio of the fly ash reactants [19], [20]. The purpose of this work is to know the effect Al/Si ratio on the microstructure properties and compressive strength of fly ash, zeolite, and rice husk ash-based geopolymer.

2. Material and methods

2.1. Materials

Fly ash (FA), natural zeolite, and rice husk ash were used to prepare the geopolymers in this study. The fly ash was collected from a coal-fired power plant in Palabuhanratu, Sukabumi, Indonesia. The natural zeolite was obtained from the Cikembar region, Sukabumi, Indonesia, and the rice husk ash was collected from the Simpenan region, Sukabumi, Indonesia. The specific gravity of fly ash ranges from 2.0-2.5 g/cm^3, while zeolite has a specific gravity of 2.0-2.4 g/cm^3, and the specific gravity of RHA ranges from 1.90-2.7 g/cm^3. NaOH 8M and Na_2SiO_3 were used as the alkali-activator solution. The comminution process using jaw crusher and pulverizer was performed on zeolite to obtain the size fraction of -40 + 80 mesh. The materials used in the experiments are shown in Figure 1.

Chemical compositions of FA, zeolite, and RHA were determined by Atomic Absorption Spectrophotometer (AAS) technique in the National Research and Innovation Agency (BRIN) laboratory using AA-7000 Atomic Absorption Spectrophotometer Serial No. A306648, as shown in Table 1. The sum of the chemical compositions of SiO_2, Al_2O_3, and Fe_2O_3 for zeolite, RHA, and FA was over 75%, respectively, which was following the requirement of ASTM C618 [21].

Fly ash used in this study was a type F because it contains low calcium, i.e., less than 10% CaO (ASTM C618). The X-ray Diffractometer (XRD) analysis of each material was performed using XRD-7000, Shimadzu, X-Ray Diffractometer, and the results are shown in Figure 2.

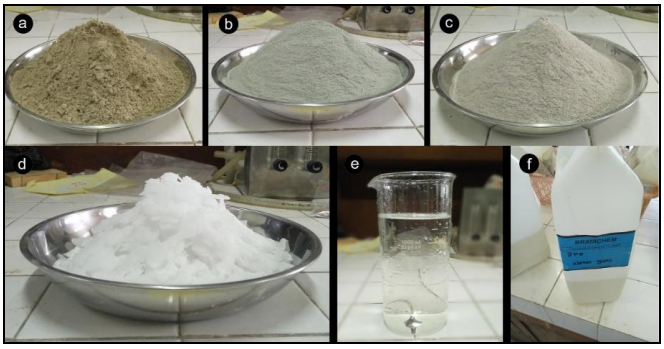

Figure 1. The materials used in the experiments: (a) fly ash; (b) zeolite; (c) rice husk ash; (d) NaOH; (e) water; (f) sodium silicate

Table 1. Chemical composition of zeolite, rice husk ash, and fly ash

Chemical analysis	Zeolite (wt. %)	RHA (wt. %)	FA (wt. %)
Siliconedioxide (SiO_2)	67.65	87.48	48.96
Titanium dioxide (TiO_2)	0.57	0.27	1.47
Alumunium trioxide (Al_2O_3)	11.27	1.66	26.38
Iron trioxide (Fe_2O_3)	1.02	0.99	9.82
Manganase oxide (MnO)	0.05	0.1	0.85
Magnesium oxide (MgO)	0.15	0.24	0.59
Calcium oxide (CaO)	0.03	-	0.29
Potassium oxide (K_2O)	1.73	2.76	0.51
Sodium oxide (Na_2O)	2.65	0.14	1.51
Phosphoric (P_2O_5)	0.48	1.53	6.76
Moisture content (H_2O-)	8.02	2.06	0.58
Volatile content (H_2O+)	3.35	2.15	1.61
LOI (Ignition loss)	14.23	4.66	2.75

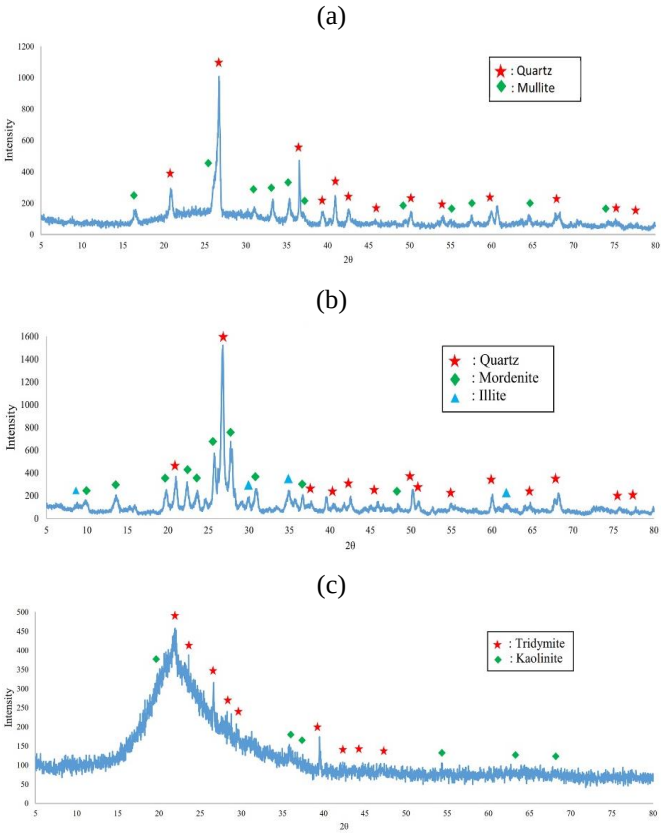

Figure 2. XRD patterns of fly ash, zeolite and rice husk ash: (a) fly ash; (b) zeolite; (c) rice husk ash

The XRD analysis showed that fly ash consists of two main crystalline phases: quartz and mullite, zeolite composed of three main crystalline phases of quartz, mordenite, and illite, while rice husk ash comprises an amorphous phase with tridymite and kaolinite crystalline phases. The burning of rice husks is carried out using a furnace, with a 500-600°C temperature for 2 hours. The temperature is lowered to 200-100°C, then decreased until it reaches room temperature.

The Scanning Electron Microscope (SEM) observation was conducted at the Laboratory of Geological Survey Institute of Indonesia by using a JEOL JSM-6360LA Analytical Scanning Electron Microscope. SEM analysis results at a magnification of 1000 times are shown in Figure 3.

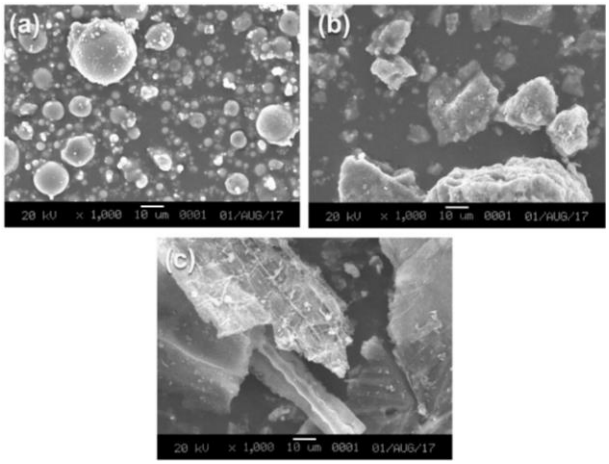

Figure 3. SEM images of (a) fly ash 1000X magnification; (b) zeolite 1000X magnification; (c) rice husk ash 1000X magnification

The SEM analysis results show that fly ash is mostly spherical with a relatively smooth surface, while the morphological form of the zeolite material appears crystallized and the cubic shape and the morphological structure of rice husk ash is irregular and porous.

2.2. Methods

In this research, five geopolymer compositions were used to know the influence of the ratio of Al/Si on the microstructure properties and compressive strength. The mixing formula was based on the ratio of Al/Si contained in raw materials, and their ratio was 1:2; 1:2.5; 1: 3; 1:3.5 and 1:4. The specimens were made with the following raw materials: fly ash (-100 mesh), RHA (-50 mesh) and zeolite (-40 + 80 mesh). The geopolymer concrete test objects were coded as BG-1, BG-2, BG-3, BG-4, and BG-5.

The geopolymer concrete mixture/composition formulation made in this study is shown in Table 2.

Table 2. Mixture proportions for the preparation of geopolymers

Sample code	Zeolite, (%)	RHA, (%)	FA, (%)	Ratio Al/Si	Alkaline-activator		Water, (%)	w/b ratio
					Sodium silicate (%)	NaOH (8M) (%)		
BG-1	10	15	75	1:2	57	23	20	1:4
BG-2	20	15	65	1:2.5	57	23	20	1:4
BG-3	30	15	55	1:3	57	23	20	1:4
BG-4	45	15	40	1:3.5	57	23	20	1:4
BG-5	60	15	25	1:4	57	23	20	1:4

Mixing and molding of geopolymer concrete materials used Indonesian National Standard (SNI) 2493: 2011 [22] method on "Procedure of concrete manufacture and maintenance of concrete specimens in the laboratory". The curing time to perform a compressive strength test was 28 days. After the formulation of the geopolymer concrete composition and calculation of the volume of materials required to create the geopolymer concrete, then the casting process of geopolymer concrete test specimens on cylinder molds of 45×90 mm size was carried out. The making process of geopolymer concrete was begun by making an alkaline activator solution of sodium silicate, NaOH, and water. Water and NaOH were mixed and stirred until it was dissolved for ±5 minutes. Sodium silicate was introduced into the aqueous solution and NaOH, and they were stirred for ±5 minutes. The solid materials (FA, zeolites, and RHA) were gently inserted into an alkaline activator solution, which was then stirred at a moderate to homogenous rate (±5 minutes). The paste formed was then poured into the cylinder mold in 3 stages (1/3 of the first part was compressed using iron rods, the second 1/3 was also compacted using the iron rod, and then the last 1/3 was too crammed by using the iron rod). The molded sample was then immobilized at room temperature and was covered using a thin plastic to prevent moisture loss in the sample for 24 hours. After 24 hours, the sample was removed from the mold, and then two types of the curing process, i.e.: (1) dried at room temperature; (2) heated by oven at 60°C gradually for 24 hours, were performed. After the curing process, a compressive strength test was performed after the test object of geopolymer concrete aged 28 days.

A compressive strength test was performed on all geopolymer concrete specimens after curing for 28 days. Compressive strength tests were performed based on the Indonesian Standard of SNI 1974-2011 [23] at the Laboratory of Center for Material and Technical Product, Bandung, Indonesia. The tools used in this test were Unitester C21-Controls CAT-21E. Three samples of each mixture proportion were subjected to the test with the final results reflecting the average values recorded for each ratio.

3. Results and discussion

The result of casting off the geopolymer concrete test object has shown that for all formulations, the geopolymer concrete can be formed into a good precision concrete and it can be released from the mold quickly without any damage to the cross-section of the concrete specimen (Fig. 4).

Figure 4. Geopolymer concrete specimens

Visual evaluation of the geopolymer concrete specimens obtained perfect cylindrical results; the prototype did not experience cracks after being cast, and the geopolymer concrete specimens were not damaged.

3.1. Compressive strength of geopolymer concrete

The compressive strength test results carried out on the geopolymer concrete test specimen by curing process at room temperature, and temperature 60°C are shown in Figures 5 and 6, respectively. The compressive strength test results show that the highest value of compressive strength in the experiment with curing process at room temperature obtained by geopolymer concrete test object with code BG-3 (Al/Si ratio 1:3), i.e., 15.02 MPa. The lowest compressive strength value obtained by geopolymer concrete test object with code BG-5 (ratio Al/Si 1:4) is 6.13 MPa. As for other geopolymer concrete test object the values of compressive strength are as follows: code BG-1 (ratio Al/Si 1:2) is 13.07 MPa, code BG-2 (ratio Al/Si 1:2.5) is 12.72 MPa, the code BG-4 (ratio Al/Si 1:3.5) is 13.49 MPa.

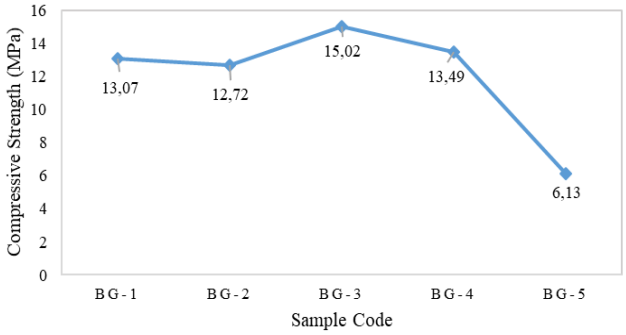

Figure 5. Compressive strength development of the geopolymer samples wit h the curing process at room temperature

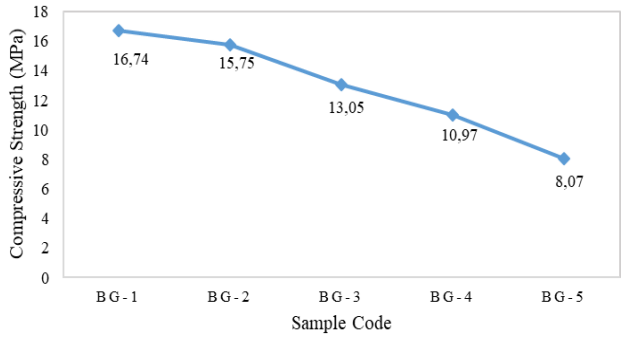

Figure 6. Compressive strength development of the geopolymer samples with the curing process at 60°C

The experimental compressive strength test results with the curing process at 60°C show that the highest value was obtained by geopolymer concrete test object with code BG-1 (ratio Al/Si 1:2), i.e., 16.74 MPa. The lowest compressive strength value was obtained by geopolymer concrete test object with code BG-5 (ratio Al/Si 1:4) i.e., 8.07 MPa. As for other geopolymer concrete test object the values of compressive strength are as follows: BG-2 code (ratio Al/Si 1:2.5) i.e. 15.75 MPa, code BG-3 (ratio Al/Si 1:3) i.e. 13.05 MPa, code BG-4 (ratio Al/Si 1:3.5) i.e. 10.97 MPa. The test results of the compressive strength of the geopolymer concrete test object showed that Al/Si's ratio influenced the compressive strength value of each geopolymer concrete test specimen.

The results of previous studies stated that the ratio of Si/Al and Na/Al at a value of 1.8-2.2 and 0.9-1.2 in geopolymer formulations could achieve a high compressive strength [24]. Davidovits [25] explained that the structure of amorphous geopolymers was originally proposed as polysialate (-Si-O-Al-O-), polysialate-siloxo (Si-O-Al-O-Si-O), and polysialate-disiloxo (Si-O -Al-O-Si-O-Si-O) when the Si/Al ratio is 1, 2, and 3, respectively. However, geopolymers can also be formed at Si/Al ratios higher than 3, and this is caused by extensive aluminosilicate, high Si content, and silicates used as alkali activators [10].

The formation of a long and complex chain of silicate oligomers and silicates' addition resulted in an increased geopolymer structure [26]. In comparison, some studies stated that soluble silicates' addition could not induce fundamental changes in the structure of geopolymers [10], [20]. Duxon et al. [20] reported that mixtures with SiO_2/Al_2O_3 ratio higher than 3.8 cause compressive strength to decrease with time; this happens occasionally and is influenced by mixed proportions. The test results of the compressive strength of the geopolymer concrete test object also showed that the curing temperature affects each geopolymer concrete test specimen's compressive strength value. Curing temperature has a significant effect on compressive strength development because it affects samples setting and hardening [27].

The geopolymerization process will increase curing specimens at initial temperatures between 45 and 95, resulting in a high compressive strength [9], [10], [28]. Geopolymer concrete shows optimal engineering properties after curing at 60 for 24 hours [29]. Fly ash experiences a prolonged reaction at room temperature [30]. The compressive strength of the sample BG-3 at room temperature curing process has increased compared to BG-1 and BG-2 compositions. The composition of BG-3 in this study consisted of 30% zeolite, 15% RHA, and 55% FA (Al/Si ratio 1:3). Increased compressive strength is likely due to the curing process at room temperature resulting in slower compressive strength progression so that the composition of BG-3 produced a higher value of compressive strength. The improvement of compressive strength may have resulted from the macroaggregates effect of fine zeolite particles [13]. With the addition of zeolite, micro aggregate zeolite particles can increase the level of geopolymerization so that the geopolymer specimen increases its compressive strength [13]. The higher surface area of zeolite gives it more opportunity to interact with the geopolymeric phase [31].

3.2. XRD analysis of geopolymer concrete

X-Ray Diffractometer analysis is one of the qualitative and semi-quantitative analysis. Qualitative research is used to determine the type of crystalline compound present in the specimen. The geopolymer concrete test object was prepared and ground to -200 mesh, and then XRD analysis was performed. XRD analysis results of geopolymer concrete tests performed by curing at room temperature and temperature of 60°C are shown in Figure 7, respectively.

The results of the XRD analysis of geopolymer concrete samples performed by curing process at room temperature and temperature of 60°C (Fig. 7) indicate that the main crystalline phases are quartz, mullite, and illite, which form the main mineral framework and are responsible for the mechanical strength of geopolymer concrete samples. The presence of sharp quartz and cristobalite peaks in the XRD pattern of geopolymer samples originating from FA and RHA, respectively, shows that the geopolymerization process involves a crystalline phase and is not reactive in the system [32]. Around the value of 2θ at an angle of 26.7° in succession from each XRD pattern of geopolymer concrete samples forming rising peaks, which may affect the geopolymer concrete's mechanical properties.

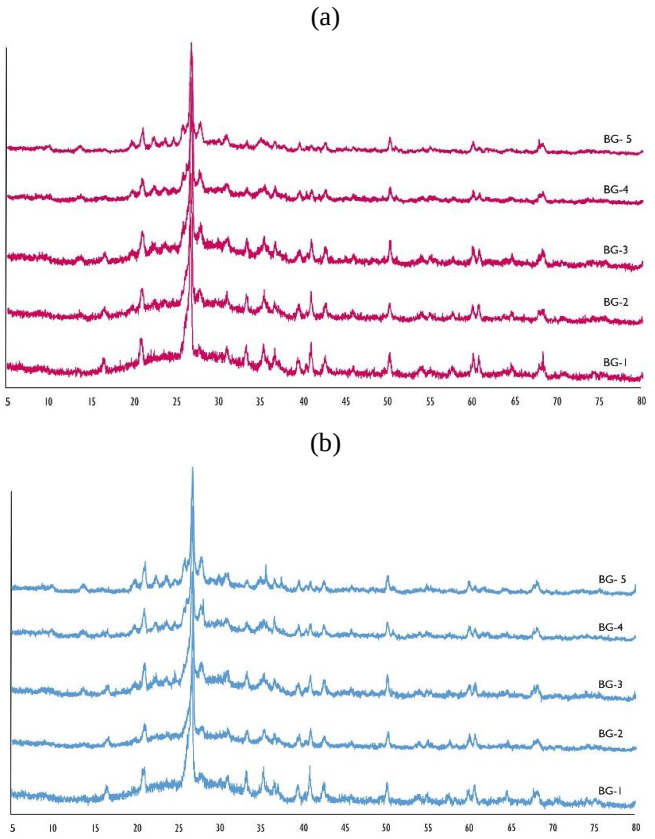

Figure 7. XRD patterns of: (a) geopolymer samples with curing process at room temperature; (b) geopolymer samples with curing process at 60°C

Increased water demand in concrete is influenced by illite and montmorillonite, with each different percentage resulting in reduced concrete's strength [33].

3.3. SEM analysis of geopolymer concrete

Microstructure study on geopolymer concrete using SEM analysis is a method to determine the quality of pores in the matrix of geopolymer concrete, which can affect the concrete's ability to maintain and distribute external loads [34].

The SEM analysis results on the geopolymer concrete sample made by the curing process at room temperature are shown in Figure 8. In Figure 8a (BG-1 sample), the raw material of geopolymer concrete in the form of fly ash, zeolite, and rice husk ash are seen evenly in all parts of geopolymer concrete. Besides, a new phase of silica has resulted from the reaction of geopolymerization between the raw material of the geopolymer concrete with the alkaline solution (i.e., sodium silicate and NaOH) used. There are voids in the BG-1 sample, which will affect the compressive strength of the geopolymer concrete. Likewise, the BG-2 sample, as shown in Figure 8b, is not much different compared to the BG-1 sample, except for the appearance of tapered silica in the BG-2 sample.

In BG-1 and BG-2 samples, there are unreacted fly ash feedstocks that will affect the geopolymer concrete's mechanical properties. The BG-3 sample (Fig. 8c) has the same tendency as BG-1 and BG-2 samples. Only in the BG-3 sample, a compact geopolymer bond is formed, giving high compressive strength. In the BG-4 sample (Fig. 8d), the denser structure is seen. Still, it is also apparent that unreacted fly ash material has appeared, which will decrease the geopolymer concrete's mechanical properties.

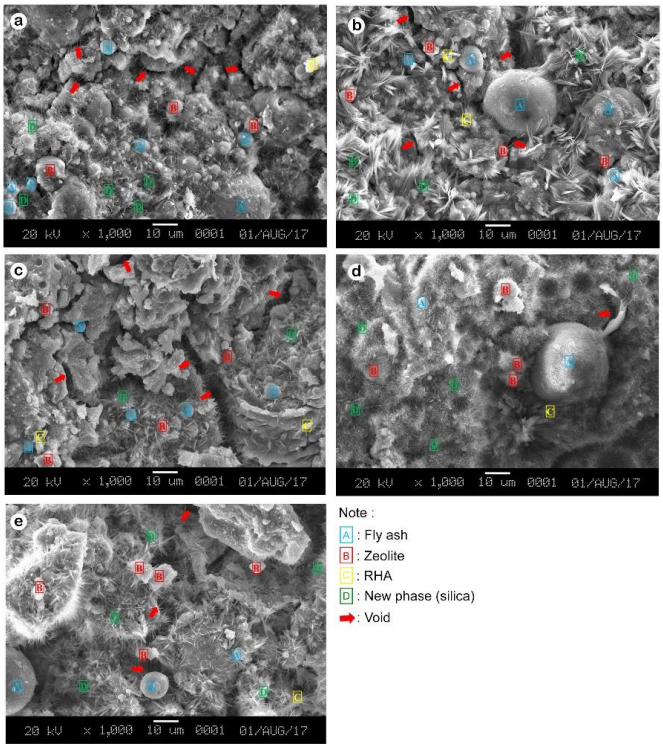

Figure 8. SEM images of geopolymer samples with curing process at room temperature: (a) BG-1; (b) BG-2; (c) BG-3; (d) BG-4; (e) BG-5

In the BG-5 sample (Fig. 8e), the geopolymer concrete material has not reacted entirely so that the geopolymerization process is also not working correctly result in low mechanical properties.

SEM analysis on the geopolymer concrete samples conducted by the curing process at 60°C is shown in Figure 9. As shown in Figure 9a (BG-1 sample), the raw material for the concoction of geopolymer, i.e., fly ash, zeolite, and rice husk ash, are seen evenly in all geopolymer concrete sections. The void formed in the BG-1 sample is shallow, and there is also an elongated geopolymer bond that will affect the high compressive strength of the geopolymer sample. BG-1 sample is a sample of geopolymer concrete with the highest compressive strength value compared to other samples.

In the BG-2 sample (Fig. 9b), voids are started to form results in a lower compressive strength value compared to the BG-1 sample (Fig. 9a). The fly ash has not reacted entirely in the BG-2 sample, but the unreacted fly ash size is not as large as the geopolymer concrete sample's size through curing at room temperature (Fig. 8b). This is probably due to the heating process at 60°C. In the BG-3 sample (Fig. 8c), it also contains a large number of voids. The constituents also appear to have reacted completely, and new phase (silica) is only formed in some parts of the sample. In the BG-4 sample (Fig. 9d), the structure is formed tightly in some parts of the sample, but quite large voids are also formed, resulting in the low mechanical properties of the geopolymer concrete.

In the BG-5 sample (Fig. 9e), the zeolite appears dominant, and voids are also formed in some parts. The ash of rice husk (RHA) is seen to be very small; this is probably because it has reacted with other constituent materials. The increasing amount of unreacted material in geopolymer concrete will result in a looser geopolymer structure related to the higher percentage of RHA.

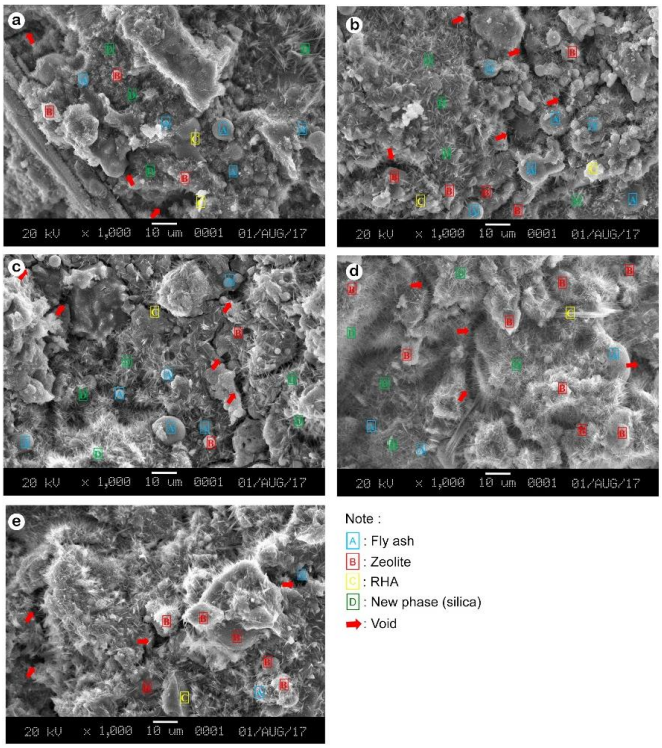

Figure 9. SEM images of geopolymer samples with curing process at 60°C: (a) BG-1; (b) BG-2; (c) BG-3; (d) BG-4; (e) BG-5

Chemical reactions from solids that take place incomplete in an alkaline environment cause many particles in the geopolymer not to react [15]. According to Assi et al. [35], it was reported that the presence of a void is due to the different grain size distribution between the raw materials of the geopolymer. The fine grain size will lead to higher polymerization rates due to the massive material surface area. Voids are also caused by fly ash particles' presence isolated in the activator solution (sodium silicate and NaOH), inhibiting the polymerization process. According to Hwang and Huynh [15], observation on the geopolymer sample's surface clearly shows the presence of a porous microstructure that is not homogeneous with micro-cracks and voids. These cracks occur due to (1) evaporation of water during the curing process, which causes shrinkage cracks, and or (2) the presence of loads formed during compression testing. The voids in the geopolymer sample formed due to several possibilities (1) during the initial mixing process, there are residual air bubbles that inserted into the geopolymer, and (2) in the initial process, space is occupied by water, but then becomes voids because of the drying process so that the water evaporates.

4. Conclusions

Based on the results of this research, it can be concluded as follows. Fly ash, zeolite, and rice husk ash raw materials with sodium silicate binder and NaOH can be formed into new functional materials in the form of geopolymer concrete, increasing the materials' added value used; The ratio of Al/Si affects the compressive strength and microstructure of the geopolymer concrete. The highest value of compressive strength (i.e., 16.74 MPa) was achieved by geopolymer concrete, which experienced a curing process at 60°C with an Al/Si ratio of 1:2.

In contrast, geopolymer concrete, which was cured at room temperature with an Al/Si ratio of 1:4, achieves the lowest value (i.e., 6.13 MPa); The curing temperature has a significant effect on compressive strength as it affects specimen settings and hardening; Voids formed on geopolymer concrete will affect the mechanical properties of the geopolymer concrete. The larger and higher percentages of voids formed, the lower the mechanical properties of the geopolymer concrete. Geopolymer concrete specimens showed the required physical and mechanical properties. Thus, geopolymer concrete can principally be utilized as a building material for wall installation and floor installation for pedestrians and parks or other uses.

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Потенційні можливості використання природного цеоліту, золи-виносу та золи рисового лушпиння для виробництва геополімерного бетону

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Мета. Експериментальне дослідження потенційних можливостей використання природного цеоліту, золи-виносу та золи рисового лушпиння при виробництві геополімерного бетону на основі впливу співвідношення Al/Si на властивості мікроструктури й міцності на стиск.

Методика. Хімічні матеріали визначали методом атомно-абсорбційного спектрофотометра AA-7000. Рентгенодифрактометричний (XRD) аналіз кожного матеріалу був виконаний з використанням XRD-7000 визначення мінералогічного складу. Спостереження структури виконано за допомогою електронного скануючого мікроскопа JEOL JSM-6360LA. У цьому дослідженні використовувалися п'ять геополімерних композицій, щоб дізнатися про вплив співвідношення Al/Si на властивості мікроструктури і міцність на стиск.

Результати. Встановлено, що зола-винос, природний цеоліт і зола рисового лушпиння можуть бути використані для виробництва нових функціональних матеріалів у вигляді геополімерного бетону з межею міцності при стисканні до 16.74 МПа. Визначено, що формула змішування базується на співвідношенні Al/Si, що міститься в сировині, і їх співвідношення становить 1:2; 1:2.5; 1:3; 1:3.5 і 1:4. Доведено, що зразки геополімерного бетону мають необхідні фізико-механічні властивості.

Наукова новизна. Оригінальність цього дослідження полягає у використанні природного цеоліту, золи-виносу та золи рисового лушпиння як сировини для виробництва геополімерного бетону. Цей підхід пропонує практичне рішення, використовуючи ці поширені та легкодоступні матеріали, багаті кремнеземом та глиноземом, для виробництва функціональних і екологічно чистих будівельних матеріалів.

Практична значимість. Це дослідження може забезпечити практичне вирішення проблеми природного цеоліту, золи-виносу та золи рисового лушпиння, багатої кремнеземом і глиноземом, які можна використовувати для виробництва геополімерного бетону. Таким чином, геополімерний бетон в основному може бути використаний як будівельний матеріал для кладки стін і підлоги в пішохідних зонах і парках тощо.

Ключові слова: *бетон, зола-винос, геополімер, зола рисового лушпиння, природний цеоліт*