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Modeling the water absorption and compressive strength of geopolymer paving block: An empirical approach

Jonbi Jonbi [a], Mohamad Ali Fulazzaky [b,c,*]

[a] Department of Civil Engineering, Faculty of Engineering, Universitas Pancasila, Indonesia

[b] Department for Management of Science and Technology Development, Ton Duc Thang University, No.19 Nguyen Huu Tho Street, Tan Phong Ward, District 7, Ho Chi Minh City, Viet Nam

[c] Faculty of Environment and Labour Safety, Ton Duc Thang University, No.19 Nguyen Huu Tho Street, Tan Phong Ward, District 7, Ho Chi Minh City, Viet Nam

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ABSTRACT

The use of fly ash as a cement substitute may reduce the increasing cement demand and prevents an increased emission of carbon dioxide (CO_2) into the atmosphere. This study aims to produce some compositions of geopolymer paving block (GPB) using different ratios of NaOH/Na_2SiO_3 combined with fly ash. The empirical models were developed to predict the performance of the GPB samples through the verification of the water absorption and compressive strength. The results showed that an optimum performance of GPB sample is predicted for the NaOH/Na_2SiO_3 ratio range of 0.4 to 0.67 to be verified at 28 d of the GPB age. The hardness of GPB sample rapidly increases by using a high enough concentration of NaOH in activator leading to significantly increase the compressive strength of paver block. A new approach of predicting the GPB performance has been proposed to support development of pavement construction in civil engineering industry.

1. Introduction

The cement industry plays an important role in supporting the increase of carbon dioxide (CO_2) into the atmosphere. It is predicted that every ton of ordinary Portland cement produced can release approximately 900 kg of CO_2 [1]. Cement production can be classified as one of the primary sources of CO_2 emissions accounting for about 4% of global warming and releases approximately 5–6% of all CO_2 generated by the human activities [2]. Cement production has been estimated at about 1.5 billion metric tons in 2015 and at about 2.4 billion metric tons in 2018 [3]. China produces the most cement globally covered over half of the world's cement production by a large margin at an estimation of 2.4 billion metric tons in 2018, followed by India at 290 million metric tons, and then by the United States at 88.5 million metric tons in the same year [1,2,4]. Without efforts to reduce demand, the production of cement is estimated to grow annually and will cause an increase in the CO_2 emissions into the atmosphere. On the other side, Indonesia as the 5th top coal producer in the world produces approximately 263 million tons of hard coal and 38 million tons of brown in 2009 [5]. A coal-fired power station produces electricity by burning coal and also produces an abundance of fly ash as a waste byproduct of power generation plant released in the area of thermal power station. It is suggested that the development of geopolymer paving block (GPB) using fly ash is an excellent alternative to overcome the abundant fly ash in Indonesia and may reduce the demand for cement.

A significant advance of the civil engineering industry may occur in the area of admixture technology with the development of GPB concrete by using a waste byproduct material. In spite of the ordinary paving block used cement as a binder can adhere to other materials to bind them together [6], the development of GPB concrete used fly ash as a binder instead of cement may adhere to other materials of gravel, sand, and water to form a typical precast concrete for use by its typical application. The use of geopolymer materials may represent an innovative technology and is considerably interested in the civil engineering industry, particularly in light of the ongoing emphasis on the material research for environmental sustainability.

An abundant quantity of fly ash in Indonesia must be used in a variety of engineering applications and would otherwise be destined annually for disposal as waste. The chemical composition of coal fly ash includes silica, alumina, iron oxide, calcium oxide, and magnesium oxide and is commonly characterized by the major constituents of silica (SiO_2) and alumina (Al_2O_3) [7]. Any source of SiO_2 and Al_2O_3 in fly ash dissolves in an alkaline solution and there-

* Corresponding author at: Ton Duc Thang University, Ho Chi Minh City, Viet Nam.

E-mail address: mohamad.ali.fulazzaky@tdtu.edu.vn (M.A. Fulazzaky).

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fore can act as geopolymer precursor and geopolymerise during the fabrication of precast concrete [8]. The use of fly ash as a cement substitute must be optimized to develop an effective high potential of geopolymer for use in the mixture of GPB concrete. Fly ash can be activated using an alkaline solution by mixing sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3) as catalyst [9]. The use of fly ash as a coal combustion waste to produce the various forms of GPB concrete may reduce CO_2 emission into the atmosphere. Therefore, fly ash as a waste byproduct can be recycled for use in the civil engineering industry to avoid costly contamination of the power generation waste.

The increasing demand for typical precast concrete of paving block to hardening the parking lot for many vehicles in the cities has further driven the market in civil engineering industry. The use of paving block in the pavement construction is considered environmentally friendly technology based on its working capability and can help preserve the environment through effectiveness and efficiency of the groundwater conservation and the reduction of the harmful waste. The concrete block pavement technology can be used to develop many kinds of paving blocks, which are easily installed and maintained, and ensures the reliability of the paving blocks to set the most competitive price in the market.

Many different types of the mathematical models have been developed to provide a theoretical understanding of the behavioral change. The development of the mass transfer factor models by Fulazzaky [10] has been used to study the adsorption kinetics of atrazine and simazine on granular activated carbon in hydrodynamic column [11] and the isotherm adsorption of Cd(II) ions onto the beads of titania polyvinylalcohol-alginate in batch experiment [12]. A corrosion pit growth model has been developed based on the experimental data to predict the corrosion penetration rate in estimating the service life of nitrogen ion implanted commercially pure titanium [13]. An empirical model of plotting the compressive strength against the age of concrete has been developed to investigate the mechanical properties and durability of the concrete by inserting a natural nanosilica in the high-performance concrete [14]. The objectives of this study are: (1) to prepare the different ratios of $NaOH/Na_2SiO_3$ as independent variable for fabricating the GPB samples to be used in the verification of the water absorption and compressive strength and (2) to model the water absorption of GPB sample versus either the portion of Na_2SiO_3 in alkaline mixture of NaOH and Na_2SiO_3 or the $NaOH/Na_2SiO_3$ ratio and to model the compressive strength versus either the age of GPB sample or the portion of Na_2SiO_3 in the alkaline mixture of NaOH and Na_2SiO_3 for predicting the performance of GPB concrete.

2. Materials and methods

2.1. Materials

The fly ash used in this work was purchased from PT Adhimix Precast Indonesia originally coming from a waste byproduct of coal combustion generated by the Suralaya Power Station of Cilegon municipality in Banten province of Indonesia. The coarse aggregate was purchased from PT Adhimix Precast Indonesia originally coming from the area of Rumpin in Bogor regency of Indonesia. The fine aggregate was purchased from PT Adhimix Precast Indonesia originally coming from the Bangka island of Bangka Belitung Archipelago province of Indonesia. Two chemicals of NaOH in form of pellets and Na_2SiO_3 in form of solution with their analytical grades were purchased from a supplier of chemicals and reagents in Jakarta originally coming from PT Merck Indonesia Tbk. Fig. 1 shows all the materials used in this work consisting of coarse aggregate, fine aggregate, fly ash, NaOH, Na_2SiO_3, and water.

2.2. Experimental procedures

The concrete pavement analysis procedure consists of six consecutive steps: the preparation of the raw materials, the trial mix of fabricating the GPB concrete, the geopolymer concrete mix design for the GPB concrete, the process of making and curing the concrete test specimens, the laboratory testing of the GPB specimens, and the prediction of GPB performance by analyzing and evaluating the experimental data. An alkaline solution of 11 M NaOH (AS) was prepared by dissolving 440 g of NaOH into 800 mL of distilled water to have a final volume of 1-L AS in a 2-L glass beaker and then allowed at room temperature for 24 h. Mixing 440 g of NaOH into 800 mL of distilled water must be kept in a sealed container and allowed for 6 h due to the increasing of AS

Fig. 1. All the materials used to fabricate the GPB concrete with (a) fly ash, (b) coarse aggregate, (c) fine aggregate, (d) NaOH, (e) Na_2SiO_3, and (f) water.

temperature up to 110 °C caused by an exothermic reaction between NaOH and H_2O can drop to a level of 24–27 °C after 6 h of omission in the sealed container. The mixing of AS solution and Na_2SiO_3 solution yields an alkaline activator solution, which is called as activator. This produces the chemical reaction between NaOH and Na_2SiO_3 leading to an increase in the activator temperature to reach at 40 °C and enhances the chemical bonding in the GPB concrete [15,16]. Then the activator was allowed for 6 h in a sealed container for avoiding the formation of clots when mixing it with fly ash, which may cause a failure in the formation of geopolymer. The mixing of activator and fly ash yields a geopolymer paste used to fabricate GPB by mixing it with coarse and fine aggregates.

The concrete trial mixes of GPB sample were performed using certain amounts of the raw materials of flay ash, NaOH, H_2O, Na_2SiO_3, coarse aggregate, and fine aggregate to have a good understanding of every GPB composition for use in making and curing compression test samples of the GPB concrete in the laboratory, as shown in Table 1. The different GPB samples were fabricated using different alkaline mixtures with the NaOH/Na_2SiO_3 ratios of 2.00, 1.37, 1.00, 0.67, 0.50 and 0.40.

The *k* value of GPB sample for use in setting the geopolymer concrete mix design of every paver block was calculated by dividing the weight of activator used to produce GPB sample with its mass density of 1850 kg/m^3 to the weight of chemicals used to produce an activator, as shown in Table 2.

The mixing of fly ash and aggregates with activator to fabricate every GPB sample with its mass density of 1850 kg/m^3 was designed using the *k* value to get better understanding on the accurate composition of NaOH, H_2O, and Na_2SiO_3 in each activator. Table 3 shows the amounts of NaOH, H_2O, and Na_2SiO_3 needed to produce the only 1 m^3 of the GPB mixture. The fabrication of GPB sample was performed using the special paving block mixing machine. The printing of paver block to produce every GPB sample with its dimension of 21x10x8 cm^3 was carried out by using the special paving block compacting machine and then statically compacted to desired density by pricking with a stick and then kept at room temperature for up to 28 days.

This study used different NaOH/Na_2SiO_3 ratios of 2.00, 1.50, 1.00, 0.67, 0.5, and 0.4 (see Table 2) as independent variable for evaluating the performance of GPB sample. The dependent variables of the physical and mechanical properties of the GPB sample include the water absorption and compressive strength. The water absorption test of GPB sample was performed according to standard test method for the measurement of absorption rate of water by hydraulic-cement concretes of ASTM C1585-13 [17]. The GPB sample was weighed using the analytical balance of Precision Balance TP-4101 (Denver Instrument GmbH, Göttingen, Germany) at a weight of W_1 and then put into an oven of IKA Oven 125 basic dry (IKA® Works (Asia) Sdn Bhd, Selangor, Malaysia) at 105 °C for 72 h. Then the GPB sample was immersed in distilled water for 24 h and then cleaned the surface of GPB sample with adsorbent clots

Table 1
Composition of the concrete trial mixes to fabricate a GPB sample.

Sample	FA (kg)	NaOH (kg)	H_2O (kg)	Na_2SiO_3 (kg)	CAgr (kg)	FAgr (kg)	H_2O/FA
GPB1	11	2.20	4.00	1.10	15	28	0.364
GPB2	11	2.05	3.75	1.50	15	28	0.341
GPB3	11	1.90	3.50	1.90	15	28	0.318
GPB4	11	1.70	3.10	2.55	15	28	0.282
GPB5	11	1.55	2.80	3.10	15	28	0.255
GPB6	11	1.41	2.52	3.55	15	28	0.229

Remarked that FA means fly ash, CAgr means coarse aggregate, and FAgr means fine aggregate.

Table 2
Composition of the chemicals used to calculate the coefficient *k*.

Sample	NaOH (kg)	H_2O (kg)	Na_2SiO_3 (kg)	NaOH/ Na_2SiO_3	WCAct (kg)	WAct (kg)	*k*
GPB1	440	800	220	2.00	1460	222	152.055
GPB2	440	800	440	1.50	1565	222	142.099
GPB3	440	800	440	1.00	1680	222	132.143
GPB4	440	800	660	0.67	1900	222	116.842
GPB5	440	800	880	0.50	2120	222	104.717
GPB6	440	800	880	0.40	2242	222	93.592

Remarked that WCAct means weight of chemicals used to produce an activator, WAct means weight of activator used to produce GPB sample with its mass density of 1850 kg/m^3, and *k* means coefficient.

Table 3
Composition of the raw materials to fabricate GPB sample.

Sample	NaOH (kg)	H_2O (kg)	Na_2SiO_3 (kg)	*k* (kg)	Act 0.4 × 03 (kg)	FA 0.6 × 0.3 (kg)	G 0.3 (kg)	CAgr 0.35 × 0.7 (kg)	FAgr 0.65 × 0.7 (kg)	Agr 0.7 (kg)	WGPB 1.0 (kg)
GPB1	66.90	121.64	33.45	152.055	222	333	555	453	842	1295	1850
GPB2	62.52	114.54	45.80	142.099	222	333	555	453	842	1295	1850
GPB2	58.14	105.71	58.14	132.143	222	333	555	453	842	1295	1850
GPB3	51.41	93.47	77.15	116.842	222	333	555	453	842	1295	1850
GPB4	46.08	83.77	92.12	104.717	222	333	555	453	842	1295	1850
GPB4	41.19	74.78	105.94	93.592	222	333	555	453	842	1295	1850

Remarked that *k* means coefficient, Act means activator, FA means fly ash, G means geopolymer, CAgr means coarse aggregate, FAgr means fine aggregate, Agr means aggregate, and WGPB means total weight of GPB.

and then weighed using the same analytical balance at a weight of W_2. The absorption of water can be calculated by the formula:

$$WA = \frac{W_2 - W_1}{W_1} \times 100\% \quad (1)$$

where WA is the water absorption (in %), W_1 is the initial weight of GPB sample (in g), and W_2 is the weight of GPB sample after immersing in distilled water (in g).

The compressive strength test of GPB sample was performed according to ASTM C39 concrete cylinder compression testing [18]. This study used the cylindrical GPB sample with its dimensions of 15-cm external diameter and 30-cm high to determine the compressive strength of GPB concrete using the compression testing machine of WEW-600B (Fabiana Huang Jinan Xinluchang Testing Machine Co., Ltd, Shandong, China), as shown in Fig. 2. The compressive strength was tested for each GPB sample at 3, 7, 14, 19, 24 and 28 days of the concrete's age.

Each experiment was repeated three times for ensuring the accuracy and precision of the measurements for the GPB samples. The results of the measurements were averaged to obtain the average data to be used for mathematical modeling of the experimental data. The trend-line model will be used to explain the behavior change of GPB concrete. The empirical models were developed by plotting the water absorption of GPB sample versus either the portion of Na_2SiO_3 in alkaline mixture of NaOH and Na_2SiO_3 or the $NaOH/Na_2SiO_3$ ratio and by plotting the compressive strength versus either the age of GPB sample or the portion of Na_2SiO_3 in alkaline mixture of NaOH and Na_2SiO_3.

3. Results and discussion

3.1. Water absorption

The results (Table 4) of testing the water content of GPB sample show that the water absorption of paver block containing fly ash as

Fig. 2. Compression testing machine used to measure the compressive strength of GPB sample.

Table 4
Water absorption in the GPB sample recorded for different compositions of NaOH and Na_2SiO_3.

Sample	*A*	*P*	*E* (%)
GPB1	0.50	2.00	7.42
GPB2	0.67	1.50	5.58
GPB3	1.00	1.00	4.31
GPB4	1.50	0.67	3.27
GPB5	2.00	0.50	3.17
GPB6	2.50	0.40	2.93

Noted that *A* is the portion of Na_2SiO_3 in alkaline mixture of NaOH and Na_2SiO_3, *P* is the $NaOH/Na_2SiO_3$ ratio, and *E* is the average water absorption of GPB (in %).

geopolymer decreases from 7.42 to 5.58 to 4.31 to 3.27 to 3.17 and to 2.93% with decreasing of the $NaOH/Na_2SiO_3$ ratio from 2.00 to 1.50 to 1.00 to 0.67 to 0.50 and to 0.40, respectively. An increase in the portion of Na_2SiO_3 by 34% from 0.50 to 0.67 in the alkaline mixture of NaOH and Na_2SiO_3 leads to significantly decrease the average water absorption by 24.86% from 7.42 to 5.58% and may have greater potential of increasing the Na_2SiO_3 content to produce a good performance of GPB concrete [19]. Then the increasing of Na_2SiO_3 portion by 49.25% from 0.67 to 1.00 continues to decrease by 22.76% (from 5.58 to 4.31%) of the average water absorption. Then the increasing of Na_2SiO_3 portion by 50% from 1.00 to 1.50 continues to decrease by 24.1% (from 4.31 to 3.27%) of the average water absorption. Then a decrease in the average water absorption of 3.06% (from 3.27 to 3.17%) is becoming very little with increasing of the Na_2SiO_3 portion in an alkaline mixture of NaOH and Na_2SiO_3 by 33.33% from 1.50 to 2.00. Then a decrease in the average water absorption of 7.57% (from 3.17 to 2.93%) is still little with increasing of the Na_2SiO_3 portion in an alkaline mixture of NaOH and Na_2SiO_3 by 25% from 2.00 to 2.50. This means that an optimum performance of GPB sample achieved might be satisfactory since the portion of Na_2SiO_3 ranged from 1.50 to 2.50 was set up in the design of concrete mixture to fabricate the GPB specimen.

By plotting the water absorption of GPB sample versus the portion of Na_2SiO_3 in alkaline mixture of NaOH and Na_2SiO_3 (see Fig. 3, line-i) yields a power curve with a (=12.889%$^{-1}$) as the power coefficient and b (=1.677) as the power constant and can be written in the form of

$$A = a \times E^{-b}, \quad (2)$$

where A is the portion of Na_2SiO_3 in alkaline mixture of NaOH and Na_2SiO_3 (dimensionless), a is the power coefficient (in %$^{-1}$), E is the water absorption in GPB sample (in %), and b is the power constant (dimensionless).

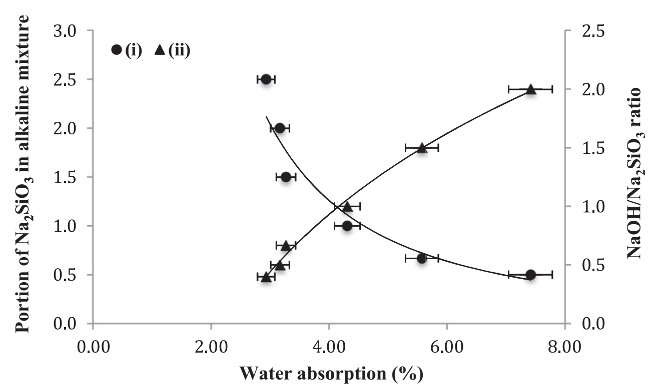

Fig. 3. Curve of modeling (i) the portion of Na_2SiO_3 in alkaline mixture of NaOH and Na_2SiO_3 versus the water absorption of GPB sample and (ii) the $NaOH/Na_2SiO_3$ ratio versus the water absorption of GPB sample.

Correlation for the parameters *a* and *b* in Eq. (2) (with R^2 = 0.95509) is very good and, therefore, the use of Eq. (2) could be useful to predict the water absorption of GPB sample at any portion of Na_2SiO_3 in the alkaline mixture of NaOH and Na_2SiO_3. The water absorption of GPB sample calculated using Eq. (2) equals 4.59% when the GPB concrete is fabricated without the portion of Na_2SiO_3 in alkaline mixture of NaOH and Na_2SiO_3. The absorption of water in GPB sample decreased with increasing of the Na_2SiO_3 portion is due to the presence of Na_2SiO_3 in GPB can react with H_2O to produce NaOH and $SiO_2{\cdot}nH_2O$ in the form of geopolymer [20] and can be described by the chemical equation: $Na_2SiO_3 + 2H_2O \rightarrow 2NaOH + SiO_2{\cdot}H_2O$ [21].

A plot (Fig. 3, line-ii) of the water absorption in the GPB sample versus the NaOH/Na_2SiO_3 ratio yields a logarithmic curve with *c* (=1.7032%$^{-1}$) as the logarithmic coefficient and *d* (=1.4298) as the logarithmic constant and can be formulated as follows:

$$P = cx\ ln(E) - d, \tag{3}$$

where *P* is the NaOH/Na_2SiO_3 ratio (dimensionless), *c* is the logarithmic coefficient (in %$^{-1}$), *E* is the water absorption of GPB sample (in %), and *d* is the logarithmic constant (dimensionless).

A very good correlation for the parameters *c* and *d* of Eq. (3) with R^2 = 0.99436 may allow us to predict the water absorption of GPB sample at any NaOH/Na_2SiO_3 ratio. The water absorption of 2.32% in GPB concrete can be calculated when the GPB sample is fabricated without added 11 M NaOH in alkaline mixture of NaOH and Na_2SiO_3. An increase in the water absorption of GPB with increasing of the NaOH/Na_2SiO_3 ratio in the alkaline mixture is due to an increased amount of the NaOH in paver block mixture can react rapidly with H_2O to form a strong base of the GPB concrete [22].

3.2. Compressive strength

A plot (Fig. 4) of the compressive strength versus age of GPB sample yields a linear curve, where *m* is the slope and *n* is the y-intercept of the line, and can be formulated in the form of

$$G = m \times H + n, \tag{4}$$

where *G* is the compressive strength of GPB sample (in MPa), *m* is the linear coefficient of compressive strength related to the GPB age (in MPa d^{-1}), *H* is the age of GPB sample (in d), and *n* is the linear constant relying compressive strength to the GPB age (in MPa).

Correlation for the parameters *m* and *n* in Eq. (4) is very good (R^2 > 0.9963; see Table 5). Meaning that the use of Eq. (4) could be useful to predict the compressive strength at any age of GPB sample. The results (Fig. 4) of testing the mechanical properties show that an increase in the compressive strength of GPB concrete

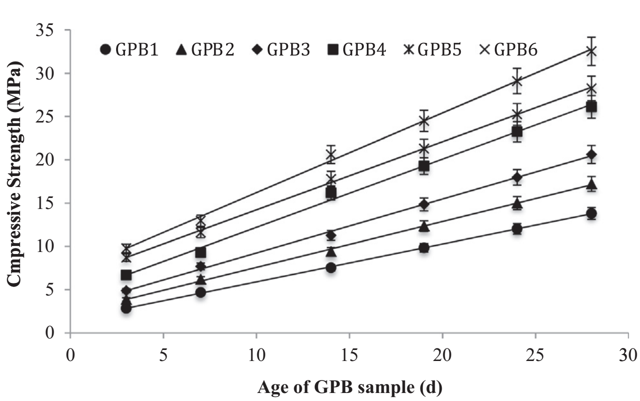

Fig. 4. Curve of plotting the compressive strength versus the age of GPB sample.

is due to the age of GPB sample increases. The increasing of compressive strength of fly-ash-based geopolymer concrete fabricated using the NaOH/Na_2SiO_3 ratio of 2.00 (GPB1) is lower than that of 1.50 (GPB2), then is lower than that of 1.00 (GPB3), then is lower than that of either 0.67 (GPB4) or 0.50 (GPB5) and then is lower than that of 0.40 (GPB6) with increasing of the GPB age from 3 to 7 to 14 to 19 to 24 and to 28 d. This can be verified that the *m* value of 0.4366 for the GPB1 sample is lower than that of 0.5300 for GPB2, then is lower than that of 0.6233 for GPB3, then is lower than that of either 0.7878 for GPB3 or 0.7868 for GPB4 and then is lower than that of 0.9202 for GPB5, as shown in Table 5. An increase in the compressive strength with increased age of GPB sample is almost similar for the fly-ash-based geopolymer concretes fabricated using the NaOH/Na_2SiO_3 ratios of 0.67 and 0.50 due to the reaction of Na_2SiO_3 with H_2O may produce an amount of the NaOH species with almost similar kinetic energy of the reactants [23]. Compressive strength measured at 28 d of GPB age increases by 24.69% from 13.81 to 17.22 MPa, then by 19.80% from 17.22 to 20.63 MPa, then by 26.56% from 20.63 to 26.11 MPa, then by 8.20% from 26.11 to 28.25 MPa, and then by 15.19% from 28.25 to 32.54 MPa with decreasing of the NaOH/Na_2SiO_3 ratio by 20% from 2.00 to 1.50, then by 33.33% from 1.50 to 1.00, then by 33% from 1.00 to 0.67, and then by 25.37% from 0.67 to 0.5, respectively. The reduction of NaOH content in alkaline mixture of NaOH and Na_2SiO_3 may lead to an increased Na_2SiO_3 content in the GPB sample of being designed with a mass density of 1850 kg/m^3. This may have a direct effect on the hardness of the GPB concrete leading to rapidly increase compressive strength of paver block with an enough concentration of NaOH in the activator [24,25].

By plotting the compressive strength of GPB sample versus the portion of Na_2SiO_3 in alkaline mixture of NaOH and Na_2SiO_3 (see Fig. 5) yields a linear curve, where *u* is the slope and *v* is the y-intercept of the line, and can be formulated in the form of

$$G = u \times A + v, \tag{5}$$

where *G* is the compressive strength of GPB sample (in MPa), *u* is the linear coefficient of compressive strength related to the Na_2SiO_3 portion (in MPa), *A* is the portion of Na_2SiO_3 in alkaline mixture of NaOH and Na_2SiO_3 (dimensionless), and *v* is the linear constant relying compressive strength to the Na_2SiO_3 portion (in MPa).

Since the correlation for the parameters *u* and *v* in Eq. (5) is very good (R^2 > 0.9713; see Table 6), the use of Eq. (5) could be useful to predict the compressive strength of GPB sample at any portion of Na_2SiO_3 in alkaline mixture of NaOH and Na_2SiO_3. The results (Fig. 5) show that the compressive strength of GPB sample increases with increasing of the Na_2SiO_3 portion in alkaline mixture of NaOH and Na_2SiO_3. An increasing trend of compressive strength for GPB age of 3 d is lower than that for GPB age of 7 d, then is lower than that for GPB age of 14 d, then is lower than that for GPB age of 19 d, then is lower than that for GPB age of 24 d, and then is lower than that for GPB age of 28 d with increasing of the Na_2SiO_3 portion in alkaline mixture of NaOH and Na_2SiO_3 from 0.50 to 0.67 to 1.00 to 1.50 to 2.00 and to 2.50. An increase of the trend line can be verified from the *u* value of 3.482 MPa for 3 d of GPB age is lower then that of 4.014 MPa for 7 d of GPB age, then is lower than that of 6.496 MPa for 14 d of GPB age, then is lower than that of 7.069 MPa for 19 d of GPB age, then is lower than that of 8.197 MPa for 24 d of GPB age, and then is lower than that of 8.911 MPa for 28 d of GPB age. An increase in the compressive strength with increased age of GPB sample may have enough time to allow the reaction of Na_2SiO_3 with fly ash to produce a strong chemical bond with increased intramolecular forces that hold atoms together in GPB concrete [15,16,26].

For 50% Na_2SiO_3 portion in alkaline mixture of NaOH and Na_2SiO_3, the compressive strength of GPB concrete increases by 64.21% from 2.85 to 4.68 MPa, then by 61.11% from 4.68 to

Table 5
Linear regression analysis of plotting the compressive strength versus age of GPB sample.

Sample	P	m (MPa d^{-1})	n (MPa)	R^2
GPB1	2.00	0.4366	1.545	0.99976
GPB2	1.50	0.5300	2.281	0.99896
GPB3	1.00	0.6233	3.020	0.99808
GPB4	0.67	0.7878	4.330	0.99633
GPB5	0.50	0.7868	6.355	0.99911
GPB6	0.40	0.9202	7.010	0.99796

Noted that P is the NaOH/Na_2SiO_3 ratio, m is the linear coefficient of compressive strength related to the GPB age, and n is the linear constant relying compressive strength to the GPB age, and R^2 is the correlation coefficient.

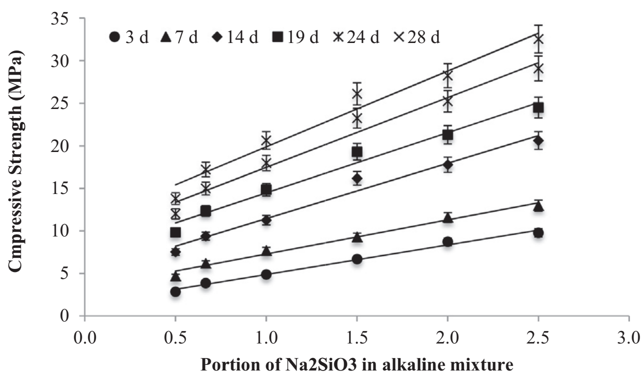

Fig. 5. Curve of plotting the compressive strength of GPB sample versus the portion of Na_2SiO_3 in alkaline mixture.

7.54 MPa, then by 30.50% from 7.54 to 9.84 MPa, then by 22.15% from 9.84 to 12.02 MPa, and then by 14.89% from 12.02 to 13.81 MPa with increasing of the GPB sample age from 3 to 7 d, then from 7 to 14 d, then from 14 to 19 d, then from 19 to 24 d, and then from 24 to 28 d, respectively. For 67% Na_2SiO_3 portion in alkaline mixture of NaOH and Na_2SiO_3, the compressive strength of GPB concrete increases by 59.95% from 3.87 to 6.19 MPa, then by 52.02% from 6.19 to 9.41 MPa, then by 31.24% from 9.41 to 12.35 MPa, then by 21.46% from 12.35 to 15.00 MPa, and then by 14.80% from 15.00 to 17.22 MPa with increasing of the GPB sample age from 3 to 7 d, then from 7 to 14 d, then from 14 to 19 d, then from 19 to 24 d, and then from 24 to 28 d, respectively. The increasing of compressive strength monitored at the GPB ages of 3 and 7 d with increasing of the Na_2SiO_3 portion is relatively slow as shown by the linear coefficients of 3.482 and 4.014 MPa d^{-1}, respectively (see Fig. 5 and Table 6), because of the reaction of fly ash with Na_2SiO_3 may produce less-dense GPB structure and still have high pores. Static segregation of the GPB materials can be evaluated using the electrical resistivity method [27].

For 100% Na_2SiO_3 portion (or the same portion with NaOH) in alkaline mixture of NaOH and Na_2SiO_3, the compressive strength of GPB increases by 57.46% from 4.89 to 7.70 MPa, then by 46.36% from 7.70 to 11.27 MPa, then by 31.85% from 11.27 to 14.86 MPa, then by 21.00% from 14.86 to 17.98 MPa, and then by 14.74% from 17.98 to 20.63 MPa with increasing of the GPB age from 3 to 7 d, then from 7 to 14 d, then from 14 to 19 d, then from 19 to 24 d, and then from 24 to 28 d, respectively. For 150% Na_2SiO_3 portion (or 1.5 times of NaOH portion) in alkaline mixture of NaOH and Na_2SiO_3, the compressive strength of GPB increases by 38.86% from 6.69 to 9.29 MPa, then by 74.27% from 9.29 to 16.19 MPa, then by 19.21% from 16.19 to 19.30 MPa, then by 20.41% from 19.30 to 23.24 MPa, and then by 12.35% from 23.24 to 26.11 MPa with increasing of the GPB age from 3 to 7 d, then from 7 to 14 d, then from 14 to 19 d, then from 19 to 24 d, and then from 24 to 28 d, respectively. The increasing of compressive strength monitored at the GPB ages of 14 and 19 d with increased Na_2SiO_3 portion is becoming more significant as shown by the linear coefficients of 6.946 and 7.069 MPa d^{-1}, respectively (see Fig. 5 and Table 6), due to the hardening concrete effect of increasing time may allow more excess reactivity of fly ash to Na_2SiO_3 before the structural dense of GPB concrete is fully compacted, which make it possible to characterize by fracture toughness [28].

For 200% Na_2SiO_3 portion (or 2 times of NaOH portion) in alkaline mixture of NaOH and Na_2SiO_3, the compressive strength of GPB increases by 32.91% from 8.72 to 11.59 MPa, then by 53.41% from 11.59 to 17.78 MPa, then by 19.80% from 17.78 to 21.30 MPa, then by 18.50% from 21.30 to 25.24 MPa, and then by 11.93% from 25.24 to 28.25 MPa with increasing of the GPB age from 3 to 7 d, then from 7 to 14 d, then from 14 to 19 d, then from 19 to 24 d, and then from 24 to 28 d, respectively. For 250% Na_2SiO_3 portion (or 2.5 times of NaOH portion) in alkaline mixture of NaOH and Na_2SiO_3, the compressive strength of GPB increases by 32.75%

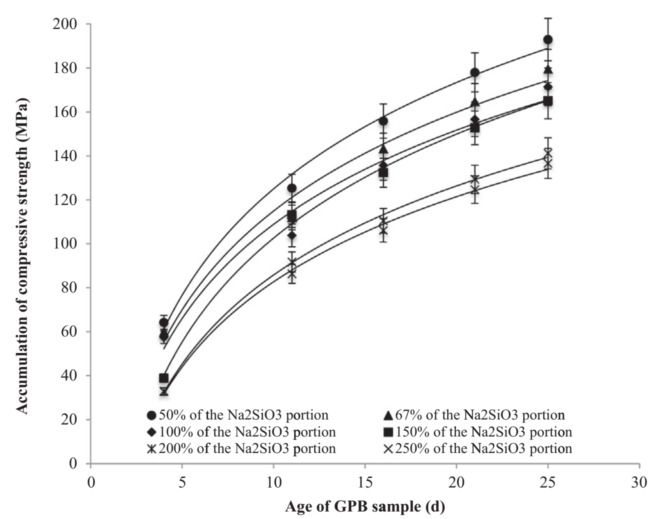

Fig. 6. Curve of plotting the accumulation of average compressive strength versus the age of GPB sample.

Table 6
Linear regression analysis of plotting the compressive strength versus the portion of Na_2SiO_3 in alkaline mixture.

Age of GPB sample (d)	A	u (MPa d^{-1})	v (MPa)	R^2
3	0.50	3.482	1.392	0.99071
7	0.67	4.014	3.274	0.98439
14	1.00	6.496	4.960	0.97693
19	1.50	7.069	7.401	0.97786
24	2.00	8.197	9.274	0.97376
28	2.50	8.911	10.964	0.97137

Noted that A is the portion of Na_2SiO_3 in alkaline mixture of NaOH and Na_2SiO_3, u is the linear coefficient of compressive strength related to the Na_2SiO_3 portion, and v is the linear constant relying compressive strength to the Na_2SiO_3 portion, and R^2 is the correlation coefficient.

from 9.77 to 12.97 MPa, then by 58.98% from 12.97 to 20.62 MPa, then by 18.77% from 20.62 to 24.49 MPa, then by 18.82% from 24.49 to 29.10 MPa, and then by 11.82% from 29.10 to 32.54 MPa with increasing of the GPB age from 3 to 7 d, then from 7 to 14 d, then from 14 to 19 d, then from 19 to 24 d, and then from 24 to 28 d, respectively. An increase in the compressive strength of GPB at the GPB ages of 24 and 28 d with increased Na_2SiO_3 portion in alkaline mixture of NaOH and Na_2SiO_3 is significantly important as shown by the linear coefficients of 8.197 and 8.911 MPa d^{-1}, respectively (see Fig. 5 and Table 6), due to the increasing of Na_2SiO_3 may lead to an increased surface hardness value of the Na_2SiO_3 reinforced GPB concrete [29,30]. Fig. 6 shows that accumulation of the average compressive strength of GPB sample increases logarithmically with increasing of the GPB concrete age where the logarithmic growth of compressive strength accumulation using 250% Na_2SiO_3 portion is almost similar to that using 250% Na_2SiO_3 portion in alkaline mixture of NaOH and Na_2SiO_3. This study suggested that an optimum composition of Na_2SiO_3 in the GPB sample might be determined by adjusting the Na_2SiO_3 portion of 200% in alkaline mixture of NaOH and Na_2SiO_3.

4. Conclusions

This study used fly ash as cement substitute with different $NaOH/Na_2SiO_3$ ratios to fabricate the GPB samples for running experiments. The water absorption of GPB sample used $NaOH/Na_2SiO_3$ ratio of 0.4 has the lowest value of 2.93% at 28 d of the GPB age. The maximum compressive strength of 32.45 MPa for the suggested GPB sample of highest workability can be verified at 28 d of the GPB age by using the Na_2SiO_3 portion of 2.5. The new empirical models of predicting the GPB performance have been suggested to contribute to the development of pavement construction to hardening the parking lot for many cities of Indonesia in the future.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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