Advanced Properties of Continuously Graded Pervious Concrete for Rigid Pavement Base Layer

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Abstract

According to previous studies, a pervious concrete using continuously graded aggregate gives a better strength and approaches the condition of aggregate gradation on the field. The aim of this research is to study a pervious concrete mix-design for Indonesian Specification input category using continuously graded pervious concrete as an alternative rigid pavement base layer. Some advanced properties are applied to represent the required criteria for pavement base layer, i.e. elastic modulus, Poisson's ratio, flexural strength, horizontal permeability, heterogeneity level, and dynamic elastic modulus. It is found that the pervious concrete with continuously graded tends to be more physically elastic when compared to normal concrete and has a better endurance against elastic deformation rather than normal concrete. Its static elastic modulus has a better relationship with horizontal permeability than flexural strength. Overall, five mix-designs have been successfully met the advanced properties criteria for rigid pavement base layer required by the Specification.

Keywords: pervious concrete, continuously graded aggregate, rigid pavement base layer, advanced properties

1. Introduction

According to previous studies, porous concrete or pervious concrete generally uses uniformly graded aggregate with specific single-sized [1] and open-graded aggregate [2]. Several experimental tests related to pervious concrete properties have been conducted in Indonesia for a few years before. Prabowo, Setyawan and Sambowo [3] states that uniformly graded pervious concrete has not met the pavement specification yet because its flexural strength is still too low for pavement surface layer. However, a pervious concrete mixture that has a higher compressive strength, elastic modulus and flexural strength has been successfully designed by Hariyadi and Tamai [4] using continuously graded aggregate. An experimental result from outside Indonesia which conducted by Chandrappa and Biligiri [5] also shows that the averaged flexural strength value of continuously graded pervious concrete can surpass the flexural strength requirement for rigid pavement base layer. These previous studies show the pervious concrete that contains continuously graded aggregate has a higher possibility to fulfill the rigid pavement base layer requirements for Indonesian standard, especially for the strength parameter.

Some recent studies also mention that the pervious concrete mixture is successfully surpassed the minimum basic properties requirements for base layer [6-7]. The compressive strength and permeability value produce by pervious concrete using continuously graded aggregate stays above the minimum limit for base layer required by Specification [8-9]. At the same time, it also produces a higher maximum compressive strength and an optimum void content at the specific value

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compared to uniformly graded pervious concrete [7]. Compared to uniformly graded pervious concrete, some of the continuously graded pervious concrete mixtures can produce a higher vertical permeability value as well. The void content test result shows that several mix-design compositions of continuously graded pervious concretes are stayed above 20% [7]. This condition can maintain a high permeability during pavement design life in zero maintenance condition [10]. These conditions illustrate that continuously graded pervious concrete is better than uniformly graded pervious concrete.

Erosion phenomenon can lead to the loss of foundation support, pavement premature distress, and short-term service life issue [11]. The increase of traffic load will aim to the use of denser, more robust, and anti-erosion base material. However, the foundation material that contains large fine creates a base layer with low permeability and slow water movement. The combination between trapped infiltration water which infiltrates through several cracks, joints and gaps alongside the edge of pavement side, and repeated traffic load will generate void between base layer surface and surface layer base (erosion). Survey results related to rigid pavement distress collected from toll road and highway in Indonesia show that pumping, faulting and longitudinal cracking distress are very plentiful [12-13]. These shorts of distress generally happened due to the loss of foundation support, poor drainage, and erosion problem in base layer [14]. Base layer with drainage type like the pervious concrete could help to handle those problems [11].

Zheng, Chen, and Wang [15] mentions that a permeable base layer must meet three requirements. First, it must have enough permeability to quickly free itself from any water that has entered and trapped in the pavement structure. Secondly, it must have sufficient strength to serve as a pavement construction platform. Finally, the design should meet the strength requirements to carry the traffic loads of the pavement structure. The continuously graded pervious concrete can replace the function of lean concrete as a pavement construction platform and aggregate class A as a drainage layer in the rigid pavement structure. Additionally, it also needs some advanced parameters like elastic modulus, Poisson's ratio, and flexural strength to complete the final requirement.

Table 1 Basic property criteria for rigid pavement base layer [8-9]

Base layer type for rigid pavement	Minimum compressive strength at 7-days (MPa)	Minimum compressive strength at 28-days (MPa)	Minimum vertical permeability (cm/sec)
Lean concrete	6.4	8.0	-
Aggregate class A	-	-	0.1

Table 2 Advanced property criteria for rigid pavement base layer [8-9]

Base layer type for rigid pavement	Minimum elastic modulus at 28-days (MPa)	Minimum modulus of rupture at 7-days (MPa)	Minimum modulus of rupture at 28-days (MPa)	Minimum horizontal permeability (cm/sec)
Lean concrete	13,300	1.7	2.1	-
Aggregate class A	-	-	-	0.1

This study is an extension of the previous study wherein some basic properties such as compressive strength, void content, and vertical permeability have already been studied before. Compressive strength, void content, and vertical permeability are included as basic mechanical properties because the specimen preparation is easy, the testing preparation is simpler and the testing fee is cheaper for Indonesian category. However, flexural strength, elastic modulus, ultrasonic pulse velocity (UPV) and horizontal permeability are included as advanced mechanical properties because the specimen preparation is difficult, the testing preparation is more complex and the testing fee is more expensive for Indonesian category. Several advanced properties are tested and analyzed in this study by vary several types of continuously graded aggregate composition. An official standard for the use of pervious concrete as the base layer has not been included in Indonesian Standard. Therefore, the limitation of property criteria is taken from several materials that generally used as rigid pavement base layer (see Table 1 and Table 2). Both of American Society for Testing Material (ASTM) standard and Standar Nasional Indonesia (SNI) are used to measure all of the criteria in Table 1 and Table 2.

The aim of this research is to study the pervious concrete mix-design for Indonesian Specification input category using continuously graded pervious concrete as an alternative rigid pavement base layer. For pavement purpose, pervious concrete has not been used widely in Indonesia and has not been included in the specification yet. The input category will be emphasized on finding suitable gradation variation that can surpass the minimum limit based on the Specification requirement for rigid pavement base layer. The continuously graded aggregate is chosen because it gives a better basic property values and approach the condition of aggregate gradation on the field [7]. Elastic modulus is a fundamental engineering property of any paving material. It refers to the material's stress-strain behavior under normal pavement loading conditions. A higher elastic modulus and Poisson's ratio values are desirable for this kind of pervious concrete material, since physically, the more elastic the material is, the stronger it will be, and it can retain against an elastic deformation which commonly appears in the rigid pavement structure. In addition to the strength of a material, the material stiffness is also important. Therefore, the flexural strength or the rupture modulus of the continuously graded pervious concrete is also required to analyze its behavior under flexural loading which commonly caused by traffic loading. Furthermore, the advanced properties of continuously graded pervious concrete from this study can also be utilized to make a pavement model that exhibits pavement service life against traffic loads.

2. Research Methodology

Experimental study of pervious concrete advanced properties criteria consists of the following three main steps: (a) pervious concrete mix-design proportion and sample production; (b) measurement of advanced property based on elastic modulus, Poisson's ratio, flexural strength, horizontal permeability and heterogeneity level; (c) Test result analysis and correlation study between the parameters. The research methodology outline from this study can be seen in Fig. 1 below.

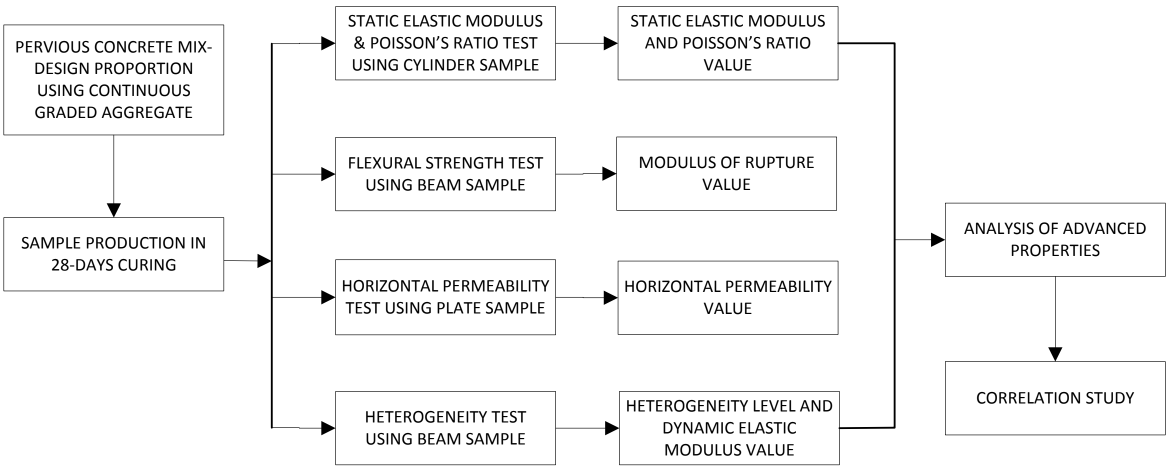


Fig. 1 Research methodology outline

3. Mix Design Proportion and Sample Preparation

Pervious concrete mixtures are designed using ACI standard [2] and some graphics from previous experimental test result [16]. The mix proportions are designed with the percent void prediction about 24.6%. Based on the void content test result, Mix-1, Mix-2 and Mix-3 have the closest void content value against the percent void prediction, i.e. 23.5%, 24.2%, and 23% [7]. All of the mixtures will consist of continuously graded coarse aggregate, portland cement type-I, water, High Range Water Reducer (HRWR), Viscosity Modifying Admixture (VMA), and Retarder. The chemical additive dosage is 2 ml for HRWR, 6 ml for VMA and 6 ml for Retarder from each 1 kg cement [17]. All of the chemical additive is used because they give better basic properties values [6]. Iron stick stabbing is used as a compaction method [7]. Polyethylene bag curing method is selected to gain optimum flexural strength [18]. All of the specimens are made by using water/cement ratio 0.30, aggregate/cement ratio 4.0, and curing time in 28-days. The aggregate proportion percentage and mix-design proportion are listed in Table 3 and Table 4.

Table 3 Aggregate proportion percentage for continuously graded pervious concrete mix-design

Sample type	Percentage of each aggregate size against total aggregate requirement in the mixture		
	Size 19.0 mm-12.7 mm	Size 9.5 mm	Size 4.75 mm-2.36 mm
Mix-1	5%	90%	5%
Mix-2	15%	80%	5%
Mix-3	25%	65%	10%
Mix-4	35%	55%	10%
Mix-5	45%	40%	15%
Mix-6	55%	30%	15%

Table 4 Continuously graded pervious concrete mix-design proportion (for 1 m^3 concrete)

Sample type	Size 19.0 mm-12.7 mm (kg)	Size 9.5 mm (kg)	Size 4.75 mm 2.36 mm (kg)	Water (liter)	Cement (kg)	Cement paste (%), Vol.	HRWR (liter)	Retarder (liter)	VMA (liter)
Mix-1	71.03	1,278.54	71.03	103.6	357.1	21.6	0.68	2.23	2.23
Mix-2	213.09	1,136.48	71.03	103.6	357.1	21.6	0.68	2.23	2.23
Mix-3	355.15	923.39	142.06	103.6	357.1	21.6	0.68	2.23	2.23
Mix-4	497.21	781.33	142.06	103.6	357.1	21.6	0.68	2.23	2.23
Mix-5	639.27	568.24	213.09	103.6	357.1	21.6	0.68	2.23	2.23
Mix-6	781.33	426.18	213.09	103.6	357.1	21.6	0.68	2.23	2.23

The mix-proportion consists of three range of continuously graded aggregate, i.e. 19.0 mm - 12.7 mm, 9.5 mm, and 4.75 mm - 2.36 mm. The aggregate percentage that passing sieve 12.7 mm as much as 100% and the aggregate percentage that passing sieve 9.5 mm as much as 0% are used as control-1 (ideal gradation condition) because they give maximum vertical permeability value and uniformly void content dispersion [6]. The aggregate percentage that passing sieve 12.7 mm as much as 41% and the aggregate percentage that passing sieve 9.5 mm as much as 19% are used as control-2 to simulate maximum gradation condition on the field. Both control-1 and control-2 are theoretical limits which are gained from split aggregate sieve analysis result and used as a reference when vary the percentage of aggregate gradation for the mixture [7]. The split aggregate sieve analysis result is showed in Table 5, whereas the aggregate gradation curve is presented in Fig. 6.

Table 5 Split aggregate sieve analysis result for simulating maximum gradation condition on the field

Sieve size (mm)	Retained percentage	Cumulative retained percentage	Cumulative passing percentage
19,0	21%	21%	79%
12,7	38%	58%	42%
9,5	23%	82%	18%
4,75	15%	97%	3%
2,36	3%	100%	0%

Table 6 Specimen amount for experimental test

Type of mix	Type of test					
	Static elastic modulus	Poisson's ratio	Dynamic elastic modulus	Heterogeneity level	Flexural strength	Horizontal permeability
Mix-1	2 cylinders	2 cylinders	2 beams	2 beams	2 beams	1 plate
Mix-2	2 cylinders	2 cylinders	2 beams	2 beams	2 beams	1 plate
Mix-3	2 cylinders	2 cylinders	2 beams	2 beams	2 beams	1 plate
Mix-4	2 cylinders	2 cylinders	2 beams	2 beams	2 beams	1 plate
Mix-5	2 cylinders	2 cylinders	2 beams	2 beams	2 beams	1 plate
Mix-6	2 cylinders	2 cylinders	2 beams	2 beams	2 beams	1 plate

All of material properties and sample preparation are tested based on the ASTM procedure. The amount of specimen for each test is listed in Table 6, whereas the illustration of sample preparation can be seen in Fig. 2 to Fig. 5. Elastic Modulus test samples are cast into a cylinder with diameter 15 cm and length 30 cm [19]. Flexural strength test samples are cast into a beam with 50 cm length, 15 cm wide and 15 cm thick [20]. Horizontal permeability test samples are cast into a plate with 75 cm length, 60 cm wide and 5 cm thick.


Fig. 2 Sample in curing condition


Fig. 3 Sample for elastic modulus test


Fig. 4 Sample for homogeneity and flexural test


Fig. 5 Sample for horizontal permeability test

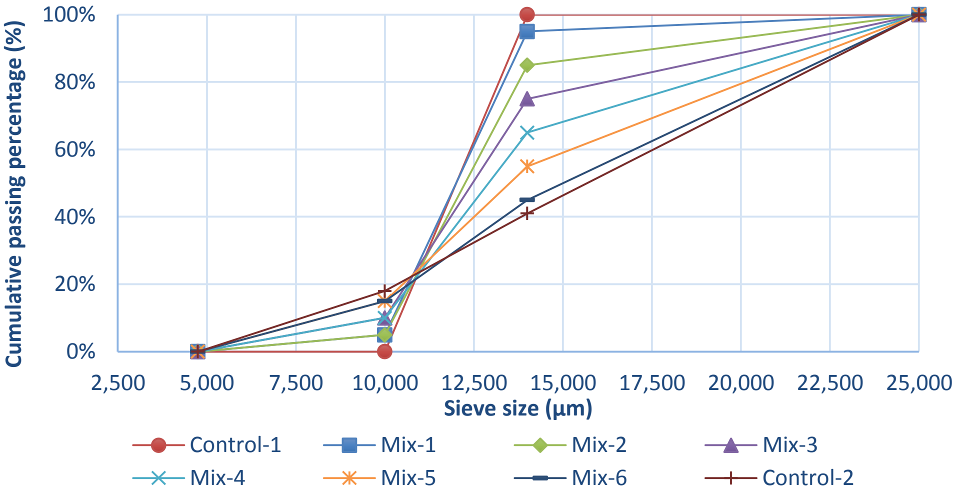


Fig. 6 Split aggregate gradation curve for simulating maximum gradation condition on the field

4. Measurement of Advanced Property

Five advanced properties are applied to represent the required criteria for pavement base layer:

(1) Elastic modulus.

(2) Poisson's ratio.

(3) Flexural strength.

(4) Horizontal permeability

(5) Heterogeneity level and dynamic elastic modulus. All of them are measured through an experimental test in Bandung Institute of Technology Structure Engineering laboratory and Centre of Research and Development for Roads and Bridges laboratory.

Compressive strength is conducted to gain maximum stress reference for static elastic modulus test for each mixture type. Ultrasonic Pulse Velocity (UPV) test is also added to observe pervious concrete's heterogeneity level and dynamic elastic modulus. As well as, permeability value in a horizontal way because horizontal water movement will play an important role when pervious concrete is used as a base layer.

4.1. Static elastic modulus

Static elastic modulus is a quantity that measures an object resistance to be deformed elastically when a stress is applied to it. In pavement structure, a static elastic modulus is needed to describe material's stress-strain behavior under loading conditions. It is difficult to measure high-stiffness materials modulus using the indirect tensile apparatus because the stiffest pavement material like portland cement concrete usually has small displacements and brittle nature. Two sensors Linear Variable Displacement Transducer (LVDT) are used to measure longitudinal strain and transverse strain of the specimen. The static elastic modulus test is conducted in accordance with ASTM C-469 [21] and calculated using the equation:

$$E = \frac{(S_2 - S_1)}{(\epsilon_2 - 0.000345)} \tag{1}$$

where E is chord modulus of elasticity (MPa), S_2 is stress corresponding to 40% of ultimate load (MPa), S_1 is stress corresponding to longitudinal strain, ϵ_1, of 344.74 millionths (MPa), ϵ_2 is longitudinal strain produced by stress S_2. The illustration of pervious concrete static elastic modulus test is presented in Fig. 5.

4.2. Poisson's ratio

Poisson's ratio (υ) is a comparison between longitudinal strain and transversal strain on a loaded sample. Its value can be ranged from 0-0.5 with the assumption that there is no volume change after loading. The Poisson's ratio value could physically describe the elasticity level of material. The Poisson's ratio test is also conducted in accordance with ASTM C-469 [21] and calculated using the equation:

$$\upsilon = \frac{(\epsilon_{t2} - \epsilon_{t1})}{(\epsilon_2 - 0.000345)} \tag{2}$$

where υ is Poisson's ratio, ϵ_{t2} is transverse strain at mid-height of the specimen produced by stress S_2, ϵ_{t1} is transverse strain at mid-height of the specimen produced by stress S_1, ϵ_2 is longitudinal strain produced by stress S_2.

4.3. Flexural strength

Flexural strength or modulus of rupture is defined as the stress in a material just before it yields in a flexure test. It represents the highest stress experienced within the material at its moment of yield. Modulus of rupture of portland cement concrete is required for the design because the flexural load from traffic will commonly work on rigid pavement structure. The four-point approach is chosen in this flexural test because pervious concrete is a non-homogeneous material and particle-composite material which composed of several materials. The flexural strength test is conducted in accordance with ASTM C-78 [20] and calculated using the equation:

$$R = \frac{P \cdot L}{b \cdot d^2} \tag{3}$$

where R is modulus of rupture (MPa), P is maximum applied load indicated by the testing machine (N), L is span length (mm), b is average width of specimen at the fracture (mm), d average depth of specimen at the fracture (mm). The illustration of porous concrete flexural strength test is presented in Fig. 8.

4.4. Horizontal permeability

Permeability describes the easiness of concrete to be penetrated or passed by liquid or gas. Horizontal permeability needs to be conducted because horizontal water movement will appear when the pervious concrete is placed as a base layer. It is measured by using modified infiltration box which can allow water to move in a horizontal way. Pervious concrete plate sample is put inside the infiltration box along with its surface cover. Impermeability gel was attached to the gap around the surface cover to prevent water to come outside (see Fig. 9). The time is immediately recorded when the water is poured from the bucket and stopped until there is no water remaining in the infiltration box. Slope simulator is placed under the infiltration box to simulate the slope of pavement cross-section on the field. The horizontal permeability test is conducted in accordance with ASTM D-5084 [22] through the constant-head approach and calculated using the equation:

$$k = \frac{Q \cdot L}{h \cdot A \cdot t} \tag{4}$$

where k is hydraulic conductivity (cm/sec), L is sample length (m), h is water level (m), A is cross-sectional area of the specimen (m^2), t is time for water to drop from h.

Fig. 7 Pervious concrete static elastic modulus test

Fig. 8 Pervious concrete flexural test through 4-point approach

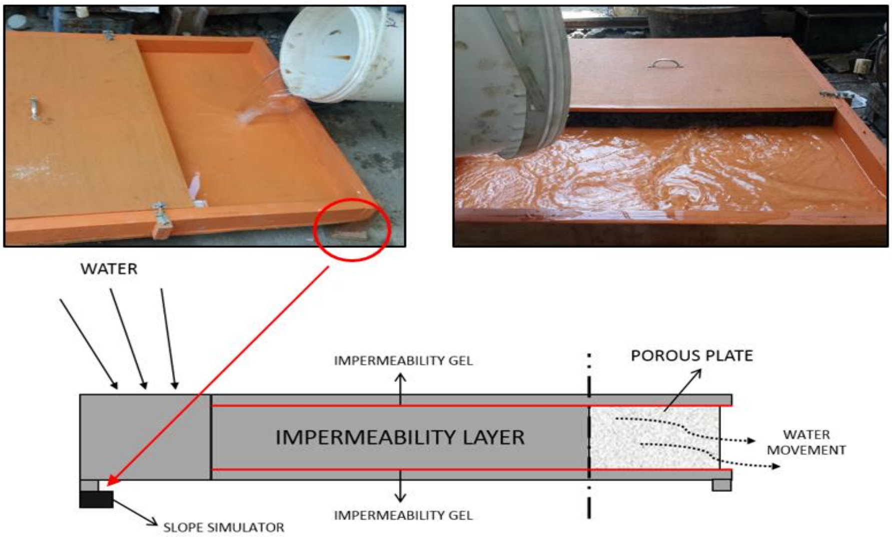


Fig. 9 Horizontal permeability test through constant-head approach by using infiltration box

4.5. Dynamic elastic modulus and heterogeneity level

Dynamic elastic modulus is assumed as tangent modulus in zero stress condition which determined from the standard test because only meaningless stress which applied during UPV measurement [23]. It is static elastic modulus that obtained using non-destructive evaluation method. Dynamic elastic modulus can be used to represent concrete elastic property because of its benefit with a practical approach and easy to apply on field condition. The dynamic elastic modulus of normal concrete has bigger value compared to static elastic modulus which calculated based on ASTM C-469 [24]. The difference between dynamic modulus and elastic modulus is based on the fact that non-homogeneous characteristic from the normal concrete influences both modulus from the different way [25]. The dynamic elastic modulus test is conducted in accordance with ASTM C-597 [26] and calculated using the equation:

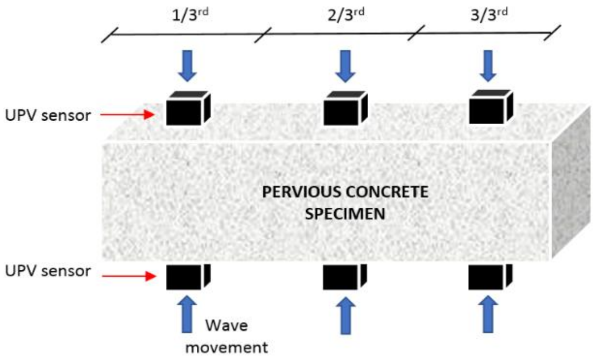
$$E_d = \frac{(1+\mu)(1-2\mu)}{(1-\mu)} \rho (UPV)^2 \tag{5}$$

where E_d is dynamic elastic modulus (MPa), μ is Poisson's ratio, ρ is density (kg/m^3), *UPV* is ultrasonic pulse velocity in longitudinal way (m/sec).

Heterogeneity test is needed to observe the pervious concrete heterogeneity level and also as a reference to choose what kind of flexural test approach must be used. UPV test can predict concrete density based on the speed of UPV wave through the concrete media. The UPV test is conducted on a 1-dimension transverse way on one-third, two-thirds, and three-thirds for heterogeneity level assessment (see Fig. 10a) and 1-dimension longitudinal way for dynamic elastic modulus assessment (see Fig. 10b). The test is conducted in accordance with IAEA [27] through a direct approach and calculated using the equation:

$$v = \frac{L}{T} \tag{6}$$

where v is longitudinal wave speed (m/sec), L is length of trajectory (m), T is ultrasonic longitudinal wave traveling time on L trajectory (sec).



(a) For heterogeneity level assessment

(b) For dynamic elastic modulus assessment

Fig. 10 1-Dimension ultrasonic pulse velocity (UPV) test

5. Experimental Test Result and Correlation Study

5.1. Experimental test result

Half of the strain in pervious concrete with weaker aggregate interlocking is applied for closing the existing void and the other half is applied for particle deformation, while the existing strain in pervious concrete with stronger aggregate interlocking is more evenly distributed so that almost all of it is applied for particle deformation. Pervious concrete strain values which composed of continuously graded aggregate varied from 25 x 10-5 to 30 x 10-5. Fig. 11 shows the relationship between 40% ultimate stress and strain produced by 40% ultimate stress from pervious concrete stress-strain analysis. According to ASTM C-469, stress corresponding to 40% of ultimate load and longitudinal strain produced by stress corresponding to 40% of ultimate load are already enough to calculate the modulus of elasticity value. Another reason is due to the limitation of LVDT sensor endurance that attaches on the specimen during the test. If the test is conducted until the failure condition, the LVDT sensor might have been broken because of the fraction from the failure specimen. Despite the curve from Fig.11 is not really smooth, it can be seen that Mix-5 that contains a lower percentage of size 9.5 mm possess a steeper line curve than Mix-1. On the other hand, Mix-1 that contains a higher percentage of size 9.5 mm possess a bit higher strain value than Mix-5. While the percentage of size 9.5 mm is decreased, the percentage of size 19.0 mm – 12.7 mm and 4.75 mm – 2.36 mm will also increase so that the mix-design with a lower percentage of size 9.5 mm tends to possess a higher density. The void content test result shows that the mix-design that contains 40% of size 9.5 mm (Mix-5) has 18.7% void, whereas the mix-design that contains 90% of size 9.5 mm (Mix-1) has 23.5% void [7]. This situation explains that continuously graded pervious concrete with a steeper line curve tends to possess a lower void inside its mixture so that almost all of the strain is applied for its particle deformation. In addition, continuously graded pervious concrete also has a smaller averaged strain value, i.e. 28 x 10-5, compared to normal concrete averaged strain value, i.e. 50 x 10-5, at the equal compressive strength value.

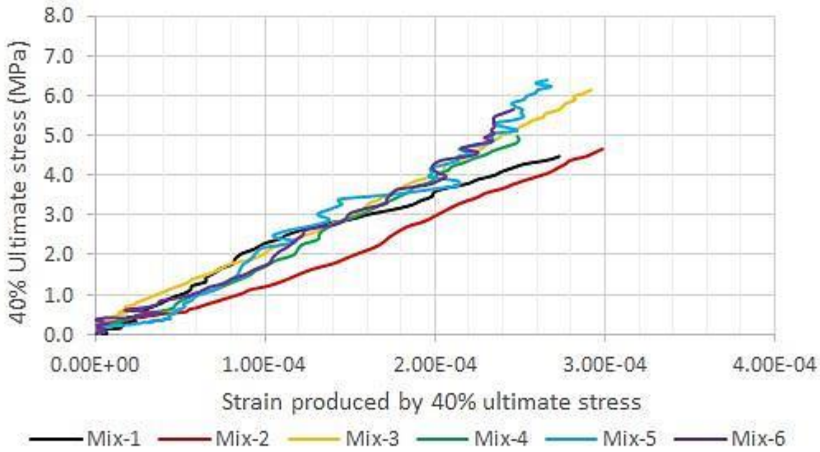


Fig. 11 Pervious concrete stress-strain relationship on the condition of 40% ultimate stress

Compared to normal concrete, the pervious concrete with continuously graded aggregate tends to be more physically elastic. Based on Fig. 12, the use of size 9.5 mm with the different percentage in each mixture causes Poisson's ratio values varied from 0.18 – 0.30 with an average value of 0.22. This value is similar when compared to the averaged Poisson's ratio value that gained from the previous study [28], but a bit higher when compared to normal concrete's Poisson's ratio that usually valued about 0.15. The variation of gradation which is used in continuously graded pervious concrete also produces an optimum Poisson's ratio value in the specific gradation percentage. Some percentages have a higher value among the others.

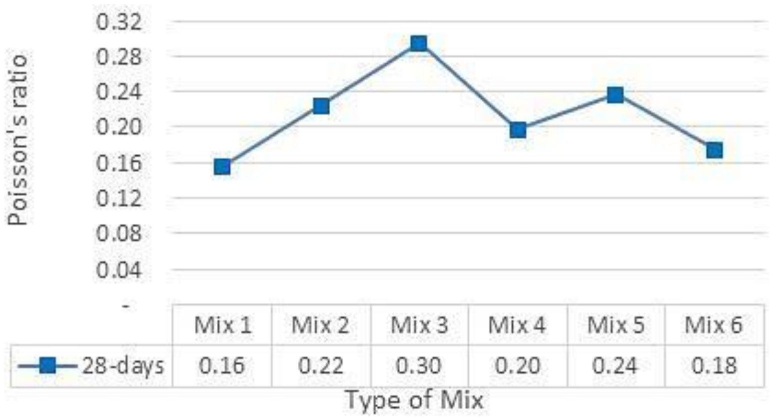


Fig. 12 Relationship between the type of mix and averaged Poisson's ratio

Continuously graded pervious concrete has a better endurance against elastic deformation rather than normal concrete. Its averaged value is 12% higher compared to normal concrete static elastic modulus which is calculated using normal concrete elastic modulus and compressive strength relationship formula. The averaged elastic modulus value of continuously graded pervious concrete, i.e. 18,900 MPa, is also 40% higher compared to the averaged elastic modulus value of uniformly graded pervious concrete, i.e. 13,260 MPa, that gained from the previous study [28]. The continuously graded pervious concrete with a higher density has a better endurance against elastic deformation rather than a lower one. Fig. 13 illustrates that continuously graded pervious concrete static elastic modulus varied from 16,570 MPa to 22,092 MPa. The static elastic modulus value rises gradually in conjunction with the drop in the percentage of size 9.5 mm wherein the highest value is owned by Mix-5. The higher density owned by Mix-5 caused its stress-strain curve becomes steeper, therefore, it causes a higher static elastic modulus value compared to other mix-designs. This condition walks the same way with the stress-strain relationship that is showed in Fig. 11. Furthermore, the static elastic modulus value produced by continuously graded pervious concrete has surpassed the minimum limit of static elastic modulus value, i.e. 13,300 MPa, for base layer required by the Specification [8].

Continuously graded pervious concrete with a lower size 9.5 mm percentage has a better dynamic static modulus value than the higher one. Based on Fig. 14, dynamic elastic modulus value varied from 21,344 MPa to 35,598 MPa with an averaged value of 28,710 MPa. The value is increased gradually along with the decrease of size 9.5 mm percentage. Decreasing size 9.5 mm percentage will increase the amount of other size percentages so that resulting in a stronger aggregate interlocking and a faster UPV wave movement inside the mixture. The bigger UPV wave value is gained, the higher dynamic elastic modulus value will appear. In addition, continuously graded pervious concrete also has an averaged dynamic elastic modulus 45% bigger compared to its averaged elastic static modulus. This situation is not a strange thing because continuously graded pervious concrete has a heterogeneous characteristic which evidenced from the heterogeneity test result.

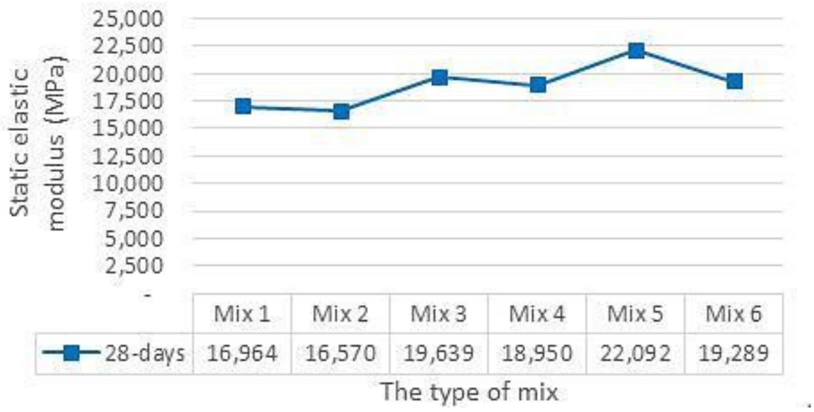


Fig. 13 Relationship between the type of mix and averaged static elastic modulus

The heterogeneity level of continuously graded pervious concrete is determined by using the help from a coefficient of variance value (see Table 7). The averaged coefficient of variance value of each mixture is averaged from its UPV wave speed. The UPV wave speed is measured on one-third, two-thirds and three-thirds span for each mixture through 1-dimensional transverse way. The wave speed is calculated from the UPV test result using Equation 6. The UPV speed values from heterogeneity assessment are varied from 4,199 m/sec to 4,754 m/sec with an averaged value about 4,451 cm/sec.

Table 7 UPV test result for pervious concrete heterogeneity assessment

<table>
<tr><th>Type of mix</th><th>UPV spot</th><th>Averaged UPV speed (m/sec)</th><th>Coefficient of variance</th><th>Averaged coefficient of variance</th><th>Type of mix</th><th>UPV spot</th><th>Averaged UPV speed (m/sec)</th><th>Coefficient of variance</th><th>Averaged coefficient of variance</th></tr>
<tr><td rowspan="3">Mix 1-A</td><td>$1/3^{rd}$</td><td rowspan="3">4,246</td><td rowspan="3">1.5%</td><td rowspan="6">1.4%</td><td rowspan="3">Mix 4-A</td><td>$1/3^{rd}$</td><td rowspan="3">4,659</td><td rowspan="3">1.1%</td><td rowspan="6">1.4%</td></tr>
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<tr><td>$3/3^{rd}$</td><td>$3/3^{rd}$</td></tr>
<tr><td rowspan="3">Mix 1-B</td><td>$1/3^{rd}$</td><td rowspan="3">4,400</td><td rowspan="3">1.3%</td><td rowspan="3">Mix 4-B</td><td>$1/3^{rd}$</td><td rowspan="3">4,636</td><td rowspan="3">1.7%</td></tr>
<tr><td>$2/3^{rd}$</td><td>$2/3^{rd}$</td></tr>
<tr><td>$3/3^{rd}$</td><td>$3/3^{rd}$</td></tr>
<tr><td rowspan="3">Mix 2-A</td><td>$1/3^{rd}$</td><td rowspan="3">4,206</td><td rowspan="3">0.6%</td><td rowspan="6">2.1%</td><td rowspan="3">Mix 5-A</td><td>$1/3^{rd}$</td><td rowspan="3">4,754</td><td rowspan="3">2.1%</td><td rowspan="6">1.4%</td></tr>
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<tr><td>$3/3^{rd}$</td><td>$3/3^{rd}$</td></tr>
<tr><td rowspan="3">Mix 2-B</td><td>$1/3^{rd}$</td><td rowspan="3">4,448</td><td rowspan="3">3.5%</td><td rowspan="3">Mix 5-B</td><td>$1/3^{rd}$</td><td rowspan="3">4,693</td><td rowspan="3">0.6%</td></tr>
<tr><td>$2/3^{rd}$</td><td>$2/3^{rd}$</td></tr>
<tr><td>$3/3^{rd}$</td><td>$3/3^{rd}$</td></tr>
<tr><td rowspan="3">Mix 3-A</td><td>$1/3^{rd}$</td><td rowspan="3">4,288</td><td rowspan="3">2.1%</td><td rowspan="6">1.7%</td><td rowspan="3">Mix 6-A</td><td>$1/3^{rd}$</td><td rowspan="3">4,551</td><td rowspan="3">1.7%</td><td rowspan="6">2.4%</td></tr>
<tr><td>$2/3^{rd}$</td><td>$2/3^{rd}$</td></tr>
<tr><td>$3/3^{rd}$</td><td>$3/3^{rd}$</td></tr>
<tr><td rowspan="3">Mix 3-B</td><td>$1/3^{rd}$</td><td rowspan="3">4,199</td><td rowspan="3">1.3%</td><td rowspan="3">Mix 6-B</td><td>$1/3^{rd}$</td><td rowspan="3">4,331</td><td rowspan="3">3.2%</td></tr>
<tr><td>$2/3^{rd}$</td><td>$2/3^{rd}$</td></tr>
<tr><td>$3/3^{rd}$</td><td>$3/3^{rd}$</td></tr>
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The layer thickness of continuously graded pervious concrete should be limited in specific value to keep the density level in good quality. From dynamic elastic modulus assessment, the UPV speed values of continuously graded pervious concrete are ranged from 3,311 m/sec to 4,329 m/sec with an averaged value about 3,859 cm/sec (see Table 8). The averaged value is categorized as "Good" according to the concrete quality [27] and almost similar compared to the averaged UPV speed value of uniformly graded pervious concrete gained from the previous research [29]. Nevertheless, when compared to the averaged UPV speed value from heterogeneity assessment, the averaged UPV speed value from the dynamic elastic modulus assessment is lower. Thicker concrete layer media tends to reduce the UPV speed value. The distance of concrete media plays an important role against the UPV speed value of continuously graded pervious concrete.

Table 8 UPV test result for pervious concrete dynamic elastic modulus assessment

Type of mix	UPV speed (m/sec)	Type of mix	UPV speed (m/sec)
Mix 1-A	3,460	Mix 4-A	4,102
Mix 1-B	4,010	Mix 4-B	3,959
Mix 2-A	3,610	Mix 5-A	4,284
Mix 2-B	3,356	Mix 5-B	4,329
Mix 3-A	4,062	Mix 6-A	3,968
Mix 3-B	3,855	Mix 6-B	3,311

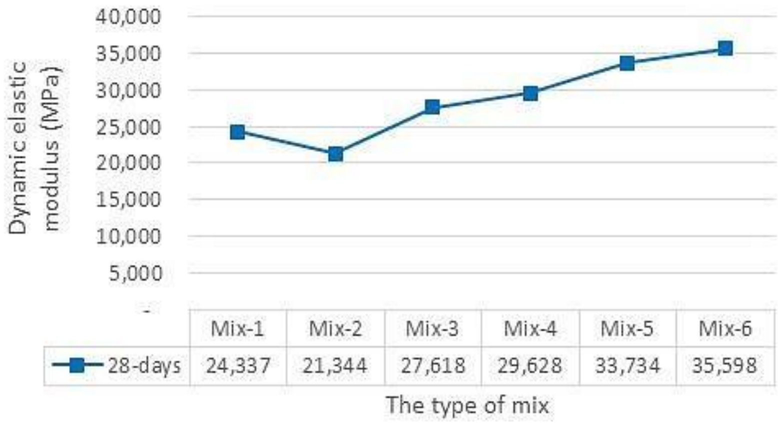


Fig. 14 Relationship between the type of mix and averaged dynamic elastic modulus

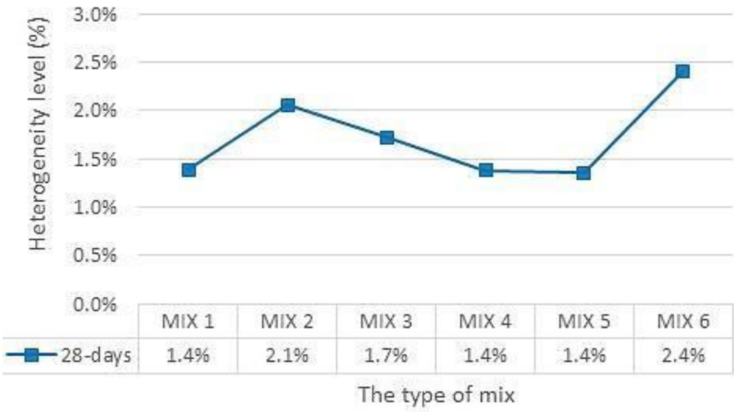


Fig. 15 Relationship between the type of mix and heterogeneity level

Pervious concrete beam that uses continuously graded aggregate is heterogeneous when it come to laboratory condition. The coefficient of variance which valued above 0% told that the density level in every spot is not similar because the cavity inside pervious concrete tends to spread randomly with different varied size. Fig. 15 indicates that pervious concrete coefficient of variance varied from 1 % to 2.4% wherein Mix-6 has the biggest value, i.e. 2.4%, among the others. This condition might happen because there is a situation where the matrix bond is dominant in one spot, whereas the interlocking effect among the aggregate is more dominant in another spot.

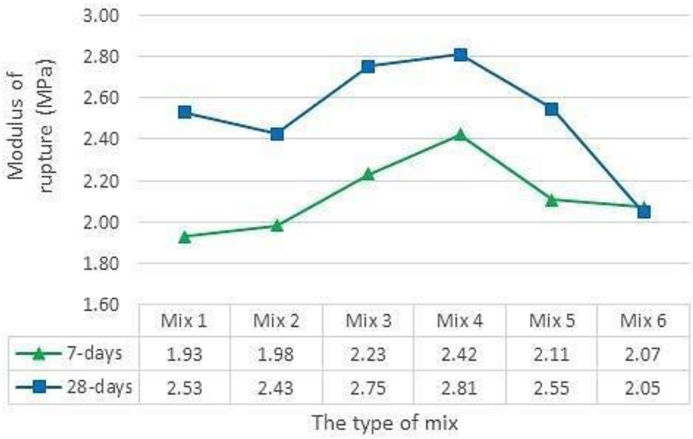


Fig. 16 Relationship between the type of mix and averaged modulus of rupture

The utilization of pervious concrete can help to accelerate the advanced work process on the field because it has a shorter time to achieve the minimum flexural strength. According to the Specification [8], every advanced work related to equipment, traffic, and project vehicle are allowed to pass on the base layer surface when it has reached its 80% strength to avoid failure. Looking at Fig. 16, continuously graded pervious concrete has a modulus of rupture value varied from 1.9 MPa to 2.4 MPa at the age of 7-days. Three mix-design compositions are capable to surpass the minimum value, i.e. 2.1 MPa, required by the Specification [8] 21-days faster wherein Mix-4 produces the highest value among the three. Additionally, the averaged flexural strength value of continuously graded pervious concrete, i.e. 2.52 MPa, is also a bit lower compared to the flexural strength value of continuously graded pervious concrete, i.e. 2.67 MPa, gained from the previous study [4].

Pervious concrete with smaller 9.5 mm size percentage tends to produce a higher modulus of rupture at the age of 28-days. According to Fig. 16, there is a gradual improvement against pervious concrete’s modulus of rupture along with a drop of 9.5 mm size percentage. The gradual improvement is not visible anymore when 9.5 mm size percentage reaches 40% on Mix-5. The bonding strength between cement paste and aggregate in the Interfacial Transition Zone (ITZ) plays an important role when the percentage of size 9.5 mm is lesser than 40%. The aggregate interlocking effect plays an important role when the percentage of size 9.5 mm is more than 40%. The modulus of rupture value also has an optimum condition in the specific percentage of size 9.5 mm wherein this condition is owned by Mix-4. In the optimum condition, both of bonding strength from ITZ and interlocking effect from aggregate gradation create a compound contribution to the pervious concrete strength. Moreover, the modulus of rupture value from Mix-6 has almost no difference between 7 and 28 days. The drop of size 9.5 mm percentage rise the percentage of size 19.0 mm–12.7 mm to 55% and the percentage of size 4.75 mm – 2.36 mm to 15% so that the aggregate surface which must be covered by cement paste will be increased. When the percentage of size 9.5 mm reaches 30%, the amount of cement paste that cover the aggregate surface becomes thinner so that reduce the bonding strength between cement paste and aggregate in the ITZ area.

Pervious concrete that utilizes three types of gradation range has a better flexural strength because the increase of well-connected aggregate can delay the crack propagation before failure. The crack propagation tends to pass through the aggregate so the continuously graded pervious concrete with a stronger interlocking will be able to increase its flexural strength because crack propagation must face more aggregate amount before failure (see Fig. 17). Failure on aggregate is marked with black-brown color, whereas failure on ITZ is marked with grey-white color. This condition is similar with the prior result gained from the prior research [30] which also uses three types of gradation range in the mix-design composition.

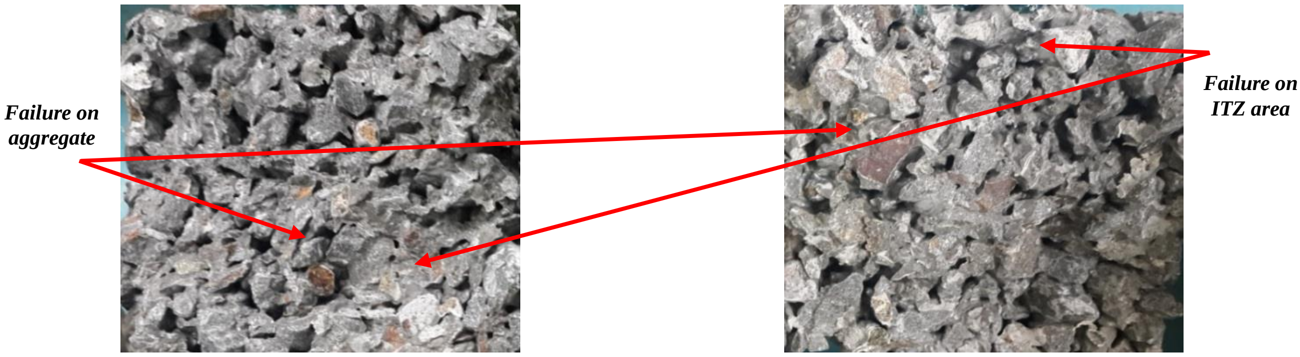
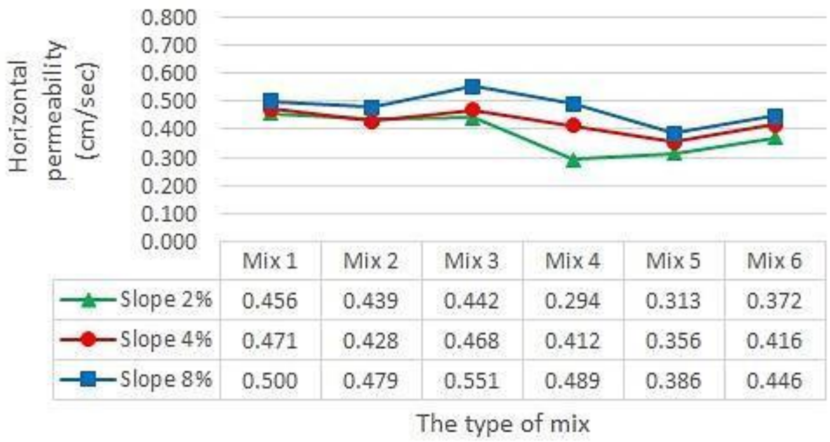


Fig. 17 cross-section image on failure area from modulus of rupture test result

Pervious concrete's horizontal permeability composed of continuously graded aggregate stays above the minimum limit, i.e. 0.1 cm/sec, required by the Specification [9]. The horizontal permeability needs to be considered as an advanced parameter because horizontal water movement will be dominant when pervious concrete is placed as a base layer. The increase of slope percentage from 2% to 8% does not give significant influence against horizontal permeability value (see Fig. 18). The minor difference which emerges among the permeability values might be caused by the gravitation force effect which commonly works in a substance with specific weight when laid on a specific slope.



	Mix 1	Mix 2	Mix 3	Mix 4	Mix 5	Mix 6
Slope 2%	0.456	0.439	0.442	0.294	0.313	0.372
Slope 4%	0.471	0.428	0.468	0.412	0.356	0.416
Slope 8%	0.500	0.479	0.551	0.489	0.386	0.446

Fig. 18 Relationship between the type of mix and horizontal permeability

The decrease of smaller aggregate size percentage also does not give too much influences against horizontal permeability value. Fig. 18 indicates that the fall of size 9.5 mm percentage does not show a significant effect against horizontal permeability. The fall of size 9.5 mm percentage creates a chance for other size percentages, i.e. size 19.00 mm - 12.7 mm and size 4.75 mm - 2.36 mm, to fill the void so it will automatically increase the density and decrease the horizontal permeability. Too much growth on density can also reduce the cement paste thickness that cover the aggregate surface so the horizontal permeability value can rise back slightly. In addition, the averaged permeability value of continuously graded pervious concrete, i.e. 0.76 cm/sec, is 50% lower compared to the averaged permeability value of uniformly graded pervious concrete, i.e. 1.15 cm/sec, gained from the previous study [28]. Similar to its vertical permeability, the horizontal permeability also has a direct relationship with its void content. When the void content increases, the permeability will increase as well [7].

5.2. Correlation study

Static elastic modulus has a better relationship with horizontal permeability than flexural strength at the age of 28-days. The relationship is moderate ($0.40 < R2 < 0.60$) in the case of horizontal permeability, but very weak ($R2 < 0.20$) in the case of modulus of rupture (see Fig. 19 and Fig. 20). According to Fig. 19, the relationship between static elastic modulus and horizontal permeability is moderate because the bonding strength in ITZ has a minor contribution against static elastic modulus and horizontal permeability. On static elastic modulus parameter, the compressive strain happened during the loading condition so that density and void play an important role in controlling deformation. On horizontal permeability parameter, both density and void have a direct contribution in controlling water movement inside the sample. Turning to Fig. 20, the correlation between static elastic modulus and flexural strength is very weak because the bonding strength in ITZ has a major contribution against flexural strength, but only a minor contribution against static elastic modulus. On flexural strength parameter, the tensile strain happened during the loading condition so density and void are not strong enough in controlling the flexural strength. This observation indicates that the variation of bonding strength in ITZ from each mixture will replace the important role from density and void in controlling the flexural strength. Moreover, each mixture in this study uses different gradation composition, in which denser gradation will produce lower bonding strength in its ITZ, but stronger aggregate interlocking effect.

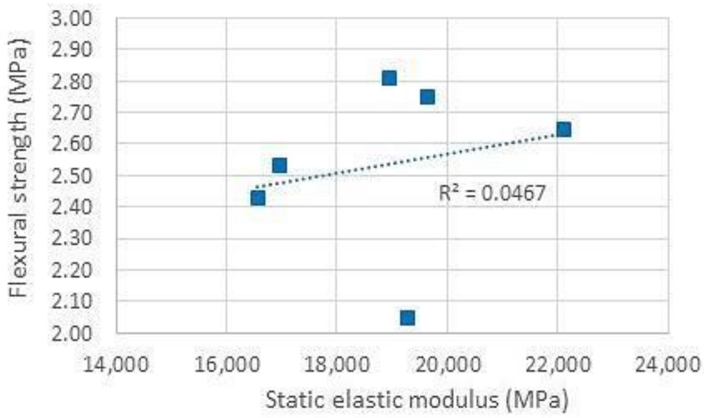


Fig. 19 Correlation between static elastic modulus and flexural strength at the age of 28-days

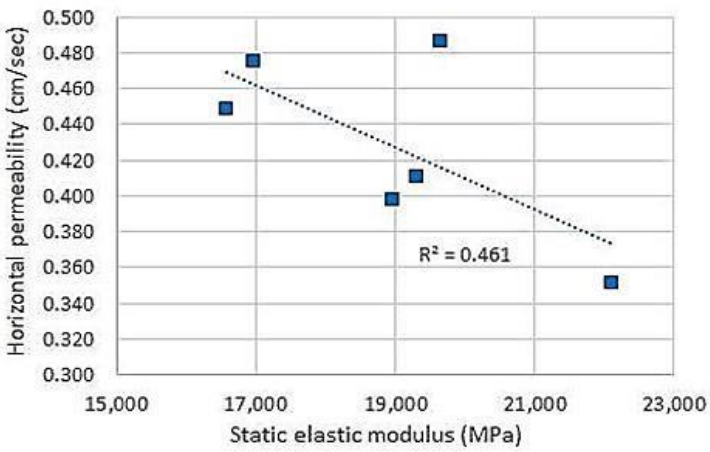


Fig. 20 Correlation between static elastic modulus and horizontal permeability at the age of 28-days

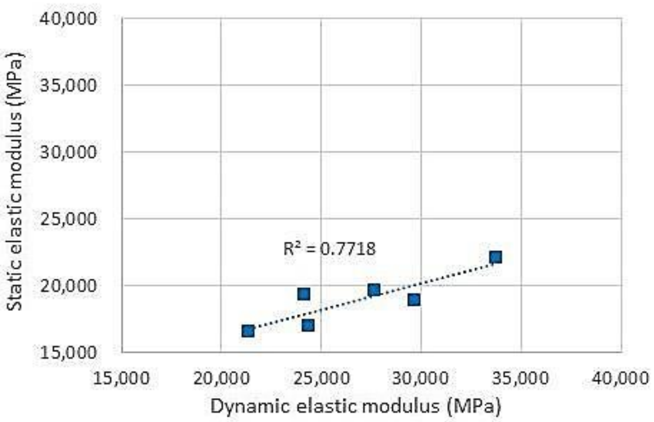


Fig. 21 Correlation between dynamic elastic modulus and static elastic modulus at the age of 28-days

Dynamic elastic modulus might be used to represent continuously graded pervious concrete elastic property on the field with a certain validation value. According to Fig. 21, the correlation between dynamic elastic modulus and static elastic modulus is good (0.60 < R2 < 0.80). The averaged dynamic elastic modulus which is calculated from longitudinal UPV test has a value 45% bigger compared to the static elastic modulus gained from ASTM C-469 test. This condition shows the connection between those two parameters possessed by continuously graded pervious concrete tends to be similar to the relationship between dynamic elastic modulus and static elastic modulus possessed by normal concrete [24]. Moreover, the fact that non-homogeneous characteristic from the normal concrete influences both modulus from the different way [25] is also happened in continuously graded pervious concrete wherein this non-homogeneous characteristic is seen from UPV test results.

The density level gained from longitudinal UPV test might also be used to represent continuously graded pervious concrete modulus of rupture. Based on Fig. 22, the correlation value between porous concrete longitudinal UPV wave and modulus of rupture is moderate ($0.40 \leq R^2 < 0.60$) so that the UPV test result from this study might create a fine potency not only for heterogeneity level assessment but also for an initial prediction about the flexural strength value from continuously graded pervious concrete itself.

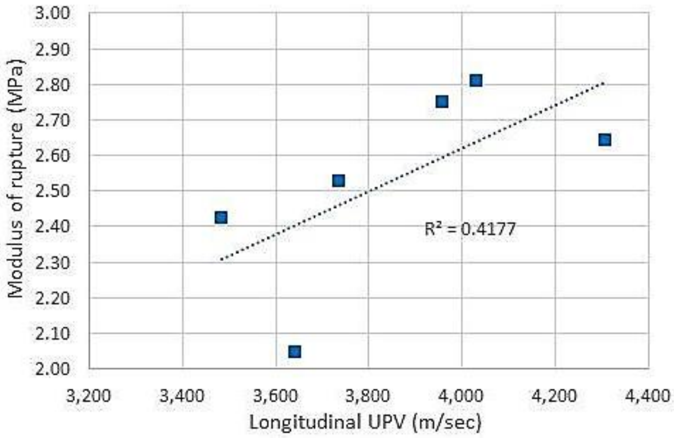


Fig. 22 Correlation between UPV wave and modulus of rupture at the age of 28-days

6. Conclusions

This paper has presented the procedure and the result of laboratory experimental research to study a mix-design input category for Indonesian Specification by using continuously graded pervious concrete as an alternative base layer for rigid pavement. Five advanced parameters, i.e. elastic modulus, Poisson’s ratio, flexural strength, horizontal permeability and heterogeneity level are used as criteria. Gradation variation which is used for mix-design-1 to mix-design-5 have been successfully surpassed the minimum advanced criteria for rigid pavement base layer required by Indonesian Specification. For all intents and purposes, those five mixtures can be recommended as an alternative for rigid pavement base layer.

Pervious concrete with continuously graded tends to be physically more elastic compared to normal concrete and has a better endurance against elastic deformation rather than normal concrete or uniform graded pervious concrete. According to the heterogeneity test result, it is heterogeneous when it comes to laboratory condition. The layer thickness of continuously graded pervious concrete should also be limited in specific value to keep the density level in a good quality. Pervious concrete which uses three types of gradation ranged has a better flexural strength because the increase of well-connected aggregate will delay the crack propagation before failure. The utilization of pervious concrete can also help to accelerate the advanced work process on the field because it has a shorter time to achieve the minimum flexural strength. The decrease of smaller aggregate size percentage in continuously graded aggregate proportion does not give an influence too much against horizontal permeability value.

In addition, static elastic modulus has a better relationship with horizontal permeability than flexural strength. This condition indicates that the variation of bonding strength in ITZ from each mixture plays an important role in controlling the flexural strength. Dynamic elastic modulus might be used to represent continuously graded pervious concrete elastic property on the field with specific validation number. The density level gained from longitudinal UPV test for dynamic elastic modulus assessment might be used to make an initial prediction about continuously graded pervious concrete's modulus of rupture value as well.

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Conflicts of Interest

The authors declare no conflict of interest.

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