ผลของอัตราส่วนปูนซีเมนต์ต่อมวลรวมและการบดอัดต่อสมบัติ ของคอนกรีตพรุนที่ทำด้วยกรวดคละสามขนาด

Effect of Cement to Aggregate Ratio and Compaction Effort on Properties of Pervious Concrete Made of Ternary-Sized Gravel

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บทคัดย่อ

งานวิจัยนี้ศึกษาผลกระทบของอัตราส่วนปูนซีเมนต์ต่อมวลรวมและผลกระทบของการบดอัด ที่มีต่อสมบัติของ คอนกรีตพรุนระบายน้ำที่ทำด้วยกรวดคละสามขนาด ซึ่งกรวดคละที่ใช้ในการทดลอง ประกอบด้วยเม็ดกรวดสามขนาดที่มี อยู่มากที่สุดในแหล่งกรวดธรรมชาติ คือ ขนาด 1/2" 3/8" และ No. 4 โดยนำมาผสมกันในอัตราส่วนร้อยละ 50:25:25 (โดยน้ำหนัก) ตามลำดับ ส่วนผสมของคอนกรีตพรุนที่ผลิตขึ้นในการวิจัยนี้แบ่งออกเป็น 3 กลุ่ม ตามอัตราส่วนปูนซีเมนต์ ต่อมวลรวม 3 ระดับ คือ 1:7 1:8 และ 1:9 (โดยน้ำหนัก) โดยใช้อัตราส่วนน้ำต่อซีเมนต์คงที่เท่ากับ 0.3 เหมือนกันทุก ส่วนผสม สำหรับการบดอัดได้ทำการแปรผันจำนวนตกกระทบของค้อนบดอัดมาตรฐาน เป็น 3 ระดับ คือ 15 20 และ 25 ครั้ง/หนึ่งชั้น จากนั้นได้ทดสอบหาค่าสมบัติต่าง ๆ ของคอนกรีตพรุน คือ อัตราส่วนช่องโพรงประสิทธิผล หน่วยน้ำหนัก กำลังอัด และสัมประสิทธิ์การซึมผ่านของน้ำ ผลการศึกษาพบว่า โดยภาพรวมคอนกรีตพรุนที่ผลิตขึ้นในงานวิจัยนี้มีค่ากำลัง อัดอยู่ระหว่าง 8.06 ถึง 13.73 เมกะปาสคาล และมีค่าสัมประสิทธิ์การซึมผ่านของน้ำ อยู่ระหว่าง 1.13 ถึง 1.82 เซนติเมตร/ วินาที นอกจากนี้พบว่าค่าสมบัติต่าง ๆ ข้างต้นของคอนกรีตพรุนที่ศึกษาในการวิจัยนี้ได้รับอิทธิพลอย่างชัดเจนจาก อัตราส่วนปูนซีเมนต์ต่อมวลรวมและระดับการบดอัด การเพิ่มขึ้นของสัดส่วนมวลรวม ทำให้ค่าอัตราส่วนช่องโพรง ประสิทธิผลและค่าสัมประสิทธิ์การซึมผ่านของน้ำเพิ่มสูงขึ้น ส่งผลให้ค่ากำลังอัดและหน่วยน้ำหนักของคอนกรีตมีค่าลด ต่ำลง ในทางตรงกันข้าม การเพิ่มระดับการบดอัดทำให้ค่าอัตราส่วนช่องโพรงประสิทธิผลและค่าสัมประสิทธิ์การซึมผ่าน ของน้ำลดต่ำลง ส่งผลให้ค่ากำลังอัดและหน่วยน้ำหนักของคอนกรีตมีค่าสูงขึ้น นอกจากนี้พบว่าหน่วยน้ำหนัก กำลังอัด และสัมประสิทธิ์การซึมผ่านของน้ำมีความสัมพันธ์เชิงเส้นกับอัตราส่วนโพรงประสิทธิผลภายในคอนกรีต

คำสำคัญ: คอนกรีตพรุนระบายน้ำ อัตราส่วนปูนซีเมนต์ต่อมวลรวม การบดอัด มวลรวมคละสามขนาด

ABSTRACT

This research work investigates the effect of the cement to aggregate ratio (c/a) and the effect of compaction effort on properties of pervious concrete made of ternary-sized river gravel. The ternary-sized gravel used in the experiment was a mix of the three most abundant particle sizes presented in natural gravel (1/2", 3/8", and No.4), with a mass composition of 50:25:25. Three concrete mixtures with different c/a ratios of 1:7, 1:8, and 1:9 (by weight) were produced using the same water to cement ratio of 0.3. The compaction effort applied for each concrete mixture was varied by dropping a standard compaction hammer either at 15, 20, or 25 blows/layer. The properties of the pervious concrete obtained in this study included the effective void content, the unit weight, the compressive strength, and the permeability coefficient. Experimental results showed that the pervious concrete made of this gravel exhibited the compressive strength ranging from 8.06–13.73 MPa, and the permeability coefficient varying from 1.13–1.82 cm/s. The results also showed that properties of the pervious concrete are strongly influenced by the cement to aggregate (c/a) ratio and the compaction effort. Increasing aggregate ratio resulted in enhancing effective void content and permeability coefficient, thus lowering the compressive strength and the unit weight of the concrete. In contrast, an increase in compaction effort resulted in a decreased effective void content and a reduced permeability coefficient, leading to an improved compressive strength and an increased unit weight of the concrete. It was also found that the unit weight, the compressive strength, and the permeability coefficient are linearly correlated with the effective void content of the hardened concrete.

Keywords: Pervious concrete, Cement to aggregate ratio, Compaction, Ternary-sized aggregate

1. Introduction

Recently, the drainage of storm water in urban areas becomes a serious problem of Thailand, because of an increased amount of built infrastructures and a decrease in permeable unpaved areas. When it is staring to rain, the depth of surface runoff rapidly increases and the drainage system gets overloaded quickly, causing road transportation problem [1]. Therefore, local administration authorities are now searching for appropriate engineering solutions to solve this problem.

Pervious concrete is a special designed concrete, consisting basically of Portland cement, water, coarse aggregates, and little or no fines. The lack of fines creates an open void structure, called "effective void", in the pervious concrete, allowing water to infiltrate from the surface down into the subsoil through these voids [2]. With this characteristic, the pervious concrete has been used as pavements of secondary roads, parking lots, and walkways, and it is currently considered as a promising solution for storm water management in Thailand.

Many researchers reported that the effective void content played a key role on functional properties of the pervious concrete, such as water permeability and compressive strength [3]. Mineiger [4] recommended that the minimum effective void content of 15% were required for water percolation.

To obtain the pervious concrete with high effective void content, a uniform sized aggregate is commonly recommended [2, 5-10]. Recently, Ibrahim et al. [2] investigated the properties of Portland cement pervious concrete made of either one or two sizes of crushed limestone aggregates. Test results showed that the void ratio of the pervious concrete mixtures ranged from 30 to 40% with unit weight ranging from 16.0 to 18.4 kN/m^3, while compressive strength and permeability varied from 1.06 to 6.95 MPa and 1.50 to 2.82 cm/s, respectively.

In Thailand, river gravel is plenty in the North and Northeastern areas. This kind of gravel has rounded particle shape with grain sizes ranging from 4.75 to 19.0 mm. It is considered as a potential source of aggregate for pervious concrete production. However, the use of only one or two particle sizes of aggregate, as reported by Ibrahim et al. [2] may need more time and cost for aggregate preparation. The goal of this research was to use this gravel with a wider range of particle sizes, in order to maximize the effectiveness of resource utilization. Hence, the concept of "ternary-sized aggregate" was investigated in the present work. In addition, it is known that workability of the pervious concrete is usually low, as a result of fine aggregate exclusion. Therefore, a certain level of compaction is needed to obtain the pervious concrete with desired compressive strength and permeability. Thus, the effect of compaction

effort should be investigated, when a specific pervious concrete mixture is developed.

The present study was carried out to study the effect of cement to aggregate (c/a) ratio and compaction effort on properties of Portland cement pervious concrete made of ternary-sized gravel. The properties investigated in this study included unit weight, effective void content, coefficient of water permeability, and compressive strength.

2. Experiments
2.1 Materials

Coarse aggregate used in this study was river gravel, commercially available in the area near to Mekong River, Nong Khai, Thailand. According to a preliminary study, it was found that the percent retained on sieve 1/2", 3/8", and No.4 of the natural river gravel were 48%, 26%, and 24%, respectively. Therefore, the above particle sizes of the gravel were selected to form a ternary-sized coarse aggregate with an adjusted mass fraction of 50:25:25, respectively. Properties of the ternary-sized aggregate are given in Table 1. An ordinary Portland cement with specific gravity of 3.15, and complying with TIS-15-2547, was used as a binder. The cement-to-aggregate ratio (c/a) was designed at three levels, including 1:7, 1:8, and 1:9 (by weight), while the water-to-cement ratio (w/c) was kept constant at 0.3 (by weight). Appropriate amounts of superplasticizer were used for different mixes to ensure uniform coating of paste on aggregate surface. Details of the concrete mix proportions are shown in Table 2.

2.2 Sample Preparations

Coarse aggregate and small amount of water were mixed by a horizontal pan laboratory mixer for one minute. Then, all cement contents and the remaining amounts of water were added gradually. Continuous mixing was performed for 4 minutes or until uniformed coating of cement paste on surfaces of gravels was observed. Fresh concrete mixture was then cast into the 10 cm by 20 cm cylindrical mold with three layers. For the first group of specimen, each layer of the concrete was compacted by applying 15 blows of standard compaction hammer. This compaction effort was increased to 20 blows/layer and 25 blows/layer, for the second and the third group of specimens. These processes represented three different levels of compaction energies, 356 kN-m/m^3 or 475 kN-m/m^3 or 594 kN-m/ m^3, respectively. After

demolding at 24 hrs, all concrete specimens were sealed and cured at 29°C for 28 days before testing for their properties. Appearances of test specimens were showed in Fig.1.

Table 1 Composition and properties of a ternary-sized aggregate.

Properties	Gravel sizes		
	1/2"	3/8"	No.4
Weight composition of individual particle size [% wt.]	50	25	25
Specific gravity	2.56		
Water absorption [%]	1.10		
Abrasion loss [%]	28.1		

Table 2 Mix proportions of pervious concrete.

Materials weight	c/a Ratio [by wt.]		
	1:7	1:8	1:9
Cement [kg/m^3]	277.3	242.6	215.5
Gravel [kg/m^3]	1,941.3	1,941.3	1,941.3
Water [kg/m^3]	83.2	73.0	63.8
S.P.[kg/m^3]	2.77	2.40	2.13
w/c Ratio [by wt.]	0.3	0.3	0.3

2.3 Test Methods

The effective void content was determined based on the principle of buoyancy force (ASTM C1754 /C1754M). The value of effective void content was determined by Eq.1.

$$\phi(\%) = \left[1 - \frac{(w_2 - w_1)}{\rho_w V} \right] \times 100 \quad (1)$$

where

ϕ is effective void content (%), V is total volume of specimen (cm^3), w_1 is water-submerged weight of specimen (g), w_2 is saturated-surface dried weight of specimen (g), and ρ_w is density of water.

Permeability of the pervious concrete was measured by a constant head permeability test setup, as shown in Fig. 2. The value of permeability coefficient was calculated by Eq.2.

$$k = \frac{QL}{AHt} \quad (2)$$

where k is water permeability coefficient (cm/s), L is specimen height (cm), H is water

head causing the flow (cm), A is cross-sectional area of specimen (cm^2), Q is volume of water permeated through test specimen (cm^3), and t is testing duration (s).

Compressive strength test was performed according to ASTM C39. Sulfur capping was also applied on both ends of the specimen.

Three specimens were used for each test and the results given in this paper are the average values.

Fig.1 Pervious concrete specimens.

Fig.2 The constant head permeability test set-up.

3. Results and Discussions
3.1 Effect of c/a Ratio and Compaction Effort

From Fig.3 (a), the effective void content increased with aggregate ratio, and decreased with compaction effort. At 15 blows/layer of hammer compaction, the effective void content increased from 22.7% to 25.9%, when c/a ratio changed from 1:7 to 1:9. At c/a = 1:7, on the other hand, the effective void content slightly decreased from 22.7% to 21.2%, when compaction effort increased from 15 blows/layer to 25 blows/layer. This finding agrees with the results reported by Suleiman et al. [8], which indicated that the use of high compaction energy resulted in a decreased void content. It should be noted that, although the lowest effective void content obtained in the present work (21.2%) was lower than that reported by Ibrahim et al. [2], it was higher than the minimum void content required

for water percolation (15%), as recommended by Mineiger [4]. Therefore, it is confirmed that the ternary-sized gravel in this study can be used as aggregate for pervious concrete production.

Fig.3 (b) illustrates that unit weight of the pervious concrete increased with compaction effort. At c/a ratio of 1:7, for example, the unit weight increased from 18.9 kN/m^3 to 19.45 kN/m^3, representing 3.0% increase, when the compaction effort increased from 15 blows/layer to 25 blows/layer. Similar trends were observed in the concrete with c/a ratio of 1:8 and 1:9. This indicates that an increase in compaction energy can produce a more compacted void structure of the pervious concrete, resulting in a higher unit weight [8]. For the same compaction energy, the unit weight decreased with the weight ratio of aggregate. At 15 blows/layer of compaction, the unit weight reduced approximately 2.2%, when c/a ratio changed from 1:7 to 1:9. This is due to the fact that the aggregate used in this study has lower specific gravity (2.56), as compared to Portland cement (3.15). Thus, an increase in weight ratio of the aggregate in the mixture leads to a reduction of Portland cement content. As a result, the overall unit weight of the pervious concrete reduces.

From Fig.3(c), the lowest compressive strength (8.06 MPa) was found in the sample with c/a = 1:9 and 15 blows/layer compaction, while the highest value of 13.73 MPa was found in the sample with c/a = 1:7 and 25 blows/layer compaction. At the same c/a ratio, the compressive strength increased with compaction effort. For example, at c/a = 1:7 the compressive strength increased 21.3%, as the compaction effort increased from 15 blows/layer to 25 blows/layer. Theoretically, strength of the pervious concrete is controlled by the contact area between aggregate particles. At high compaction effort, the internal structure of the pervious concrete is more compacted, and the contact area between aggregates increases. Therefore, compressive strength increases accordingly. In the opposite way, the compressive strength tended to decrease with increasing aggregate ratio. In the case of 15 blows/layer compaction, for instance, the compressive strength decreased 28.8%, when c/a ratio changed from 1:7 to 1:9. This can be explained by a relative decreased amount of cement paste, as compared to the aggregate. As a result, the amount of cement paste may be insufficient to bond all the aggregates surfaces

and their contact points, weakening the compressive strength of the concrete.

Fig. 3 (d) indicates that the permeability coefficient was in the range of 1.13 – 1.88 cm/s. Overall, the permeability coefficient decreased with compaction energy, and increased with aggregate ratio. At c/a ratio of 1:7, the permeability coefficient decreased from 1.52 cm/s to 1.13 cm/s, representing 25.8% reduction, as the compaction effort increased from 15 blows/layer to 25 blows/layer. At the same compaction effort, 25 blows/layer, for example, the permeability coefficient changed from 1.13 cm/s to 1.50 cm/s, representing 33.3% increase, when c/a ratio changed from 1:7 to 1:9. It is well recognized that the permeability coefficient of the pervious concrete is a function of its effective void ratio. At high aggregate content and low compaction energy, the effective void ratio of the concrete increases. Therefore, its permeability coefficient increases.

3.2 Correlations between various properties

Fig.4 (a) and Fig.4 (b) show that unit weight and compressive strength of pervious concrete decreases linearly with an increase in effective void content. Regardless of c/a ratio and compaction effort, the correlation between unit weight and effective void content can be expressed as a single linear equation ($\rho = -0.189\phi + 23.35$) with $R^2 = 0.915$, where ρ is the unit weight (kN/m^3) and ϕ is effective void content (%). Similarly, the correlation between compressive strength and effective void content can be expressed as $\sigma = -1.222\phi + 39.25$ with $R^2 = 0.922$, where σ is the compressive strength (MPa).

In contrast, Fig.4 (c) shows that permeability coefficient of pervious concrete increases linearly with an increase in effective void content. Their correlation can be expressed as $k = 0.131\phi - 1.55$ with $R^2 = 0.887$, where k is the permeability coefficient (cm/s).
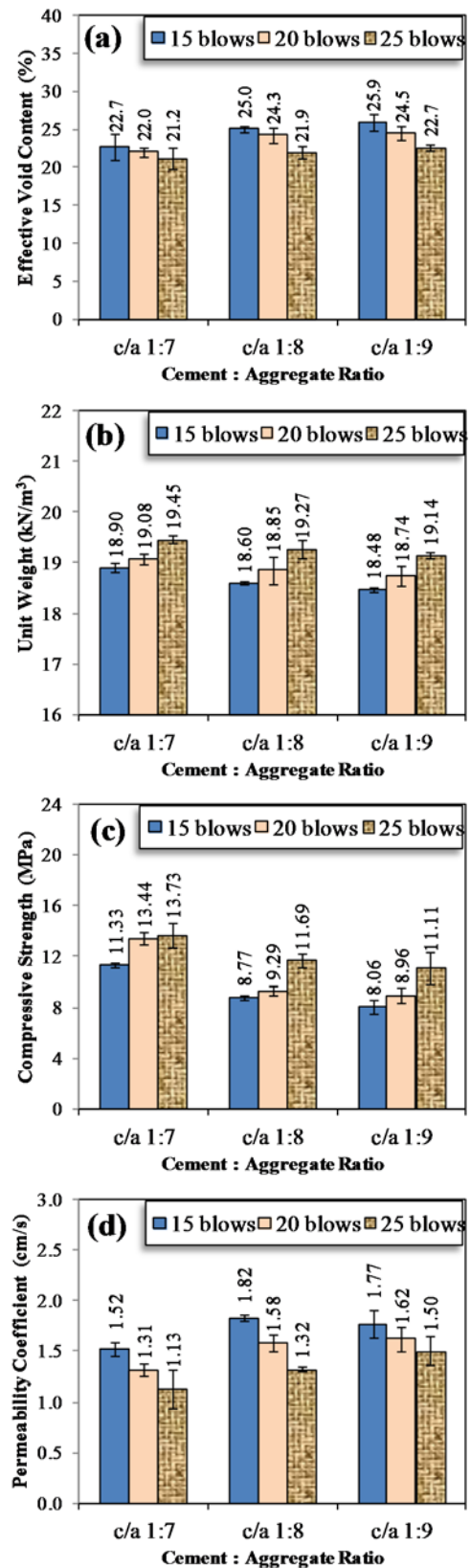

Fig.3 Effect of c/a ratio and compaction effort on pervious concrete properties: (a) effective void content, (b) unit weight, (c) compressive strength, and (d) permeability coefficient.
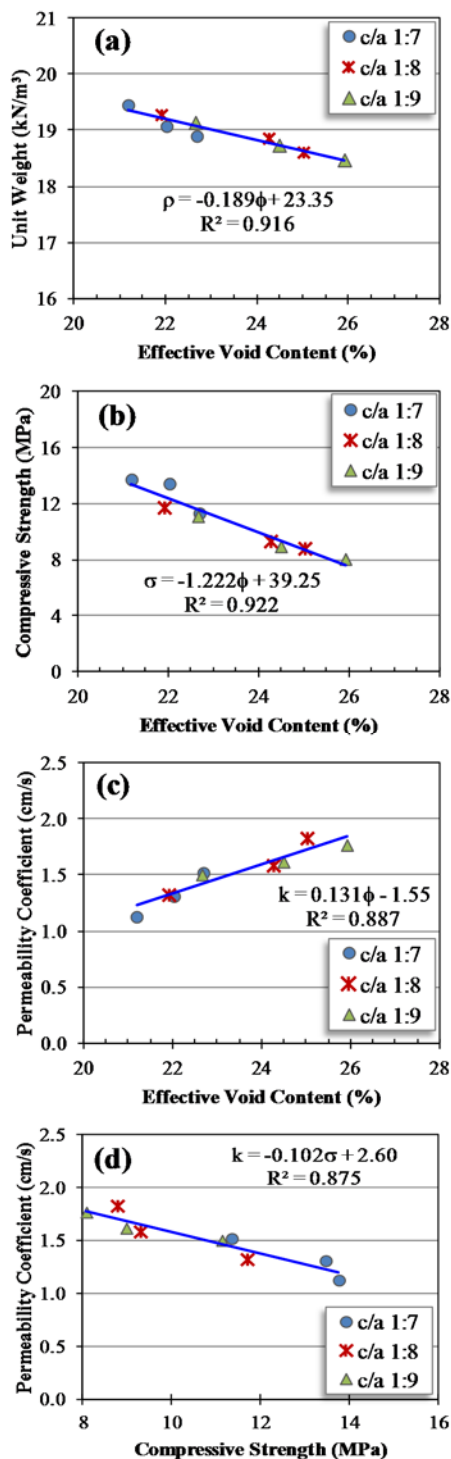
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Fig.4 Correlations between various concrete properties: (a) effective void content and unit weight, (b) effective void content and permeability coefficient, (c) effective void content and compressive strength, and (d) permeability coefficient and compressive strength.

As expected, Fig. 4 (d) shows that the permeability coefficient decreases with an increase in compressive strength. The correlation between these two quantities can be expressed as $k = -0.102\sigma + 2.60$ with $R^2 = 0.875$.

It should be noted that correlations among various properties of the pervious concrete made of the ternary-sized gravel in this study are all in a linear fashion. This finding is in line with previous researches. Wang et al. [7], Suleiman et al. [8], Crouch et al. [11], and Kevern et al. [12] reported that unit weight and compressive strength of the pervious concrete made of different single-sized aggregates were linearly correlated with void content. While, Bhutta et al. [13] and Hesami et al. [14] have found that the permeability coefficient and void content of numerous pervious concrete mixtures were also linear correlated. From the above experimental results, it is obvious that the effective void content is a key parameter governing all properties of the pervious concrete. Different concrete samples with the same effective void content tend to exhibit the same compressive strength and permeability, although they are made with different c/a ratios and compaction efforts. Therefore, it is essential to optimize the effective void content in order to achieve the desired permeability with an acceptable compressive strength.

4. Conclusions

From experimental results of this study, the following conclusions can be drawn.

(a) The ternary-sized river gravel can be used to produce pervious concrete. With c/a ratio ranged between 1:7–1:9 and compaction effort varied from 15–25 blows/layer, the pervious concrete made of this aggregate exhibited compressive strength ranging from 8.06–13.73 MPa, permeability coefficient varied from 1.13–1.82 cm/s.

(b) The properties of the pervious concrete are strongly influenced by the cement to aggregate (c/a) ratio and the compaction effort. Increasing aggregate ratio resulted in enhancing effective void content and permeability coefficient, thus lowering the compressive strength and the unit weight of the concrete. In contrast, an increase in compaction effort resulted in a decreased effective void content and a reduced permeability coefficient, leading to an

improved compressive strength and an increased unit weight of the concrete.

(c) A single linear equation can be used to describe the correlation between the effective void content and other properties of the pervious concrete, regardless of c/a ratio and compaction effort.

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