Properties of pervious concrete with various types and sizes of aggregate

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Abstract. The benefit of pervious concrete lies in its ability to transport a large volume of water through its pores to the underlying strata, and it often serves as a pavement for vehicles and pedestrians. This research aimed to determine the properties of pervious concrete based on trials in the laboratory. The method used in this research was a laboratory experiment in accordance with the appropriate standards. The local material used in the mixture was a material composition with Portland Cement Composite with a water-cement (W/C) ratio 0.27 to 0.34, with aggregates of various types and sizes and fly ash and superplasticizer as the added ingredients. The mixture for the trial used 4.25 for the aggregate-cement ratio (A/C) with a proportion of 6% for the fine aggregate (sand), 15% flay ash and a low dosage of superplastizer. The test results showed a slight difference in compressive strength and split tensile strength alongside variations in the W/C, including the use of different aggregate types and sizes. The permeability when using natural aggregate was more porous compared to the crushed stone. The effect of the aggregate size from small to large will result in decreased density (unit weight) and increased void in the mixture. Good agreement was reached in the 0.30 wcr mixture with an aggregate size that passed through a 12.5 mm sieve, that was retained at 9.5 mm and that provided suitable compressive strength.

1 Introduction

Changes in climate are recognized as one of the major factors responsible for land degradation affecting sustained development. Water resources are also inextricably associated with climate change. Annual ordinary river runoff and water availability are projected to rise by 10-40 percent at high latitudes, in wet tropical areas, and at mid-latitudes. In the dry tropics, this has decreased by 10-30 percent [1]. Moreover, climate change can and is producing a wide array of impacts that can affect infrastructure on a broad scale. An infrastructure's assets and vulnerability to climate change are also highly context sensitive, with the location and adaptive capacity of local businesses, governments, and communities all being influential [2]. As a result, the use of environmentally-friendly (green) materials is now an unavoidable choice, including in construction. The utilization of green concrete in construction is being increasingly adopted by the construction industry,

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owing to the drawbacks of conventional concrete and the numerous inherent benefits of green concrete.

Green concrete offers numerous environmental, technical and economic benefits such as high strength, increased durability, improved workability and pumpability, reduced permeability, controlled bleeding, superior resistance to acid attack, and the reduction of plastic shrinkage cracking [3]. Its impact on transportation systems and in the literature are now emerging, including related to how climate change affects explicitly pavement systems and what adaptation strategies might be pursued [4, 5]. However, a traditional pavement on paved surfaces can help to reduce runoff by infiltrating any rainwater. The use of alternative materials, which includes pervious asphalt, pervious concrete, interlocking pavers, and plastic grid pavers, allows for rain and snowmelt to seep through the surface down to the underlying layers of soil and gravel.

Permeable pavements can filter out the pollutants that contribute to water pollution [6], and also reduce any harmful content. As a kind of material that is applied in a road's base course and used in coarse pavement, porous concrete is required to have satisfactory strength, permeability, dynamic stability, scouring resistance and volume stability [7]. Therefore, the use of pervious concrete is the solution to overcoming a lot of problems. Environmental advantages, such as reducing tire-pavement interaction noise, moderating storm-water runoff, and limiting the pollutants entering the groundwater, mean that an aggregate storage bed will reduce the stormwater runoff volume, rate, and pollutants appropriately [4, 8–12].

A pervious concrete solution for parking, walkways, and landscaping enables fast water drainage, and easy absorption avoids surface water, reduces flood risks and is cost efficient [13] by reducing the size of the drainage system needed. It also affects durability by reducing the surface temperature of the paved area. Thus, the main function of pervious concrete lies in its ability to transport a large volume of water through its pores to the underlying strata, and it serves as a pavement for vehicles and pedestrians [14–18].

2 Materials and methods

Based on the description above, this research was conducted using a trial method in a laboratory to obtain the optimal proportions for a pervious concrete mixture that could provide optimal concrete compressive strength, split tensile strength and high permeability. The local material (Fig. 1) used in the mixture included variations in the aggregate type and size. The amount of cement used in this research study was sorted into three proportions (350 kg, 400 kg and 450 kg) and the water-cement ratios were 0.27, 0.30 and 0.34 respectively.

2.1 Materials

Portland Cement Composite (PCC), as per the Indonesian National Standard/SNI [19], was used for this experiment in proportions of 350, 400 and 450 kg/m^3. The physical properties have been presented in Table 1. Fly-ash was added in the mixture to a percentage of 15% fly-ash [20, 21]. The results of the Fly-ash Scanning Electron Microscopy (SEM) have been shown in Table 2, with SiO_2 + Al_2O_3 + Fe_2O_3 = 50.57% included in class C with a minimum requirement of 70% [22]. The average specific gravity test for fly ash was 2.30. Potable water was available in the laboratory with a normal pH, conforming to the SNI (Indonesia National Standard) requirements. This was used for mixing the concrete and curing the specimens [23].

Fig. 1. Local materials.

Table 1. Portland cement properties.

Description	Standard tests	Results
Specific Gravity	SNI 2531:2015 (ASTM C188-17)	3.053
Consistency test	SNI 03-6826-2002 (ASTM C187-11)	29.5%
Initial setting time	ASTM 191-18	73 minutes
Final setting time	SNI 03-6827-2002 (ASTM 191-18)	455 minutes
Bulk density (kg/m^3)	-	1420 kg/m^3

Table 2. Results of the fly-ash Scanning Electron Microscopy (SEM).

Atom	Mass (%)	Relative mass %	Oxide results
O	45.03	16	Silicon dioxide (SiO_2) = 27.81 Aluminium oxide (Al_2O_3) = 10.73 Iron oxide (Fe_2O_3) = 12.03
C	29.86	12	
Al	14.83	27	
Si	5.05	28	
Ca	3.61	40	
Fe	1.62	56	
	100	100	Total = 50.57%

The required physical properties of the coarse aggregate used in porous (pervious) concrete are that it should be clean, hard and durable [24–26]. Two types of locally available coarse aggregate were used in the research, i.e., crushed stone and rounded river gravel or natural aggregate [27, 28]. The physical properties have been described in Tables 3 and 4. The sieve analysis procedure of the aggregates had the result of being under ASTM C136:2012 for both the sand and coarse aggregates. There are three different grades for coarse aggregate; passing through the 19 mm sieve and retained on the 12.5 mm sieve, passing through 12.5 mm sieve and retained on the 9.5 mm sieve, and passing through the 9.5 mm sieve and retained on the 4.75 mm sieve. The proportion of mixed aggregates was 6% fine aggregate (sand) and 94% coarse aggregate in this experimental research. The result of the aggregates when combined have been shown in Fig. 2 for the natural aggregate and Fig. 3 for the crushed stone. The upper and lower gradation limit for the combined aggregate gradations has been referred to by some scholars [16, 27] for pervious concrete. The upper gradation limit of the mixture was too rocky for manual placement techniques, and the surface was too open to be classed as having a smooth texture. The lower gradation limit represents an area below which low to zero permeability becomes probable.

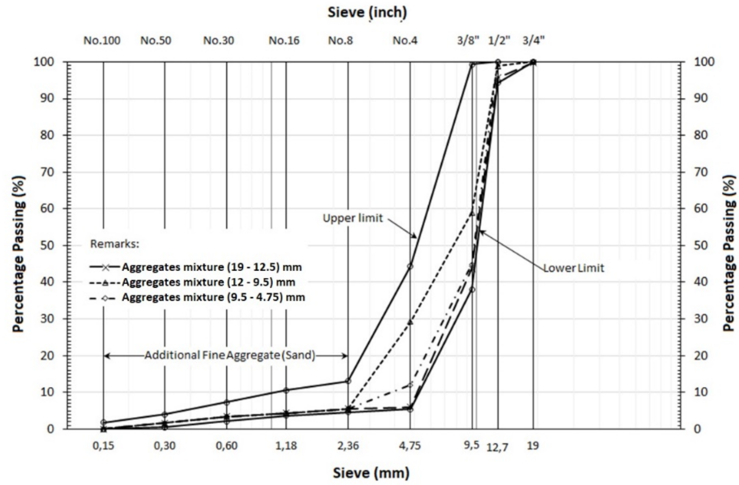


Fig. 2. Aggregates combined with crushed stone of various sizes.

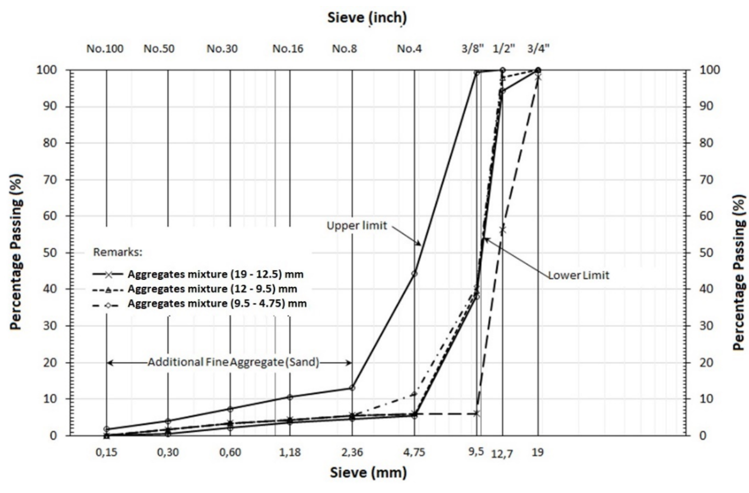


Fig. 3. Aggregates combined with natural aggregates of various sizes.

The chemical admixtures using Sika® ViscoCrete®1003 superplasticizer technology in this research made up 0.2% of the cement and were dissolved in part of the mixing water. The dosage of the admixtures was according to EN 206-1, where admixture quantities for low dosages < 0.2% of the cement are only allowed if they are dissolved in part of the mixing water [29].

Table 3. Properties of coarse aggregate.

Description	Standard tests	Average result					
		Natural aggregates (mm)			Crushed aggregates (mm)		
		A	B	C	A	B	C
Specific Gravity	SNI 1970:2016 (ASTM C127-15)	2.518	2.535	2.573	2.461	2.503	2.576
Bulk density (kg/m^3)	SNI 03-4804-1998 (ASTM C29/29M-17a)	1580	1597	1608	1610	1595	1627
Absorption (%)	SNI 1970:2016 (ASTM C127-15)	1.158	1.032	0.956	1.020	0.960	0.770
Note: A = passed 19 mm and retained at 12.5 mm; B = passed 12.5 mm and retained at 9.5 mm; C = passed 9.5 mm and retained at 4.75 mm.							

Table 4. Properties of fine aggregate.

Description	Standard tests	Results
Water content	SNI 8319:2016 (ASTM C70-13)	1.075 %
Specific Gravity	SNI 1970:2016 (ASTM C128-15)	2.822 gr/cm^3
Absorption	SNI 1970:2016 (ASTM C128-15)	4.589 %
Clay lumps & friable particles	ASTM C142 / C142M - 17	3.77 %
Organic impurities	SNI 2816:2014 (ASTM C40/C40M-11)	Organic Plate No. 3

2.2 Methods

The proportion of materials has been shown in Table 5.

Table 5. Previous concrete mixture for natural aggregate, crushed with max. aggregates of 19 mm, 12.5 mm, 9.5 mm and 4.25 A/C (1 m^3 pervious concrete).

Material	Water Cement Ratio (wcr)		
	0.27	0.30	0.34
Portland Cement Composite (kg)	350	400	450
Water (L)	94.5	120	153
Coarse aggregate (kg)	1398.25	1598	1797.75
Fine aggregate (kg)	89.25	102	114.75
Fly ash (kg)	52.5	60	67.5
Superplasticizer (L)	0.7	0.8	0.9
Total	1985.2	2280.8	2583.9

The method used in this research was an experiment conducted in the laboratory on a trial basis. The coarse aggregate content [27] was varied to achieve the proper thickness of the paste surrounding the aggregate through trial and error, based on a mixed proportion of non-fine concrete [14]. A total of ten sets of the mixture were designed in a standard manner [30]. A water-cement (W/C) ratio of 0.27, 0.3 and 0.34 was used in the trial mixtures. The A/C ratio was 4.25, with 6% sand, 15% fly-ash and 0.2% superplasticizer for all ten sets of mixtures used [10, 22, 23, 25, 31, 32].

2.2.1 Mixing, casting and compacting

The mixing and casting procedure was following SNI 7974:2013 [33]. The compaction method is one of the most influential factors in the specimen preparation for pervious concrete. Two compaction methods were assessed [34] in this research; one was compacting using a drop hammer, and the other was compacting using a tamping rod [34, 35]. However, although the hammer compaction packed the aggregate particles together more tightly, the density of the porous concrete samples increased along with a loss of permeability.

As the impaction strength of a falling hammer was strong enough to crush the weak aggregate and create weak layers, the vibration method is more suitable for the majority of aggregates. However, for the sake of achieving maximum cohesion between the aggregate particles, a combined compaction method was attempted. Not only did we apply the standard rod compaction method, but we also incorporated the drop hummer compactor. This compaction allowed most of the coarse aggregate not to deform under compaction whilst increasing the contact surface and alignment of the aggregate particles, which was believed to be a substantial part of increasing the strength of porous concrete [34].

2.2.2 Density, void, compression and permeability

The density and void content of the pervious concrete was calculated based on the measured mass of the consolidated concrete specimen, the volume of the measure, and the total mass of materials batched [36]. Theoretical density is a laboratory determination, and the density is assumed to remain constant for all batches made using identical component ingredients and proportions [36]. The calculation was as follows:

$$T = Ms / Vs \tag{1}$$

where, T is the theoretical density of the concrete computed on an air-free basis, kg/m^3, Ms is the total mass of all materials batched in kg, and Vs, is the sum of the absolute volumes of the component ingredients in the batch, m^3. Vs was used to calculate the mass of the concrete and its saturated surface density (MSSD) by subtracting the mass of the concrete in the water, MW. Density (Unit Weight), D was calculated by dividing the net mass of the concrete by the volume of the measure, V_m. The mass of the concrete was calculated by subtracting the mass of the measure, M_m, from the mass of the measure filled with concrete, M_c. The calculation was as follows:

$$D = (M_c - M_m) / V_m \tag{2}$$

The void content is a percentage of the void as in Eq. 3, and the results are in Fig. 1.

$$U = (T - D) / T \tag{3}$$

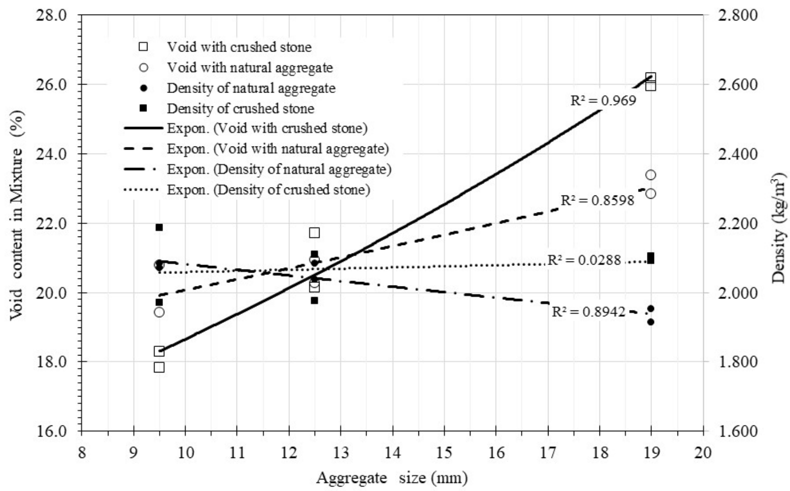


Fig. 4. Void content and density in the concrete mixtures with various types and sizes of aggregate.

The cast cylinders were demolded after 24 hours, labeled and weighted for various tests. The samples were cured in water [33]. For each batch, two samples were prepared for permeability testing, and the others were prepared for compression. Compressive strength (f'c) describes the typical concrete ability to receive compressive force per unit area. The compressive strength test was conducted following ASTM C-39. Three samples were tested at 3 days, 7 days and 28 days respectively. The testing of the splitting tensile strength was according to SNI 2491:2014 [40]. The split tensile strength test was carried out at 28 days, with two samples for each mixture. The compressive strength testing of the concrete specimens was carried out in the laboratory [37, 38]. Before the loading process, the caps were placed on the ends of the samples. The type of capping used depended on the surface condition of the concrete samples. Sulfur capping was used for samples with a rough surface like porous concrete as shown in Fig. 5.

(a) (b)

Fig. 5. (a) Sample capping, (b) Compressive strength test sample.

The permeability or infiltration test was expressed in millimeters per second (mm/s), since porous concrete generally has a much higher permeability compared to normal dense concrete. The permeability test method for the infiltration rate in place of pervious concrete is appropriate according to ASTM C1701 [39]. In addition, to determine the rate of infiltration, the cylindrical pervious concrete was wrapped in plastic. With the inline duck type, the pipe was placed tightly to inhibit water leakage along the sides and the top of the sample (Fig. 8). The infiltration rate was calculated using the following equation:

$$I = (KM)/(D^2 t) \tag{4}$$

where I is the surface infiltration rate (mm/min), K=76,394,433.33 ($mm^3 \cdot s/(kg \cdot min)$), M is the mass of the infiltrated water (kg), D is the ring's inside diameter (mm), and t is the time required for the water used in the test to infiltrate the surface (s).

3. Results and discussion

During the mixing process, the nature of the fresh mixture's workability was controlled visually [41]. A greater aggregate mixture with the potential of segregation was prevented by mixing manually. The W/C ratio with 0.34 had more plasticity compared to 0.27. The low dosage of superplasticizer was 0.2% mixed in with the water, which did not show a significant change in the plasticity of the fresh concrete.

3.1 Effect of aggregate type and size on void and density

Based on Fig. 4, the unit weight (density) and void in the mixture of the pervious concrete using natural aggregates and crushed stone indicated that the coarse aggregates that passed 19 mm and were retained at 12.5 mm will have an increased amount of void in the mixture and decreased density. The smaller aggregate size that passed 9.5 mm and was maintained at 4.75 mm will increase the unit weight of the pervious concrete and reduce the void in the mixture. Increased void in the mixture will raise the concrete's permeability as indicated by the high rate of infiltration. The results of the research correlate with the results of the previous studies, which stated that the water permeability coefficient and connected porosity increased as the size of the aggregate was increased. [42].

The results were all average values as shown in Fig. 6 (a) for W/C 0.27, for W/C 0.30 and 0.34 as shown in Fig. 6 (b) and (c). The compressive strength and the results at 3 days, 7 days and 28 days with various aggregate types and sizes for the different W/Cs have been shown in Fig. 7 (a), (b) and (c).

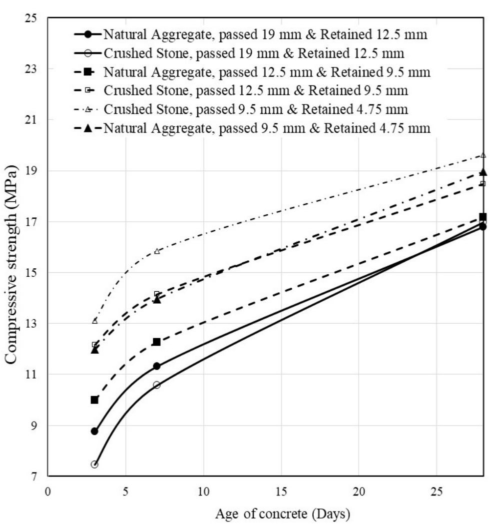
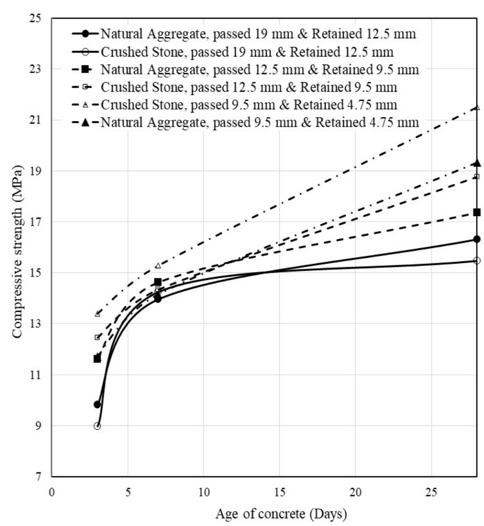


Fig. 5. (a) Compressive strength of various types and sizes of aggregate for W/C 0.27.



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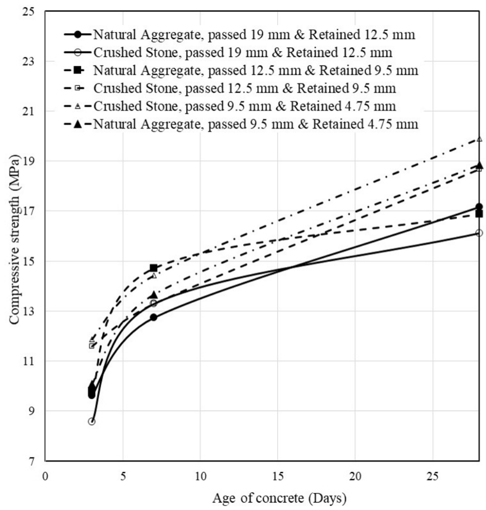

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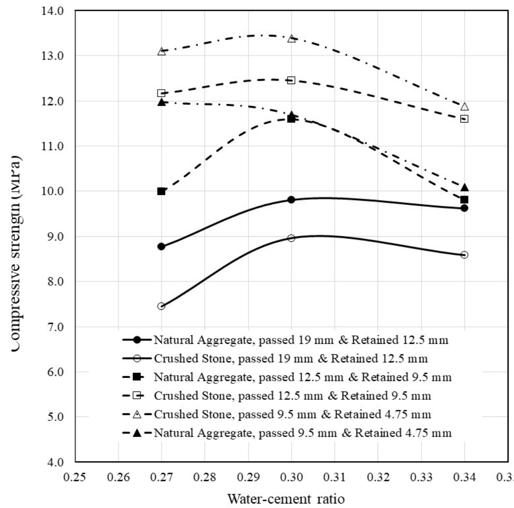
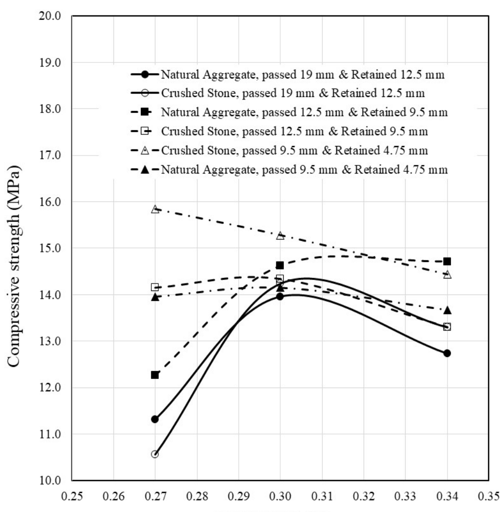
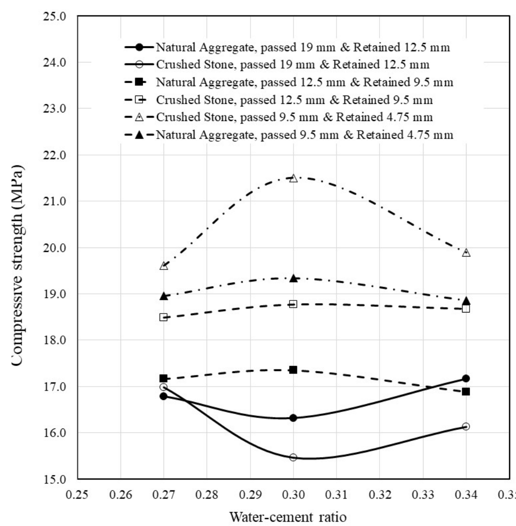


Fig. 6. (a) Compressive strength at 3-days for various types and sizes of aggregate.



Error! Reference source not found.. **(b)** Compressive strength at 7-days of various types and sizes of aggregate.



Error! Reference source not found.. **(c)** Compressive strength at 28-days of various types and sizes of aggregate.

3.2 Effect of aggregate type and size on compressive strength

With the compressive strength at the age of 3 days as shown in Fig. 7 (a), the average test results indicated that the higher the cement water ratio in the pervious concrete mixture using natural aggregates and crushed stone, the more there was a compressive strength increase of about 10%. On the contrary, increasing the size of the aggregate will reduce the compressive strength of the concrete. The optimal concrete compressive strength was achieved by using a 12.5 mm aggregate that was retained at 9.5 mm, as shown in Fig. 7 (a).

The same values were shown for the compressive strength at 7 days and 28 days as indicated in Fig. 7 (b) and (c). The typical failure is shown in Fig. 8.

The results of the tests showed that the highest water-cement ratio would produce low compressive strength following the data. This result was not clearly shown in this study as the difference in wcr ranged from 0.27 to 0.34 as we used an added admixture with a low dosage of 0.2% of the weight of the cement. Consequently, the difference could be seen clearly by using superplasticizer (SP) as an admixture, which is close to the maximum number. The use of SP will increase the workability of reaching the highest consistency with equal compressive strength.

Fig. 7. Typical failure of compressive strength.

Fig. 8. Permeable test in the experiment.

3.3 Effect of aggregate type and size on split tensile strength

The splitting tensile strength results are shown in Table 6.

Table 6. Result of the average splitting tensile strength (MPa).

Aggregates	W/C of natural aggregate			W/C of crushed stone		
	0.27	**0.3**	**0.34**	**0.27**	**0.3**	**0.34**
Passed 19 mm, retained 12.5 mm	2.49	2.57	2.71	2.54	2.68	2.80
Passed 12.5 mm, retained 9.5 mm	2.44	2.58	2.73	2.50	2.69	2.88
Passed 9.5 mm, retained 4.75 mm	2.49	2.55	2.69	2.57	2.68	2.77

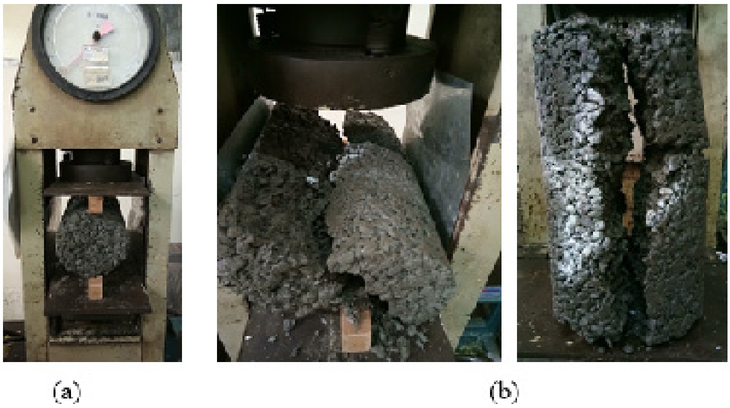


Fig. 10. (a) Testing of splitting tensile strength; (b) typical failure.

Splitting tensile strength is generally greater than direct tensile strength and lower than flexural strength (modulus of rupture). The strength of the split tensile shows there to be a slight difference between natural aggregates and crashed stone based on the compressive strength of the pervious concrete. The optimal value was obtained at W/C 0.3 with aggregates that passed through 12.5 mm and were retained at 9.5 mm. This result is pertinent to the conclusion, which states that a higher amount of small aggregate fractions yields higher density concrete mixtures and greater flexural or split tensile strength [43]. The typical failure is shown in Fig. 10.

3.4 Effect of aggregate type and size on permeability

The increased void in the mixture will boost the concrete's permeability as indicated by the high rate of infiltration. As referred to in the results of the permeability test (Table 7), the small aggregates will provide void in the pervious concrete mixtures, so the rate of infiltration in the pervious concrete using aggregates that passed through 9.5 mm and were retained at the 4.75 mm will produce a lower permeability than the concrete which used aggregates that passed through 19 mm and was retained at 12.5 mm. As a result, the larger aggregate size will increase the void in the mixture and increase the rate of infiltration (permeability), as shown in Fig. 11. This is similar to the previous studies which stated that by increasing the maximum size of the aggregate, the strength of the porous concrete decreases and the permeability increases [44-46]. The use of different water-cement ratios, in Fig. 12, still resulted in permeability in the wcr (0.3) for all aggregate sizes and types.

Table 7. Results of the average permeability test (mm/min).

Aggregates	W/C of natural aggregate			W/C of crushed stone		
	0.27	**0.30**	**0.34**	**0.27**	**0.30**	**0.34**
Passed 19 mm, retained 12.5 mm	23.76	19.82	14.25	23.45	17.10	11.98
Passed 12.5 mm, retained 9.5 mm	22.69	20.26	15.18	18.30	18.57	14.13
Passed 9.5 mm, retained 4.75 mm	20.94	20.39	11.62	18.59	17.62	13.02

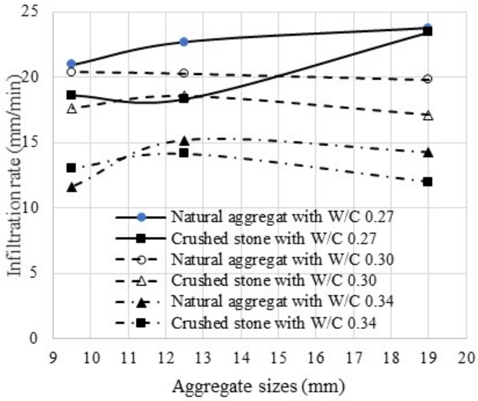


Fig. 9. Permeability with various aggregates.

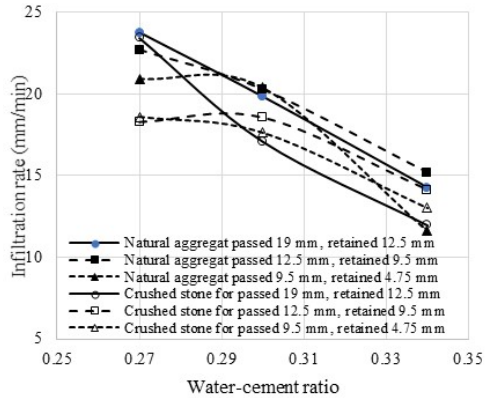


Fig. 10. Permeability with various W/C ratios.

The use of natural aggregates in this study has not shown infiltration consistently, which has resulted in a big difference in the wcr variations. The various sizes and types of aggregate have only slight differences. To conclude, conducting the test with various wcr showed that the infiltration rate decreased, while the concrete consistency increased.

4. Conclusions

The results of the laboratory experiment on the effect of aggregate size and type on compressive strength with different W/C ratios in pervious concrete mixes could not be demonstrated since the differences in the water-cement ratio in a mixture between 0.27 and 0.34 were small and therefore statistically insignificant. Therefore, it is necessary for there to be a more significant difference in the water-cement ratio or, if using a water-cement ratio in the same range, then there should be chemical additives added with values that are close to the maximum according to the manufacturer's recommendations. The most significant difference can increase both the compressive strength and flexural strength. The use of different types of aggregate in the pervious concrete mixtures with variations in the W/C ratio (0.27 to 0.34) resulted in a permeability level of approximately 20%. The optimization of the proportion of the aggregate size proposed in this study was that the bet aggregate to use passed through the 12.5 mm sieve and was retained at 9.5 mm. The results of using the aggregates with a W/C ratio 0.3 were that they provided compressive strength from 8-14 MPa for 3 days and 7 days, whereas for 28 days it was 15-22 MPa. The split tensile strength was different depending on the size and type of the aggregate. The resulting density was between 2.0 and 2.15 kg/m^3 with a void in the mixture at intervals of 20-22%. The resulting permeability ranged from 17 to 21 mm/min.

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