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Article

Properties of Pervious Concrete Aiming for LEED Green Building Rating System Credits

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Abstract. Pervious concrete is a special type of concrete with high porosity. The use of pervious concrete may achieve many potential LEED green building rating system credits. The objective of this paper is to investigate the appropriate mix proportion which provides the high LEED points and also the good mechanical properties. Nine mix proportions based on possible LEED points were examined. The replacement of cement by fly ash (20% - 60%) and coarse aggregate by recycled aggregate (20% - 100%) were used. Properties of pervious concrete relating to LEED credits and design values such as permeability, void content, compressive strength and splitting tensile strength were evaluated. It was found that the proposed pervious concrete can achieve the stormwater design-quantity control, recycled content and recycled materials credits. According to the results, the mix proportions which cement was replaced by 40% and 60% of fly ash archived the highest LEED credit points and also provided the sufficient mechanical properties. Therefore, these mix proportions are recommended for green construction.

Keywords: Pervious concrete, LEED, permeability, void content, fly ash, recycled aggregate.

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1. Introduction

Nowadays, our world is facing various environmental problems. These environmental problems are caused by increasing world pollution, increasing production and consumption of material goods. These problems have serious consequences for the health of human beings and also affect severely the natural ecosystems. To lessen these environmental problems as a civil engineer, some construction materials could be developed because construction sector play an important role in the development of high-performance and sustainable buildings. Among construction materials, one of the most popular materials is concrete that is needed to be "green" for buildings. The green buildings indicate the efficiency of buildings in their use of energy, water, and materials used during construction and reduce the building's impact on the human health and environment. One of the ways to obtain a certification for a "green buildings", Leadership in Energy and Environmental Design (LEED) points [1] must be earned for an individual project. It means that construction materials in the project that meet a requirement of LEED points can possibly increase overall LEED points of the whole project.

Pervious or porous concrete is a special type of concrete with continuous voids which are interconnected in concrete mass [2]. Pervious concrete is not a new technology because it has been used for over 30 years in England and United States and also widely in Europe and Japan as a road surface [3]. This concrete is a mixture of coarse aggregate, water, Portland cement, and often contains admixture and little to no sand. Previous researchers have studied the effect mix proportion on the properties of concrete [4-7]. Pervious concrete has typically void content of 15 to 30% [8]. The most important property of pervious concrete is permeability that allows stormwater runoff to percolate into the ground below. Thus, pervious concrete may percolate large quantities of water in a short time, and thereby recharge groundwater supplies [8]. Moreover, it can reduce the demands for expensive stormwater drainage and retention systems, thus allowing for more effective land use. Due to the high porosity, pervious concrete has lower strength compared to the conventional concrete [5, 9]. But sufficient strength is readily achieved for many applications. Pervious concrete can be used in many applications such as permeable concrete for pavement [9], concrete bed for vegetation or living organism, noise absorbing and thermal insulated concrete [2]. From these properties, pervious concrete has a possibility to become a useful material to earn LEED Green Building Rating System credits.

Fly ash and recycled aggregate can be used as the replacement material for cement [10-12] and aggregate [13-15], respectively. Fly ash is added to concrete to increase the overall strength [16-17] and is considered a greener way to build. Meanwhile, using recycled concrete aggregate can increase the porosity but the mechanical properties of the recycled concrete may reduce [18-20].

In this study, the possibility of earning LEED points from pervious concrete was systematically reviewed. Then, the replacement of fly ash and recycled aggregate for the cement and aggregate with various mix proportion based on possible LEED points will be proposed. Next, properties of pervious concrete such as permeability, void content, compressive strength and splitting tensile strength are determined. Finally, the appropriate mix proportion and the calculation of LEED points that can possibly earn from the proposed mix proportion are presented.

2. Potential LEED Green Building Rating System Credits for Pervious Concrete

In the LEED 2009 for New Construction and Major Renovation [1], there are seven main areas such as sustainable sites, water efficiency, energy and atmosphere, materials and resources, indoor environment quality, innovation and design process and regional priority. In each of these areas, the useful information is presented for the designer and the contractor in achieving LEED points. LEED certification can be achieved at 4 levels based on how many of the 110 possible LEED credits are awarded. These levels are certified (40-49 points), silver (50-59 points), gold (60-79 points) and platinum (80 points and above). The level of environmental performance of a building may be quantified using LEED certification.

Pervious concrete has many benefits and can earn many LEED categories. The possible LEED credits are listed in Table 1. Compared with conventional concrete, it has high porosity that allows water from precipitation and can cumulate heat and sound [5]. These pores could support the trees to grow normally and also reduce the runoff from a site and recharge ground water levels and aquifers. Pervious concrete can be used for many types of applications such as permeable concrete for pavements, concrete bed for vegetation and living organisms, noise absorbing concrete, and thermal insulting concrete [8]. Though, it is used primarily for the pavements. For these usages, pervious concrete is an important application for sustainable construction and one technique that protect water quality. Therefore, pervious concrete is possible to achieve credit in the topic of stormwater design-quantity control (Credit 6.1).

In the materials and resources section, supplementary cementitious materials can substitute partially for cement and recycled aggregate can replace for newly mined gravel. In this study, the two types of local recycle materials (i.e., fly ash and recycled aggregate) are used. Therefore, it is possible to earn LEED Credit 4 (Recycled Content) and LEED Credit 5 (Regional Materials) as summarized in Table 1.

Table 1. Potential LEED credits related to pervious concrete [1].

Issue		**Intent**	**Possible Points**
Sustainable Sites			
Credit 6.1	Stormwater Design-Quantity Control	To limit disruption of natural water flows by minimizing stormwater runoff, increasing on-site infiltration and reducing contaminants.	1
Materials and Resources			
Credit 4	Recycled Content	To increase demand for building products that incorporate recycled content materials.	1-2
Credit 5	Regional Materials	To increase demand for building materials and products that are extracted and manufactured within 500 miles of the project sites.	1-2
Total Possible Points			**5**

3. Experimental Investigation

3.1. Parameter and Materials

In this research, Portland cement type I was used in all mixes and the cement had a specific gravity of 3.15. Three series (Series C, Series F and Series R) were used to test mechanical properties of pervious concrete as shown in Table 2. All mixtures were proportioned using a blend of No.4 (passing 9.5 mm [0.38 in.], retained on a 4.75 mm [0.19 in] sieve) and No.8 (passing 4.75 mm [0.19 in], retained on a 2.36 mm [0.095 in] sieve). In addition of these constituents, recycled aggregate and fly ash were also used to the mix proportion of pervious concrete to achieve LEED points. The mix proportion of pervious concrete is shown in Table 3. Three percentages of fly ash between 20-60% and three amounts of recycled aggregate between 20-100% were used in this experiment. Fly ash was obtained from Mae Moh electricity power plant, Lampang, Thailand. The chemical and physical properties of fly ash are summarized in Table 4 and Table 5. The Class L recycled aggregate [13], which is for backfill concrete, blinding concrete and leveling concrete, was used in this study. The specific gravity of recycled aggregate is 2.31 while the specific gravity of normal aggregate is 2.62. Type F superplasticizer (SP) at a dosage of 1% were the admixture used.

3.2. Specimen Preparation

A pan mixer (30 liter/batch) was used for mixing the pervious concrete. First, Portland cement Type I, water, fly ash (if any) and admixture were mixed for 270 seconds to produce the cement paste. After this step, the two sizes of coarse aggregates and recycled aggregates (if any) were added to the cement paste and mixed for 120 seconds. Then, the mixture was placed into Ø 150 mm × 300 mm cylindrical molds and 10 cm × 10 cm × 10 cm cube molds. The rectangular specimens were placed by rodding 25 times in each layer while the cylindrical specimens were applied a vibration for 20 seconds. The specimens were removed out of the molds after 24 hours and kept into the curing room until testing age. Figure 1 presents the specimens of pervious concrete made with recycled aggregate.

3.3. Test Method

In this section, the standard test methods are expressed to characterize the properties of pervious concrete mixes, including void content, permeability, compressive strength and splitting tensile strength.

Table 2. Test parameters.

Series	Mixes	Water to Binder Ratio (*w*/*b*)	% Replacement		No. of Specimens	
			Fly Ash	Recycled Aggregate	Cylinder	Rectangular
C	C0.23	0.23	-	-	7	3
	C0.25	0.25	-	-	7	3
	C0.35	0.30	-	-	7	3
F	F20	0.25	20%	-	7	3
	F40	0.25	40%	-	7	3
	F60	0.25	60%	-	7	3
R	R20	0.25	-	20%	7	3
	R50	0.25	-	50%	7	3
	R100	0.25	-	100%	7	3

Table 3. Mix proportion of pervious concrete.

Mixes	Water (kg/m^3)	Cement (kg/m^3)	Coarse Aggregate (kg/m^3)	Fly Ash (kg/m^3)	Recycled Aggregate (kg/m^3)
C0.23	89.6	407.2	2035.9	-	-
C0.25	96.9	403.9	2019.5	-	-
C0.30	114.8	359.9	1979.5	-	-
F20	95.7	318.9	1992.8	79.7	-
F40	94.4	236.1	1966.9	157.3	-
F60	93.2	155.3	1941.6	233.0	-
R20	95.0	395.8	1582.8	-	395.7
R50	92.2	384.1	960.1	-	960.1
R100	87.8	366.1	-	-	1830.2

Table 4. Chemical composition of fly ash.

Chemical Composition	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Na_2O	K_2O	Free CaO	Moisture
Value (%)	41.68	24.20	13.24	11.13	2.23	2.83	0.74	2.58	0.71	0.16

Table 5. Physical properties of fly ash.

Physical Properties	Value
Specific gravity (g/cm^3)	2.07
Blaine fineness (cm^2/g)	3290
Fineness: % retained on sieve #325 (%)	45.11
Loss on ignition (%)	0.38

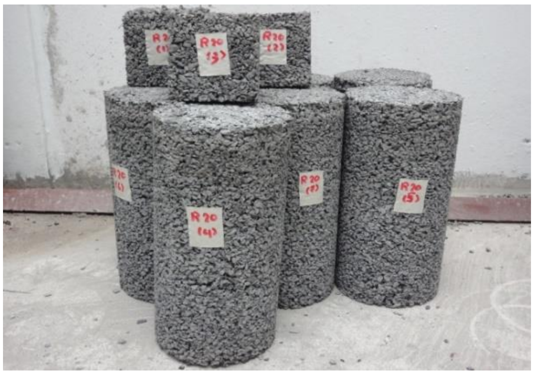


Fig. 1. Specimens of pervious concrete.

3.3.1. Void content

Void ratio is required to obtain sufficiently in order to acquire adequate strength and other desired functions. Void content of the pervious concrete was determined by using the following equation.

$$A = \left[1 - \left(\frac{W_2 - W_1}{\rho_w V_1} \right) \right] \times 100(\%) \tag{1}$$

where; A = Total void ratio of the pervious concrete (%)
W_2 = Weight of specimen under water (kg)
W_1 = Weight of specimen dried in air for 24 hours (kg)
ρ_w = Density of water (kg/cm^3)
V_1 = Volume of specimen (cm^3)

Void content is tested at 28 days. The result for void content is an average of three tests.

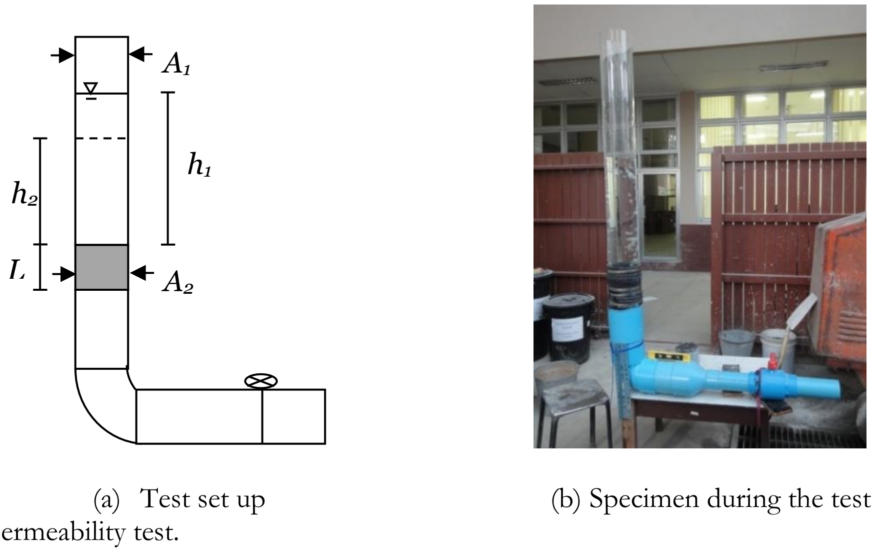
3.3.2. Permeability

Permeability is the parameter that shows the ability of a porous media to allow the passage of a fluid. The falling head permeability test apparatus is used to measure the permeability of the pervious concrete samples. The coefficient of permeability (k in cm/s) is calculated using Darcy's Law shown in the following equation.

$$K = \frac{A_1 L}{A_2 t} \ln\left(\frac{h_1}{h_2} \right) \tag{2}$$

where K = Coefficient of permeability (cm/s)
A_1 = Cross sectional area of the standpipe (cm^2)
A_2 = Cross sectional area of the specimen (cm^2)
L = Length of the specimen (cm)
t = Time required for water to fall from h_1 to h_2 (seconds)
h_1 = Initial water level (cm)
h_2 = Final water level (cm)

Figure 2 shows the test set up. Permeability test was measured at 3, 7, 14 and 28 days. The results are reported from an average of three tests.



(a) Test set up (b) Specimen during the test

Fig. 2. Water permeability test.

3.3.3. Compressive strength

The compressive strength was measured in accordance with ASTM C 39. This strength test was measured at 28 days. The results are reported from an average of three tests.

3.3.4. Splitting tensile strength

Tensile strength is measured according to ASTM C 496. For this test, three specimens are tested and the results are reported from an average of three tests.

4. Experimental Results and Discussion

4.1. Effect of w/c on the Properties of Pervious Concrete

Table 6 presents the properties of the pervious concrete mixes from the experiment. Effect of *w/c* can be discussed based on specimens in Series C, where different water-to-cement ratios (*w/c*) were used. For the given mix proportion in Series C, pervious concrete made with *w/c* of 0.25 had higher void content but lower compressive strength than the other two mixes. However, C0.30 which was the highest *w/c* gave the highest compressive strength. It is because C03.0 had the lowest void content. In addition, the experimental results reveals that C0.25 had the highest coefficient of permeability at every testing age.

Table 6. Experimental results of the pervious concrete.

Series	Mixes	*w/b*	Paste Volume (m^3/m^3)	Void Content (%)	Coefficient of Permeability (cm/s)				Compressive Strength (MPa)	Splitting Tensile Strength (MPa)
					3-day	7-day	14-day	28-day		
C	C0.23	0.23	0.219	26.7	0.660	0.646	0.615	0.541	10.9	2.55
	C0.25	0.25	0.225	31.1	1.37	1.38	1.27	1.24	10.0	2.35
	C0.30	0.30	0.229	25.1	0.626	0.660	0.564	0.649	12.8	2.65
F	F20	0.25	0.235	20.8	0.913	0.685	0.692	0.637	14.7	3.14
	F40	0.25	0.245	23.2	0.714	0.701	0.644	0.649	10.1	2.45
	F60	0.25	0.255	21.4	0.251	0.413	0.357	0.340	10.2	2.35
R	R20	0.25	0.221	49.3	0.961	1.2	1.13	0.569	10.7	2.55
	R50	0.25	0.214	46.9	0.960	0.971	0.984	0.959	9.5	2.06
	R100	0.25	0.204	64.4	2.26	2.04	1.8	1.498	2.5	1.08

4.2. Effect of Fly Ash Content on the Properties of Pervious Concrete

The effect of fly ash content on the properties of pervious concrete is discussed from Series F in Table 6. Although the fly ash was used to replace some cement, the desired void content (≥15%) was still achieved. In addition, by comparing Series F with Mix C0.25, it can be seen that the replacement of cement by fly ash improves the compressive and tensile strength. This result can be explained by two reasons. First, the void content of the pervious concrete in Series F is decreased due to filler effect from fly ash. Consequently, F20, F40 and F60 show higher compressive strength than C0.25. Second, the higher compressive strength of concrete is because the pozzolanic reaction from fly ash which reacts at the later age (after 28 days). However, the compressive strength and splitting tensile strength decreased with the increased amount of fly ash replaced for cement as shown in Table 6. In Mix F20 (with 20% of fly ash content) had the lowest void content but compressive and splitting tensile strength was the highest.

4.3. Effect of Recycled Aggregate Content on the Properties of Pervious Concrete

As shown in Table 6, three different amounts of recycled aggregate were used to the pervious concrete (Series R). The void content, coefficient of permeability, compressive strength and splitting tensile strength of the pervious concrete were measured. It is observed that the compressive strength and tensile strength were reduced when the content of the recycled aggregate exceeded 50%. In the Mix R100 (with 100% recycled aggregate content), the void content and coefficient of permeability was the highest but the strength was the lowest.

4.4. Relationships Among the Properties of Pervious Concrete

The following Fig. 3 to Fig. 6 illustrate the relationships among the properties of pervious concrete. Figure 3 demonstrates the test results of the compressive strength of the pervious concrete. The compressive strength decreased as the void content increased. This behavior relates to the volume of paste as shown in Fig. 4. When the volume of paste increased, the void content decreased (Fig. 4(a)). As a result, the compressive strength of pervious concrete tended to increased (Fig. 4(b)). Figure 5 illustrates the relationship between the 28-day compressive and splitting tensile strength of the pervious concrete. The linear tendency can be observed. Relatively lower strengths can be found in Series R which recycled aggregate is used. Figure 6 shows that the coefficient of permeability increased with the increased void content.

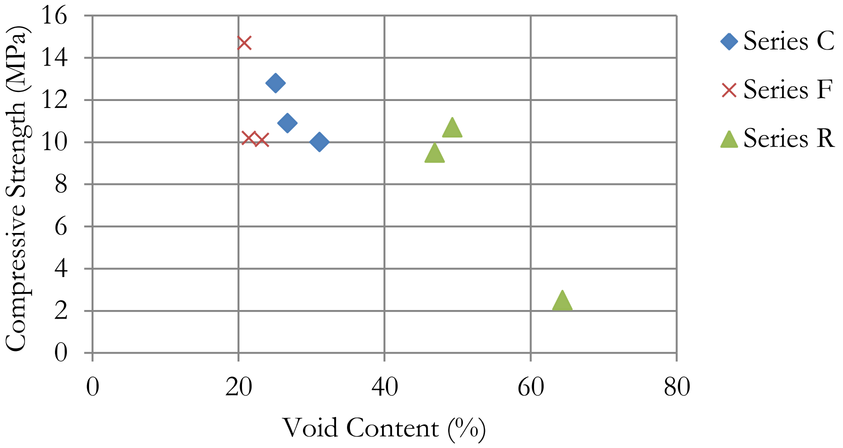
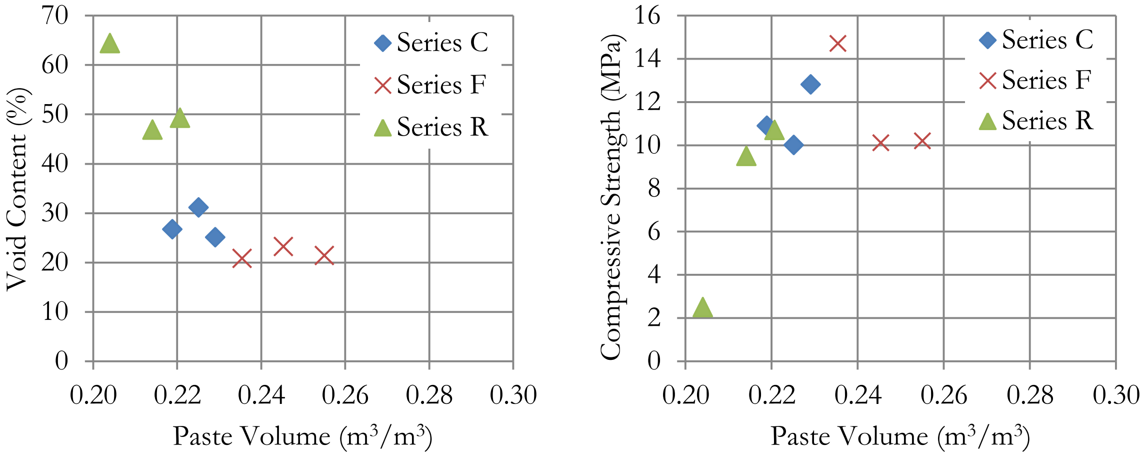


Fig. 3. Relationship between void content and compressive strength.



(a) Effect on void content (b) Effect on compressive strength

Fig. 4. Effect of past volume on properties of pervious concrete.

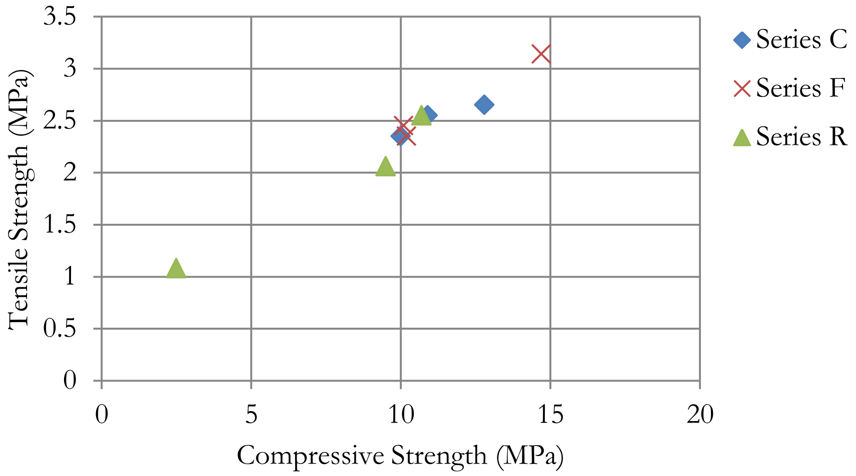


Fig. 5. Relationship between compressive strength and splitting tensile strength.

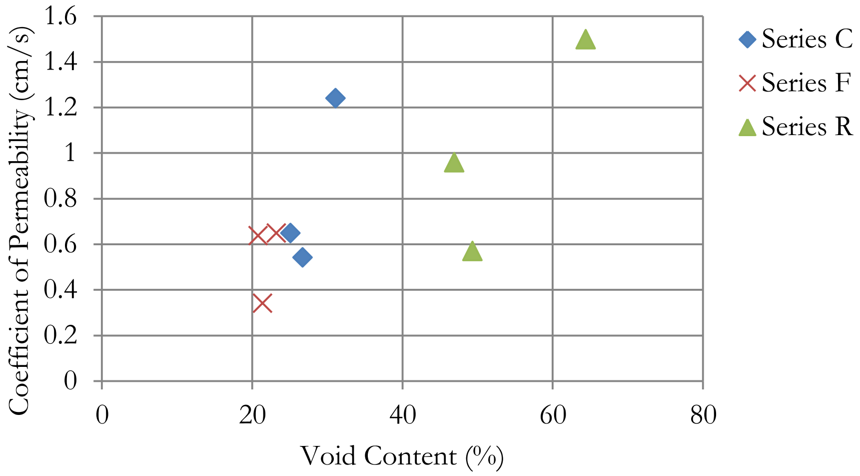


Fig. 6. Relationship between void content and coefficient of permeability.

5. Calculation of LEED points

As mention in Section 2, the possible LEED points are discussed in this section.

5.1. Stormwater Design: Quantity Control

If the concrete is pervious and contains no fine aggregates or little, this type of concrete can percolate the stormwater runoff. Using the pervious concrete pavements reduces the rate and quantity of stormwater runoff because this type of pavements increases infiltration of strormwater. Pervious concrete contains sufficient cement paste to bind the aggregate and provides interconnected voids between the coarse aggregate. If the concrete with a high void content (15% to 25%) and high permeability that allows water to flow through easily, this concrete is identified as a strategy to achieve this credit. The pervious concrete has more than 15% of void content, the concrete can achieve this credit. The coefficient of permeability and void content of pervious concrete are expressed in the following Table 6. According the data from Table 6, the void content for all mixes in this study is higher than 15%. Therefore, the mix proportions in this research can earn this credit by one point as summarized in Table 7.

5.2. Recycled Content

In this study, the different percent amount of fly ash and recycled aggregate are used to mix proportion of pervious concrete. Supplementary cementitious materials, such as fly ash, silica fume, and slag cement are considered as pre-consumer recycled content. Using recycled aggregate instead of virgin aggregate is considered as post-consumer recycled content. Table 8 presents calculation of recycled content calculation for each mixes of pervious concrete. Percent of recycle materials is computed based on the total weight of mix. The recycled content can be calculated from the percent of post-consumer plus half of the percent of pre-consumer (post-consumer + ½ pre-consumer).

In Series C, the two sizes of coarse aggregates were only used in the mix proportion of pervious concrete. Therefore, both of the post-consumer and pre-consumer recycled content are 0% for all mix proportions of Series C and thereby recycled content are also 0%. In Series F and R, the different percent amount of fly ash and recycled aggregate were used to replace cement and coarse aggregate, respectively. When the amount of fly ash and recycled aggregate were increased, the recycled content was also increased.

If the recycled content archives 10%, one credit can be obtained while two credits can be earned if recycled content reaches 20%. The archived LEED credits in the issue are summarized in Table 7.

5.3. Regional Materials

If the building materials used in the construction projects are extracted, harvested and manufactured within 500 miles of the project sites, this credit point can be achieved. The materials used in this study are manufactured in Thailand, especially the fly ash is used from Lam Pang province, in the north of Thailand that is the province mainly produces fly ash in Thailand and locates within 500 miles from the sites. Thus, two possible LEED points can earn by using these local materials in this study as shown in Table 7.

5.4. Discussion of Possible LEED Points

Pervious concrete is designed to attain the compressive strength ranging from 2.7 MPa to 27.5 MPa (28 ksc to 281 ksc). The pervious concrete in this study can be used to the application of the pathways that should have at least the compressive strength of 9.8 MPa (100 ksc). Therefore, Mix R50 and Mix R100 are not considered in calculating the possible LEED credit points. Table 7 presents the possible LEED credit points.

Mixes C0.23, C0.25 and C0.30 are the mix proportions that have three possible LEED points. Mix C0.25 has the highest void content and coefficient of permeability but the lowest compressive and splitting tensile strength as shown in Table 6. Mix C0.30 has the highest compressive strength and void content. The values of Mix C0.23 and C0.30 are not quite different.

Table 7. LEED Points for pervious concrete.

Series	Mixes	LEED Points			
		Stormwater Design: Quantity Control	Recycled Content	Regional Materials	Total
C	C0.23	1	0	2	3
	C0.25	1	0	2	3
	C0.30	1	0	2	3
F	F20	1	1	2	4
	F40	1	2	2	5
	F60	1	2	2	5
R	R20	1	1	2	4
	R50	1	2	2	-*
	R100	1	2	2	-*

**R50 and R100 are excluded from the discussion of LEED credits since their compressive strengths are less than 9.8 MPa.*

Table 8. Calculation of recycled content.

Mixes	Component	Recycled Materials				Recycled Content (%)
		Pre-Consumer		Post-Consumer		
		Weight (kg)	%	Weight (kg)	%	
C0.23	Recycled cementitious	0	0	0	0	
	Recycled aggregate	0	0	0	0	
	Total		**0**		**0**	**0**
C0.25	Recycled cementitious	0	0	0	0	
	Recycled aggregate	0	0	0	0	
	Total		**0**		**0**	**0**
C0.30	Recycled cementitious	0	0	0	0	
	Recycled aggregate	0	0	0	0	
	Total		**0**		**0**	**0**
F20	Recycled cementitious	2.7	19.7	0	0	
	Recycled aggregate	0	0	0	0	
	Total		**19.7**		**0**	**10**
F40	Recycled cementitious	5.4	40	0	0	
	Recycled aggregate	0	0	0	0	
	Total		**40**		**0**	**20**
F60	Recycled cementitious	8.0	59.7	0	0	
	Recycled aggregate	0	0	0	0	
	Total		**59.7**		**0**	**29.9**
R20	Recycled cementitious	0	0	0	0	
	Recycled aggregate	0	0	13.6	16	
	Total		**0**		**16**	**16**
R50	Recycled cementitious	0	0	0	0	
	Recycled aggregate	0	0	30.5	40	
	Total		**0**		**40**	**40**
R100	Recycled cementitious	0	0	0	0	
	Recycled aggregate	0	0	58.2	80	
	Total		**0**		**80**	**80**

The mix proportions that have four possible LEED points are Mix F20 and R20. The compressive and splitting tensile strengths of Mix F20 are higher than that of Mix R20. But the void content and coefficient of permeability of Mix F20 are lower than that of Mix R20. From these facts, Mix F20 is chosen as the appropriate mix proportion for the second type.

Mix F40 and F60 are the mix proportions that have five possible LEED points. Mix F40 has higher void content and coefficient of permeability than that of Mix F60. The differences of compressive and splitting tensile strength in Mix F40 and F60 are not significant. Therefore, F40 is the appropriate mix proportion according to these properties.

Finally, it may be concluded that Mix F40 is the appropriate mix proportion among these nine mix proportions. This proportion has the highest possible LEED points and can get the required properties of pervious concrete.

6. Conclusion

1. Replacing the fly ash in the cement can enhance the strength of the pervious concrete.
2. Using recycled aggregate instead of virgin aggregate can significantly increase the coefficient of permeability and void content but the compressive and splitting tensile strength decreased.

3. The mix proportion of pervious concrete in this research can earn the Stormwater Design-Quantity Control, Recycled Content, and Regional Materials Credits using the fly ash and recycled aggregate replacing in the cement and coarse aggregate, respectively.
4. The mix proportions which cement is replaced by 40% and 60% of fly ash can achieve the highest possible LEED credit points. Using 40% of fly ash provides higher the coefficient of permeability, thus it is the appropriate mix proportion of pervious concrete for satisfying both mechanical properties and LEED Credits.

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