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ลิขสิทธิ์ของจุฬาลงกรณ์มหาวิทยาลัย

DEVELOPMENT OF PERVIOUS CONCRETE TO EARN LEED POINTS

Miss Than Mar Swe

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คอนกรีตพรุน คือ คอนกรีตชนิดพิเศษที่มีปริมาณช่องว่างอากาศในคอนกรีตมากและช่องว่างเหล่านั้นเรียงตัวต่อเนื่องกัน ทำให้สามารถระบายน้ำได้ดี โดยคอนกรีตพรุนนั้นประกอบด้วยปูนซีเมนต์ หิน น้ำ และสารลดน้ำ โดยอาจจะมีส่วนผสมของทรายเล็กน้อยหรือไม่มีเลย คอนกรีตพรุนสามารถประยุกต์ใช้ประโยชน์ได้หลากหลาย เช่น การปูเป็นพื้นทางเดิน ทำเป็นกำแพงเพื่อกันเสียง ซึ่งในการศึกษานี้มีความพยายามที่จะพัฒนาคอนกรีตพรุนให้เป็นมิตรกับสิ่งแวดล้อมมากขึ้น โดยการใช้เถ้าลอย และมวลรวมรีไซเคิลในการทดแทนปูนซีเมนต์และมวลรวมหยาบตามลำดับ ให้ได้รับคะแนน แอลอีอีดี โดยจากการศึกษาพบว่าคอนกรีตพรุนสามารถทำคะแนน แอลอีอีดี ได้ตามหมวดต่างๆ เช่น หมวดการควบคุมปริมาณน้ำฝนออกแบบ หมวดวัสดุรีไซเคิล และหมวดวัสดุท้องถิ่น เป็นต้น สำหรับสัดส่วนผสมคอนกรีตในงานวิจัยนี้ มี 3 สัดส่วนผสมที่มีการแทนที่มวลรวมหยาบด้วยมวลรวมรีไซเคิลในช่วงปริมาณร้อยละ 20 ถึง 100 และมี 3 สัดส่วนผสมที่มีการแทนที่ปูนซีเมนต์ด้วยเถ้าลอยในช่วงปริมาณร้อยละ 20 ถึง 60 เพื่อจะให้ได้คะแนนตามข้อกำหนดแอลอีอีดี นอกจากนั้นมีการแสดงอิทธิพลของเถ้าลอยและมวลรวมรีไซเคิลที่มีต่อคุณสมบัติของคอนกรีตพรุน โดยทดสอบคุณสมบัติด้านกำลังอัด กำลังดึงแยก การนำความร้อน ปริมาณช่องว่าง และค่าสัมประสิทธิ์การซึมผ่านของน้ำ และในตอนท้ายมีการอภิปรายเกี่ยวกับสัดส่วนผสมคอนกรีตที่เหมาะสม และคะแนนแอลอีอีดีที่คำนวณได้จากสัดส่วนผสมคอนกรีตทั้งหมดที่ทำการศึกษา

ศูนย์วิทยทรัพยากร
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The research proposes the development of pervious concrete to earn LEED points. Pervious concrete is a special type of concrete with high porosity to protect the environmental impacts and support sustainable growth. Pervious concrete can be used in many applications such as parking areas, areas with light traffic, walkways, and greenhouses, etc. Therefore, pervious concrete becomes a useful material for sustainable construction. And then, the use of pervious concrete may achieve many LEED credits. LEED is a rating system that evaluates the environmental performance of a building. In this research, it could be earned in Storm water Design-Quantity Control, Recycled Content and Regional Materials LEED credits. The replacement of fly ash (20%-60%) and recycled aggregate (20%-100%) for the cement and coarse aggregate were used to earn LEED credit point (Recycled Content). Eight different mix proportions based on possible LEED credit points were proposed. Next, the properties of pervious concrete relating to LEED points such as permeability, void content, compressive strength, splitting tensile strength and thermal conductivity were also presented. Finally, the appropriate mix proportion and the calculation of LEED points that could be earned form the proposed mix proportions were discussed.

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ศูนย์วิทยทรัพยากร
จุฬาลงกรณ์มหาวิทยาลัย

CONTENTS

LIST OF TABLES

LIST OF FIGURES

ศูนย์วิทยทรัพยากร
จุฬาลงกรณ์มหาวิทยาลัย

CHAPTER I

INTRODUCTION

1.1 General

Nowadays, our world is facing various environmental problems. These environmental problems are caused by increasing world pollution, increasing production and consumption of material goods and widening of the income gap between very rich and very poor countries. Some of these environmental problems are air pollution, water pollution, noise and rising temperature. These problems have serious consequences for the health of human beings and also affect severely the natural ecosystems. It is the responsibility of everybody to reduce these problems for the sustainable future. "Sustainability" is the ability of the earth's various natural systems and human cultural systems and economies to survive and adapt to changing environmental conditions [1]. 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. In order to obtain a certification for a "green buildings", Leadership in Energy and Environmental Design (LEED) points 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 into concrete mass. 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. This concrete is an innovative material that has environmental, economic, and structural advantages. This type of concrete is a mixture of coarse aggregate, water, Portland cement, and often contains admixture and little to no sand. Compared with conventional concrete, it has high porosity that allows water from precipitation and can cumulate heat and sound [2]. These pores could support the trees to grow normally and also reduce the runoff from a site and recharge ground water levels and aquifers. The shade of the trees is needed to lessen the effects of heat and also reduces the heat island effects in the urban areas [3]. Then, the trees produce a cooling effect for the paving. Therefore, pervious concrete pavement is suitable to protect trees in a paved environment. Pervious concrete has light color that resists heat absorption so that it can reduce the heat reflected back into the environment and help to lower the heat island effects [3]. To sum up, 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 [4]. 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. From these properties, pervious concrete has a possibility to become a useful material to earn LEED Green Building Rating System credits.

In this study, the possibility of earning LEED points from pervious concrete will be systematically discussed. 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, porosity, void content, thermal conductivity, compressive strength and splitting tensile strength will be determined. Finally, the appropriate mix proportion and the calculation of LEED points that can possibly earn from the proposed mix proportion will be presented.

1.2 Objectives of Study

1. To know the possibility of achieving of LEED points using pervious concrete with various mix proportion.

2. To evaluate the mechanical properties such as compressive and splitting tensile strength and physical properties such as permeability, porosity, void content and thermal conductivity from the proposed mix proportion for this research.

3. To determine the appropriate mix proportion that can get the highest possible LEED credit points and can still give the sufficient strength, void content, and permeability for this research.

1.3 Scope of Thesis

1. LEED credit system for the whole building project is focused just only for a construction material level that is pervious concrete.

2. In this study, all mixtures are proportioned using a blend of No.8 and No.4 coarse aggregate. Lime stone are used for both sizes of coarse aggregate.

3. The replacement amount of fly ash is 20-60% of Portland cement. And, coarse aggregate is replaced by 20-100% by recycled aggregate.

4. The coefficient of permeability is determined using a falling head permeability test apparatus.

5. The compressive strength and splitting tensile strength according with ASTM-C 39 and ASTM-C 496, respectively.

6. The thermal conductivity of pervious concrete is measured using hot disk thermal constant analyzer.

ศูนย์วิทยทรัพยากร
จุฬาลงกรณ์มหาวิทยาลัย

7. The pervious concrete in this study is used for the application of pavements.

1.4 Expected Outcomes

1. The possibility of achieving LEED points using pervious concrete with various mix proportion can be systematically shown.

2. The relationship between mix proportion of pervious concrete and concrete properties such as permeability, void content, porosity, and compressive and splitting tensile strength and thermal conductivity can be seen.

3. The appropriate mix proportion with sufficient strength, void content and permeability to get the highest possible LEED credit points can be proposed.

ศูนย์วิทยทรัพยากร
จุฬาลงกรณ์มหาวิทยาลัย

CHAPTER II

LITERATURE REVIEW

Many researchers and developers have studied and written about the pervious concrete. This type of concrete has many advantages on the application of the construction. The pervious concrete can contribute to earn the credits offered by the Leadership in Energy and Environmental Design (LEED). In this section, there may be divided into four main parts. In the first part, it is introduced about the LEED credits. Second, the pervious concrete, its benefits, and the applications of pervious concrete and how LEED points can be earned using pervious concrete are explained. Then, fly ash and recycled aggregate are presented in the third and forth parts.

2.1 Leadership in Energy and Environmental Design (LEED)

LEED is a rating system developed by the U.S Green Building Council (USGBC) to evaluate the environmental performance of a building [4]. This is also the voluntary rating system for designing and building high-performance, sustainable buildings. LEED rating system allows the projects to earn LEED points during construction and use of a building. LEED is required to get “green buildings” that result in energy and cost savings over the life of a structure. The developers may choose the LEED rating system for designing and constructing the buildings to minimize the negative environmental impacts and improve the health of human beings. The LEED Green Building Rating System for New Construction promotes the sustainable buildings to improve outdoor and indoor building quality, the conservation of resources, and the reduction of waste during the building process.

Therefore, some companies try to build new headquarters using LEED certification. The projects that satisfied the LEED certification may get many advantages. Some of these advantages are as follows:

- It provides the healthier and comfortable living environment.

- It reduces the heat island effects of the urban development.
- It reduces the polluting.
- It creates the sustainable and low maintenance projects.
- It reduces the energy cost.

LEED provides a framework to evaluate the building performance and meet sustainability goals through many credit categories such as sustainable site, water efficiency, energy and atmosphere, material and resources, indoor environmental quality and regional priority [2]. In order to obtain a certification for a “green buildings”, LEED points must be earned for and individual project. The credit categories and the possible LEED points are shown in Table 2.1 [4].

Table 2.1 Potential LEED Credits [4]

Sustainable Sites		26 Possible Points
Prerequisite 1	*Construction Activity Pollution Prevention*	Required
Credit 1	*Site Selection*	1
Credit 2	*Development Density and Community Connectivity*	5
Credit 3	*Brownfield Redevelopment*	1
Credit 4.1	*Alternative transportation-Public Transportation Access*	6
Credit 4.2	*Alternative transportation-Bicycle Storage and Changing Rooms*	1
Credit 4.3	*Alternative transportation-Low-Emitting and Fuel-Efficient Vehicles*	3
Credit 4.4	*Alternative transportation-Parking Capacity*	2
Credit 5.1	*Site Development-Protect or Restore Habitat*	1
Credit 5.2	*Site Development-Maximize Open Space*	1
Credit 6.1	*Storm water Design-Quantity Control*	1

Credit 6.2	*Storm water Design-Quality Control*	1
Credit 7.1	*Heat Island Effect-Non roof*	1
Credit 7.2	*Heat Island Effect-Roof*	1
Credit 8	*Light Pollution Reduction*	1
Water Efficiency		10 Possible Points
Prerequisite 1	*Water Use Reduction*	Required
Credit 1	*Water Efficient Landscaping*	2-4
Credit 2	*Innovative Wastewater Technologies*	2
Credit 3	*Water Use Reduction*	2-4
Energy and Atmosphere		35 Possible Points
Prerequisite 1	*Fundamental Commissioning of Building Energy Systems*	Required
Prerequisite 2	*Minimum Energy Performance*	Required
Prerequisite 3	*Fundamental Refrigerant Management*	Required
Credit 1	*Optimize Energy Performance*	1-19
Credit 2	*Onsite Renewable Energy*	1-7
Credit 3	*Enhanced Commissioning*	2
Credit 4	*Enhanced Refrigerant Management*	2
Credit 5	*Measurement and Verification*	3
Credit 6	*Green Power*	2
Materials and Resources		14 Possible points
Prerequisite 1	*Storage and Collection of Recyclables*	Required
Credit 1.1	*Building Reuse-Maintain Existing Walls, Floors and Roof*	1-3
Credit 1.2	*Building Reuse- Maintain Existing Interior Nonstructural Elements*	1-2
Credit 2	*Construction Waste Management*	1-2

ศูนย์วิทยทรัพยากร จุฬาลงกรณ์มหาวิทยาลัย

Credit 3	*Materials Reuse*	1-2
Credit 4	*Recycled Content*	1-2
Credit 5	*Regional Materials*	1-2
Credit 6	*Rapidly Renewable Materials*	1
Credit 7	*Certified Wood*	1

As shown in Table 2.1, 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. The LEED rating system offers four certification levels for new construction such as certified (40-49 points), silver (50-59 points), gold (60-79 points), and platinum (80 points and above). The level of environment performance of a building may be quantified using LEED certification.

2.2 Pervious Concrete and its possible relation with LEED points

Pervious concrete is a special type of concrete to address environmental impacts and support sustainable growth. This is also known as no-fines concrete, porous concrete, permeable concrete, gap-graded concrete and enhanced porosity concrete. Pervious concrete is a mixture of coarse aggregate, cementitious materials, carefully controlled amounts of water, and often contains little to no sand that creates a substantial void content. It is a high porosity concrete that allows rainwater to seep into the ground. Thus, pervious concrete can reduce the runoff from a site and recharge ground water levels. Then, snow-covered pervious concrete clears more quickly than other pavements because its voids allow for more rapid thawing. This ability reduces the environmental problems.

Pervious concrete can be used for a number of applications but it is primarily used for pavements. The majority of pavement applications for porous concrete are low volume road surfacing, parking lots and pavement edge drains. Other applications are drainage media for hydraulic structures, parking lots, tennis courts, greenhouses, and pervious base layers under heavy-duty pavements. The following shows the applications of pervious concrete.

Applications of Pervious Concrete

- Low-volume pavements
- Residential roads, alleys, and driveways
- Sidewalks and pathways
- Parking areas
- Low water crossings
- Tennis courts
- Subbase for conventional concrete pavements
- Patios
- Artificial reefs
- Slope stabilization
- Well linings
- Tree grates in sidewalks
- Foundations / floors for greenhouses, fish hatcheries, aquatic amusement centers, and zoos
- Hydraulic structures
- Swimming pool decks
- Pavement edge drains
- Groins and seawalls
- Noise barriers

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[www.hiltonproducts.co.nz] [www.crystalblueobx.com]

Figure 2.1 Pressure washing and Vacuuming

Pervious concrete possesses many advantages such as reducing noise, improving skid resistance, reducing owner cost, preserving native ecosystems, and minimizing the heat island in large cities, etc. The disadvantages of pervious concrete include yearly or bi-yearly maintenance to reduce clogging of voids and restore permeability, and the possibility of contaminating the ground water depending on the soil conditions. To prevent clogging of voids, regular sweeping or vacuuming, pressure washing may be required (Figure 2.1).

In 2003, Yang and Jiang [5] presented about the pervious concrete pavement material used for roadway. The authors concluded that strength of the pervious concrete was low by using the common material and proportion of mixture because of its voids. The strength of pervious concrete can be improved greatly using smaller sized aggregate, silica fume, and superplasticizer in the mix proportion. The compressive strength and the flexural strength of the pervious materials could reach 50 MPa and 6 MPa, respectively. The authors also stated that water penetration, abrasion resistance, and freezing and thawing durability of the materials were high. Then, it also stated that this concrete could be applied to both the footpaths and the vehicle roads.

In 2005, Park et al. [2] studied an evaluation of the physical and mechanical properties and sound characteristics of porous concrete. The results demonstrated that the difference between the designed void ratio and the measured void ratio was less than 1.7%. The compressive strength of the sound absorbing pervious concrete using recycled aggregate reduced as the target void ratio and recycled aggregate content increased. It also stated that the sound absorption area ratio (SAA) increased as the target void ratio increased. The optimum void ratio was 25% and the recycled aggregate content was 50% for the sound absorption characteristics of the pervious concrete using the recycled waste concrete aggregate.

In 2006, Wang et al. [6] proposed the development of mix proportion for functional and durable pervious concrete. In this paper, Portland cement pervious concrete (PCPC) mixes made with various types and amounts of aggregates, cementitious materials, fibers, and chemical admixtures were evaluated. The results indicated that the PCPC made with single-sized coarse aggregates generally had high permeability, though not adequate strength. Using a small amount of fine sand to the mixes enhanced the concrete strength and freezing-thawing resistance while maintaining adequate water permeability. And also, addition of a small amount of fiber to the mixes increased the concrete strength, freezing-thawing resistance and void content. This study concluded that properly designed and constructed PCPC could have an excellent serviceability under cold weather conditions.

Properties of pervious concrete strongly depend on the mix proportion. In 2008, Chareerat et al. [7] indicated that cement paste characteristics depends on the water to cement ration (w/c) or water to binder ratio (w/b), amount and type of admixture and mixing time. Good concrete with relatively high strength were produced using high flow cement paste with low void ratio. Top surface vibration of 10 seconds with vibrating energy of 90 kN m/m^2 was effective in compacting pervious concrete. Finally, it is concluded that the characteristics of compressive strength of pervious concrete could be expressed by the equation of strength and void ratio of pervious brittle material.

In 2009, Chareerat et al. [8] presented the influence of binder strength and aggregate size on the compressive strength and void ratio of pervious concrete.

The results indicated that for the same aggregate, the rates of strength reduction due to the increases in void ratio were the same for binders with different strengths. The rate of reduction in compressive strength with small aggregate size was higher than that with larger aggregate size. The developed general equation for pervious concrete was useful in relating the compressive strength and void ratio for different binder strength and aggregate sizes.

Pervious concrete has many benefits and can earn many LEED categories. This type of concrete can filter storm water and help to control the amount of pollutants in the waterways. This ability can contribute to LEED Credit 6 (Table 2.1) in the sustainable sites section. Pervious concrete has light color so that it reduces the heat island effect in urban areas. This property is not clearly approved for achieving LEED Credit 7 (Table 2.1). In the materials and resources section, supplementary cementitious materials can be substituted partially for cement and recycled aggregate can replace for newly mined gravel. Recycled content can contribute to LEED Credit 4 (Table 2.1). LEED points relating with the pervious concrete are discussed in the following sections:

2.2.1 Sustainable Site

Credit 6.1: Stormwater Design-Quantity Control [1 possible point]

Credit 6.2: Stormwater Management-Quality Control [1 possible point]

The intent of these credits is to limit disruption and pollution of natural water flows by managing the storm water runoff, increasing on-site infiltration and eliminating contaminants. The pervious concrete has high porosity and interconnected voids so that the storm water flow percolates into the ground water. For this property, using the pervious concrete contributes to achieve this credit points.

ศูนย์วิทยทรัพยากร
จุฬาลงกรณ์มหาวิทยาลัย

2.2.2 Materials and Resources

Credit 4: Recycled Content [2 possible points]

The intent of this credit is to increase demand for building products that incorporate recycled content material, thereby reducing impacts resulting from extraction and processing of virgin materials. The use of fly ash and recycled aggregate into the mix proportion of pervious concrete can contribute to this Recycled Content Credit.

Credit 5: Regional Materials [2 possible points]

The intent of this credit is to increase demand for building materials and products that are extracted, harvested or recovered and manufactured within 500 miles of the project sites, thereby supporting the use of resources and reducing the environmental impacts resulting from transportation.

2.2.3 Innovation and Design Process

Credit 1: Innovation in Design [5 possible points]

The intent of this credit is to provide design teams and projects the opportunity to be awarded points for exceptional performance above the requirements set by the LEED Green Building Rating System and/or innovative performance in green building categories not specifically addressed by LEED.

ศูนย์วิทยทรัพยากร
จุฬาลงกรณ์มหาวิทยาลัย

2.3 Fly ash in Concrete

Today, the supplementary cementitious materials (SCMs) have become common materials in concrete production. Among these materials, fly ash is the most common SCMs used in this region. Fly ash is widely used as a constituent of cement for making concrete. It can partially replace in various percentages of the Portland cement content of concrete. Fly ash is the fine residue powder byproduct from coal-fired electric generating plants as shown in Figure 2.2. It is the best known and one of the most commonly used pozzolans in the world.

Fly ash typically decreases the permeability of the concrete and allows lower water contents. The use of fly ash replacing into cement reduces the production of carbon dioxide. Thus, fly ash may reduce the emission of carbon dioxide and greenhouse gas related to climate change. Next, fly ash may improve concrete performance and quality, and make concrete stronger, more durable, and more resistant to chemical attack. Fly ash that has recycled content can directly contribute in the achievement of the LEED Credit MR-C 4.1 and MR-C 4.2 (Table 2.1). There are some benefits of using fly ash for cement in concrete such as lower life cycle costs, longer concrete life, reduced maintenance costs, and encourage sustainable development, etc. Fly ash is added to concrete to increase the overall strength and is considered a greener way to build. It can also create the environment benefits. The advantages of fly ash are improved workability, permeability, sulfate resistance, alkali reactivity, lower heat of hydration, reduced CO_2 emissions and landfill. The disadvantages are slower setting times, strength gain, salt scaling and inconsistencies.

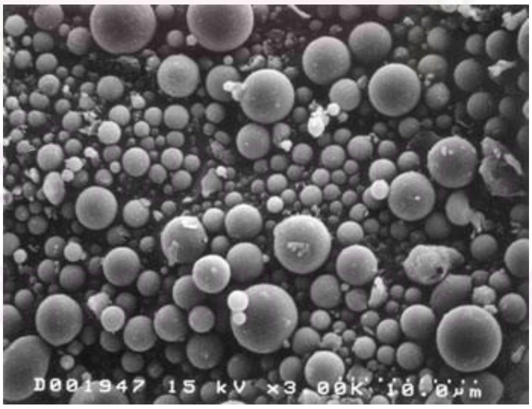

Figure 2.2 Fly ash particles [www.fhwa.dot.gov]

In 1995, Naik et al. [9] undertook this research to determine the engineering properties of high-lime (ASTM Class C) fly ash concretes. The results of this study showed that high-performance concrete incorporating Class C fly ash at 30% cement replacement was proportioned for high-strength applications. Generally, concrete mixtures up to 50% cement replacement with fly ash offered sufficient performance with appropriate strength and physical durability properties for structural applications. Up to 70% cement replacement with fly ash, abrasion resistance of concrete decreased. And then, shrinkage of concrete decreased slightly with increasing amounts of fly ash. Finally, this study concluded that the mixtures, up to 50% cement replacements with the fly ash, can be used for structural applications.

In 1999, Thomas et al. [10] showed that combinations of relatively small levels of silica fume (eg. 3 to 6%) and moderate levels of high CaO fly ash (20 to 30%) were very effective in reducing expansion due to alkali silica reactivity (ASR) and also produced a high level of sulphate resistance. Thus, concrete made with these proportions showed excellent fresh and hardened properties due to the combination of silica fume and fly ash. The researchers concluded that ternary cementitious blends of Portland cement, silica fume, and fly ash offered significant advantages and greater enhancements over plain Portland cement. Using the silica fume improved the early age performance of concrete and also fly ash refined the properties of hardened concrete as it matures. And then, this paper described to determine whether the improvements were maintained in the long term.

In 2003, Siddique [11] investigated the effects of replacement of cement with three percentages of fly ash and the effect of addition of natural fibers on the slump, compressive strength, splitting tensile strength, flexural strength. The test results indicated that the replacement of cement with three percentages of fly ash (35%, 45%, and 55%) increased the workability (slump), decreased compressive strength, splitting tensile strength and flexural strength. The addition of fibers reduced the workability, did not affect the compressive strength, and increased the splitting tensile strength and flexural strength as the percentage of fibers increased.

In 2009, Barbhuiya et al. [12] presented that the addition of hydrated lime and silica fume improved the early age compressive strength of fly ash concrete. This paper also indicated that silica fume was added to increase the 28 days strength significantly. Concrete containing lime and silica fume decreased the permeability compared to the concrete without them. The addition of hydrated lime and silica fume lowered the total porosity of fly ash cement pastes.

In 2010, Chalee et al. [13] presented the performance of 7-year fly ash concrete exposure in marine conditions. This paper also concluded that the increase of fly ash replacement in concrete reduced the chloride penetration, chloride penetration coefficient and steel corrosion in concrete. Concrete made with 25-50% of fly ash as a cement replacement and having a w/b ratio of 0.65 have equivalent or better resistance of steel corrosion than that of cement concrete with a w/b ratio of 0.45 at 7-year exposure in sea water.

2.4 Recycled Aggregate in Concrete

Recycled aggregates are the aggregates derived from the construction and demolition wastes in construction. To get these aggregates, the existing concrete is required to do breaking, removing, and crushing. Recycled aggregate consists of original aggregates and adhered mortar. Recycled aggregates are needed to use more than before due to the shortage of natural aggregates resources [2]. The use of recycled aggregate reduces bonding between aggregate and cement paste. Therefore, recycled aggregates must be clean that could protect the alteration of the hydration and bond of the cement paste.

Recycled aggregate has higher absorption than the conventional aggregate. The use of recycled aggregates can save money for local governments and other purchasers, conserve diminishing aggregate resource, and save energy when recycling is done on site. Although, an adequate compressive strength can be obtained by using recycled aggregate into concrete, it reduces rapidly if exceeded 50% [2].

The LEED rating system recognizes recycled aggregates in its point system. Using recycled aggregates contributes to earn LEED Credits MR-C 4.1 and MR-C 4.2 [2], [4]. Recycled aggregate can be divided into three kinds based on JIS [14] as follows:

Japan Industrial Standard (JIS) of Recycled Aggregate

- JIS A 5021 (March 2005) [14]
  - Recycled aggregates for concrete- Class H
- JIS A 5022 (March 2006) [14]
  - Recycled concrete using recycled aggregate- Class M
- JIS A 5023 (March 2007) [14]
  - Recycled concrete using recycled aggregate- Class L

The following Table 2.2 and Table 2.3 show the specified values of recycled aggregate in JIS and applications of recycled aggregate respectively.

Table 2.2 Specified Values of Recycled Aggregate in JIS [14]

	Class – H		Class - M		Class – L	
	Coarse	*Fine*	*Coarse*	*Fine*	*Coarse*	*Fine*
Oven-dry density (g/cm³)	Not less than 2.5	Not less than 2.5	Not less than 2.3	Not less than 2.2	-	-
Water Absorption (%)	Not more than 3.0	Not more than 3.5	Not more than 5.0	Not more than 7.0	Not more than 7.0	Not more than 13.0

Material Passing 75 µm sieve (%)	Not more than 1.0	Not more than 7.0	Not more than 1.5	Not more than 7.0	Not more than 2.0	Not more than 10.0

Table 2.3 Application of Recycled Aggregate [14]

	Scope of Application
Class – H	No limitations are put on the type and segment for concrete and structures with a nominal strength of 45MPa or less
Class – M	Members not subjected to drying or freezing-and-thawing action, such as piles, underground beam, concrete filled in steel tubes
Class – L	Backfill concrete, blinding concrete and leveling concrete

In 2002, Gomez-Soberron [15] introduced the experimental analysis of samples of recycled concrete with replacement of natural aggregate by recycled aggregate produced form the concrete. The results of the tests showed some variation in the properties of the recycled concrete with respect to ordinary concrete. Natural aggregate was replaced by recycled concrete aggregate to increase the porosity. The mechanical properties of the recycled concrete reduced compared with ordinary concrete when porosity increased. Finally, the author concluded that correlation between the properties of recycled concrete and total porosity was difficult to determine.

In 2004, Levy et al. [16] concluded that concrete with recycled aggregates (20%, 50%, and 100% replacement) from old concrete could achieve the same fresh workability and compressive strength of concrete made by natural aggregates. Water absorption and total pore volume for the recycled aggregates concrete were minimized at 20% replacement. And also, the carbonation depth decreased when the replacement was 20% or 50%. When the aggregate was replaced by 20% of the recycled aggregates form old concrete, the resulting recycled concrete can achieve the same and sometimes better behavior than the reference concrete made with natural aggregates

In 2004, Nelson, S. C. [17] carried out to determine and compare the high strength concrete by using different percentages of recycled aggregates. This study showed that the compressive strength could reach 48 MPa when the water/cement ratio was decreased. The workability of concrete for this research reduced as the amount of recycled aggregate increased. The results also showed that compressive strength, tensile strength and modulus of elasticity decreased gradually as the percentage of recycled aggregate used in the specimens increased.

In 2007, Etxeberria et al. [18] observed that the influence of amount of recycled coarse aggregate and production process on properties of recycled aggregate concrete. Concrete made with 100% of recycled coarse aggregates had less compressive strength (20-25%) than conventional concrete at 28 days but the same effective w/c ratio (w/c = 0.50) and cement quantity (325 kg of cement/m^3). And also, the high amount of cement was required to achieve a high compressive strength. The mix proportion of four concretes (made with 0%, 25%, 50% and 100% of recycled coarse aggregates) were designed in order to obtain the same compressive strengths.

In 2010, Malesev et al. [19] presented that a comparative analysis of test results of the basic properties of concrete with three different percentages of coarse recycled aggregate content (0%, 50%, and 100%). Recycled aggregate for concrete mixtures influences the concrete workability. Bulk density of fresh concrete was slightly decreased with increasing quantity of recycled aggregate. Compressive strength of the concrete depended on the quality of recycled aggregate. Water absorption depended on the porosity of cement matrix of the recycled concrete. Then, the modulus of elasticity of concrete also decreased with increasing recycled aggregate content.

CHAPTER III

METHODOLOGY

The flow chart of the research methodology is shown in Figure 3.1.

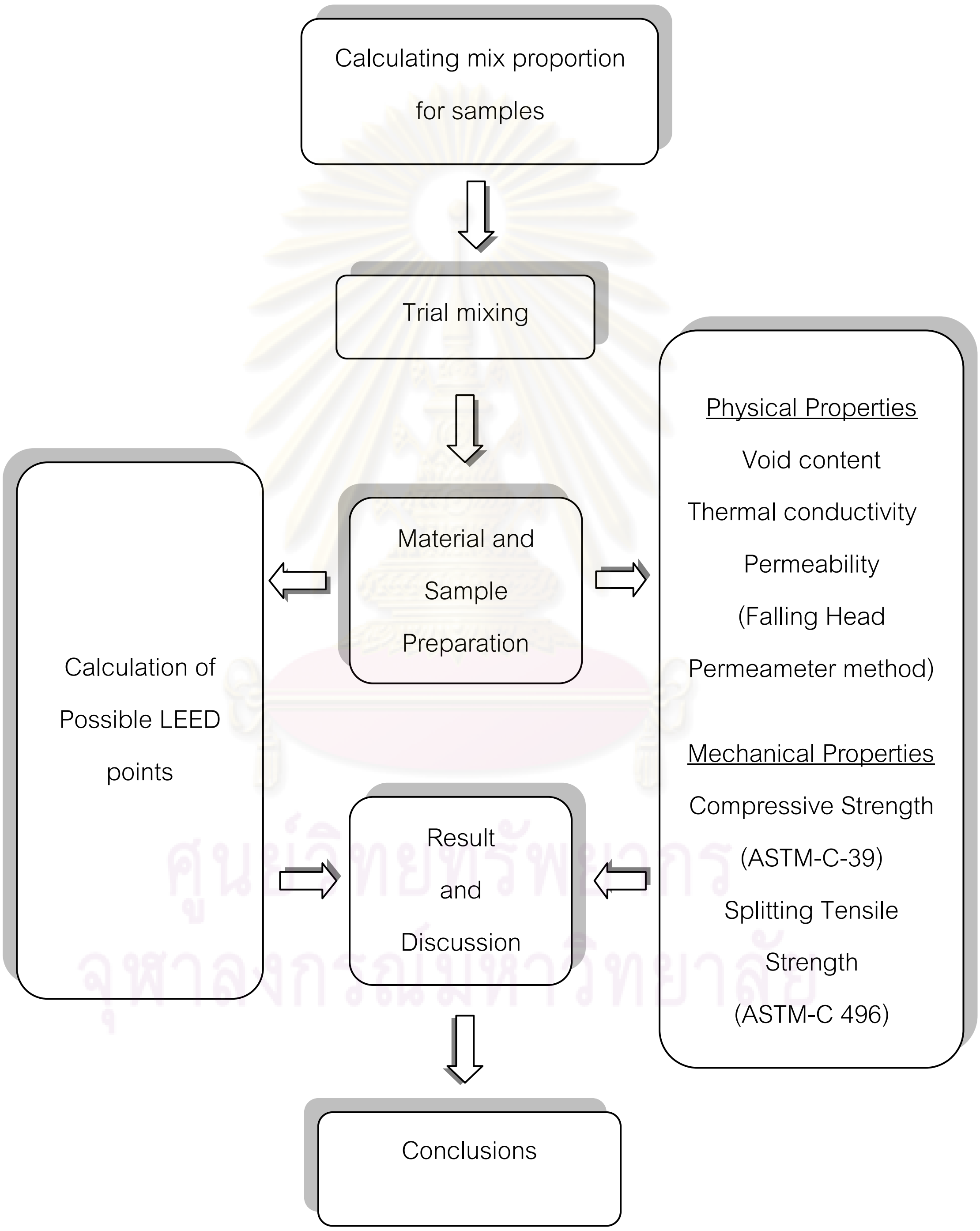

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Figure 3.1 Process of the flow path of the research methodology

3.1 Materials

In the mix proportion of the sample, ordinary Portland cement Type I, water, coarse aggregate, and admixtures were used. The proportions of mixes used to investigate the properties of pervious concrete are summarized in Table 3.1. In addition this constituents, recycled aggregate and fly ash were used in the mixture of pervious concrete for this study. 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] and No.8 (passing 4.75 mm [0.19 in], retained on a 2.36 mm [0.095 in] sieve) as shown in Figure 3.2. Class L recycled aggregate and superplasticizer Type F were also used in this study. Recycled aggregates used in this study were produced by crushing the old concrete and then the crushed aggregates were sieved to get the required sizes of aggregates that use as recycled aggregate. Therefore, recycled aggregate can be defined as the aggregate which has a combination of cement and mortar. Type F superplasticizer (SP) at a dosage of 1% were the admixture used. Three percentages of fly ash between 20-60% and three amounts of recycled aggregate between 20-100% were used in this experiment. Figure 3.3 shows the specimens of pervious concrete made with recycled aggregate.

Figure 3.2 Coarse aggregate No.4 and No.8

Figure 3.3 Specimens of pervious concrete

Table 3.1 Mixture Proportions for the Pervious Concretes used in this study

Mixes	Water (g)	Cement (kg)	Coarse Aggregate (kg)	Recycled Aggregate (%)	Fly Ash (%)
C2	3340.3	13.9	69.6	-	-
C3	3956.3	13.6	68.9	-	-
F20	3296.1	11.0	68.7	-	20
F40	3253.2	8.1	67.8	-	40
F60	3211.4	5.4	66.9	-	60
R20	3272.6	13.6	54.5	20	-
R50	2931.6	8.1	30.5	50	-
R100	2794.3	5.4	-	100	-

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3.2 Sample Preparation

The mixture proportions were mixed in a pan mixer (30 Liter/batch) [Figure 3.4]. All mixtures were prepared to perform the physical properties of pervious concrete such as void content, permeability and thermal conductivity and the mechanical properties such as compressive strength and splitting tensile strength. Portland cement Type I, water, fly ash (if any) and admixture were mixed first for 270 seconds. After mixing the cement paste, the two sizes of coarse aggregate and recycled aggregate (if any) were added and mixed for next 120 seconds. Then, the mixtures were placed into Ø 150 mm × 300 mm cylindrical molds and 10 × 10 × 10 cm cube molds. Cube molds were used to test the compressive strength and void content. The specimens were applied a vibration for 20 seconds in each layer using a vibrator [Figure 3.5]. The specimens were remolded at 24 hours and kept into the curing room until testing age.

Figure 3.4 A Pan mixer used in the study

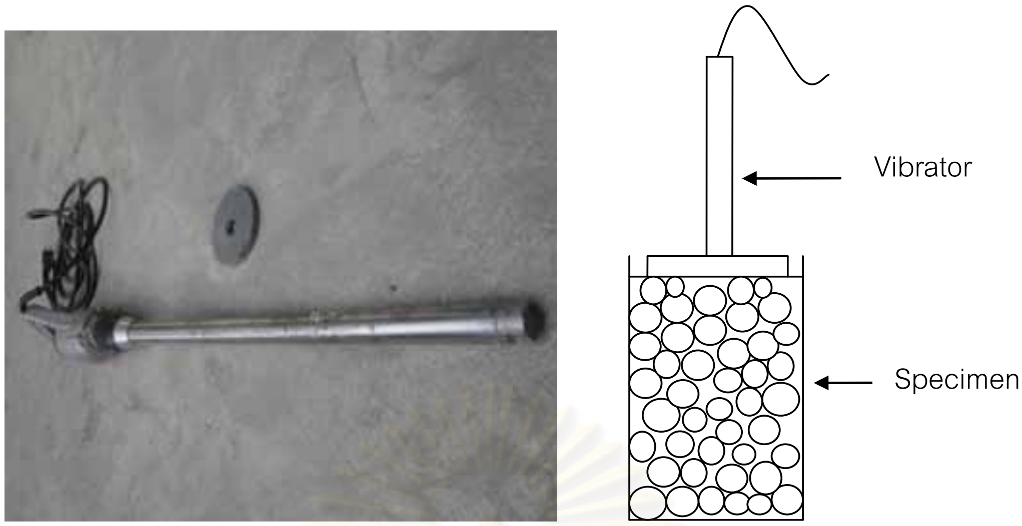

Figure 3.5 A vibrator used in this study and compaction of pervious concrete using a vibrator

3.3 Test Methods

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

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 measured using 10 × 10 × 10 cm rectangular samples by taking the difference between oven dry weight and weight under water using Equation 1 [21].

$$A = \left[1 - \left(\frac{W_2 - W_1}{\rho_w V_1}\right)\right] \times 100(\%) \tag{3.1}$$

Where: A = Total void ratio of the pervious concrete, (%)

W_2 = Weight of specimen dried in an oven for 2 days (kg)

W_1 = Weight of specimen under water (kg)

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ρ_w = Density of water (kg/cm³)

V_1 = Volume of specimen (cm³)

The specimens were measured the weight under water as illustrated in Figure 3.6 and kept into the oven for two days. Void content was tested at 7 days and 28 days. The result for void content was an average of three tests.

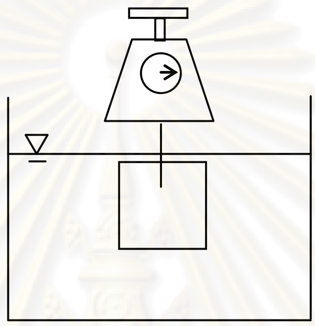

Figure 3.6 Sketch of measuring the weight under water

3.3.2 Permeability

Permeability is the parameter that shows the ability of a porous media to allow the passage of a fluid. A falling head permeability test apparatus was used to measure the permeability of the pervious concrete mixtures [Figure 3.7]. Ø 150 mm × 300 mm cylindrical specimens were used. Before doing the permeability test, the top and bottom of the specimens were cut by 2.5 cm. Then, the plastic gum was used around the top perimeter of the sample to prevent water leakage along the sides of the sample. Water was allowed to pass through the specimens and the time (t) required for water to fall from a head h_1 to h_2 was measured. The permeability coefficient (K in cm/s) was determined by the following equation [16].

$$K = \frac{aL}{At} \ln\left(\frac{h_1}{h_2}\right) \quad (3.2)$$

Where; K = Coefficient of permeability (cm/s)

a = Cross sectional area of the standpipe (cm²)

A = Cross sectional area of the specimen (cm²)

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)

Permeability test was done at 3 days, 7days, 14 days and 28 days. The results were from an average of three tests.

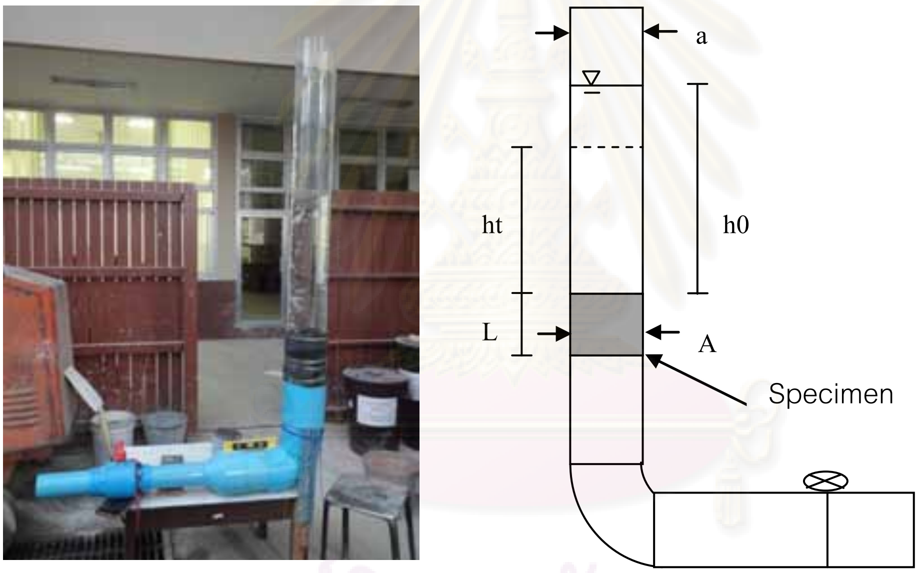

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Figure 3.7 Water permeability test apparatus set up

3.3.3 Compressive Strength

Compressive strength is a very important parameter for judging concrete quality and performance as shown in Figure 3.8. The compressive strength of the pervious concrete is less than the conventional concrete for its low cement paste content and high porosity. The strengths of the paste and aggregates, and void ratio influence on the compressive strength of the pervious concrete. In this study, the compressive strength was measured in accordance with ASTM-C 39, Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens. This strength test was measured at 28 days. The results were reported from an average of three tests.

Figure 3.8 Compressive test on pervious concrete

3.3.4 Splitting Tensile Strength

Tensile strength was measured according to ASTM-C 496 [Figure 3.9]. For this test, three specimens were tested and the results were reported from an average of three tests. The splitting tensile strength was calculated using the following equation;

$$T = \frac{2P}{dL\pi} \tag{3.3}$$

Where; T = Splitting Tensile Strength, (kPa)

P = Maximum applied load indicated by the testing machine, (kN)

d = Diameter, (m)

L = Length, (m)

Figure 3.9 Splitting tensile strength test of pervious concrete

3.3.5 Thermal Conductivity

Thermal conductivity is the property of concrete reflecting its ability to conduct heat. It can predict the rate of energy loss through a piece of concrete. Thermal conductivity can be measured by "Thermal constant analyzers (TCA)" apparatus as shown in Figure 3.10. The results are reported from an average of two tests.

Figure 3.10 Apparatus for testing the thermal conductivity

3.4 Test Parameters

The mix proportion of pervious concrete in this study will vary based on the previous research and possible LEED points. The mechanical and physical properties of all proposal mix proportion will be tested with methods in section 3.3.

Table 3.2 Test Parameters

Series	Specimens	w/c	%replacement	Cylinder	Rectangular
C	C2	*0.25*	-	*7*	*3*
	C3	*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*
			Total	*56*	*24*

3.5 Data Analysis

The following Table 3.3 shows the parameters and data for this study.

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Table 3.3 Analysis of Parameter and Data

Parameters	**Data**
1. Fly Ash content	1. Permeability
2. Recycled Aggregate content	2. Void Content
3. w/c ratio	3. Compressive Strength
	4. Splitting Tensile Strength
	5. Thermal Conductivity

CHAPTER IV

RESULTS AND DISCUSSION

4.1 Fresh Concrete Test (Slump Test)

A standard slump cone test (ASTM C 143) was used to determine the workability of the fresh concrete. Table 4.1 shows the results of workability of all mix proportions of the pervious concrete. Mix C2 is chosen as the control mix for having zero slump. Series F and R have higher workability as compared to the control mix (Mix C2). The relationship between workability of series F and R is illustrated in Figure 4.1. As seen in this figure, the workability of series F and R has no significant difference. Figure 4.2 shows the slump test for Mix F40.

Table 4.1 Results of workability for all mix proportions

<table>
<tr><th>Mixes</th><th>w/c</th><th>Slump (cm)</th></tr>
<tr><td>C2</td><td>0.25</td><td>0.0</td></tr>
<tr><td>C3</td><td>0.3</td><td>16.5</td></tr>
<tr><td>F20</td><td rowspan="7">0.25</td><td>17.0</td></tr>
<tr><td>F40</td><td>19.5</td></tr>
<tr><td>F60</td><td>18.5</td></tr>
<tr><td>R20</td><td>18.0</td></tr>
<tr><td>R50</td><td>17.0</td></tr>
<tr><td>R100</td><td>N/A</td></tr>
</table>

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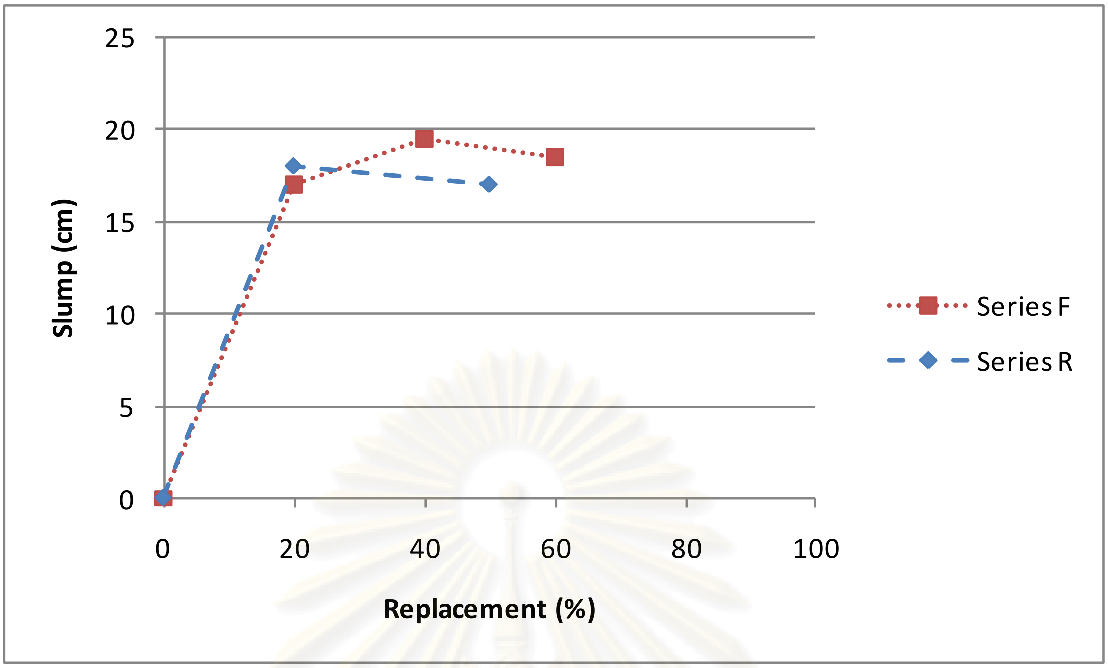

Figure 4.1 Results of workability for series F and R

Figure 4.2 Slump test (Mix F40)

4.2 Permeability Test

Table 4.2 presents the properties of the pervious concrete mixes, where different replacement of fly ash and recycled aggregate were used for making the pervious concrete. The coefficient of permeability was measured at 3 days, 7 days, 14 days and 28 days. Figure 4.3 provides the relationship between coefficient of permeability and water-to-cement ratio (w/c). As seen in this figure, the difference between the values of permeability for all testing ages is not significant in each mix proportion. The effects of fly ash and recycled aggregate on the pervious concrete are plotted in Figure 4.4-4.5. Figure 4.4 illustrates the relationship between the coefficient of permeability and fly ash content. As seen in the figure, the mix proportions with fly ash has lower coefficient of permeability than Mix C2 (with 0.25% of w/c and without fly ash). The coefficient of permeability lowered when the increased replacement of fly ash (20%, 40% and 60%). In Mix F20, the coefficient of permeability is high at the early age and is lowered after 28 days. The values of coefficient of permeability in Mix F40 and F60 are not much different for every testing age.

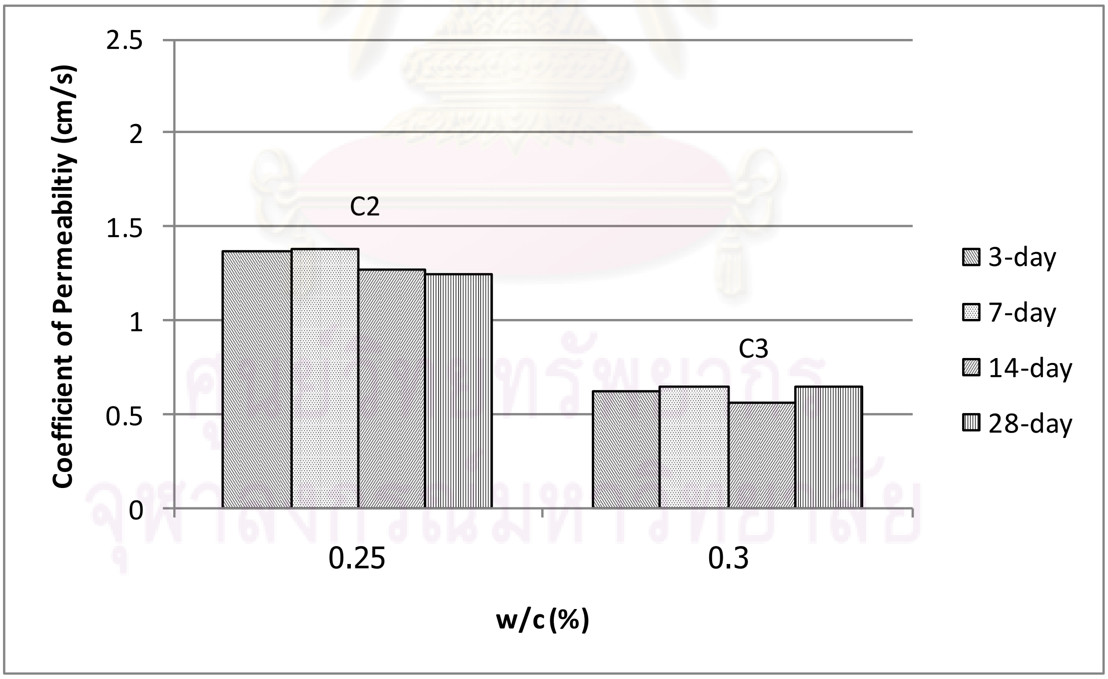

Figure 4.3 Relationship between coefficient of permeability and w/c

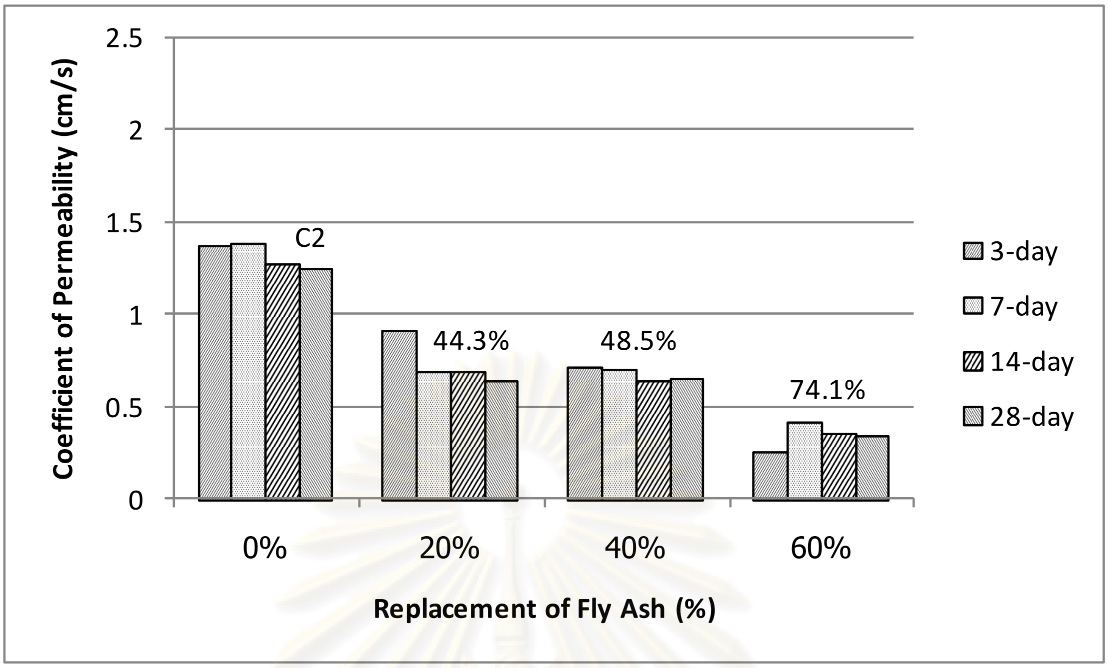

Figure 4.4 Relationship between coefficient of permeability and fly ash content

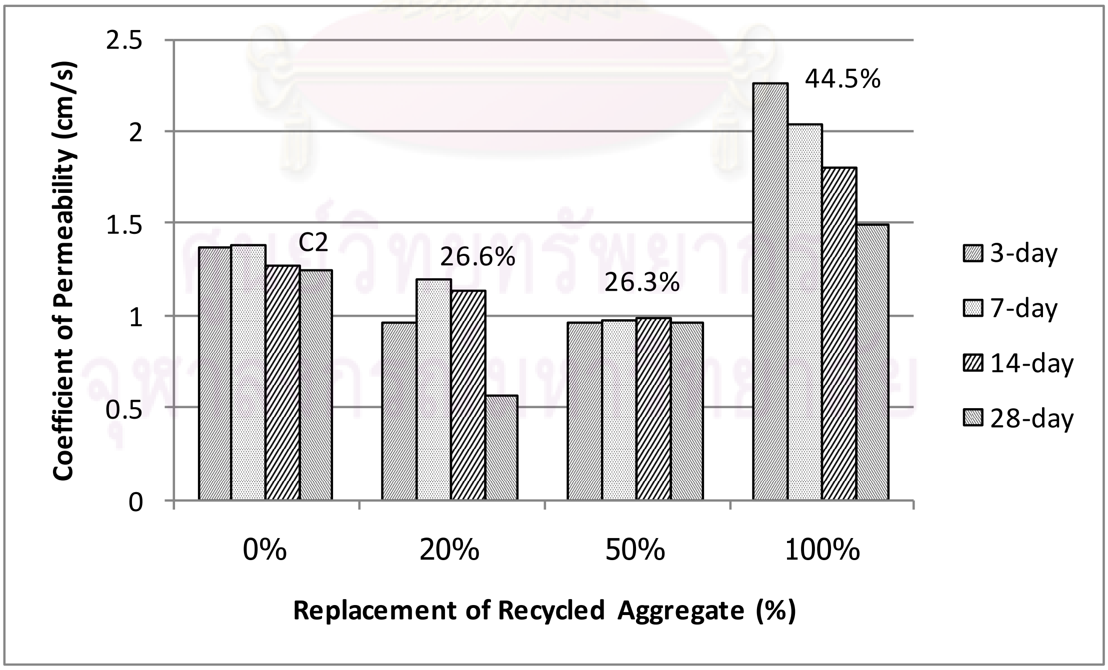

Figure 4.5 Relationship between coefficient of permeability and recycled aggregate content

Table 4.2 Results for all tests for each type of pervious concrete

Mixes	Void Content (%)	Coefficient of Permeability (cm/s)				Compressive Strength (ksc)	Splitting Tensile Strength (ksc)	Thermal Conductivity
		3-day	7-day	14-day	28-day			
C2	31.1	1.37	1.38	1.27	1.24	102	24	1.2322
C3	25.1	0.626	0.660	0.564	0.649	130	27	1.4883
F20	20.8	0.913	0.685	0.692	0.637	150	32	1.3093
F40	23.2	0.714	0.701	0.644	0.649	103	25	1.3729
F60	21.4	0.251	0.413	0.357	0.340	104	24	1.3196
R20	49.3	0.961	1.2	1.13	0.569	109	26	1.2918
R50	46.9	0.960	0.971	0.984	0.959	97	21	1.1460
R100	64.4	2.26	2.04	1.8	1.498	25	11	-

Figure 4.5 shows the relationship between the coefficient of permeability and replacement of recycled aggregate. This figure shows that as replacement of recycled aggregate is increased, the coefficient of permeability is also increased. In Mix R50 (with 50% recycled aggregate), the differences of the values of coefficient of permeability in all ages are not too much. However, in Mix R100 (with 100% recycled aggregate) has significant difference of coefficient of permeability for every age.

4.3 Void Content Test

The results of void content of the pervious concrete using various water-to-cement ratio (w/c) are described in Table 4.3 and 4.4. Generally, the void content for series C is constant at any age of testing. Figures 4.6 and 4.7 show the void content of different replacement of pervious concrete using fly ash and recycled aggregate respectively. As seen in the Figure 4.6, the void content of pervious concrete with the replacement of fly ash is lower than that of pervious concrete without fly ash. Figure 4.7 shows the effect of recycled aggregate on the void content of pervious concrete. The results show that the pervious concrete with addition of recycled aggregate has higher void content than the pervious concrete without recycled aggregate. The values of void content of pervious concrete with fly ash replacement at the age of 7 days and 28 days are not much different. However, the pervious concrete with recycled aggregate has significantly different values of void content for all testing ages.

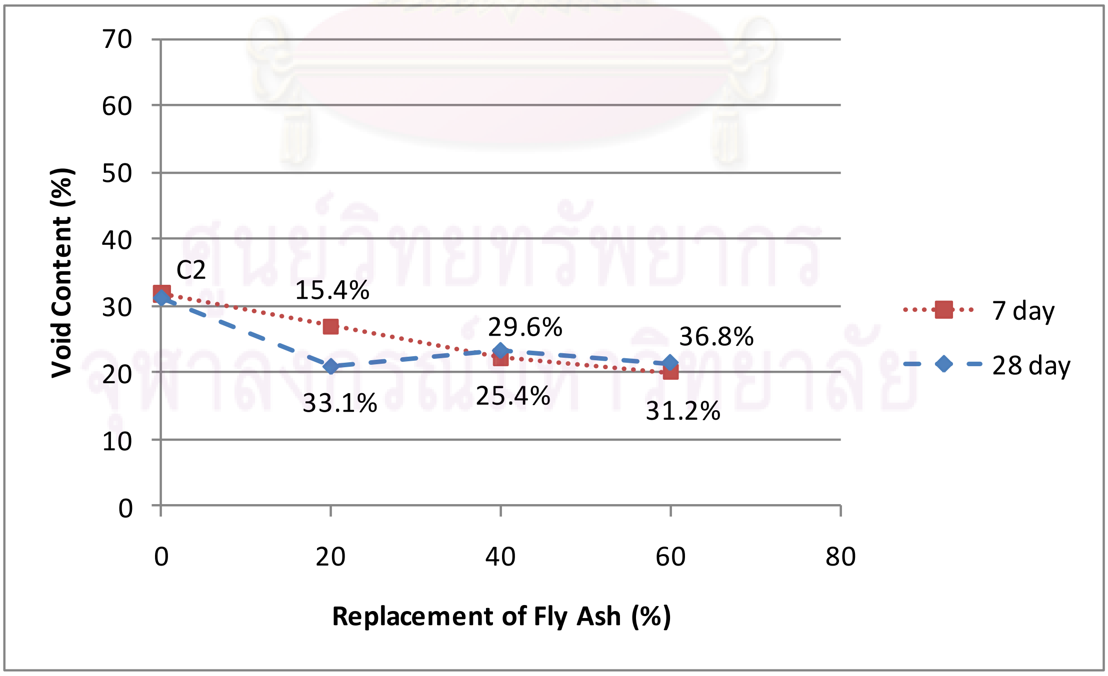

Figure 4.6 Results of void content using various replacement of fly ash

Figure 4.8 illustrates the relationship between compressive strength and void content of pervious concrete. As illustrated in this figure, the compressive strength of pervious concrete is related to void content. Due to the property of increasing concrete density, fly ash yields concrete of low permeability with low void contents. As the void content of Series F and R become larger, the compressive strength tends to decrease. When the replacement of fly ash was increased, the desired void content (≥ 15%) was easily achieved. In Mix R100 (with 100% of recycled aggregate content) has the lowest compressive strength but the void content is the highest. It is observed that the compressive strength was reduced when the replacement of recycled aggregate exceeded 50%.

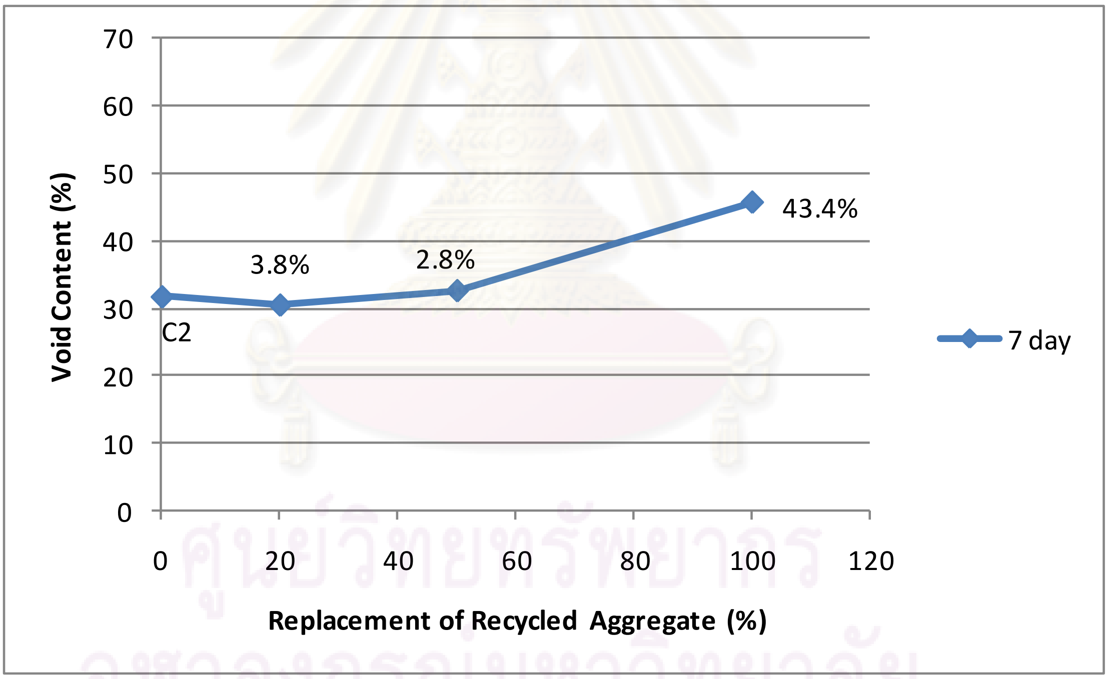

Figure 4.7 Results of void content using various replacement of recycled aggregate

According to the data from Table 4.2, the fly ash and recycled aggregate affect on the coefficient of permeability. Replacing the fly ash to the cement can fill into the void so that the values of permeability of series F are lower than that of pervious concrete without fly ash. However, in series R has different mechanism compared to series F. As seen in the Table 4.2, the value of permeability is low although the void content is high in some mix proportions of pervious concrete with the replacement of recycled aggregate. The reason is that though using recycled aggregate can get higher void content, these increased voids cannot be interconnected into the concrete mass. Therefore, the values of permeability lowered in some mix proportions.

The following Table 4.3 and 4.4 describe the values of void content at 7-day and 28-day for all mix proportions of pervious concrete.

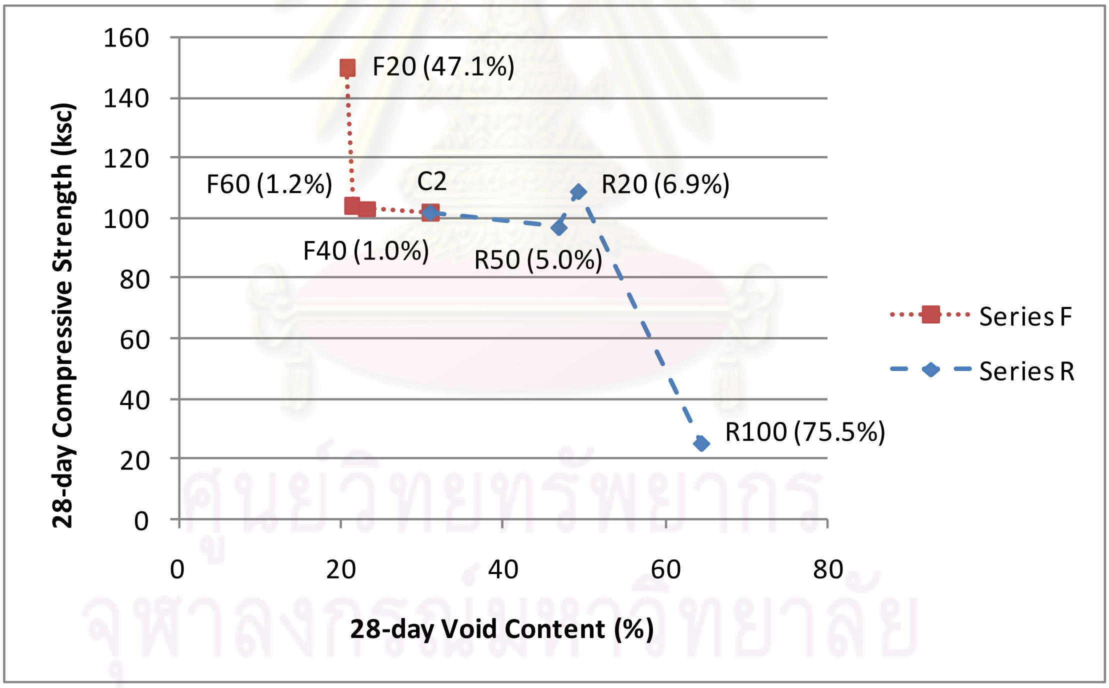

Figure 4.8 Relationship between 28-day compressive strength and 28-day void content

Table 4.3 Results of void content for all mix proportions of pervious concrete (7-day)

Mixes	Dimensions			Weight under water (g)	Oven dry weight (g)	Void Content (%)
	Width (cm)	Length (cm)	Height (cm)			
C2	10.0	10.0	10.1	1113.5	1802.0	31.8
C3	10.0	9.9	10.0	1103.4	1855.0	24.1
F20	10.0	10.0	10.0	1246.0	1976.8	26.9
F40	10.0	10.2	9.8	1160.8	1936.2	22.4
F60	10.0	9.8	10.1	1183.8	1974.3	20.1
R20	10.1	10.2	10.0	1125.0	1840.2	30.6
R50	10.1	10.1	9.9	1092.9	1772.7	32.7
R100	9.1	10.0	10.5	887.9	1408.1	45.6

Table 4.4 Results of void content for all mix proportions of pervious concrete (28-day)

Mixes	Dimensions			Weight under water (g)	Oven dry weight (g)	Void Content (%)
	Width (cm)	Length (cm)	Height (cm)			
C2	10.0	10.0	10.1	1111.4	1807.0	31.1
C3	10.0	9.9	10.0	1112.4	1854.1	25.1
F20	10.0	10.0	10.0	1184.8	1976.7	20.8

ศูนย์วิทยทรัพยากร
จุฬาลงกรณ์มหาวิทยาลัย

F40	10.0	10.2	9.8	1172.4	1939.9	23.2
F60	10.0	9.8	10.1	1182.8	1960.5	21.4
R20	10.1	10.2	10.0	1230.0	1752.4	49.3
R50	10.1	10.1	9.9	1242.2	1778.8	46.9
R100	9.1	10.0	10.5	999.3	1339.0	64.4

4.4 Compressive Strength Test

Table 4.5 illustrates the results of 28-day compressive strength of all mix proportions of pervious concrete. The results of 28-day compressive strength of series C are related to the void content as shown in Table 4.3 and 4.4. The effect of fly ash and recycled aggregate content on the 28-day compressive strength of pervious concrete is given in Figure 4.9. As observed in Figure 4.9, Mix F40 and Mix F60 showed no significant difference in their compressive strengths compared to Mix C2 (without fly ash). However, in Mix F20 has higher compressive strength than pervious concrete without fly ash. The compressive strength of pervious concrete using recycled aggregate is lower than that of pervious concrete without recycled aggregate.

Table 4.5 Results of 28-day compressive strength of all mix proportions

Mixes	Diameter (cm)	Length (cm)	Unit Weight (kg/m^3)	28-day Compressive Strength (ksc)
C2	15	30	1846	102
C3	15	30	1883	130
F20	15	30	1940	150

F40	15	30	1927	103
F60	15	30	1959	104
R20	15	30	1921	109
R50	15	30	1833	97
R100	15	30	1620	25

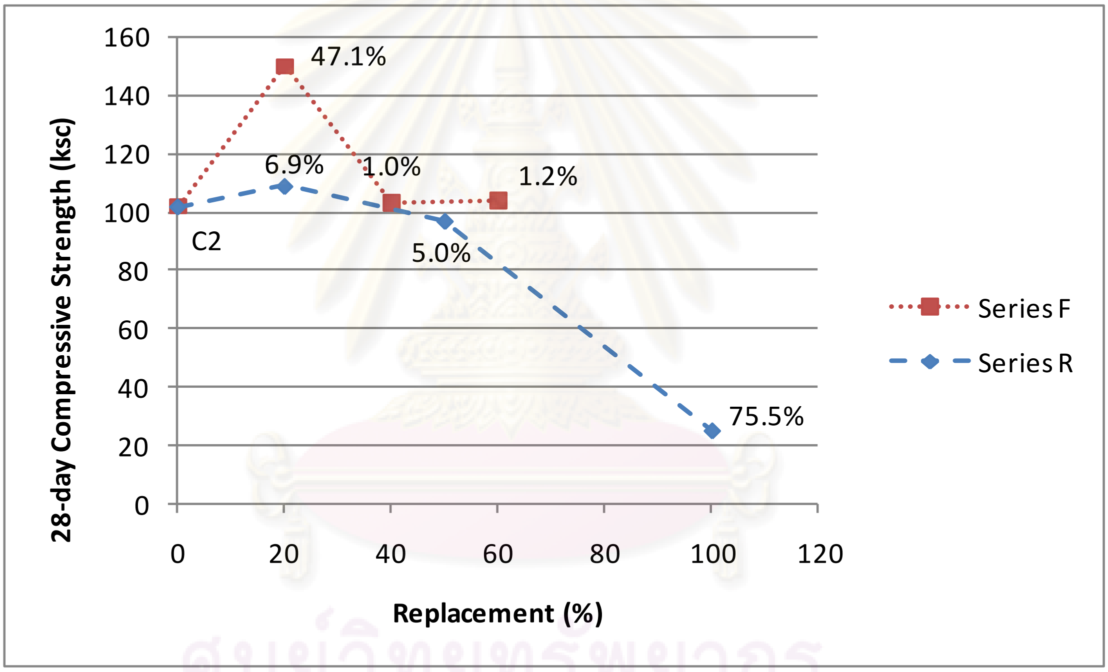

Figure 4.9 28-day Compressive strength for series F and R

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4.5 Splitting Tensile Strength Test

According the data from Table 4.2, the results of splitting tensile strength are related to the compressive strength. The results of the 28-day splitting tensile strength tests for series F and R are presented in Figure 4.10. The trend lines of splitting tensile strength for both series are almost the same as that of the compressive strength.

As shown in Figure 4.10, the trend lines are similar as the trend lines of the compressive strength.

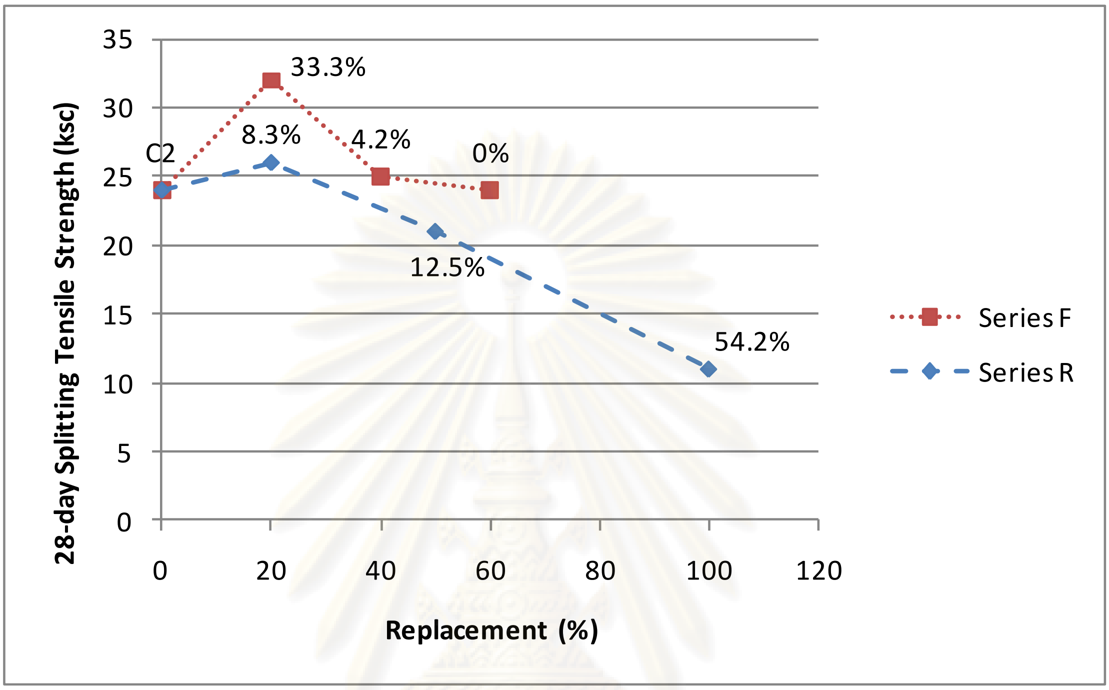

Figure 4.10 28-day Splitting tensile strength for series F and R

4.6 Thermal Conductivity Test

Figure 4.11 shows the results of thermal conductivity with the replacement of fly ash and recycled aggregate. The results are compared to the thermal conductivity of conventional concrete. The values of the thermal conductivity for both series are under the values of conventional concrete. Figure 4.12 and 4.13 describe the relationships between the thermal conductivity and void content using fly ash and recycled aggregate. The results of thermal conductivity for all mixes of pervious concrete are shown in Table 4.6.

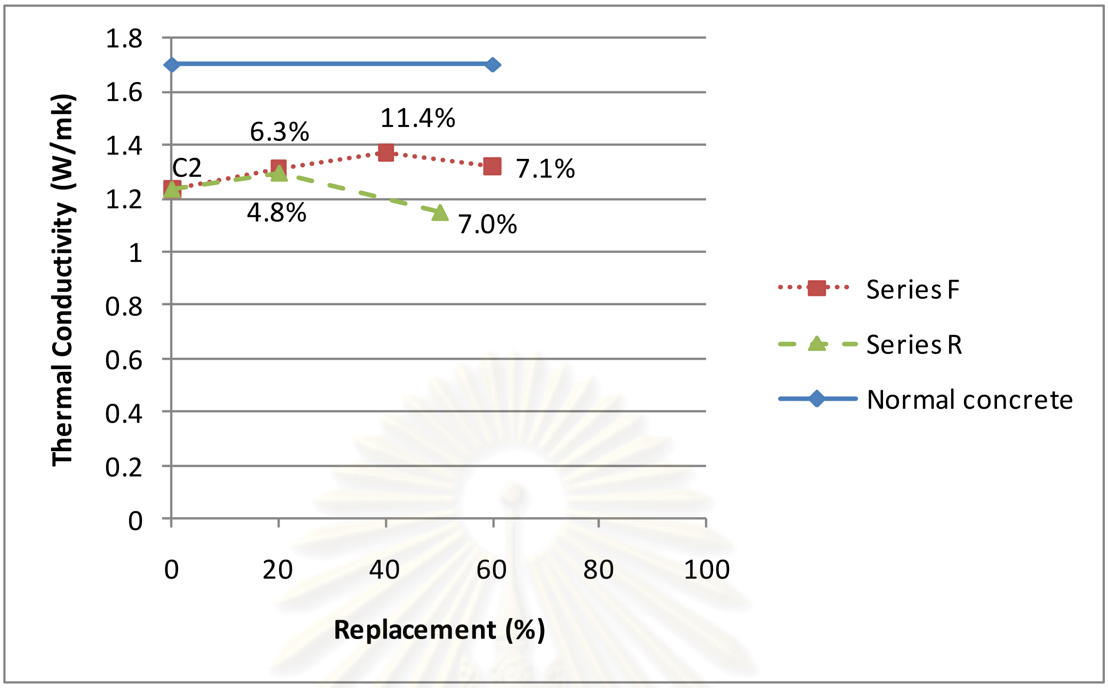

Figure 4.11 Results of thermal conductivity for series F and R

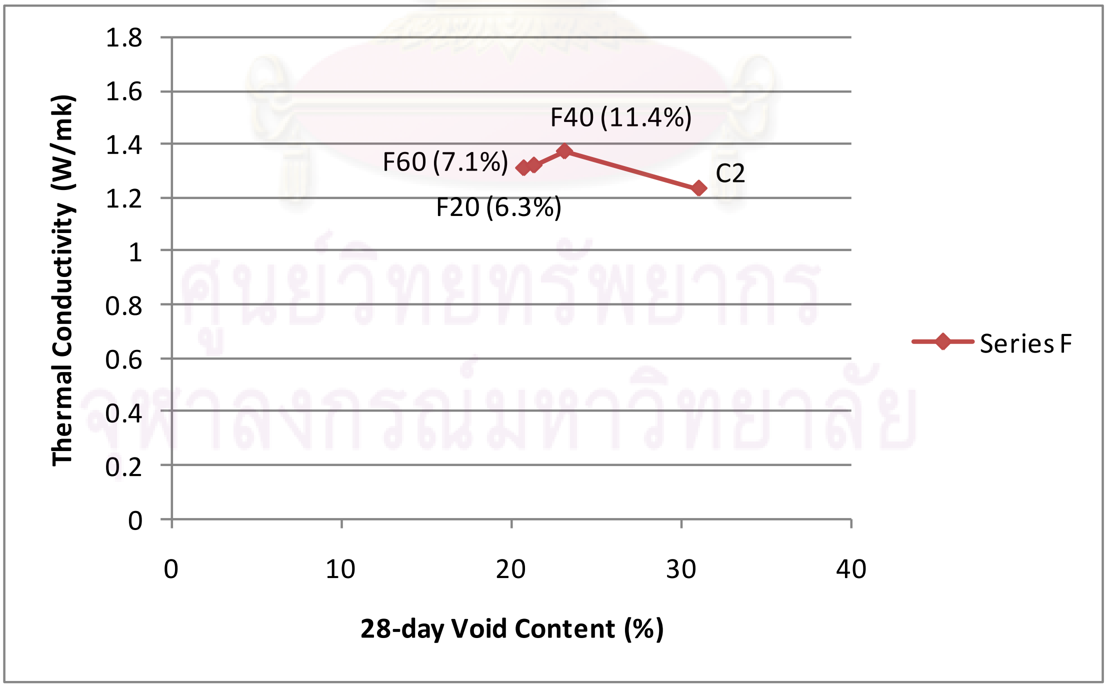

Figure 4.12 Relationship between thermal conductivity and 28-day void content for series F

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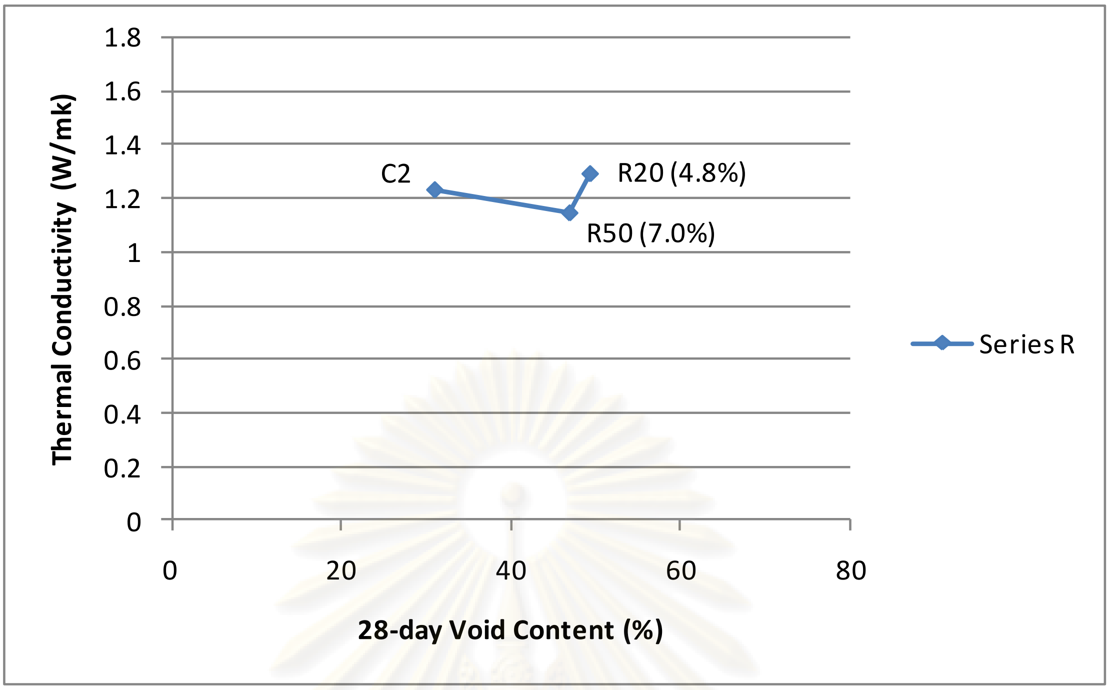

Figure 4.13 Relationship between thermal conductivity and void content for series R

Table 4.6 Results of thermal conductivity for all mixes of pervious concrete

Mixes	Thermal Conductivity (W/mk)			
	1	2	3	Average
C2	1.2185	1.2322	1.2443	1.2322
C3	1.4852	1.5019	1.4778	1.4883
F20	1.3158	1.3044	1.3076	1.3093
F40	1.3749	1.3773	1.3664	1.3729
F60	1.3167	1.3197	1.3222	1.3196
R20	1.3000	1.2994	1.2761	1.2918

ศูนย์วิทยทรัพยากร
จุฬาลงกรณ์มหาวิทยาลัย

R50	1.1422	1.1453	1.1504	1.1460
R100	N/A	N/A	N/A	N/A

4.7 Calculation of Possible LEED Points

In this part, how many possible LEED points can be earned from the proposed mix proportions of pervious concrete are presented. This study considers only for the pavement as the whole project to calculate the possible LEED points. As explained before, the mix proportion of pervious concrete in this research are different, thus the possible LEED points in each mix proportion may be different.

4.7.1 Storm water Design: Quantity Control

If the concrete is pervious and contains no fine aggregates or little, this type of concrete can percolate the storm water runoff. This concrete is known as "Pervious concrete". 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 4.7. According the data from Table 4.7, the void content for all mixes in this study is higher than 15%. Therefore, using the mix proportions in this research can earn this credit by one point.

Table 4.7 Void content and coefficient of permeability of pervious concrete

Mixes	Void Content (%)	28-day Coefficient of Permeability (cm/sec)
C2	31.1	1.24
C3	25.1	0.649
F20	20.8	0.637
F40	23.2	0.649
F60	21.4	0.34
R20	49.3	0.569
R50	46.9	0.959
R100	64.4	1.498

4.7.2 Recycled Content: 10% (post-consumer + ½ pre-consumer) (Material & Resources Credit 4.1)

Recycled Content: 20% (post-consumer + ½ pre-consumer) (Material & Resources Credit 4.2)

In this study, the different percent amounts of fly ash and recycled aggregate are used to the 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 are considered post-consumer recycled content. The following Tables 4.8-4.15 present the recycled content calculation for each series of pervious concrete. 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 recycled content and pre-consumer are

0% for all mix proportions of Series C and thereby recycled content are also 0%. In Series F and R, the different percent amounts 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.

ศูนย์วิทยทรัพยากร
จุฬาลงกรณ์มหาวิทยาลัย

Table 4.8 Recycled Content Calculation of C2

C2							
Method Applicable to all Construction Products							
	Virgin Materials	Recycled Materials				Total	
		Pre-consumer		Post-consumer			
Component	Weight, kg	Weight, kg	%	Weight, kg	%	Weight, kg	%
Sand and gravel	0	0	0	0	0	0	0
Other aggregate	69.6	0	0	0	0	69.6	80
Recycled aggregate	0	0	0	0	0	0	0
Portland cement	13.9	0	0	0	0	13.9	16
Recycled cementitious	0	0	0	0	0	0	0
Water	3.3403	0	0	0	0	3.3403	3.8
Superplasticizer	0.1392	0	0	0	0	0.1392	0.2
Total						86.9795	100

Pre-consumer	0.0%	Post-consumer	0.0%
	Recycled content		0.0%

ศูนย์วิทยทรัพยากร
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Table 4.9 Recycled Content Calculation of C3

C3							
Method Applicable to all Construction Products							
	Virgin Materials	Recycled Materials				Total	
		Pre-consumer		Post-consumer			
Component	Weight, kg	Weight, kg	%	Weight, kg	%	Weight, kg	%
Sand and gravel	0	0	0	0	0	0	0
Other aggregate	68.2	0	0	0	0	68.2	79.4
Recycled aggregate	0	0	0	0	0	0	0
Portland cement	13.6	0	0	0	0	13.6	15.8
Recycled cementitious	0	0	0	0	0	0	0
Water	3.9563	0	0	0	0	3.9563	4.6
Superplasticizer	0.1364	0	0	0	0	0.1364	0.2
Total						85.8927	100

Pre-consumer	0.0%	Post-consumer	0.0%
	Recycled content		0.0%

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Table 4.10 Recycled Content Calculation of F20

F20							
Method Applicable to all Construction Products							
	Virgin Materials	Recycled Materials				Total	
		Pre-consumer		Post-consumer			
Component	Weight, kg	Weight, kg	%	Weight, kg	%	Weight, kg	%
Sand and gravel	0	0	0	0	0	0	0
Other aggregate	68.7	0	0	0	0	68.7	80
Recycled aggregate	0	0	0	0	0	0	0
Portland cement	11	0	0	0	0	11	12.8
Recycled cementitious	0	2.7	3.1	0	0	2.7	3.1
Water	3.2961	0	0	0	0	3.2961	3.8
Superplasticizer	0.1374	0	0	0	0	0.1374	0.2
Total						85.8335	100

Pre-consumer	3.1%	Post-consumer	0.0%
	Recycled content		1.6%

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จุฬาลงกรณ์มหาวิทยาลัย

F20							
Alternative Method for Concrete Products							
	Virgin Materials	Recycled Materials				Total	
		Pre-consumer		Post-consumer			
Component	Weight (kg)	Weight (kg)	%	Weight (kg)	%	Weight (kg)	%
Portland cement	11	0	0	0	0	11	80
Recycled cementitious	0	2.7	19.7	0	0	2.7	20
Total						13.7	100

Pre-consumer	20%	Post-consumer	0.0%
	Recycled content		10%

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Table 4.11 Recycled Content Calculation of F40

F40							
Method Applicable to all Construction Products							
	Virgin Materials	Recycled Materials				Total	
		Pre-consumer		Post-consumer			
Component	Weight, kg	Weight, kg	%	Weight, kg	%	Weight, kg	%
Sand and gravel	0	0	0	0	0	0	0
Other aggregate	67.8	0	0	0	0	67.8	80.1
Recycled aggregate	0	0	0	0	0	0	0
Portland cement	8.1	0	0	0	0	8.1	9.6
Recycled cementitious	0	5.4	6.4	0	0	5.4	6.4
Water	3.2532	0	0	0	0	3.2532	3.8
Superplasticizer	0.1356	0	0	0	0	0.1356	0.2
Total						84.6888	100

Pre-consumer	6.4%	Post-consumer	0.0%
	Recycled content		3.2%

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F40							
Alternative Method for Concrete Products							
	Virgin Materials	Recycled Materials				Total	
		Pre-consumer		Post-consumer			
Component	Weight (kg)	Weight (kg)	%	Weight (kg)	%	Weight (kg)	%
Portland cement	8.1	0	0	0	0	8.1	60
Recycled cementitious	0	5.4	40	0	0	5.4	40
Total						13.5	100

Pre-consumer	40%	Post-consumer	0.0%
	Recycled content		20%

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Table 4.12 Recycled Content Calculation of F60

F60							
Method Applicable to all Construction Products							
	Virgin Materials	Regional Materials				Total	
		Pre-consumer		Post-consumer			
Component	Weight, kg	Weight, kg	%	Weight, kg	%	Weight, kg	%
Sand and gravel	0	0	0	0	0	0	0
Other aggregate	66.9	0	0	0	0	66.9	80
Recycled aggregate	0	0	0	0	0	0	0
Portland cement	5.4	0	0	0	0	5.4	6.5
Recycled cementitious	0	8	9.6	0	0	8	9.6
Water	3.2114	0	0	0	0	3.2114	3.8
Superplasticizer	0.1338	0	0	0	0	0.1338	0.2
Total						83.6452	100

Pre-consumer	9.6%	Post-consumer	0.0%
	Recycled content		4.8%

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F60							
Alternative Method for Concrete Products							
	Virgin Materials	Recycled Materials				Total	
		Pre-consumer		Post-consumer			
Component	Weight (kg)	Weight (kg)	%	Weight (kg)	%	Weight (kg)	%
Portland cement	5.4	0	0	0	0	5.4	40.3
Recycled cementitious	0	8	59.7	0	0	8	0
Total						13.4	100

Pre-consumer	59.7%	Post-consumer	0.0%
	Recycled content		29.9%

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Table 4.13 Recycled Content Calculation of R20

R20							
Method Applicable to all Construction Products							
	Virgin Materials	Regional Materials				Total	
		Pre-consumer		Post-consumer			
Component	Weight, kg	Weight, kg	%	Weight, kg	%	Weight, kg	%
Sand and gravel	0	0	0	0	0	0	0
Other aggregate	54.5	0	0	0	0	54.5	64
Recycled aggregate	0	0	0	13.6	16	13.6	16
Portland cement	13.6	0	0	0	0	13.6	16
Recycled cementitious	0	8	9.6	0	0	0	0
Water	3.2726	0	0	0	0	3.2726	3.8
Superplasticizer	0.1364	0	0	0	0	0.1364	0.2
Total						85.109	100

Pre-consumer	0.0%	Post-consumer	16%
	Recycled content		16%

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Table 4.14 Recycled Content Calculation of R50

R50							
Method Applicable to all Construction Products							
	Virgin Materials	Regional Materials				Total	
		Pre-consumer		Post-consumer			
Component	Weight, kg	Weight, kg	%	Weight, kg	%	Weight, kg	%
Sand and gravel	0	0	0	0	0	0	0
Other aggregate	30.5	0	0	0	0	30.5	40
Recycled aggregate	0	0	0	30.5	40	30.5	40
Portland cement	12.2	0	0	0	0	12.2	16
Recycled cementitious	0	8	9.6	0	0	0	0
Water	2.9316	0	0	0	0	2.9316	3.8
Superplasticizer	0.1222	0	0	0	0	0.1222	0.2
Total						76.2538	100

Pre-consumer	0.0%	Post-consumer	40%
	Recycled content		40%

ศูนย์วิทยทรัพยากร
จุฬาลงกรณ์มหาวิทยาลัย

Table 4.15 Recycled Content Calculation of R100

R100							
Method Applicable to all Construction Products							
	Virgin Materials	Regional Materials				Total	
		Pre-consumer		Post-consumer			
Component	Weight, kg	Weight, kg	%	Weight, kg	%	Weight, kg	%
Sand and gravel	0	0	0	0	0	0	0
Other aggregate	0	0	0	0	0	0	0
Recycled aggregate	0	0	0	58.2	80	58.2	80
Portland cement	11.6	0	0	0	0	11.6	16
Recycled cementitious	0	0	9.6	0	0	0	0
Water	2.7943	0	0	0	0	2.7943	3.8
Superplasticizer	0.1164	0	0	0	0	0.1164	0.2
Total						72.7107	100

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Pre-consumer	0.0%	Post-consumer	80%
	Recycled content		80%

4.7.3 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 of the project site. Thus, two possible LEED points can be earned by using these local materials in this study.

Table 4.16 Relationship between the properties of pervious concrete and possible LEED points

Mixes	Void Content (%)	28-day Compressive Strength (ksc)	28-day Splitting Tensile Strength (ksc)	28-day Coefficient of Permeability (cm/s)	Possible LEED Credit Points
C2	31.1	102	24	1.24	3
C3	25.1	130	27	0.649	3
F20	20.8	150	32	0.637	4
F40	23.2	103	25	0.649	5
F60	21.4	104	24	0.340	5
R20	49.3	109	26	0.569	4
R50	46.9	97	21	0.959	5
R100	64.4	25	11	1.498	5

Table 4.16 presents the properties of pervious concrete such as void content, thermal conductivity, and coefficient of permeability, compressive strength, splitting tensile strength and the possible LEED points that can earn from the proposed mix proportions of pervious concrete in this research.

4.8 Discussion of Possible LEED Points

In this study, the mix proportions of the pervious concrete are different. Therefore, the possible LEED points of each mix proportion of pervious concrete are also different. In this research, there are three series of pervious concrete such as Series C, Series F and Series R.

In Series C, the two values of water-to-cement ratios are 0.25 and 0.3. The two mix proportions of Series C are C2 and C3. Among these proportions, Mix C2 is chosen as the control mix proportion for other two series according to the data. In Series F, the variations are the replacement of fly ash by 20%, 40% and 60%. F20, F40 and F60 are the mix proportions of Series F. 0.25% of water-binder ratio is used for Series F and Series R. In Series R, the replacement of recycled aggregate is the variation of this series. Three recycled aggregate contents between 20%-100% are used in this series.

When the possible LEED points are calculated, three types of possible LEED points can be divided in the following.

1. Three possible LEED points
   - Storm water Design- Quantity Control (1 possible point)
   - Recycled Content (0 possible point)
   - Regional Materials (2 possible point)

Mixes C2 and C3 are the mix proportions that have three possible LEED points. Mix C2 has the highest void content and coefficient of permeability but the lowest compressive and splitting tensile strength. Mix C3 has the highest compressive strength and lowest coefficient of permeability. According to these facts, Mix C2 is the best mix proportion in this type.

2. Four possible LEED points
   - Storm water Design- Quantity Control (1 possible point)
   - Recycled Content (1 possible point)
   - Regional Materials (2 possible point)

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.

3. Five possible LEED points
   - Storm water Design- Quantity Control (1 possible point)
   - Recycled Content (2 possible point)
   - Regional Material (2 possible point)

In this type, Mix F40, F60, R50 and R100 are the mix proportions that have five possible LEED points. Mix F40 has higher void content and coefficient of permeability that that of Mix F60. The differences of compressive and splitting tensile strength in Mix F40 and F60 are not too much. For this type, 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 eight mix proportions. This proportion (Mix F40) has the highest possible LEED points and can get the required properties of pervious concrete.

CHAPTER V

CONCLUSIONS

From this study, the following conclusions can be made.

1. The mix proportion of pervious concrete in this research can earn the Storm water Design-Quantity Control, Recycled Content, and Regional Materials Credits using the fly ash and recycled aggregate replacing in the cement and coarse aggregate, respectively.

2. The mechanical properties and physical properties of pervious concrete can conclude as the following.

   2.1 Replacing the fly ash in the cement can get additional strength as compared to the pervious concrete without fly ash.

   2.2 The use of 100% recycled aggregate instead of virgin aggregate can increase the coefficient of permeability and void content but the compressive strength and splitting tensile strength are the lowest.

   2.3 The pervious concrete has low strength due to its high void content but sufficient strength for many applications can be achieved.

3. Mix F40, F60, R50 and R100 can achieve the highest possible LEED credit points. Among these mixes, Mix F40 is the appropriate mix proportion that can aslo give sufficient properties of pervious concrete.

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