รายงานวิจัยฉบับสมบูรณ์

โครงการการใช้เศษคอนกรีตเก่าเป็นมวลรวมร่วมกับเถ้าจากโรงไฟฟ้าในงานคอนกรีต

โดย

ดร. วีรชาติ ตั้งจิรภัทร

มิถุนายน 2556

สัญญาเลขที่ MRG5480180

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สนับสนุนโดยสำนักงานกองทุนสนับสนุนการวิจัย

(ความเห็นในรายงานนี้เป็นของผู้วิจัย
สกว.ไม่จำเป็นต้องเห็นด้วยเสมอไป)

Abstract

Project Code : MRG5480180

Project Title : Utilization of Recycled Aggregate Mixed with Ashes from Thermal Power Plant in Concrete

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Project Period : 2 years (15 June 2011 – 14 June 2013)

This study proposes the use of fly ash and ground palm oil fuel ash (POFA) to improve the properties of concrete containing high amount of recycled concrete aggregates. A portion of ordinary Portland cement type I (OPC) was replaced by fly ash and ground POFA at 20, 35, and 50% by weight of binder.

The results indicate that the slump loss of recycled aggregate concrete with fly ash was reduced to lower than that of the recycled aggregate concrete without fly ash when the fineness of the fly ash was increased, which increased the slump loss of fresh concrete. Fly ash can be used to increase the compressive strength of recycled aggregate concrete, depending on its fineness and the degree of fly ash replacement. The addition of fly ash with different fineness in recycled aggregate concrete had no significant effect on the splitting tensile strength and the modulus of elasticity of the recycled aggregate concrete.

Ground POFA could improve the compressive strength and reduce the water permeability of recycled aggregate concretes. The modulus of elasticity of recycled aggregate concrete with and without ground POFA was lower than that of the conventional concrete by approximately 25%. Finally, ground POFA could be used effectively to reduce the expansion of recycled aggregate concrete. As the replacement of ground POFA in concrete is increased, the expansion of recycled aggregate concrete due to sodium sulfate attack decreased.

Keywords : fly ash / palm oil fuel ash / recycled concrete aggregate

บทคัดย่อ

รหัสโครงการ : MRG5480180

ชื่อโครงการ : การใช้เศษคอนกรีตเก่าเป็นมวลรวมร่วมกับเถ้าจากโรงไฟฟ้าในงานคอนกรีต

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การศึกษานี้แสดงผลการศึกษาการใช้ประโยชน์จากเถ้าถ่านหินและเถ้าน้ำมันปาล์มเพื่อปรับปรุงคุณสมบัติของคอนกรีตที่ใช้เศษคอนกรีตเก่าเป็นมวลรวมในปริมาณสูงโดยแทนที่ปูนซีเมนต์ปอร์ตแลนด์ประเภทที่ 1 ด้วยเถ้าถ่านหินและเถ้าปาล์มน้ำมันในอัตราร้อยละ20, 35, และ 50 โดยน้ำหนักของวัสดุประสาน

ผลการศึกษาพบว่าการใช้เถ้าถ่านหินสามารถลดการสูญเสียค่ายุบตัวของคอนกรีตที่ใช้เศษคอนกรีตเก่าเป็นมวลรวมได้ และการสูญเสียค่ายุบตัวมีค่าเพิ่มขึ้นเล็กน้อยเมื่อความละเอียดของเถ้าถ่านหินเพิ่มขึ้นเถ้าถ่านหินยังสามารถเพิ่มกำลังอัดของคอนกรีตที่ใช้มวลรวมจากเศษคอนกรีตได้ โดยขึ้นอยู่กับความละเอียดและอัตราการแทนที่ปูนซีเมนต์ของเถ้าถ่านหิน นอกจากนี้ความละเอียดของเถ้าถ่านหินไม่ส่งผลกระทบต่อกำลังดึงแบบผ่าซีกและโมดูลัสยืดหยุ่นของคอนกรีตที่ใช้เศษคอนกรีตเก่าเป็นมวลรวม

เถ้าปาล์มน้ำมันบดละเอียดสามารถเพิ่มกำลังอัดและลดอัตราการซึมของน้ำผ่านคอนกรีตที่ใช้เศษคอนกรีตเก่าเป็นมวลรวมโมดูลัสของความยืดหยุ่นของคอนกรีตที่ใช้เศษคอนกรีตเก่าเป็นมวลรวมทั้งที่มีและไม่มีเถ้าปาล์มน้ำมันในส่วนผสมมีค่าต่ำกว่าคอนกรีตที่ใช้มวลรวมจากธรรมชาติโดยประมาณร้อยละ25 อย่างไรก็ตามเถ้าปาล์มน้ำมันสามารถลดการขยายตัวเนื่องจากสารละลายโซเดียมซัลเฟตของคอนกรีตที่ใช้เศษคอนกรีตเก่าเป็นมวลรวมได้ โดยค่าการขยายตัวของคอนกรีตมีค่าลดลงเมื่ออัตราการแทนที่เถ้าปาล์มน้ำมันในปูนซีเมนต์เพิ่มขึ้น

คำหลัก : เถ้าถ่านหิน / เถ้าปาล์มน้ำมัน / มวลรวมที่ได้จากเศษคอนกรีต

UTILIZATION OF RECYCLED CONCRETE AGGREGATES MIXED WITH ASHES FROM THERMAL POWER PLANT IN CONCRETE

1. Introduction

Concrete is one of the most widely used construction materials in the world. Typically, concrete contains approximately 70 to 80% aggregates (coarse and fine) and 20 to 30% cement paste by mass. Therefore, aggregate is an essential component of concrete and has a significant effect on fresh and hardened concrete properties. In Thailand, recent statistics have shown that more than 180 million tons of natural aggregates (Department of Primary Industry and Mines, 2010) is used in the concrete industry each year; this value is showing a rapidly increasing trend due to industry expansion and economic growth, while the natural resources for producing aggregate are limited. At the same time, many old buildings and structures have reached their limit of use and need to be demolished. It is estimated that an average of 1.1 million tons per year of demolition waste concrete is produced in Thailand (Kofoworola et al., 2009), but its utilization is minimal and unmanaged. One application for using demolished concretes is as a low-value material for backfill in construction areas. Thus, almost all demolished concrete is dumped or disposed of as waste in landfills.

Recycled aggregate concrete is a concrete composed of a recycled aggregate or combination of recycled aggregates and other aggregates (Hansen, 1992) Recycled aggregate is typically derived from crushed old concrete, which consists of 65-70% by volume of natural coarse and fine aggregates and 30-35% by volume of old cement paste (Poon et al., 2004). Numerous studies investigated the use of aggregate from demolished concrete, and the studies concluded that the compressive strength and durability of concrete decreased when recycled aggregate was used (Hansen and Boegh, 1985; Oliveira and Vazquez, 1996; Katz, 2003). Chen et al. (2003) reviewed the effect of recycled aggregate on the compressive strength of concrete and found that the compressive strength of concrete containing 100% coarse recycled aggregate could be as low as 60% of that of concrete made from normal aggregate. The results obtained by Limbachiya et al. (2012) showed that the resistance of concrete to carbonation and chloride penetration decreased as the recycled concrete aggregate content increased.

From previous studies, it should be noted that the compressive strength and durability of recycled aggregate concrete are worse than those of conventional concrete; thus, many researchers have attempted to improve the properties of recycled aggregate concrete. For cases in which the water to binder ratio is high, Otsuki et al. (2003) used a double mixing method to increase the strength, chloride penetration and carbonation resistance of concrete containing recycled aggregates. Montgomery (1998) treated the recycled aggregate with a ball mill to remove the old cement paste from the aggregate and found that this method could be used to increase the strength of recycled aggregate concrete. Katz (2004) treated the recycled aggregate by impregnation of silica fume solution and ultrasonic cleaning. He found that the compressive strength increased by 30% and 15% at the ages of 7 and 28 days, respectively, after the silica fume treatment, and the compressive strength increased by 7% after the ultrasonic treatment. Another method for overcoming these shortcomings is the incorporation of a pozzolanic material in the concrete mixture.

Fly ash is known to be a good pozzolanic material and has been used to increase the ultimate compressive strength and workability of fresh concrete (Mehta 1985). Naik and Ramme (1989) produced concrete mixes containing large quantities of fly ash which achieved compressive strengths of 21 and 28 MPa. within 28 days. Influence of fly ash as a cement replacement on the compressive strengths, tensile strengths, and static modulus of elasticity values of recycled aggregate concrete was also shown in studies by Kou et al. (2007). They found that the mentioned properties decreased as the recycled aggregate and the fly ash content increased. It should be noted that fly ash used in this study did not have high fineness. High fineness of fly ash is accepted to be an excellent pozzolanic material. It was found that high fineness of fly ash (mean diameter, d_{50}, about 3.8 micron) can be used to produce high strength concrete of 70 MPa at the age of 7 days (Jaturapitakkul et al., 2004). In Thailand, the Mae Moh power plant is the largest producer of fly ash, approximately 9000 tons per day or 3 million tons per year. Because of this massive quantity, considerable funds are expended on transporting and disposing of the fly ash and minimizing environmental impacts. Therefore, using high fineness of fly ash as a cement replacement in concrete can not only increase the compressive strength and workability of concrete, but also increase use of fly ash and reduce the amount of fly ash sent to landfills.

Palm oil fuel ash (POFA), a by-product from thermal power plants, contains high amounts of silicon and aluminum oxides in the amorphous state and was recently accepted as a pozzolanic material (Hussin and Awal, 1998; Tangchirapat et al., 2007; Sata et al., 2007). More than 100,000 tons of POFA is produced annually in Thailand, and this amount continues to increase each year because palm oil is a major raw material in the production of ethanol. However, the utilization of POFA is minimal compared to the amount produced. Thus, most POFA is disposed of in landfills, resulting in environmental degradation and other problems. Hussin and Awal (1998) studied the expansion of mortar mixed with 30% POFA and found that POFA had a good potential for reducing the expansion of mortar due to sulfate attack. Tangchirapat et al. (2007) reported that the compressive strength of concrete containing unground POFA was very low due to the large particle size and high porosity of POFA. However, concrete containing 10 to 20% ground POFA with high fineness resulted in a compressive strength higher than that of the control concrete after 90 days of curing. Furthermore, Sata et al. (2007) reported that concrete containing ground POFA with high fineness could be used as a pozzolanic material to produce high-strength concrete with a compressive strength of greater than 80 MPa at 28 days. The previous studies indicate that ground POFA with high fineness is a good pozzolanic material and can be used in concrete in a similar manner as other pozzolans, such as fly ash and silica fume.

Therefore, the aim of this study was to utilize fly ash and ground POFA with high fineness as a cement replacement in concrete containing high levels of recycled aggregate; the concretes were made from 100% coarse recycled aggregate and 100% coarse and fine recycled aggregates. The purpose of using fly ash and ground POFA as a cement replacement in recycled aggregate concretes is not only to improve the properties of recycled aggregate concrete, but also to reduce the amount of fly ash and POFA at landfills. The fresh and hardened properties of recycled aggregate concretes were investigated and compared to those of the conventional concrete (concrete produced from normal aggregates). Utilization of these waste materials, fly ash, POFA, and recycled aggregates, will reduce the waste disposal volume and make a better environment. Moreover, the use of recycled aggregate also helps the conservation of natural aggregates.

2. Objectives

1. To develop recycled concrete aggregates as new aggregates to replace natural aggregates in concrete work.
2. To study properties of fresh and hardened concrete containing recycled concrete aggregates such as slump loss, compressive strength, tensile strength, modulus of elasticity, and water permeability.
3. To study optimum cement replacement of pozzolanic materials, fly ash and ground POFA, in concrete containing recycled concrete aggregates.

3. Scope of the Study

Fly ash and palm oil fuel ash were ground in order to improve reactivity. After that, the physical properties such as specific gravity, particle size distribution, and particle morphologies by scanning electron microscopy (SEM) were determined. Chemical compositions of the materials were investigated by X-Ray Fluorescence (XRF).

In this study, the recycled aggregate concretes were divided into two groups. The first group was prepared by using 100% coarse recycled aggregate and local river sand, denoted as the A series of recycled aggregate concrete. For the other group, crushed limestone and local river sand were fully replaced by both coarse and fine recycled aggregates, denoted as the B series of recycled aggregate concrete. In addition, original fly ash, ground fly ash, and ground POFA were used to replace OPC at rates of 20, 35, and 50% by weight of binder. The properties of the recycled aggregate concretes with and without pozzolanic materials were investigated and compared with that of conventional concrete in which crushed limestone and local river sand were used as aggregates.

4. Experimental Program

4.1. Materials

4.1.1 Cement

Type I ordinary Portland cement (OPC) was used in both conventional concrete (CON) and recycled aggregate concretes.

4.1.2. Fly Ash

Lignite fly ash collected from the Mae Moh power plant in Thailand was used in this investigation. It is burnt by a pulverized coal combustion process at a temperature of 1,300-1,400 degree Celsius. Original fly ash (OF) received directly from the power plant was ground by a grinding machine to reduce its size until the particles retained on a No. 325 sieve (45-micron opening) were less than 3% by weight; this was termed GF.

4.1.3. Palm Oil Fuel Ash (POFA)

The palm oil fuel ash (POFA) used in this study was obtained from a palm oil industry located in southern Thailand, at which palm fiber, shell, and empty fruit bunches were burnt as a fuel at a controlled temperature of approximately 800-1000 degree Celsius to produce stream for the generation of electricity. The POFA directly received from this site had large particles; thus, it was ground to increase the fineness using a grinding machine until the particles retained on a No. 325 sieve (45-μm opening) were less than 3% by weight and identified as GP.

4.1.4. Natural Aggregates

In this experiment, local river sand was used as a fine aggregate. Crushed limestone was used as a coarse aggregate.

4.1.5. Recycled Concrete Aggregates

In this investigation, cylinder concretes of 150x300 mm were obtained from various construction sites around Bangkok province. These concretes were sent to our laboratory in order to determine the compressive strength. To avoid the difference of properties of recycled concrete aggregates caused by quality of the obtained concrete, the compressive strengths of concrete were controlled in the range of 25-40 MPa. After being tested for compressive strength, the tested concretes were crushed by swing hammer mills. The crushed concrete was then screened by sieving to separate coarse and fine recycled concrete aggregates, which were denoted as CRA and FRA, respectively.

4.2. Method of Study

4.2.1. Mixture Proportions of Concrete

The mixture proportions of recycled aggregate concretes containing ground fly ash are summarized in Table 1. Constant effective water to binder ratio (W/B) of 0.48 was used for all concrete mixtures with ground fly ash. Since the recycled concrete aggregates had higher water absorption than the natural aggregates, this resulted in recycled aggregate concrete mixtures requiring more water to maintain the slump of fresh concrete between 50 and 100 mm. Therefore, the amount of mixing water was adjusted to compensate for the water absorbed by the recycled concrete aggregates.

The recycled aggregate concretes were divided into two groups. The first group was prepared by using 100% coarse recycled aggregate and local river sand, denoted as the A series of recycled aggregate concrete. For the other group, crushed limestone and local river sand were fully replaced by both coarse and fine recycled aggregates, denoted as the B series of recycled aggregate concrete. In addition, ground fly ash was used to replace OPC at rates of 20, 35, and 50% by weight of binder.

Table 1 - Mixture proportions of recycled aggregate concretes containing fly ash.

Mix	Mix Proportion (kg/m^3)								W/B	Slump (mm)
	OPC	Fly Ash	Limestone	Sand	FRA	CRA	Mixing Water	Effective Water		
CON	380	-	1006	800	-	-	191.0	182.4	0.48	60
AF	380	-	-	800	-	1006	214.5	182.4	0.48	70
AOF20	304	76	-	790	-	994	214.0	182.4	0.48	80
AOF35	247	133	-	780	-	982	213.5	182.4	0.48	90
AOF50	190	190	-	770	-	970	213.0	182.4	0.48	100
AGF20	304	76	-	795	-	1000	214.3	182.4	0.48	70
AGF35	247	133	-	790	-	994	214.0	182.4	0.48	80
AGF50	190	190	-	785	-	988	213.8	182.4	0.48	85
BF	380	-	-	-	800	1006	256.5	182.4	0.48	50
BOF20	304	76	-	-	790	994	255.8	182.4	0.48	60
BOF35	247	133	-	-	780	982	254.9	182.4	0.48	70
BOF50	190	190	-	-	770	970	254.1	182.4	0.48	90
BGF20	304	76	-	-	795	1000	256.2	182.4	0.48	60
BGF35	247	133	-	-	790	994	255.8	182.4	0.48	70
BGF50	190	190	-	-	785	988	255.4	182.4	0.48	80

For the mixture proportion of the recycled aggregate concretes with and without ground POFA as summarized in Table 2, the concretes were divided into two groups as the same that of recycled aggregate concrete containing ground fly ash, which were A and B series of recycled aggregate concrete. The compressive strength of concrete was designed to be approximately 30 MPa at 28 days with slump of fresh concrete in the range of 50-100 mm. The ratio of fine to coarse aggregates was 45:55 by volume. The effective water to binder (cement plus ground POFA) ratio of concretes was controlled to be 0.65. To maintain the slump of fresh concrete at between 50-100 mm, the amount of mixing water was adjusted to compensate for water absorption by the recycled aggregates, and a type F superplasticizer was employed in the recycled aggregate concrete mixture to maintain the slump of fresh concrete as that of the CON concrete (50-100 mm). Furthermore, ground POFA was used to replace OPC at the rates of 20, 35, and 50% by weight of binder in the recycled aggregate concrete.

Table 2 - Mixture proportions of the concretes.

Sample	Mixture Proportion of Concrete (kg/m^3)									W/B	Slump (mm)
	OPC	Ground POFA	Fine Aggregate		Coarse Aggregate		Super P.	Mixing Water	Effective Water		
			Normal	Recycled	Normal	Recycled					
CON	295	-	828	-	1054	-	-	204	192	0.65	90
CR00	295	-	777	-	-	899	-	247	192	0.65	75
CR20	236	59	772	-	-	893	0.30	247	192	0.65	80
CR35	192	103	769	-	-	889	0.44	246	192	0.65	75
CR50	148	148	764	-	-	884	0.74	246	192	0.65	60
FR00	325	-	-	631	-	797	-	312	211	0.65	70
FR20	260	65	-	626	-	790	0.49	312	211	0.65	55
FR35	211	114	-	622	-	786	0.81	311	211	0.65	80
FR50	163	163	-	618	-	780	1.14	311	211	0.65	80

All fresh concretes were prepared using a rotating drum mixer in laboratory. The first step of mixing was to place fine and coarse aggregates into the mixer along with the water about one-half of effective water, and then mixed for 60 seconds. At this step, surface aggregates were wetted and absorbed some fractions of the water into aggregate particles. After that, the binder was being added, then with the remaining effective water and the mixture was mixed for another 60 seconds. Finally, the remaining mixing water was gradually added and the mixing continues for the last 120 seconds in order to obtain the slump of fresh concrete between 50-100 mm.

It was noted that all natural aggregates and recycled concrete aggregates used in this experiment had the same condition i.e., they were in the air-dried moisture state (as-received) and did not pre-wet or pre-soak prior batching. Generally, for the large scale production of normal strength concrete, the optimal moisture condition is the air-dried moisture state. In addition, Oliveira and Vazquez (1996) and Poon et al. (2004) reported that the compressive strengths of recycled aggregate concretes prepared with air-dried and saturated surface dried aggregates were slightly different.

4.2.2. Testing of Specimens

4.2.2.1. Test for Slump Loss of Concrete

In this study, the slump loss of fresh recycled aggregate concrete containing ground fly ash was measured using a standard slump test apparatus as described in ASTM C143 (2001). The initial slump value was recorded immediately after mixing, and slump values were then measured every 15 minutes until the slump value of the fresh concrete was zero.

4.2.2.2. Test for Compressive Strength of Concrete

Concrete cylinder samples with a diameter of 100 mm and length of 200 mm were cast. After casting for 24 hours, the specimens were removed from the molds and cured in water. They were tested to determine the compressive strengths in accordance with the ASTM C39 (2001) at the ages of 7, 28, 90, and 180 days. Three concrete cylinders were tested and used for each data point.

4.2.2.3. Test for Modulus of Elasticity of Concrete

Concrete cylinders of 100 mm in diameter and 200 mm in height were cast and used to determine the modulus of elasticity. The modulus of elasticity of concrete was determined according to the ASTM C469 (2001) at the ages of 28 and 90 days.

4.2.2.4. Test for Splitting Tensile Strength of Concrete

The splitting tensile strength of concrete was determined according to the ASTM C496 (2001) and concrete cylinders of 100 mm in diameter and 200 mm in height were used.

4.2.2.5. Test for Water Permeability of Concrete

The water permeability test began with the sawing of a slice 40 mm thick from the middle of the 100x200 mm concrete cylinder. The sliced concrete was then cast around with 25 mm thick epoxy resin and was allowed to harden for 24 hours. The specimen was installed in a permeability housing cell as shown in Figure 1, a water pressure of 0.5 MPa or 5.0 bars was then applied to the cell. The amount of water flowing through the concrete specimen was measured by reading the water level drop in the manometer tube. The results were plotted to obtain a relationship between the cumulative amounts of flowing water and cumulative time to determine a steady-state flow. At this stage, the steady flow rate was obtained, and a coefficient of permeability was calculated using Darcy's law and the equation of continuity, as shown in equation (1). This experimental setup for testing the water permeability of concrete was recommended and used by Khatri et al. (1997), Chindaprasirt et al. (2007), and Wongpa et al. (2010). The water permeability of concrete was investigated at the ages of 28 and 90 days. At each testing age, the average of three concrete specimens was used to represent the water permeability of concrete.

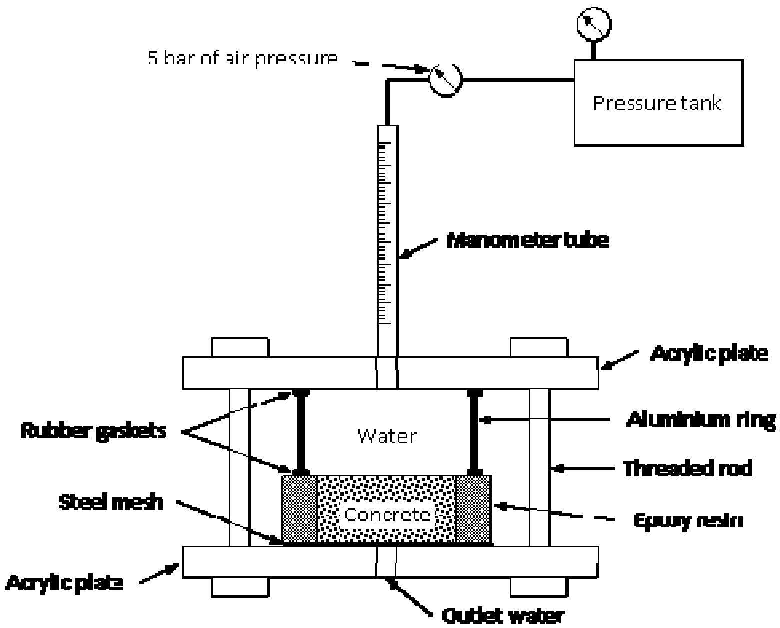


Figure 1 - Experimental setup for testing the water permeability of the concrete.

$$K = \frac{\rho LgQ}{PA} \text{ ---------------- (1)}$$

where K = coefficient of water permeability (m/sec)

ρ = density of water (kg/m^3)

g = acceleration due to gravity, 9.81 (m/s^2)

Q = flow rate (m^3/s)

L = length of the concrete sample (m)

P = water pressure (Pa)

A = cross-sectional area of the concrete sample (m^2)

4.2.2.6. Test for Expansion of Concrete in a 5% Na_2SO_4 Solution

The expansion of concrete due to sulfate attack was measured on three prismatic concrete specimens having a cross section of 75x75 mm^2 and length of 285 mm. The concrete bars were immediately immersed in a 5% Na_2SO_4 solution after being removed from the molds (24 hours after casting). The expansions of the concrete bars due to sulfate attack were measured monthly for 9 months using a length comparator apparatus according to ASTM C490 (2001).

5. Results and Discussions

5.1. Physical Properties of Fly Ash and Palm Oil Fuel Ash

Figure 2 shows the particle shape of OPC along with those of fly ash with and without grinding by using scanning electron microscope (SEM). OPC had solid, angular, and irregular shape (Figure 2a). Particles of original fly ash were spherical and solid (Figure 2b), whereas ground fly ash was irregular and crushed shape (Figure 2c).

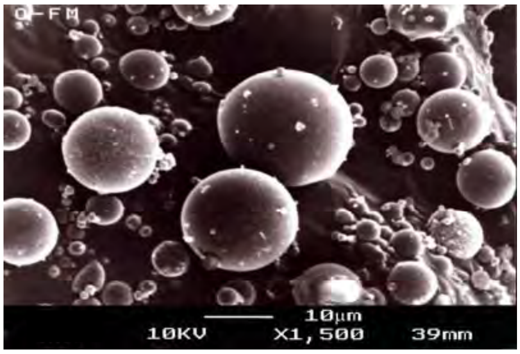
For the particle morphology of the ground POFA as shown in Figure 2d, the ground POFA consisted of irregular particles with a crushed shape and had a median particle size of 10.7 μm. The fineness in term of the weight of particles retained on a No. 325

sieve and the specific gravity of the materials are shown in Table 4. The amount of the ground POFA particles retained on a sieve No. 325 was 1.7%, and the ground POFA had a specific gravity of 2.53

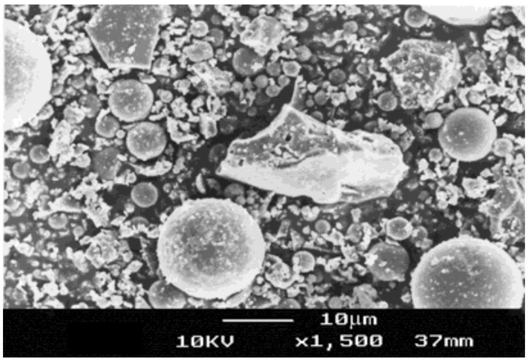
Table 3 - Physical properties of OPC, fly ash, and ground POFA.

Sample	Specific gravity	Retained on a 45-µm sieve (No. 325) (%)	Median particle size, d_{50} (µm)
OPC	3.15	N/A	14.6
Original Fly Ash (OF)	2.19	42.5	27.1
Ground Fly Ash (GF)	2.72	1.2	7.7
Ground POFA	2.53	1.7	10.7

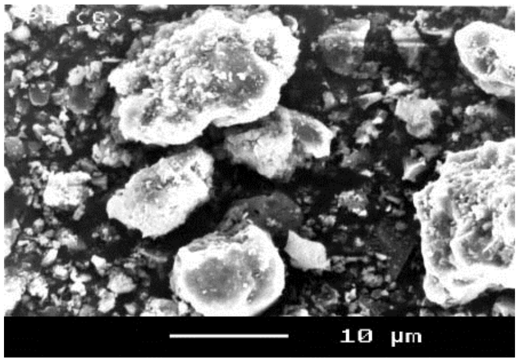
(a) OPC



(b) Original fly



(d) Ground fly ash



(c) Ground POFA

Figure 2 - Particle morphologies of materials.

5.2. Chemical Properties of Fly Ash and Palm Oil Fuel Ash

Table 4 shows the chemical composition of materials used in this study, the total amount of SiO_2, Al_2O_3, and Fe_2O_3 was 76.1% with 13.9% of CaO. The LOI and SO_3 were within the limits of 6.0 and 4.0%, respectively as specified by ASTM C618 (2001). According to the chemical compositions, GFA could be classified as Class F fly ash as prescribed by ASTM C618 (2001).

The chemical composition of the ground POFA is reported in Table 2. The major chemical composition of the ground POFA was SiO_2 (55.5%), while the total amount of the ground POFA composed of SiO_2, Al_2O_3, and Fe_2O_3 was 70.3%. The amounts of LOI and SO_3 were 7.9 and 2.3%, respectively. It should be noted that the chemical composition of the ground POFA used in this study could be classified as class N pozzolan, as prescribed by ASTM C618 (2001). Furthermore, the strength activity index of the ground POFA was much greater than the minimum value (75%) specified by ASTM C618 (2001), and the strength indices at the ages of 7 and 28 days were 105 and 109%, respectively.

Table 4 - Chemical compositions of OPC, fly ash, and ground POFA.

Chemical Composition (%)	OPC	Original Fly Ash (OF)	Ground Fly Ash (GF)	Ground POFA
Silicon Dioxide (SiO_2)	20.9	40.5	41.9	55.5
Aluminium Oxide (Al_2O_3)	4.7	21.6	21.5	9.2
Iron Oxide (Fe_2O_3)	3.4	12.3	12.7	5.6
Calcium Oxide (CaO)	65.4	14.8	13.9	12.4
Magnesium Oxide (MgO)	1.2	3.0	2.6	4.6
Sodium Oxide (Na_2O)	0.2	0.9	2.7	0.0
Potassium Oxide (K_2O)	0.3	3.0	2.5	0.0
Sulfur Trioxide (SO_3)	2.7	1.8	0.6	2.3
Loss on Ignition (LOI)	0.9	1.2	0.7	7.9

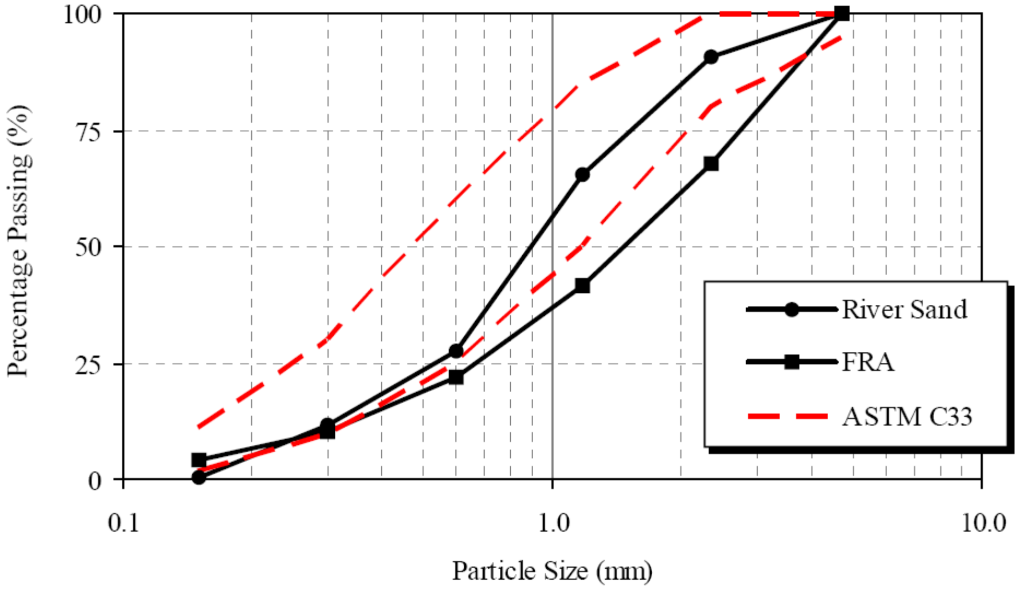
5.3. Physical Properties of Recycled Concrete Aggregates

The physical properties of the recycled concrete aggregates (CRA and FRA) are reported in Table 5. Figures 3(a) and 3(b) show the grading size of the recycled concrete aggregates compare with the ASTM C33 (2001) requirements for fine and coarse aggregates, respectively. The CRA and FRA had a fineness modulus of 6.40 and 3.55, respectively. The fineness modulus of the CRA met the ASTM C33 (2001) grading requirements, while the FRA had a fineness modulus slightly coarser than the limit specified by ASTM C33 (2001).

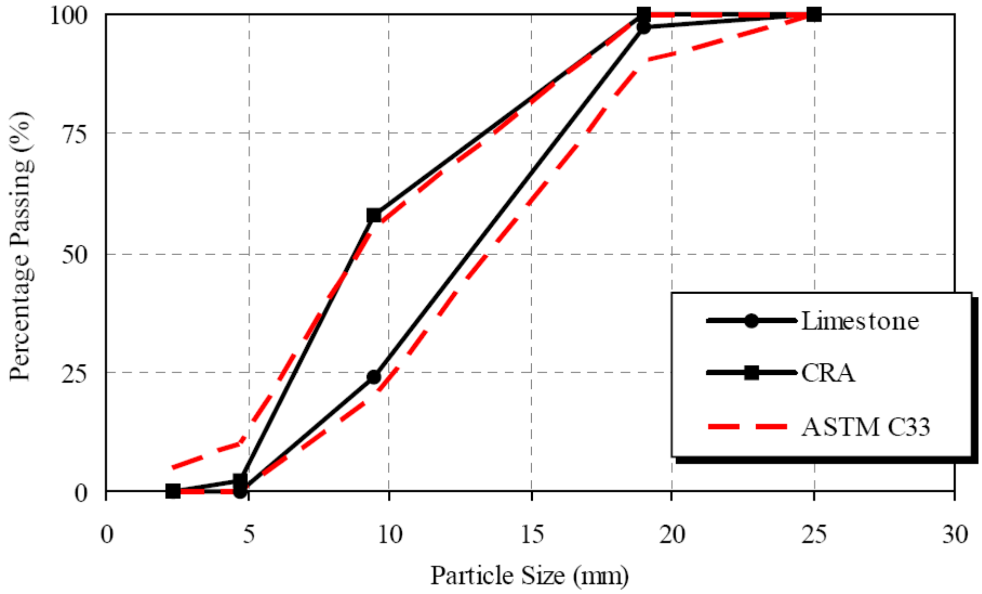
The specific gravities of the CRA and FRA were 2.45 and 2.31, respectively, while the water absorption was 5.61 and 11.91%, respectively. These values conformed to the investigation reported by B.C.S.J. (1978) from which the specific gravity of coarse recycled concrete aggregate varied between 2.29 and 2.51, and fine recycled concrete aggregate between 2.19 and 2.32. The water absorption ranged from 3.6 to 8.0% for coarse recycled concrete aggregate and 8.3 to 12.1% for fine recycled concrete aggregate. It should be noted that the recycled concrete aggregates had a lower specific gravity and higher water absorption than the natural aggregates. This was due to the residue from old mortar that adhered to the natural aggregate (Katz, 2003; Rao et al., 2007). Moreover, the CRA had a Los Angeles abrasion of 33.08%, which was higher than that of the crushed limestone (21.70%). The high Los Angeles value of the CRA was caused by the adhering cement paste and mortar, which is usually weaker and has a lower density than natural aggregate (Shayan and Xu, 2003).

Table 3. Physical properties of natural and recycled concrete aggregates.

Properties	Natural Aggregates		Recycled Concrete Aggregates	
	River Sand	Limestone	Fine	Coarse
Fineness Modulus	3.04	6.79	3.55	6.40
Specific Gravity (SSD)	2.60	2.67	2.31	2.45
Absorption (%)	0.94	0.46	11.91	5.61
Los Angeles Abrasion Loss (%)	N/A	21.70	N/A	33.08



(3a) river sand and fine recycled concrete aggregate (FRA)



(3b) limestone and coarse recycled concrete aggregate (CRA).

Figure 3 - Particle size distributions of river sand, limestone, and recycled concrete aggregates (FRA and CRA).

5.4. Recycled Aggregate Concretes Containing Fly Ash

5.4.1. Slump Loss

The slump losses of the CON concrete and recycled aggregate concretes are shown in Figure 4. The slump loss of the CON concrete reached zero at approximately 105 minutes after mixing, while the AF and BF concretes had zero slump loss values at 90 and 60 minutes, respectively. The recycled aggregate concretes exhibited a faster slump loss than the CON concrete because of the high water absorption of the recycled concrete aggregate, which quickly reduced the amount of water in the mixture.

The slump loss of the fresh recycled aggregate concrete decreased when the fly ash replacement was increased. For example, the concrete samples made of 100% CRA, 100% river sand, and 0, 20, 35, or 50% original fly ash by weight of binder had slump loss to zero value at 90, 105, 120, and 150 minutes after mixing, respectively. Moreover, the slump loss for the AOF20 concrete was similar to that of the CON concrete, while the slump loss of the BOF50 concrete occurred more slowly than that of the CON concrete. This finding indicates that the use of fly ash can reduce the slump loss of recycled aggregate concrete and is similar to the results of Ravina (1984), who reported that fly ash can reduce slump loss when it is used to partially replace cement in conventional concrete. The slower slump loss may be due to two factors: first, the use of fly ash in concrete typically increases the setting time of the concrete, and second, the cement content in the concrete mixture decreases due to the fly ash replacement (Kiattikomol et al., 2001).

After increasing the fineness of fly ash by grinding, the slump loss of the AF and BF series of recycled aggregate concretes varied from 75 to 120 and from 45 to 90 minutes, respectively. It should be noted that when the fineness of the fly ash was increased, the slump loss of the recycled aggregate concrete also increased because the fineness of the ground fly ash had a greater surface area for reacting with water. Additionally, the sample with 20% GF as a cement replacement exhibited the lowest slump loss of the recycled aggregate concretes, with times of 75 and 45 minutes for the AF and BF series of recycled aggregate concretes, respectively. With 35 and 50% GF replacement, however, the slump loss of the recycled aggregate concretes was increased and higher than that of the recycled aggregate concrete without fly ash.

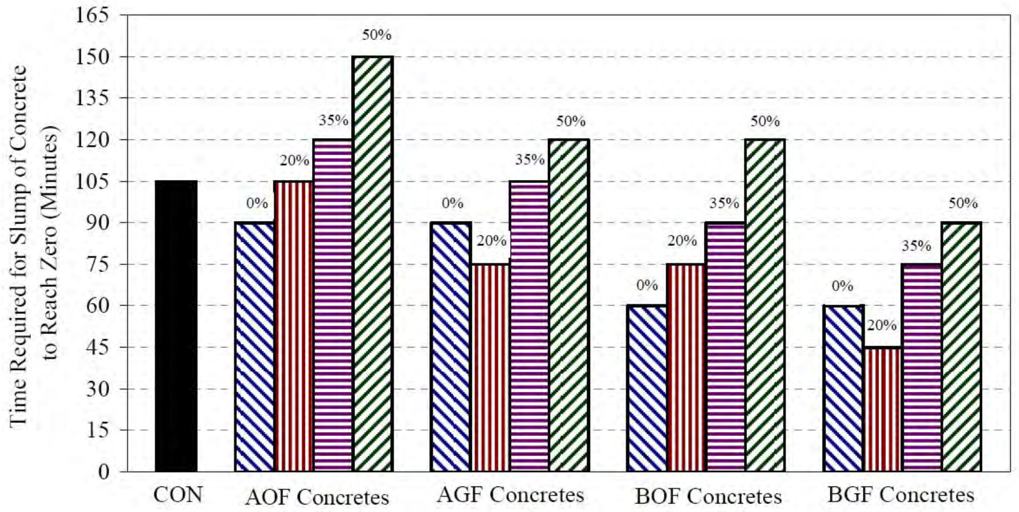


Figure 4 -. Slump loss of concretes containing recycled concrete aggregates (values above the bars indicate the percentage of fly ash replacement).

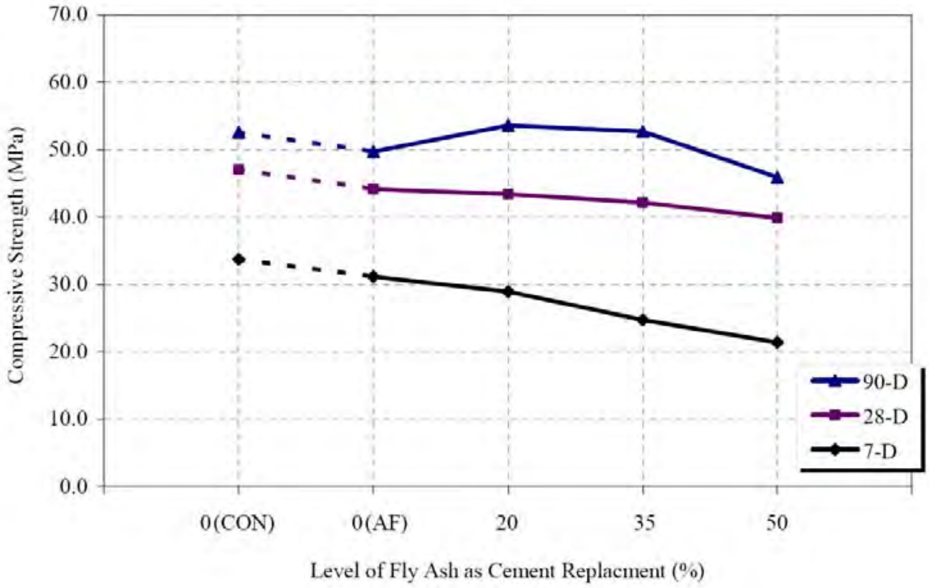
5.4.2. Compressive Strength

The compressive strengths of the recycled aggregate concretes with and without fly ash as compared with that of the CON concrete are shown in Figure 5. The compressive strength of the CON concrete at the age of 28 days was 47.0 MPa, while the AF concrete had a slightly lower compressive strength than the CON concrete, 44.1 MPa or 94% of the CON concrete strength at the same age. This indicated that the use of 100% CRA had not much effect on reducing the compressive strength of the concrete. The results agree with those of Gerardu and Hendriks (1985), who found that the compressive strength of concrete made with coarse recycled concrete aggregate and river sand was similar to or slightly lower than that of the conventional concrete. It should be noted that the results of compressive strength of concrete containing coarse recycled concrete aggregate obtained from this study had slightly lower than the conventional concrete, while the other studies showed that the compressive strength of that concrete had much lower (Chen et al. 2003) or slightly greater than the conventional concrete (Wade et al. 1997). This can be attributed to the difference of the original aggregate quality, crushing and mixing processes, and adhered mortar volume, which have large influences on the mechanical properties of the recycled aggregate concrete. It was also noted that recycled concrete aggregates used in this experiment were in air-dried conditions and did not pre-wet prior batching, thus the additional mixing water reserved for aggregate absorption may not be fully absorbed by the aggregates in the period of mixing. Therefore, some of the additional mixing water was still remaining in the paste, resulted in an increasing the W/B ratio of concrete. This manner may effect on reducing the compressive strength of the AF concrete.

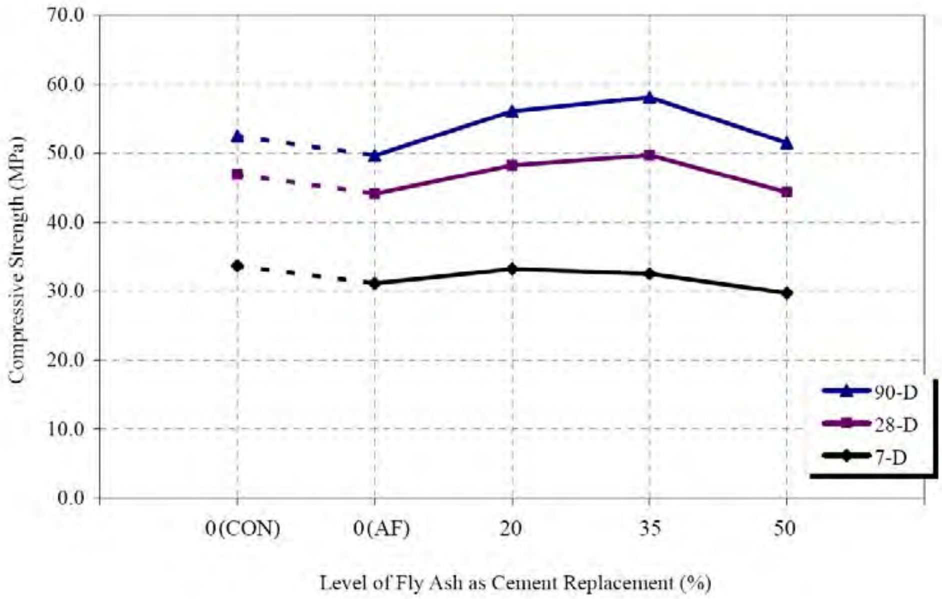
For the BF concrete, the compressive strength at 28 days was 35.9 MPa or 76% of that of the CON concrete. This result suggested that the use of both 100% coarse and fine recycled concrete aggregates had a strong effect on reducing the compressive strength of recycled aggregate concretes. Hansen and Narud (1983) and Topcu and Guncan (1995) observed a similar relationship for large quantities of concrete made from coarse and fine recycled concrete aggregates, which resulted in lower compressive strength as compared to the CON concrete. The results also found that the compressive strength at 28 days of AF concrete was only reduced 6% from CON concrete, while that of BF concrete was 24%. This result suggested that the use of fine recycled concrete aggregate had more effect on reducing the compressive strength of recycled aggregate concrete than the use of coarse recycled concrete aggregate. The lower compressive strength of BF concrete as compared with those of CON and AF concretes could be explained from two reasons; 1) the mortar strength of BF concrete was reduced due to the lower strength of fine recycled concrete aggregate as compared with natural river sand (Chen et al. 2003). 2) BF concrete required high amount of mixing water due to high water absorption of fine recycled concrete aggregate leading to the lower of compressive strength.

Figure 5a shows the relationship between the compressive strength and the level of fly ash replacement for concrete made from 100% CRA, 100% river sand, and original fly ash (OF). It was found that at 28 days, the AOF20, AOF35, and AOF50 concretes had compressive strengths of 43.4, 42.2, and 39.8 MPa, respectively. This finding implied that the higher the replacement of OF, the lower the compressive strength in the AOF concretes. At 90 days, however, the compressive strength of the AOF20 and AOF35 concretes increased to 53.6 and 52.7 MPa, respectively, which was 5-7% higher than that of the recycled aggregate concrete without OF.

For recycled aggregate concrete containing ground fly ash (AGF concretes), as shown in Figure 5b, the AGF20 concrete had a compressive strength of 48.3 MPa at 28 days, which was higher than that of the AF concrete. The highest compressive strength of the AGF concretes was found for the AGF35 concrete, which was approximately 111% of the CON concrete at 90 days. The increased compressive strength of the recycled aggregate concrete mixed with ground fly ash could be attributed to the fineness of the ground fly ash particles, which filled the voids between the cement and the recycled concrete aggregates, and to the presence of SiO_2 and Al_2O_3 in the ground fly ash, which reacted with the $Ca(OH)_2$ generated by the hydration process to form additional calcium silicate hydrates (C-S-H), thus improving interfacial bonding between the recycled concrete aggregate and pastes (Poon, 2004; Li et al., 2009). These characteristics improved the compressive strength of the recycled aggregate concretes. In addition, the use of 50% GF in replacing the cement gave a compressive strength of 44.4 MPa at 28 days, which increased to 51.5 MPa at 90 days, corresponding to the strength of 94 and 98% of that of the CON concrete, respectively.



(a) A-Series concretes with original fly ash (OF)

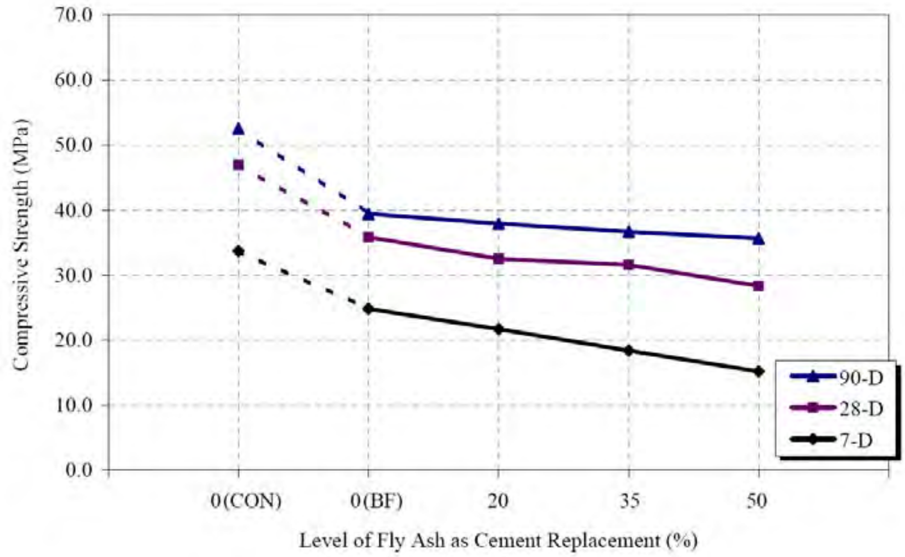


(b) A-Series concretes with ground fly ash (GF)

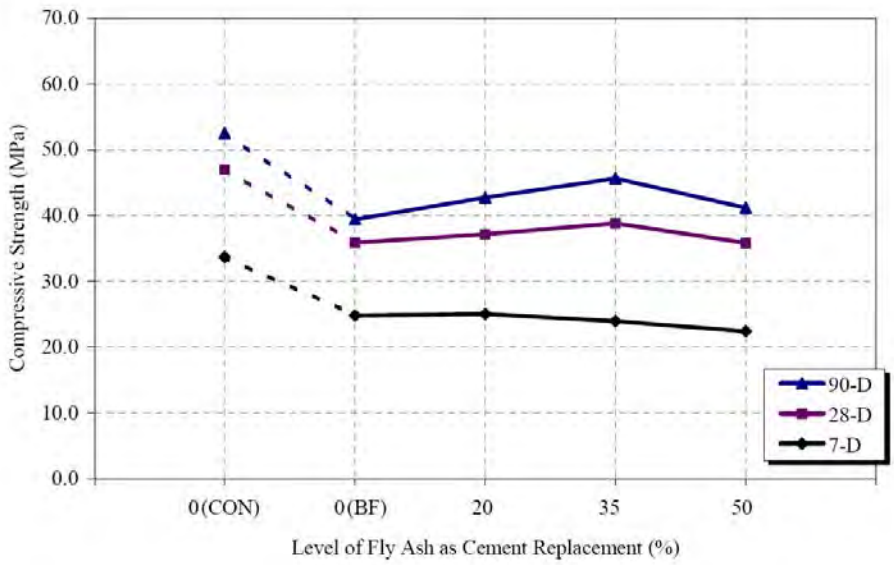
Figure 5 - Relationship between compressive strength and level of fly ash as cement replacement of concrete containing 100% CRA and 100% river sand.

The results for concretes containing 100% CRA, 100% FRA, and OF at 20, 35, or 50% by weight of binder are shown in Figure 6a. It was found that the recycled aggregate concretes containing original fly ash had a lower compressive strength than the BF concrete at all tested ages and that the compressive strength of the recycled aggregate concretes decreased with increasing OF replacement. This result revealed that the increase in compressive strength of the recycled aggregate concrete due to the pozzolanic reaction between the SiO_2 and Al_2O_3 in the OF and $Ca(OH)_2$ cannot compensate for the reduction in compressive strength of the recycled aggregate concrete caused by sand replacement by FRA.

After increasing the fineness of the fly ash by grinding, the compressive strength of the recycled aggregate concrete was increased (see Figure 6b). For example, the BGF20, BGF35, and BGF50 concretes had compressive strengths of 37.2, 38.8, and 35.8 MPa (79, 83, and 76% of CON concrete) at 28 days, respectively. Moreover, at 90 days, the compressive strength of the recycled aggregate concretes with 20-50% ground fly ash had compressive strengths higher than that of the BF concrete, which tended to increase over time. The higher compressive strength of the recycled aggregate concretes can be explained by the greater fineness of the ground fly ash, which promotes the pozzolanic reaction and fills the voids of the recycled aggregate concrete.



(a) BF-Series concretes with original fly ash (OF)



(b) BF-Series concretes with ground fly ash (GF).

Figure 6 - Relationship between compressive strength and level of fly ash as cement replacement of concrete containing 100% CRA and 100% FRA.

The above results suggests that fly ash can be used to increase the ultimate compressive strength of concrete containing high amounts of recycled concrete aggregates, depending on the fly ash fineness and its degree of replacement. Concrete made from 100% CRA and river sand has an optimum cement replacement by original and ground fly ash of 20 and 35% by weight of binder, respectively. For this mixture proportion, the compressive strength of the recycled aggregate concrete at 90 days is expected to be as high as that of the CON concrete. For concrete made from both 100% CRA and FRA, the original fly ash did not show any significant improvement in the compressive strength of the recycled aggregate concrete. When the fly ash was processed to have high fineness, however, the compressive strength of the recycled aggregate concrete with ground fly ash was increased and could be higher than that of recycled aggregate concrete with original fly ash. Additionally, the replacement of cement by 35% ground fly ash resulted in a compressive strength of recycled aggregate concrete higher than 85% of that of the CON concrete.

5.4.3. Splitting Tensile Strength

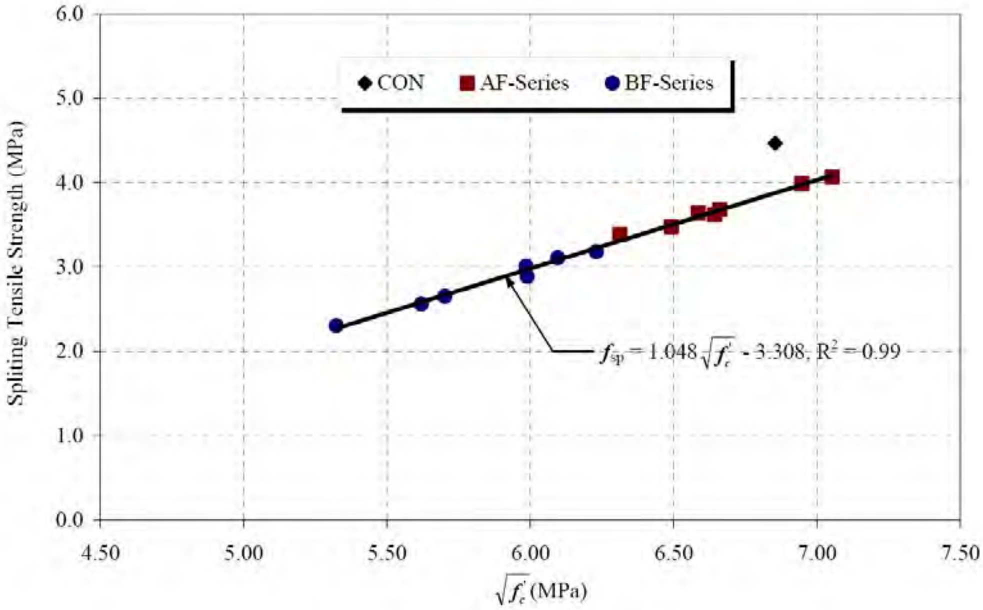
The relationship between the splitting tensile strength and square root of compressive strength of the recycled aggregate concretes is shown in Figure 7a. Equation (2) expresses the best fit equation for splitting tensile strength based on data from this experiment. The splitting tensile strength of the recycled aggregate concretes with and without fly ash in the present experiment varied from 2.30 MPa in the BOF50 concrete to 4.07 MPa in the AGF35 concrete, while that of the CON concrete was 4.46 MPa. It should be noted that all of the recycled aggregate concretes had a lower splitting tensile strength than the concrete made from natural aggregate. In addition, the highest and lowest values of splitting tensile strength were occurred in AGF35 and BOF50 concretes, respectively which was similar to the result of compressive strength. Moreover, the splitting tensile strength of the recycled aggregate concretes tended to increase with increasing compressive strength.

$$f_{sp} = 1.048\sqrt{f'_c} - 3.308 \quad \text{---------------} \quad (2)$$

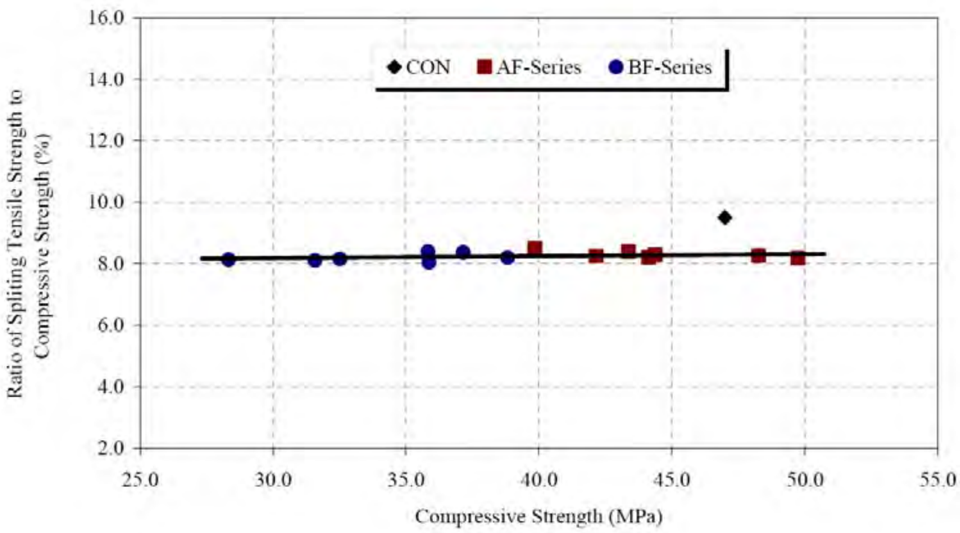
where f_{sp} = splitting tensile strength of recycled aggregate concrete (MPa)
f_c' = compressive strength of recycled aggregate concrete (MPa)

Figure 7b shows the relationship between the ratio of the splitting tensile strength to the compressive strength and the compressive strength of the recycled aggregate concretes. The ratio of the splitting tensile strength to the compressive strength of the CON concrete was 9.5%, while those of the AF and BF concretes were 8.2 and 8.0%, respectively. It is noted that the splitting tensile strength of the recycled aggregate concrete seems to be slightly lower than that of the CON concrete. Similar result was obtained by Corinaldesi and Moriconi (2009), who found that the splitting tensile strength of recycled aggregate concrete is approximately 10% lower than that of conventional concrete because the adhered mortar in the recycled aggregate has a lower strength than natural aggregate, causing the concrete made from recycled concrete aggregate to be weaker. In addition, by visual inspection, as shown in Figure 8, it was observed that the failure of the recycled aggregate concrete after the splitting tensile strength testing occurred through the old cement paste or mortar adhering to the recycled concrete aggregate.

Considering the effect of fly ash fineness and its replacement on the splitting tensile strength of recycled aggregate concrete, it was found that recycled aggregate concretes containing original and ground fly ash (OF and GF) exhibited maximum and minimum ratios values of splitting tensile strength to compressive strength of 8.1 and 8.5%, respectively, which was the same as those of recycled aggregate concretes without fly ash (AF and BF concretes). As found in this experiment, the incorporation of either original or ground fly ash did not have a great effect on the splitting tensile strength of the recycled aggregate concrete.



(a) Relationship between splitting tensile strength and square root of compressive strength of recycled aggregate concrete.



(b) Relationship between ratio of splitting tensile strength to compressive strength and compressive strength of recycled aggregate concrete.

Figure 7 - Splitting tensile strength of concrete.

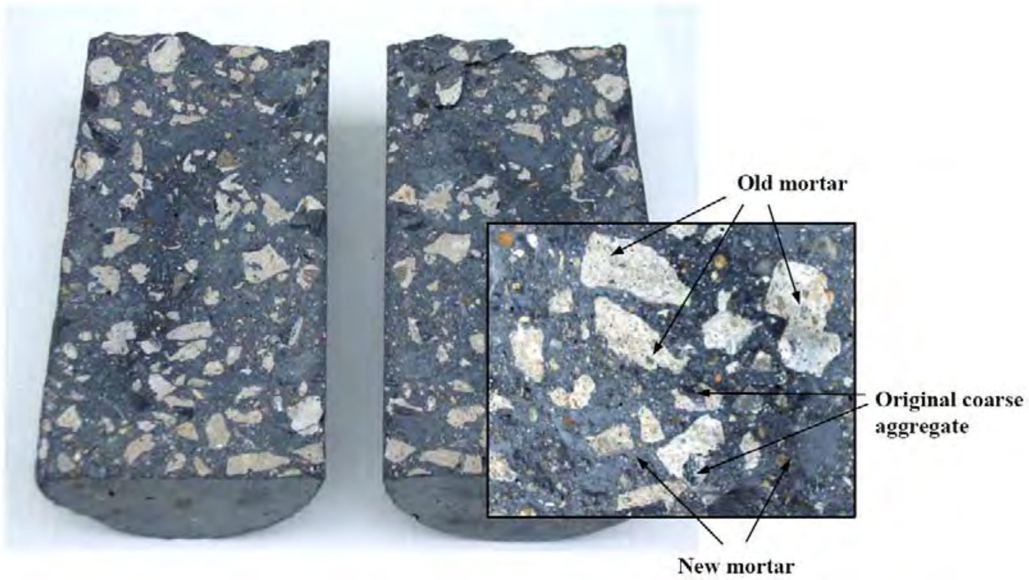


Figure 8 - Failure of recycled aggregate concrete sample after splitting tensile strength testing.

5.4.4. Modulus of Elasticity

The modulus of elasticity measured after 28 days of curing for the recycled aggregate concretes based on 100 mm-diameter and 200 mm-length cylindrical concrete is shown in Figure 9. The AF and BF concretes had an average modulus of elasticity of 31.0 and 26.7 GPa, respectively, which is 11 and 24% lower than that of the CON concrete (34.9 GPa). This result indicates that the incorporation of recycled concrete aggregate into the new concrete decreased the modulus of elasticity, particularly when both coarse and fine recycled concrete aggregates were used. Hansen (1992) reported that due to the large amount of old mortar with a comparatively low modulus of elasticity adhering to the original aggregate particles in recycled concrete aggregates, the modulus of recycled aggregate concrete is always lower than that of conventional concrete. Furthermore, recycled concrete aggregate had high uncompacted void content, providing a low modulus of elasticity to the recycled aggregate concrete (Topcu and Sengel 2004). Neville (1997) and Evangelista and Brito (2007) concluded that the modulus of elasticity of concrete was strongly related to the stiffness of the coarse aggregates, the stiffness of the mortar, and their porosity and bond of the mortar. Therefore, for BF concrete, it could be concluded that the lower stiffness and bond of the mortar as well as the porosity in fine recycled concrete aggregate were also significantly influenced to reduce the modulus of elasticity of concrete.

The recycled aggregate concretes mixed with original and ground fly ash had lower modulus of elasticity values than the CON concrete, even though some mixtures of recycled aggregate concretes had equivalent or greater compressive strengths than the CON concrete. For example, the modulus of elasticity of the AGF35 concrete was 32.4 GPa, with a corresponding compressive strength of 49.7 MPa, while that of the CON concrete was 34.9 GPa, with a compressive strength of 47.0 MPa. This behavior occurs because the modulus of elasticity of typical concrete is usually related to the strength of the aggregate rather than the strength of the cement paste (Corinaldesi and Moriconi, 2009; Neville, 1997). In addition, the use of fly ash as a cement replacement slightly decreases the aggregate content of the concrete mixture when compared with that of the CON concrete, resulting in a decreased modulus of elasticity (Cetin and Carrasquillo, 1998).

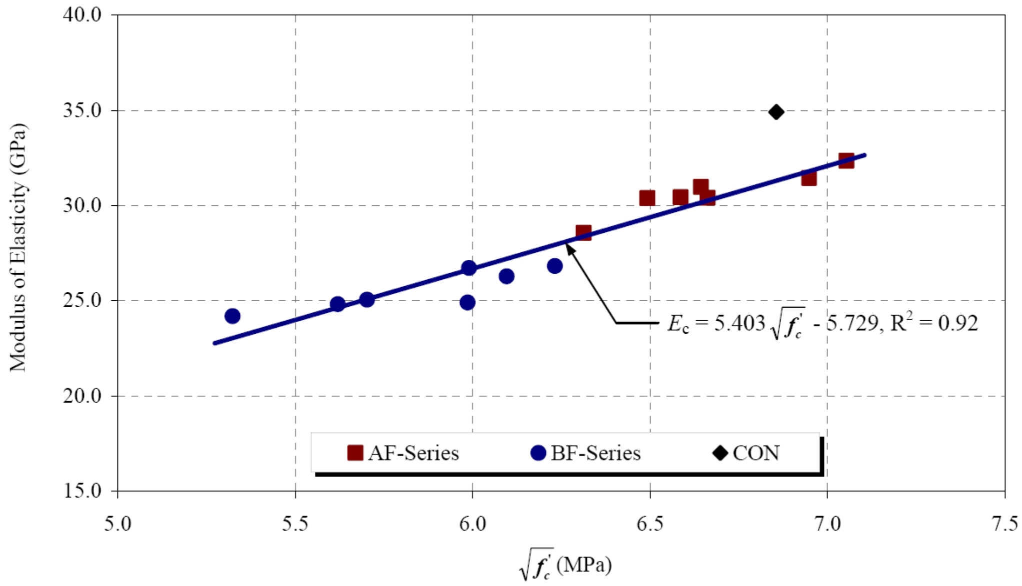


Figure 9 - Relationship between modulus of elasticity and square root of compressive strength of recycled aggregate concrete.

Equation (3) was used to predict the modulus of elasticity values of the recycled aggregate concretes with and without fly ash having the compressive strength varied between 30 and 50 MPa. The coefficient of determination (R^2) was found using least square linear regression analysis for the best type of equation that fit the data. A very strong correlation was found for the relationship between square root of compressive strength and modulus of elasticity of recycled aggregate concrete with and without fly ash (R^2 = 0.92). The results indicate that the modulus of elasticity values of the recycled aggregate concretes (with and without fly ash) are lower than that of the CON concrete by approximately 12% for the same compressive strength. This result agrees with those of Hansen and Boegh (1985), who reported that the modulus of elasticity of recycled aggregate concrete was reduced by approximately 14-28%, depending on the quality of the recycled concrete aggregate. Similar to the results of splitting tensile strength, the addition of original or ground fly ash did not have an effect on the modulus of elasticity of the concrete. The modulus of elasticity of the recycled aggregate concrete containing fly ash was still related to its compressive strength, i.e., it increases with the compressive strength.

$$E_C = 5.403\sqrt{f_c'} - 5.729 \text{ --------------- } (3)$$

where E_C = modulus of elasticity of recycled aggregate concrete (GPa)
f_c' = compressive strength of recycled aggregate concrete (MPa)

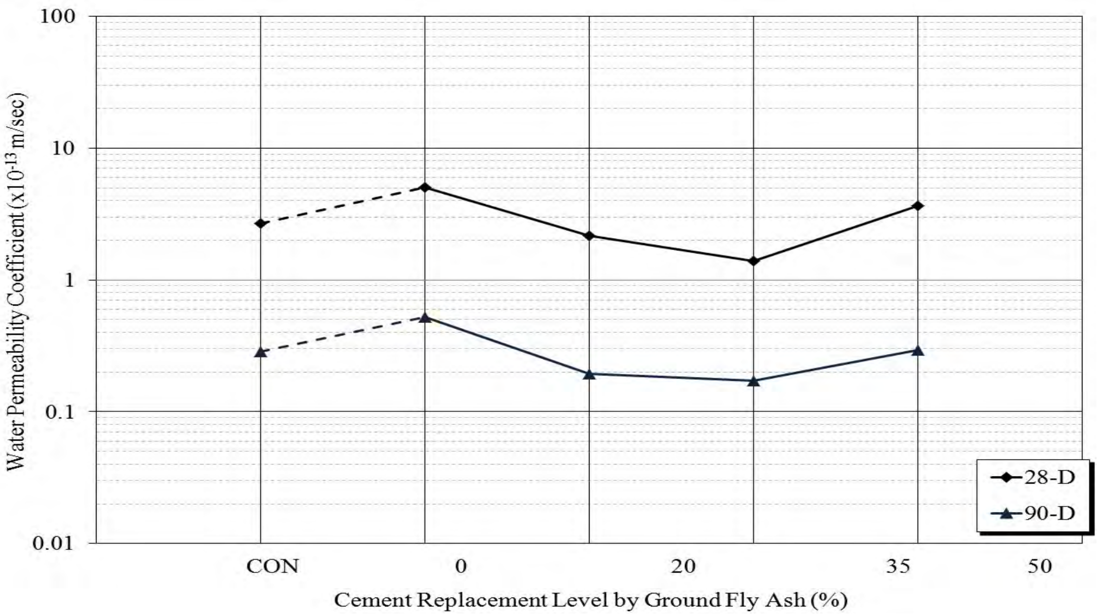
5.4.4. Water Permeability

The values of water permeability coefficient of AF and BF series concretes with and without ground fly ash as compared with CON concrete are shown in Figure 10, respectively. AF and BF concretes had water permeability coefficient values of $5.04\text{x}10^{-13}$, $6.69\text{x}10^{-13}$ m/sec and $0.52\text{x}10^{-13}$, $0.87\text{x}10^{-13}$ m/sec at 28 and 90 days, respectively, while the water permeability coefficient values of CON concrete at 28 and 90 days were $2.67\text{x}10^{-13}$ and $0.29\text{x}10^{-13}$ m/sec, respectively. It is worth noticing that the use of recycled concrete aggregate made the concrete more impervious, particularly in the concrete incorporating both coarse and fine recycled concrete aggregates. This can be attributed to the high porosity of recycled concrete aggregates due to the adhering cement paste compared with normal aggregates (CRA and FRA had water absorptions of 4.55 and 6.46%, respectively, while crushed limestone and river sand had water absorptions of 0.46 and 0.91%, respectively).

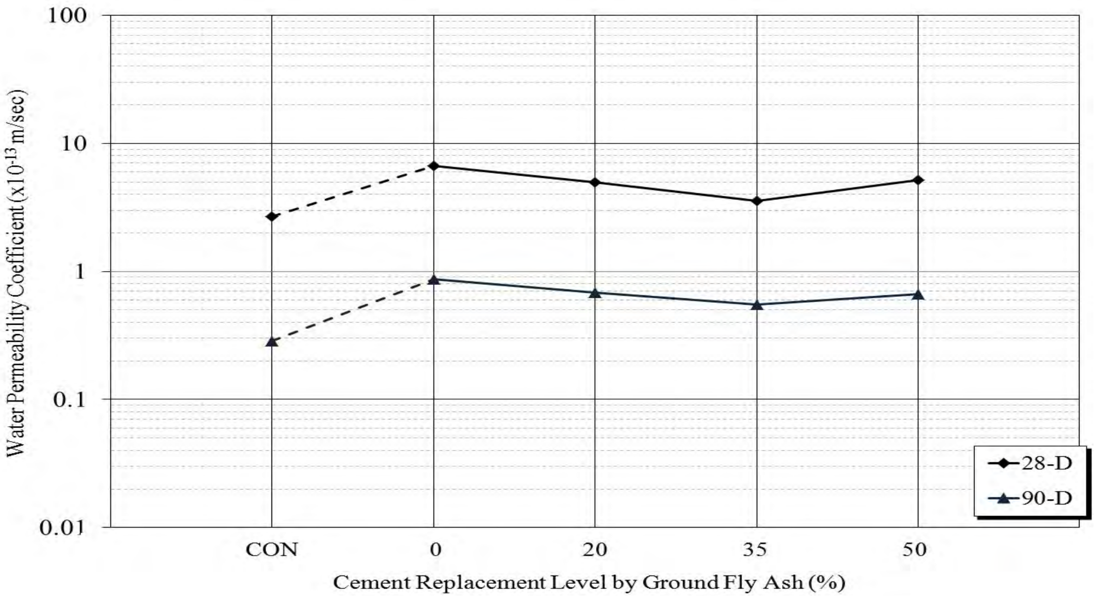
Figure 10a shows the values of water permeability coefficient of AF series concretes with and without ground fly ash. At 28 days, the values of water permeability coefficient of AGF20, AGF35, and AGF50 concretes were $2.16\text{x}10^{-13}$, $1.39\text{x}10^{-13}$, and $3.64\text{x}10^{-13}$ m/sec, respectively and this reduced to $0.19\text{x}10^{-13}$, $0.17\text{x}10^{-13}$, and $0.29\text{x}10^{-13}$ m/sec at 90 days. These results indicated that the use of ground fly ash at all cement replacement rates reduced the water permeability of recycled aggregate concretes. In addition, the lowest value of water permeability coefficient was found in the sample incorporating 35% ground fly ash. Furthermore, with 20 and 35%

replacement of OPC by ground fly ash, the water permeability coefficient values of concrete were lower than CON concrete. The lower water permeability coefficient values of the resulting concrete were affected by the pozzolanic reaction and packing effect of the small ground fly ash particles, which produced concrete with a denser matrix and lower permeation.

As shown in Figure 10b, the values of water permeability coefficient of concretes contained 100% both CRA and FRA were higher than those of concretes made from 100% CRA and 100% river sand at both testing ages. BGF20, BGF35, and BGF50 concretes had water permeability coefficient values of 4.94×10^{-13}, 3.54×10^{-13} and 5.14×10^{-13} m/sec, respectively, at 28 days. At 90 days, the water permeability coefficient values of the concretes were 0.68×10^{-13} and 0.55×10^{-13}, and 0.67×10^{-13} m/sec, respectively. The high values of water permeability coefficient of AF series concretes as compared with those of BF series concretes because the mixtures requires more mixing water to achieve the same workability of fresh concrete (AF series concretes required mixing water ranged from 213.8 to 214.5 kg/m3, while BF series concretes were 255.4 to 256.5 kg/m3). It should be also noted that even though AF series concretes with ground fly ash had higher water permeability than CON concrete, the value was still lower than that of concrete without ground fly ash.



(a) AF-Series concretes with ground fly ash (GF).



(b) BF-Series concretes with ground fly ash (GF).

Figure 10 - Relationship between the water permeability and cement replacement level of the recycled aggregate concrete.

5.5. Recycled Aggregate Concretes Containing Ground Palm Oil Fuel Ash

5.5.1. Compressive Strength

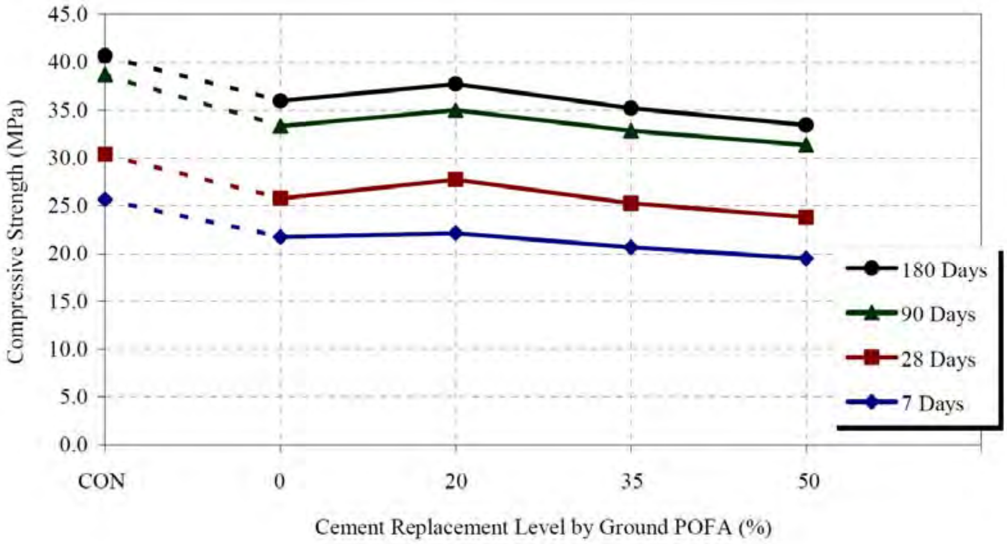
Figure 11 presents the compressive strengths of the recycled aggregate concretes. At 28 days, the CR00 concrete had a compressive strength of 25.8 MPa, which was 85% of the CON concrete's compressive strength; the CR00 concrete's compressive strength increased to 36.0 MPa or 88% of that of the CON concrete at 180 days. The compressive strengths of the CON concrete were 30.4 and 40.7 MPa at the ages of 28 and 180 days, respectively. The results indicated that the use of 100% CRA reduced the compressive strength of concrete by approximately 12-15% compared to the CON concrete. Hansen and Narud (1983) and Topcu and Guncan (1995) observed a similar behavior caused by concretes containing large quantities of coarse recycled aggregates, with a 15-20% reduction in the compressive strength. For the FR00 concrete, the compressive strengths at 28 and 180 days were 25.2 and 35.4 MPa or 83 and 87% of the CON concrete, respectively; these strengths were the same as that of the CR00 concrete. This result also revealed that the addition of 10% of the binder content in the FR00 concrete could compensate for the reduction in the concrete's compressive strength when using high amounts of recycled fine aggregate in the concrete mixture.

As shown in Figure 11a, the concretes made from 100% CRA, 100% river sand, and those containing ground POFA (CR concretes) had lower compressive strengths than the CON concrete. At a cement replacement by ground POFA of 20%, the compressive strength of concrete was higher than that of concrete without ground POFA at all of the testing ages, however, it was 7% lower than that of the CON concrete at 180 days due to the compressive strength contributed by the ground POFA with high fineness through a pozzolanic reaction and the packing effect provided by the small particles of the ground POFA (Isaia et al., 2003 and

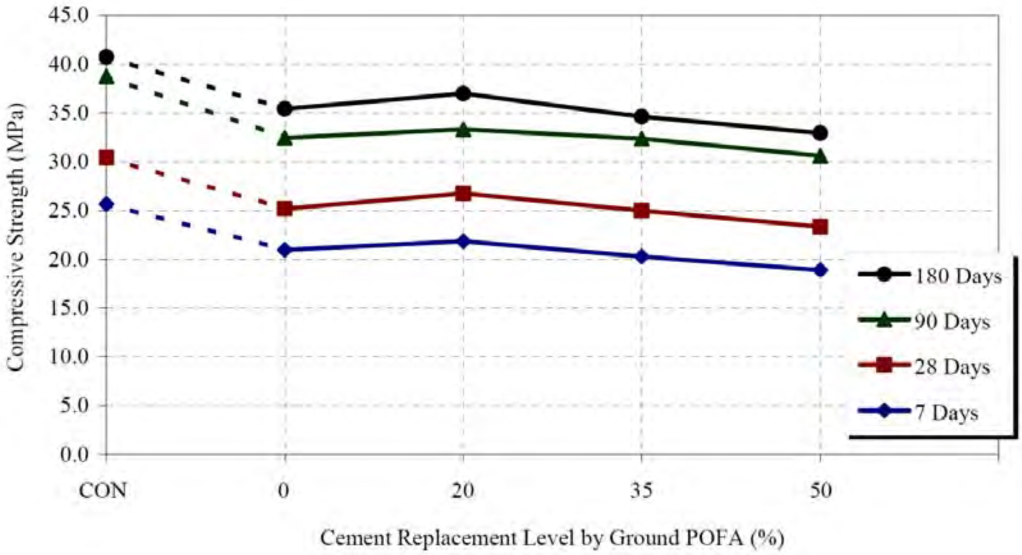
Tangpagasit et al., 2005). Furthermore, at 180 days, the use of 35% ground POFA to replace OPC resulted in a compressive strength of 35.2 MPa, which was 87% of the compressive strength of the CON concrete.

Figure 11b shows the relationship between the compressive strength and the amount of cement replaced by ground POFA for the concrete made from 100% coarse and fine recycled aggregates (FR concretes). The compressive strengths of the FR20, FR35, and FR50 concretes at 28 days were 26.8, 25.0, and 23.3 MPa, or 88, 82, and 77% of the CON concrete's compressive strength, respectively; at 180 days, these strengths increased to 37.0, 34.6, and 33.0 MPa or 91, 85, and 81% of the CON concrete's compressive strength, respectively. At 20% cement replacement by ground POFA, the compressive strength of concrete was higher than that of concrete without ground POFA at 7 days. However, the compressive strength of the recycled aggregate concretes decreased as the amount of ground POFA in the recycled aggregate concrete increased.

These findings on the compressive strengths of recycled aggregate concrete indicated that ground POFA could increase the overall compressive strength of recycled aggregate concrete. The optimum replacement of ground POFA was 20% by weight of binder for concrete made from 100% CRA and river sand and concrete made from 100% CRA and FRA. At 180 days, the recycled aggregate concrete mixed with 20% ground POFA produced a compressive strength more than 90% of that of the CON concrete.



(11a) CR concretes.



(11b) FR concretes.

Figure 11 - Relationship between the compressive strength of the concrete and ground POFA replacement level.

5.5.2. Modulus of Elasticity

The modulus of elasticity of the recycled aggregate concretes with and without ground POFA was determined using 100 x 200 mm concrete cylinders. The results are shown in Figure 12. The modulus of elasticity of the CON concrete at 28 and 90 days was 35.0 and 38.6 GPa, respectively. For the recycled aggregate concretes, the modulus of elasticity of the concretes varied from 24.9 to 27.2 GPa in the CR concretes and 23.3 to 27.1 GPa in the FR concretes, depending on the compressive strength of the concrete. Considering the same compressive strength, the use of recycled aggregate decreased the modulus of elasticity of concrete by approximately 30% compared with the CON concrete. BSCJ (1978) and Zagurskij and Zhadanovskij (1985) and reported a decrease in the modulus of elasticity for recycled aggregate concretes made with recycled coarse aggregate and natural sand of between 10 and 30% compared with conventional concrete. For recycled aggregate concretes made with 100% coarse and fine recycled aggregates, the modulus of elasticity was 25 to 40% lower than that of the corresponding normal aggregate concrete. Hansen (1992) noted that because a large amount of old mortar with a comparatively low modulus of elasticity adhered to the original aggregate particle in the recycled aggregates, the modulus of elasticity of recycled aggregate concretes was always lower than that of conventional concrete.

For the recycled aggregate concrete mixed with ground POFA, the values of the modulus of elasticity ranged from 22.2 to 28.0 GPa, which were lower than that of the CON concrete. It should be noted that the use of ground POFA did not significantly affect the modulus of elasticity of recycled aggregate concrete compared with the recycled aggregate concrete without ground POFA. Similar results were found for the concretes made from normal aggregate and containing pozzolanic materials, such as fly ash, silica fume, rice husk-bark ash, and palm oil fuel ash (Ghosh and Timusk, 1981; Nassif et al., 2005; Sata et al., 2007). These results indicated that the modulus of elasticity of concrete was typically related to the strength of the aggregates rather than the strength of the cement paste (Neville, 1997).

In addition, the modulus of elasticity of recycled aggregate concretes with and without ground POFA was still related with the compressive strength, i.e., the modulus of elasticity increased with the increased in the compressive strength.

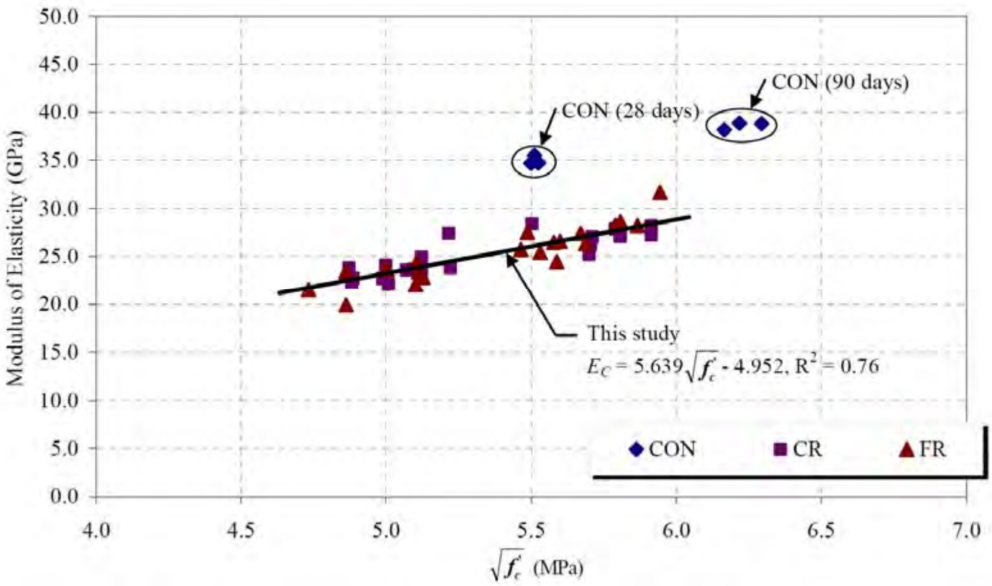


Figure 12 - Relationship between modulus of elasticity and square root of the compressive strength of recycled aggregate concrete.

The empirical equation for predicting the modulus of elasticity of recycled aggregate concretes is expressed by equation (4). It was noted that the modulus of elasticity of recycled aggregate concrete with and without ground POFA was approximately 25% lower than that of concrete made with normal aggregate for a given compressive strength. This result agreed with those obtained by Hansen and Boegh (1985), who reported that the modulus of elasticity of recycled aggregate concrete decreased by approximately 14-28%, depending on the quality of the recycled concrete aggregate.

$$E_c = 5.639\sqrt{f_c'} - 4.952 \text{ -------------------- (4)}$$

where E_c = modulus of elasticity of concrete (GPa)

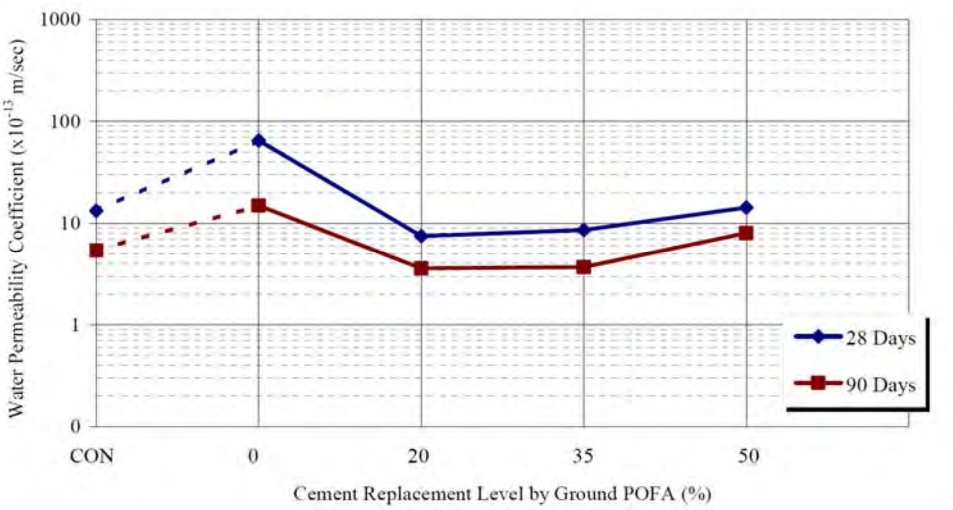
f_c' = compressive strength of concrete (MPa)

5.5.3. Water Permeability

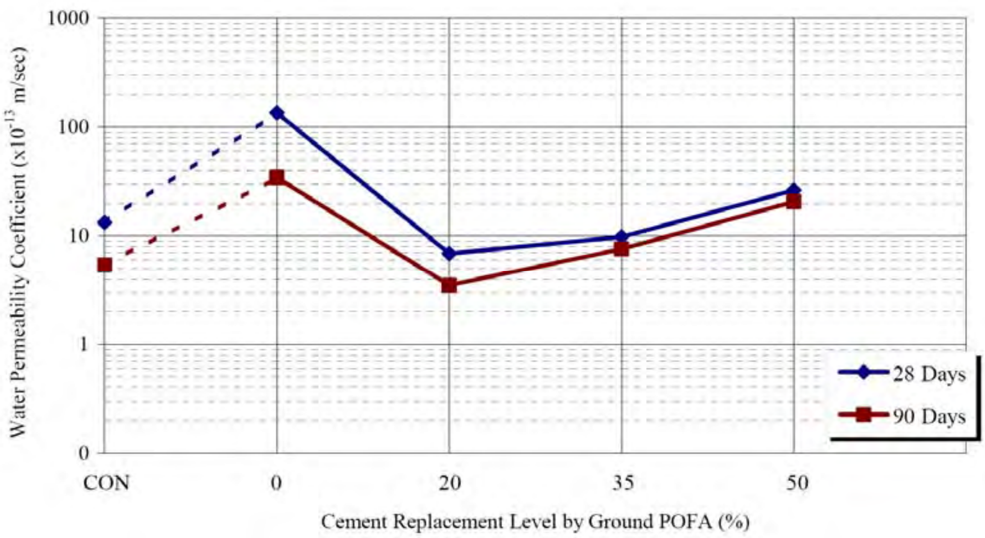
Figures 13a and 13b show the water permeability coefficient values of recycled aggregate concretes at 28 and 90 days for the CR and FR concrete groups, respectively. The CON concrete had water permeability coefficient values of 13.3×10^{-13} and 5.4×10^{-13} m/sec at 28 and 90 days, respectively, while the water permeability coefficient values of the CR00 concrete at 28 and 90 days were 64.8×10^{-13} and 15.0×10^{-13} m/sec, respectively, and those of the FR00 concrete were 135.5×10^{-13} and 34.5×10^{-13} m/sec, respectively. These results indicate that the use of recycled aggregate concrete made the concrete more impervious, particularly in the concrete incorporating both coarse and fine recycled aggregates. Recycled aggregate concrete had a higher water permeability than the CON concrete due to the high porosity of recycled aggregate resulting from adhering cement paste compared with normal aggregates; this feature was clearly shown from the water absorption results (CRA and FRA had water absorptions of 4.55 and 6.46%, respectively, while crushed limestone and river sand had water absorptions of 0.46 and 0.91%, respectively). Additionally, the CR00 and FR00 concretes had low compressive strengths compared with the CON concrete and thus exhibited higher water permeability coefficient values.

Concretes made from 100% coarse recycled aggregate and 100% river sand and containing ground POFA (as shown in Figure 13a) had lower water permeability coefficient values than the recycled aggregate concrete without ground POFA at both testing ages. Furthermore, with 20 and 35% replacement of OPC by ground POFA, the water permeability coefficient values of concrete were lower than the CON concrete. At 28 days, the water permeability coefficient values of the CR20 and CR35 concretes were 7.5×10^{-13} and 8.6×10^{-13} m/sec, respectively, and at 90 days, these values decreased to 3.6×10^{-13} and 3.7×10^{-13} m/sec, respectively. The lower water permeability coefficient values of the resulting concrete were affected by the pozzolanic reaction and packing effect of the small ground POFA particles, which produced concrete with a denser matrix and lower permeation (Chindaprasirt et al., 2007; Abdelkader et al., 2010). When the cement replacement by ground POFA increased to 50%, the concrete had higher water permeability coefficient values than the CON concrete, which were 14.3×10^{-13} and 8.0×10^{-13} m/sec at 28 and 90 days, respectively. However, the water permeability coefficient value of the CR50 concrete was still lower than that of the recycled aggregate concrete without ground POFA.

When the concretes contained 100% CRA and 100% FRA (Figure 13b), the FR20, FR35, and FR50 concretes had water permeability coefficient values of 6.9×10^{-13}, 9.8×10^{-13} and 26.4×10^{-13} m/sec, respectively, at 28 days. At 90 days, the water permeability coefficient values of the concretes were 3.5×10^{-13} and 7.6×10^{-13}, and 20.7×10^{-13} m/sec, respectively. The water permeability coefficient values of the concretes decreased slightly for all of the mixtures at the later age. Furthermore, the FR20 concrete had lower water permeability than the concretes with other replacement rates, and the water permeability of the concrete increased dramatically when more than 20% of the cement was replaced by ground POFA. Concrete containing 35% ground POFA had the same water permeability coefficient value as the CON concrete. Although the FR50 concrete had higher water permeability than the CON concrete, the value was still lower than that of concrete without ground POFA.



(13a) CR concretes.



(13b) FR concretes.

Figure 13 - Relationship between the water permeability and cement replacement level of the recycled aggregate concrete.

The relationship between compressive strength and water permeability coefficient of concrete at 28 and 90 days is illustrated in Figure 14. The water permeability coefficient values of concrete with ground POFA was somewhat decreased as the compressive strength increased. It was also clearly indicated that the water permeability coefficient values of the recycled aggregate concrete with ground POFA were very low compared to the one without ground POFA when the compressive strength of both concretes were approximately the same. For example, the CR35 concrete had a compressive strength of 23.5 MPa and a water permeability coefficient value of 8.6×10^{-13} m/sec at 28 days, while the CR00 concrete had a compressive strength of 25.8 MPa and a water permeability coefficient value of 64.8×10^{-13} m/sec at the same age. Moreover, some mixes of recycled aggregate concrete with ground POFA had lower water permeability than the CON concrete, even though the compressive strength of concrete was lower. This result may indicated that the incorporation of ground POFA to partially replace cement led to make concrete denser and was a very effective method for reducing the water permeability of the recycled aggregate concrete.

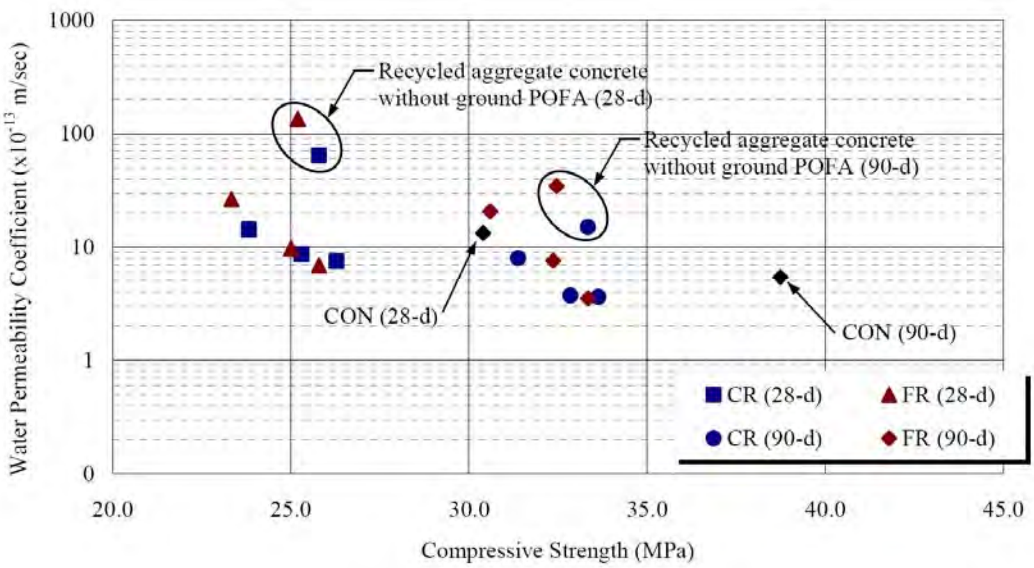


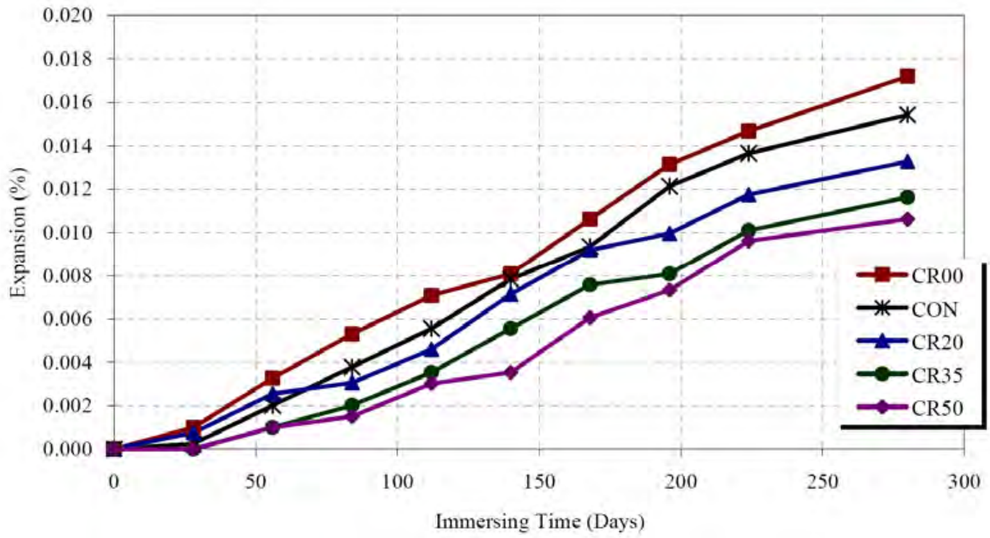
Figure 14 - Relationship between the compressive strength and water permeability of the recycled aggregate concrete.

5.5.4. Expansion Due to Sulfate

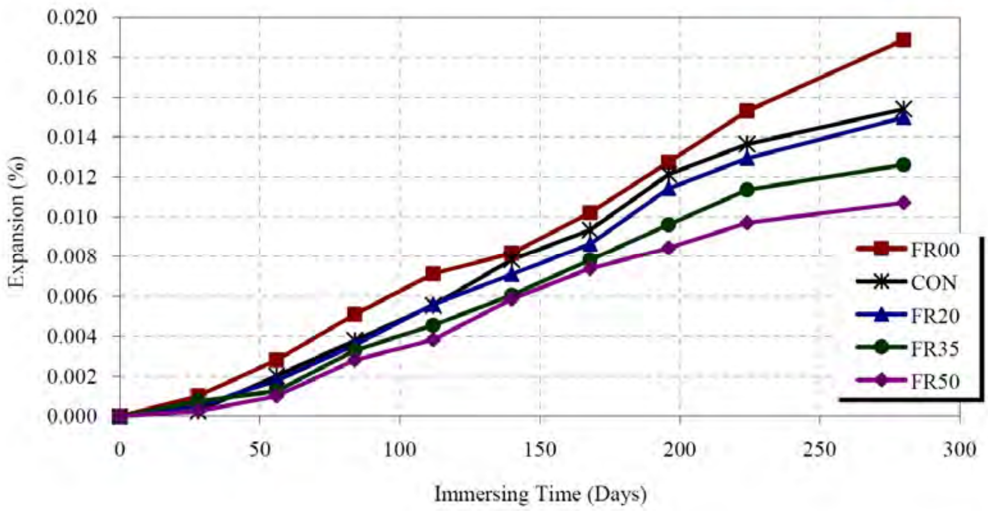
The expansion test results of the recycled aggregate concretes immersed in a 5% Na_2SO_4 solution for up to 9 months are shown in Figure 15. At 9 months, the CON concrete expanded by 0.015%, while the CR00 and FR00 concretes expanded by 0.017 and 0.019%, respectively. These results indicated that the use of recycled aggregate negatively influenced the sulfate resistance of the concrete. The higher expansion of the recycled aggregate concrete compared to the CON concrete could be attributed to the adhering mortar, which had a high water absorption and caused an increase in the W/B ratio of the concrete mixture, resulting in a decrease in the sulfate resistance of the concrete (Lee et al., 2005).

The expansions of the concretes made from 100% CRA and 100% river sand and those containing ground POFA are presented in Figure 15a. The results showed that the use of ground POFA at all replacement rates could reduce the expansion of concrete compared to the recycled aggregate concrete without ground POFA, and the concretes using ground POFA expanded less than the CON concrete. At 9 months, the CR20, CR35, and CR50 concretes expanded by 0.013, 0.012, and 0.011%, respectively. The replacement of Portland cement by ground POFA reduced the amounts of $Ca(OH)_2$ and C_3A in the hardened concrete. The reductions in $Ca(OH)_2$ and C_3A reduced the gypsum formation and ettringite recrystallization (Cao et al., 1997; Sezer et al., 2008). Furthermore, the use of ground POFA with high fineness was also responsible for the pozzolanic reaction and refined the pore structure, resulting in a highly impermeable matrix (Jaturapitakkul et al., 2011; Cheng et al., 2012). This could clarify the reason for why the recycled aggregate concretes incorporating ground POFA had higher sulfate resistance than the CON concrete and recycled aggregate concretes without ground POFA.

When the concrete contained 100% CRA and 100% FRA (Figure 15b), the FR20, FR35, and FR50 concretes expanded by 0.015, 0.013, and 0.011%, respectively. It should be noted that the expansions of the FR concretes were slightly lower than those of the CR concretes. This result confirmed that higher recycled aggregate contents in the concrete mixture resulted in lower concrete sulfate resistances. Furthermore, the expansions decreased with the increased of ground POFA replacement. Considering the expansions and compressive strength of the FR concretes mixed with ground POFA, the optimum replacement of ground POFA was 20% for increasing the resistance of sulfate attack and producing a compressive strength higher than that of the recycled aggregate concrete without ground POFA.



(15a) CR concretes.



(15b) FR concretes.

Figure 15 - Expansion of the concrete immersed in 5% Na_2SO_4 solution for 9 months.

6. Conclusions

Based on the experimental results of compressive strength and durability of concrete containing palm oil fuel ash and rice husk-bark ash, the conclusions can be drawn as follows:

6.1. Recycled Aggregate Concretes Containing Fly Ash

1. Concretes containing recycled concrete aggregates had slump loss faster than the conventional concrete which was in the range of 15-45 minutes. However, use of fly ash in replacing type I Portland cement was effective to slow the slump loss of the recycled aggregate concrete, depending on the degree of fly ash replacement. The use of finer fly ash gave a slightly increased slump loss for the recycled aggregate concrete as compared to coarser fly ash. However, the slump loss of the recycled aggregate concrete containing 35% ground fly ash by weight of binder was slower than that of the recycled aggregate concrete without fly ash.
2. Both original and ground fly ash (OF and GF) can be used to increase the compressive strength of recycled aggregate concrete, with strengths equal to or higher than that of concrete made from natural aggregate. In the case of concrete made of 100% CRA and FRA, the replacement of cement by 35% ground fly ash gave a desirable compressive strength of the recycled aggregate concrete at 85% of that of the CON concrete.
3. The incorporation of original or ground fly ash did not alter the splitting tensile strength of the recycled aggregate concrete. The splitting tensile strength of the recycled aggregate concrete with or without fly ash ranged from 8.1 to 8.5% of its compressive strength, which was slightly lower than that of the conventional concrete (approximately 10%).
4. The addition of fly ash in the recycled aggregate concrete did not have a significant effect on the modulus of elasticity values of the recycled aggregate concrete. The modulus of elasticity of the recycled aggregate concretes was still related to its compressive strength.

6.2. Recycled Aggregate Concretes Containing Ground Palm Oil Fuel Ash

1. The use of ground POFA with high fineness in recycled aggregate concrete could result in a higher compressive strength than that of recycled aggregate concrete without ground POFA. The compressive strength of concrete made from 100% CRA and 100% river sand was the same or slightly lower than that of the normal aggregate concrete when Portland cement was replaced by ground POFA at 20-35% by weight of binder.
2. For concrete made from 100% CRA and 100% FRA, the addition of 10% of the binder content in recycled aggregate concrete could compensate for the reduction in the concrete's compressive strength due to the high amount of fine recycled aggregate. When 20% of the Portland cement was replaced by ground POFA, the compressive strength of the recycled aggregate concrete at 90 days was more than 90% of that of CON concrete.
3. The modulus of elasticity of the recycled aggregate concrete with and without ground POFA was approximately 25% lower than that of the concrete made from normal aggregate for the same compressive strength. Furthermore, the use of ground POFA with high fineness did not change the characteristics of the modulus of elasticity of the recycled aggregate concrete, i.e., it still increased with the increased in the compressive strength of the concrete.
4. The use of ground POFA with high fineness as a cement replacement in recycled aggregate concrete exhibited good results with respect to the concrete's water permeability, depending on the cement replacement level.
5. After being immersed in a 5% Na_2SO_4 solution for 9 months, the use of ground POFA to replace Portland cement at all rates in concrete increased the sulfate resistance in terms of the expansion compared to the recycled aggregate concrete without ground POFA.

7. Suggestions

Based on the results from this study, the following suggestions are offered for future investigation:

1. From this study, recycled aggregate concretes could be achieved by using ground fly ash and ground POFA, therefore, the other properties in actual work should be studied such as the carbonation, creep, and other chemical attacks determined by immersing the specimens in sea water or waste water.
2. The results from this experimental study concluded that the fineness of fly ash and POFA is one of the major factors to increase the compressive strength of concrete and grinding process could increase theirs fineness. Therefore, grinding method and grinding machine should be studied to reduce the grinding cost.

8. Acknowledgements

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10. Output

International Publications (Published)

1. Weerachart Tangchirapat, Supat Khamklai, and Chai Jaturapitakkul. Use of ground palm oil fuel ash to improve strength, sulfate resistance, and water permeability of concrete containing high amount of recycled concrete aggregates. Mater Design 2008; 41(October): 150-157. (IF = 2.200)
2. Weerachart Tangchirapat, Chaiyanunt Rattanashotinunt, Rak Buranasing, and Chai Jaturapitakkul. Influence of fly ash on slump loss and strength of concrete fully incorporating recycled concrete aggregates. J Mater Civ Eng (ASCE) 2013; 25(2): 243–251. (IF = 0.733)

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Technical Report

Use of ground palm oil fuel ash to improve strength, sulfate resistance, and water permeability of concrete containing high amount of recycled concrete aggregates

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ABSTRACT

This study proposes the use of ground palm oil fuel ash (POFA) with high fineness to improve the mechanical properties and durability of concrete containing high amount of recycled concrete aggregates. The mixture proportions of the recycled aggregate concretes were separated into two groups; the first group was composed of 100% coarse recycled aggregate and natural river sand, while the second group was composed of 100% both coarse and fine recycled aggregates. A portion of ordinary Portland cement type I (OPC) was replaced by ground POFA at 20%, 35%, and 50% by weight of binder for both recycled aggregate concrete groups. The results showed that ground POFA could improve the compressive strength and reduce the water permeability of recycled aggregate concretes. With 20% replacement of OPC by ground POFA, the compressive strength of recycled aggregate concretes was only 7% lower than that of the conventional concrete. The modulus of elasticity of recycled aggregate concrete with and without ground POFA was lower than that of the conventional concrete by approximately 25%. Finally, ground POFA could be used effectively to reduce the expansion of recycled aggregate concrete. As the replacement of ground POFA in concrete is increased, the expansion of recycled aggregate concrete due to sodium sulfate attack decreased.

1. Introduction

Recycled aggregate concrete is a concrete composed of a recycled aggregate or combination of recycled aggregates and other aggregates [1]. Recycled aggregate is typically derived from crushed old concrete, which consists of 65–70% by volume of natural coarse and fine aggregates and 30–35% by volume of old cement paste [2]. Numerous studies investigated the use of aggregate from demolished concrete, and the studies concluded that the compressive strength and durability of concrete decreased when recycled aggregate was used [3–6]. Chen et al. [7] reviewed the effect of recycled aggregate on the compressive strength of concrete and found that the compressive strength of concrete containing 100% coarse recycled aggregate could be as low as 60% of that of concrete made from normal aggregate. The results obtained by Limbachiya et al. [6] showed that the resistance of concrete to carbonation and chloride penetration decreased as the recycled concrete aggregate content increased.

From previous studies, it should be noted that the compressive strength and durability of recycled aggregate concrete are worse than those of conventional concrete; thus, many researchers have attempted to improve the properties of recycled aggregate concrete. For cases in which the water to binder ratio is high, Otsuki et al. [8] used a double mixing method to increase the strength, chloride penetration and carbonation resistance of concrete containing recycled aggregates. Montgomery [9] treated the recycled aggregate with a ball mill to remove the old cement paste from the aggregate and found that this method could be used to increase the strength of recycled aggregate concrete. Katz [10] treated the recycled aggregate by impregnation of silica fume solution and ultrasonic cleaning. He found that the compressive strength increased by 30% and 15% at the ages of 7 and 28 days, respectively, after the silica fume treatment, and the compressive strength increased by 7% after the ultrasonic treatment. Another method for overcoming these shortcomings is the incorporation of a pozzolanic material in the concrete mixture.

Palm oil fuel ash (POFA), a by-product from thermal power plants, contains high amounts of silicon and aluminum oxides in the amorphous state and was recently accepted as a pozzolanic material [11–13]. More than 100,000 tons of POFA is produced annually in Thailand, and this amount continues to increase each year because palm oil is a major raw material in the production of ethanol. However, the utilization of POFA is minimal compared to the amount produced. Thus, most POFA is disposed of in landfills, resulting in environmental degradation and other problems.

Hussin and Awal [11] studied the expansion of mortar mixed with 30% POFA and found that POFA had a good potential for

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reducing the expansion of mortar due to sulfate attack. Tangchirapat et al. [12] reported that the compressive strength of concrete containing unground POFA was very low due to the large particle size and high porosity of POFA. However, concrete containing 10–20% ground POFA with high fineness resulted in a compressive strength higher than that of the control concrete after 90 days of curing. Furthermore, Sata et al. [13] reported that concrete containing ground POFA with high fineness could be used as a pozzolanic material to produce high-strength concrete with a compressive strength of greater than 80 MPa at 28 days.

The above studies indicate that ground POFA with high fineness is a good pozzolanic material and can be used in concrete in a similar manner as other pozzolans, such as fly ash and silica fume. However, there are a limited number of studies that address the use of ground POFA for improving the mechanical properties and durability of recycled aggregate concrete. To obtain experimental data for publication and use POFA effectively, the properties of recycled aggregate concretes incorporating ground POFA are investigated.

Therefore, the aim of this study was to utilize the ground POFA with high fineness as a cement replacement in concrete containing high levels of recycled aggregate; the concretes were made from 100% coarse recycled aggregate and 100% coarse and fine recycled aggregates. The mechanical properties of recycled aggregate concretes, such as the compressive strength and modulus of elasticity, were investigated and compared with that of the conventional concrete. The durability of recycled aggregate concrete in terms of water permeability and sulfate resistance was also determined.

The research significance on using POFA as a cement replacement in recycled aggregate concretes is not only to increase the ultimate strength and durability of recycled aggregate concrete, also reduce the amount of POFA in landfills. Furthermore, the findings of this research will encourage further research on the use of recycled aggregates in concrete as well as the use of other by-product materials from biomass power plants, which will ultimately lead to their development as a more environmentally friendly way of generating energy.

2. Experimental program

2.1. Materials

2.1.1. Cement

Ordinary Portland cement type I (OPC) was used in this study. Its physical and chemical properties are given in Tables 1 and 2, respectively.

2.1.2. Palm oil fuel ash (POFA)

The palm oil fuel ash (POFA) used in this study was obtained from a palm oil industry located in southern Thailand, at which palm fiber, shell, and empty fruit bunches were burnt as a fuel at a controlled temperature of approximately 800–1000 °C to produce stream for the generation of electricity. The POFA directly received from this site had large particles; thus, it was ground to increase the fineness using a grinding machine until the particles retained on a No. 325 sieve (45-μm opening) were less than 3% by weight and identified as ground POFA.

The particle morphology of the ground POFA is shown in Fig. 1. The ground POFA consisted of irregular particles with a crushed shape and had a median particle size of 10.7 μm. The fineness in term of the weight of particles retained on a No. 325 sieve and the specific gravity of the materials are shown in Table 1. The amount of the ground POFA particles retained on a sieve No. 325 was 1.7%, and the ground POFA had a specific gravity of 2.53.

The chemical composition of the ground POFA is reported in Table 2. The major chemical composition of the ground POFA was SiO_2 (55.5%), while the total amount of the ground POFA composed of SiO_2, Al_2O_3, and Fe_2O_3 was 70.3%. The amounts of LOI and SO_3 were 7.9% and 2.3%, respectively. It should be noted that the chemical composition of the ground POFA used in this study could be classified as class N pozzolan, as prescribed by ASTM C618 [14]. Furthermore, the strength activity index of the ground POFA was much greater than the minimum value (75%) specified by ASTM C618 [14], and the strength indices at the ages of 7 and 28 days were 105% and 109%, respectively.

2.1.3. Normal aggregates

Table 3 shows the physical properties of normal aggregate. Local river sand with a fineness modulus of 3.07 was used as a fine aggregate. The fine aggregate had a specific gravity of 2.62 and water absorption of 0.91%. Crushed limestone with a maximum size of 19 mm was used as a coarse aggregate. The coarse aggregate

Table 1
Physical properties of the materials.

Physical properties	OPC	Ground POFA	ASTM C618 [14]
Specific gravity	3.14	2.53	–
Retained on a 45-μm sieve (No. 325) (%)	13.5	1.7	⩽34.0
Median particle size, d_{50} (μm)	14.6	10.7	–
Strength activity index (%)			
7 days	–	105	⩾75.0
28 days	–	109	⩾75.0

Table 2
Chemical compositions of the materials.

Chemical compositions (%)	OPC	Ground POFA	ASTM C618 [14]
Silicon dioxide (SiO_2)	20.9	55.5	–
Aluminum oxide (Al_2O_3)	4.7	9.2	–
Iron oxide (Fe_2O_3)	3.4	5.6	–
Calcium oxide (CaO)	65.4	12.4	–
Magnesium oxide (MgO)	1.2	4.6	–
Sodium oxide (Na_2O)	0.2	0.0	–
Potassium oxide (K_2O)	0.3	0.0	–
Sulfur trioxide (SO_3)	2.7	2.3	⩽4.0
Loss on ignition (LOI)	0.9	7.9	⩽10.0
$SiO_2 + Al_2O_3 + Fe_2O_3$	–	70.3	⩾70.0

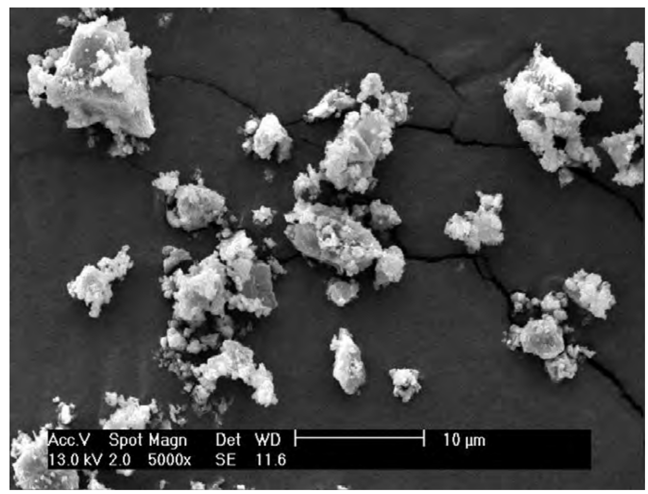

Fig. 1. Particle morphologies of the ground POFA.

Table 3
Physical properties of normal and recycled aggregates.

Properties	Normal aggregates		Recycled aggregates	
	River sand	Limestone	Fine	Coarse
Fineness modulus	3.07	6.90	3.27	6.55
Specific gravity	2.62	2.73	2.40	2.48
Dry rodded weight (kg/m^3)	1726	1652	1485	1421
Absorption (%)	0.91	0.45	6.46	4.55
Los Angeles abrasion loss (%)	N/A	23.41	N/A	29.14

Note: N/A = not applicable.

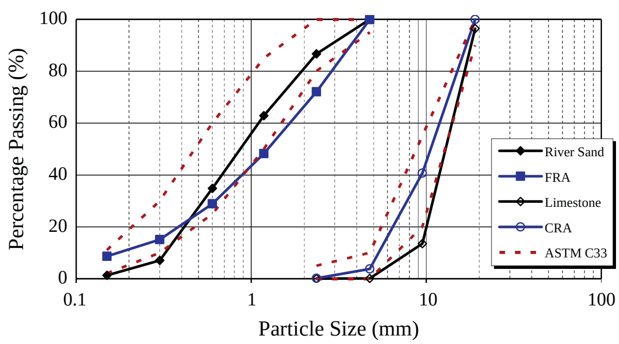

Fig. 2. Particle size distributions of the river sand, limestone, and recycled aggregates (CRA and FRA).

had a specific gravity and water absorption of 2.73 and 0.45%, respectively.

2.1.4. Recycled aggregates

The cylindrical concrete samples (150 × 300 mm), which were collected from many construction sites and had compressive strengths between 25 and 40 MPa, were crushed using swing hammer mills. The crushed concrete was screened by an ASTM No. 4 sieve to separate coarse recycled aggregate (CRA) and fine recycled aggregate (FRA), and did not grade before use in concrete mixture. Table 3 lists the physical properties of the recycled concrete aggregates. Fig. 2 compares the grading size of the recycled concrete aggregates with the ASTM C33 [15] requirements for fine and coarse aggregates. The FRA had a fineness modulus of 3.27, which was slightly coarser than the limit specified by ASTM C33 [15] while the grading size of the CRA was within the ASTM C33 [15] grading requirements. Although some size factions of the FRA did not fall within the ASTM C33 [15] grading requirements, the gradation curve of the FRA was still the well-graded aggregate.

The CRA and FRA had specific gravities of 2.40 and 2.48 and water absorptions of 6.46 and 4.55%, respectively. The low specific gravity and high water absorption of the recycled concrete aggregates were caused by old mortar residue [7]. The CRA had a Los Angeles abrasion of 29.14%, which was higher than that of crushed limestone (23.41%), due to the adhering cement paste, which was typically weaker than the normal aggregate [16].

2.2. Test specimens

2.2.1. Mixture proportions and slump of fresh concrete

The mixture proportion of the conventional concrete (concrete made from normal aggregates and referred to as CON) and recycled aggregate concretes are summarized in Table 4. The compressive strength of the CON concrete was designed to be approximately 30 MPa at 28 days with slump of fresh concrete in the range of 50–100 mm. The ratio of fine to coarse aggregates was 45:55 by volume.

For the recycled aggregate concrete, the concrete mixtures were separated into two groups. The first group composed of natural river sand and 100% CRA (denoted as CR), while the second group composed of 100% CRA and FRA (denoted as FR) and had a 10% higher binder content than the first group to prevent the segregation of concrete. The effective water to binder (cement plus ground POFA) ratio of all concretes was controlled to be 0.65. To maintain the slump of fresh concrete at between 50 and 100 mm, the amount of mixing water was adjusted to compensate for water absorption by the recycled aggregates, and a type F superplasticizer was employed in the recycled aggregate concrete mixture to maintain the slump of fresh concrete as that of the CON concrete (50–100 mm). Furthermore, ground POFA was used to replace OPC at the rates of 20%, 35%, and 50% by weight of binder in the recycled aggregate concrete.

2.2.2. Test for compressive strength and modulus of elasticity

All of the fresh concrete mixtures were prepared using a rotary drum mixer. Concrete cylinder samples with a diameter of 100 mm and length of 200 mm were cast. After casting for 24 h, the specimens were removed from the molds and cured in water. They were tested to determine the compressive strengths in accordance with the ASTM C39 [17] at the ages of 7, 28, 90, and 180 days. The modulus of elasticity of the concretes was also determined according to the ASTM C469 [18] at the ages of 28 and 90 days. Three concrete cylinders were tested and used for each data point.

2.2.3. Test for water permeability

The water permeability test began with the sawing of a slice 40 mm thick from the middle of the 100 × 200 mm concrete cylinder. The sliced concrete was then cast around with 25 mm thick epoxy resin and was allowed to harden for 24 h. The specimen

Table 4
Mixture proportions of the concretes.

Sample	Mixture proportion of concrete (kg/m^3)										
	OPC	Ground POFA	Fine aggregate		Coarse aggregate		Super P.	Mixing water	Effective water	W/B	Slump (mm)
			Normal	Recycled	Normal	Recycled					
CON	295	–	828	–	1054	–	–	204	192	0.65	90
CR00	295	–	777	–	–	899	–	247	192	0.65	75
CR20	236	59	772	–	–	893	0.30	247	192	0.65	80
CR35	192	103	769	–	–	889	0.44	246	192	0.65	75
CR50	148	148	764	–	–	884	0.74	246	192	0.65	60
FR00	325	–	–	631	–	797	–	312	211	0.65	70
FR20	260	65	–	626	–	790	0.49	312	211	0.65	55
FR35	211	114	–	622	–	786	0.81	311	211	0.65	80
FR50	163	163	–	618	–	780	1.14	311	211	0.65	80

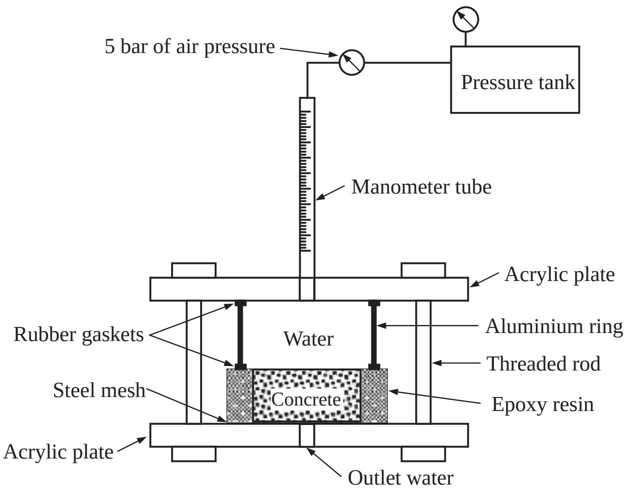

Fig. 3. Experimental setup for testing the water permeability of the concrete [19–21].

was installed in a permeability housing cell as shown in Fig. 3, a water pressure of 0.5 MPa or 5.0 bars was then applied to the cell. The amount of water flowing through the concrete specimen was measured by reading the water level drop in the manometer tube. The results were plotted to obtain a relationship between the cumulative amounts of flowing water and cumulative time to determine a steady-state flow. At this stage, the steady flow rate was obtained, and a coefficient of permeability was calculated using Darcy's law and the equation of continuity, as shown in Eq. (1). This experimental setup for testing the water permeability of concrete was recommended and used by Khatri et al. [19], Chindaprasirt et al. [20], and Wongpa et al. [21]. The water permeability of concrete was investigated at the ages of 28 and 90 days. At each testing age, the average of three concrete specimens was used to represent the water permeability of concrete.

$$K = \frac{\rho LgQ}{PA} \tag{1}$$

where K = coefficient of water permeability (m/s); ρ = density of water (kg/m^3); g = acceleration due to gravity, 9.81 (m/s^2); Q = flow rate (m^3/s); L = length of the concrete sample (m); P = water pressure (Pa); A = cross-sectional area of the concrete sample (m^2).

2.2.4. Test for expansion in a 5% Na_2SO_4 solution

The expansion of concrete due to sulfate attack was measured on three prismatic concrete specimens having a cross section of 75 × 75 mm^2 and length of 285 mm. The concrete bars were immediately immersed in a 5% Na_2SO_4 solution after being removed from the molds (24 h after casting). The expansions of the concrete bars due to sulfate attack were measured monthly for 9 months using a length comparator apparatus according to ASTM C490 [22].

3. Results and discussion

3.1. Compressive strength

Fig. 4 presents the compressive strengths of the recycled aggregate concretes. At 28 days, the CR00 concrete had a compressive strength of 25.8 MPa, which was 85% of the CON concrete's compressive strength; the CR00 concrete's compressive strength increased to 36.0 MPa or 88% of that of the CON concrete at 180 days. The compressive strengths of the CON concrete were 30.4 and 40.7 MPa at the ages of 28 and 180 days, respectively.

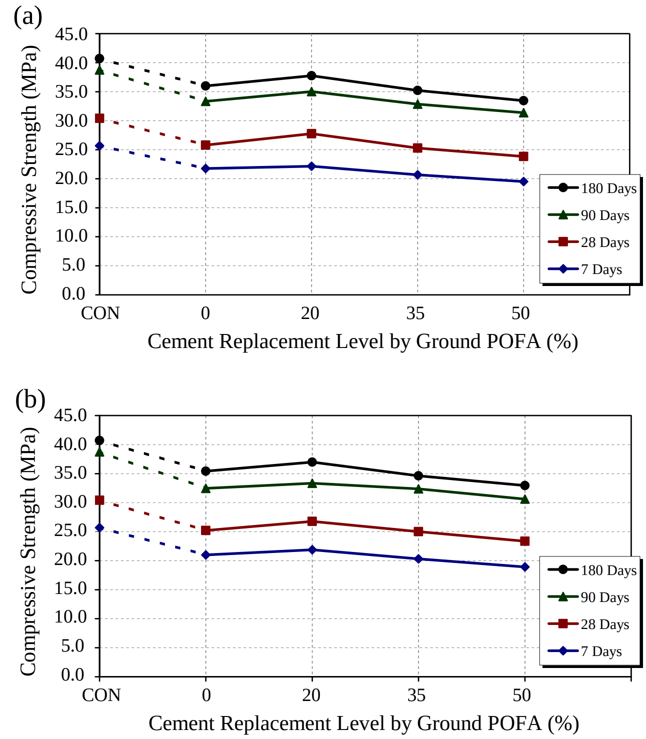

Fig. 4. Relationship between the compressive strength of the concrete and ground POFA replacement level. (a) CR concretes, (b) FR concretes.

The results indicated that the use of 100% CRA reduced the compressive strength of concrete by approximately 12–15% compared to the CON concrete. Hansen and Narud [23] and Topcu and Guncan [24] observed a similar behavior caused by concretes containing large quantities of coarse recycled aggregates, with a 15–20% reduction in the compressive strength. For the FR00 concrete, the compressive strengths at 28 and 180 days were 25.2 and 35.4 MPa or 83% and 87% of the CON concrete, respectively; these strengths were the same as that of the CR00 concrete. This result also revealed that the addition of 10% of the binder content in the FR00 concrete could compensate for the reduction in the concrete's compressive strength when using high amounts of recycled fine aggregate in the concrete mixture.

As shown in Fig. 4a, the concretes made from 100% CRA, 100% river sand, and those containing ground POFA (CR concretes) had lower compressive strengths than the CON concrete. At a cement replacement by ground POFA of 20%, the compressive strength of concrete was higher than that of concrete without ground POFA at all of the testing ages, however, it was 7% lower than that of the CON concrete at 180 days due to the compressive strength contributed by the ground POFA with high fineness through a pozzolanic reaction and the packing effect provided by the small particles of the ground POFA [25,26]. Furthermore, at 180 days, the use of 35% ground POFA to replace OPC resulted in a compressive strength of 35.2 MPa, which was 87% of the compressive strength of the CON concrete.

Fig. 4b shows the relationship between the compressive strength and the amount of cement replaced by ground POFA for the concrete made from 100% coarse and fine recycled aggregates (FR concretes). The compressive strengths of the FR20, FR35, and FR50 concretes at 28 days were 26.8, 25.0, and 23.3 MPa, or 88%, 82%, and 77% of the CON concrete's compressive strength, respectively; at 180 days, these strengths increased to 37.0, 34.6, and 33.0 MPa or 91%, 85%, and 81% of the CON concrete's compressive strength, respectively. At 20% cement replacement by ground

POFA, the compressive strength of concrete was higher than that of concrete without ground POFA at 7 days. However, the compressive strength of the recycled aggregate concretes decreased as the amount of ground POFA in the recycled aggregate concrete increased.

These findings on the compressive strengths of recycled aggregate concrete indicated that ground POFA could increase the overall compressive strength of recycled aggregate concrete. The optimum replacement of ground POFA was 20% by weight of binder for concrete made from 100% CRA and river sand and concrete made from 100% CRA and FRA. At 180 days, the recycled aggregate concrete mixed with 20% ground POFA produced a compressive strength more than 90% of that of the CON concrete.

3.2. Modulus of elasticity

The modulus of elasticity of the recycled aggregate concretes with and without ground POFA was determined using 100×200 mm concrete cylinders. The results are shown in Fig. 5. The modulus of elasticity of the CON concrete at 28 and 90 days was 35.0 and 38.6 GPa, respectively. For the recycled aggregate concretes, the modulus of elasticity of the concretes varied from 24.9 to 27.2 GPa in the CR concretes and 23.3 to 27.1 GPa in the FR concretes, depending on the compressive strength of the concrete. Considering the same compressive strength, the use of recycled aggregate decreased the modulus of elasticity of concrete by approximately 30% compared with the CON concrete. Zagurskij and Zhadanovskij [27] and BSCJ [28] reported a decrease in the modulus of elasticity for recycled aggregate concretes made with recycled coarse aggregate and natural sand of between 10% and 30% compared with conventional concrete. For recycled aggregate concretes made with 100% coarse and fine recycled aggregates, the modulus of elasticity was 25–40% lower than that of the corresponding normal aggregate concrete. Hansen [1] noted that because a large amount of old mortar with a comparatively low modulus of elasticity adhered to the original aggregate particle in the recycled aggregates, the modulus of elasticity of recycled aggregate concretes was always lower than that of conventional concrete.

For the recycled aggregate concrete mixed with ground POFA, the values of the modulus of elasticity ranged from 22.2 to 28.0 GPa, which were lower than that of the CON concrete. It should be noted that the use of ground POFA did not significantly affect the modulus of elasticity of recycled aggregate concrete compared with the recycled aggregate concrete without ground POFA. Similar results were found for the concretes made from normal aggregate and containing pozzolanic materials, such as fly ash, silica fume, rice husk-bark ash, and palm oil fuel ash [13,29,30].

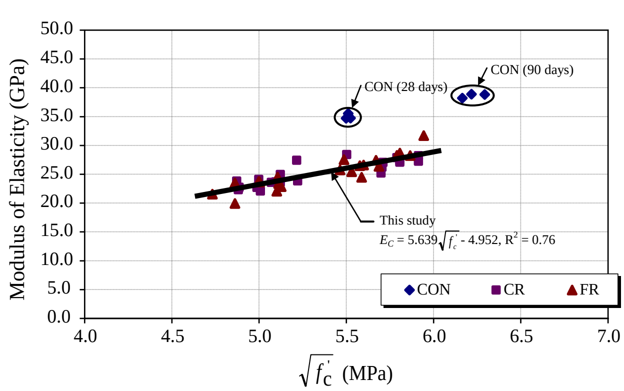

Fig. 5. Relationship between modulus of elasticity and square root of the compressive strength of recycled aggregate concrete.

These results indicated that the modulus of elasticity of concrete was typically related to the strength of the aggregates rather than the strength of the cement paste [31]. In addition, the modulus of elasticity of recycled aggregate concretes with and without ground POFA was still related with the compressive strength, i.e., the modulus of elasticity increased with the increased in the compressive strength.

The empirical equation for predicting the modulus of elasticity of recycled aggregate concretes is expressed by Eq. (2). It was noted that the modulus of elasticity of recycled aggregate concrete with and without ground POFA was approximately 25% lower than that of concrete made with normal aggregate for a given compressive strength. This result agreed with those obtained by Hansen and Boegh [3], who reported that the modulus of elasticity of recycled aggregate concrete decreased by approximately 14–28%, depending on the quality of the recycled concrete aggregate.

$$E_c = 5.639\sqrt{f_c'} - 4.952 \qquad (2)$$

where E_c = modulus of elasticity of concrete (GPa); f_c' = compressive strength of concrete (MPa)

3.3. Water permeability

Figs. 6a and b show the water permeability coefficient values of recycled aggregate concretes at 28 and 90 days for the CR and FR concrete groups, respectively. The CON concrete had water permeability coefficient values of 13.3×10^{-13} and 5.4×10^{-13} m/s at 28 and 90 days, respectively, while the water permeability coefficient values of the CR00 concrete at 28 and 90 days were 64.8×10^{-13} and 15.0×10^{-13} m/s, respectively, and those of the FR00 concrete were 135.5×10^{-13} and 34.5×10^{-13} m/s, respectively. These results indicate that the use of recycled aggregate concrete made the concrete more impervious, particularly in the concrete incorporating both coarse and fine recycled aggregates. Recycled aggre-

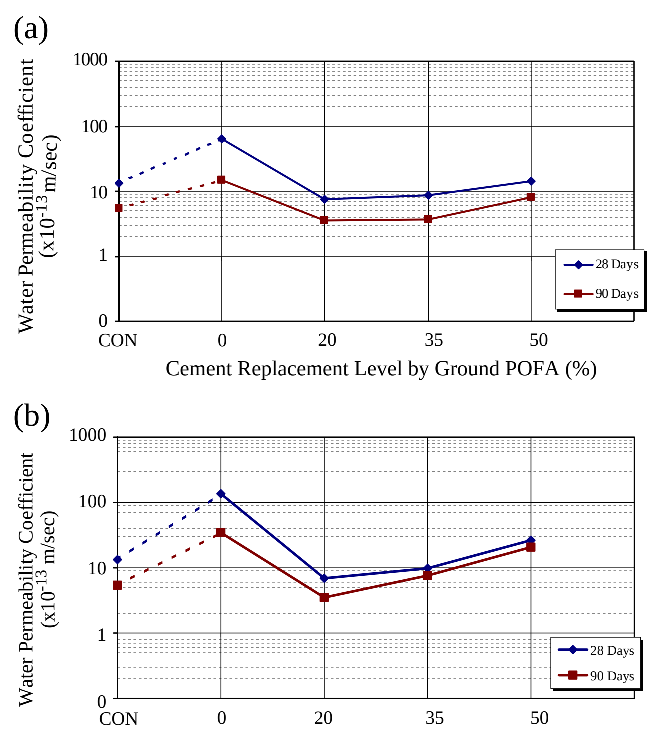

Fig. 6. Relationship between the water permeability and cement replacement level of the recycled aggregate concrete. (a) CR concretes. (b) FR concretes.

gate concrete had a higher water permeability than the CON concrete due to the high porosity of recycled aggregate resulting from adhering cement paste compared with normal aggregates; this feature was clearly shown from the water absorption results (CRA and FRA had water absorptions of 4.55 and 6.46%, respectively, while crushed limestone and river sand had water absorptions of 0.46 and 0.91%, respectively). Additionally, the CR00 and FR00 concretes had low compressive strengths compared with the CON concrete and thus exhibited higher water permeability coefficient values.

Concretes made from 100% coarse recycled aggregate and 100% river sand and containing ground POFA (as shown in Fig. 6a) had lower water permeability coefficient values than the recycled aggregate concrete without ground POFA at both testing ages. Furthermore, with 20 and 35% replacement of OPC by ground POFA, the water permeability coefficient values of concrete were lower than the CON concrete. At 28 days, the water permeability coefficient values of the CR20 and CR35 concretes were 7.5×10^{-13} and 8.6×10^{-13} m/s, respectively, and at 90 days, these values decreased to 3.6×10^{-13} and 3.7×10^{-13} m/s, respectively. The lower water permeability coefficient values of the resulting concrete were affected by the pozzolanic reaction and packing effect of the small ground POFA particles, which produced concrete with a denser matrix and lower permeation [20,32]. When the cement replacement by ground POFA increased to 50%, the concrete had higher water permeability coefficient values than the CON concrete, which were 14.3×10^{-13} and 8.0×10^{-13} m/s at 28 and 90 days, respectively. However, the water permeability coefficient value of the CR50 concrete was still lower than that of the recycled aggregate concrete without ground POFA.

When the concretes contained 100% CRA and 100% FRA (Fig. 6b), the FR20, FR35, and FR50 concretes had water permeability coefficient values of 6.9×10^{-13}, 9.8×10^{-13} and 26.4×10^{-13} m/s, respectively, at 28 days. At 90 days, the water permeability coefficient values of the concretes were 3.5×10^{-13} and 7.6×10^{-13}, and 20.7×10^{-13} m/s, respectively. The water permeability coefficient values of the concretes decreased slightly for all of the mixtures at the later age. Furthermore, the FR20 concrete had lower water permeability than the concretes with other replacement rates, and the water permeability of the concrete increased dramatically when more than 20% of the cement was replaced by ground POFA. Concrete containing 35% ground POFA had the same water permeability coefficient value as the CON concrete. Although the FR50 concrete had higher water permeability than the CON concrete, the value was still lower than that of concrete without ground POFA.

The relationship between compressive strength and water permeability coefficient of concrete at 28 and 90 days is illustrated in Fig. 7. The water permeability coefficient values of concrete with ground POFA was somewhat decreased as the compressive strength increased. It was also clearly indicated that the water permeability coefficient values of the recycled aggregate concrete with ground POFA were very low compared to the one without ground POFA when the compressive strength of both concretes were approximately the same. For example, the CR35 concrete had a compressive strength of 23.5 MPa and a water permeability coefficient value of 8.6×10^{-13} m/s at 28 days, while the CR00 concrete had a compressive strength of 25.8 MPa and a water permeability coefficient value of 64.8×10^{-13} m/s at the same age. Moreover, some mixes of recycled aggregate concrete with ground POFA had lower water permeability than the CON concrete, even though the compressive strength of concrete was lower. This result may indicated that the incorporation of ground POFA to partially replace cement led to make concrete denser and was a very effective method for reducing the water permeability of the recycled aggregate concrete.

3.4. Expansion due to sulfate

The expansion test results of the recycled aggregate concretes immersed in a 5% Na_2SO_4 solution for up to 9 months are shown in Fig. 8. At 9 months, the CON concrete expanded by 0.015%, while the CR00 and FR00 concretes expanded by 0.017% and 0.019%, respectively. These results indicated that the use of recycled aggregate negatively influenced the sulfate resistance of the concrete. The higher expansion of the recycled aggregate concrete compared to the CON concrete could be attributed to the adhering mortar, which had a high water absorption and caused an increase in the W/B ratio of the concrete mixture, resulting in a decrease in the sulfate resistance of the concrete [33].

The expansions of the concretes made from 100% CRA and 100% river sand and those containing ground POFA are presented in Fig. 8a. The results showed that the use of ground POFA at all replacement rates could reduce the expansion of concrete compared to the recycled aggregate concrete without ground POFA,

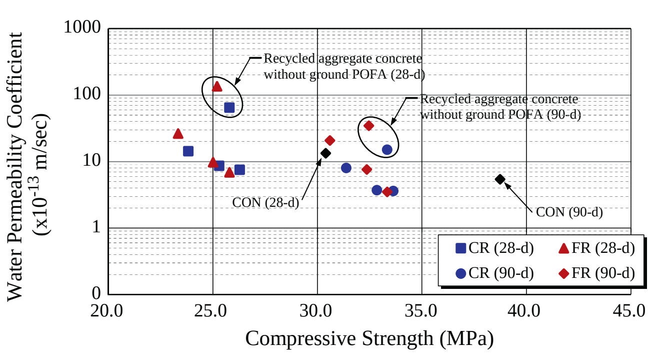

Fig. 7. Relationship between the compressive strength and water permeability of the recycled aggregate concrete. (a) CR concretes. (b) FR concretes.

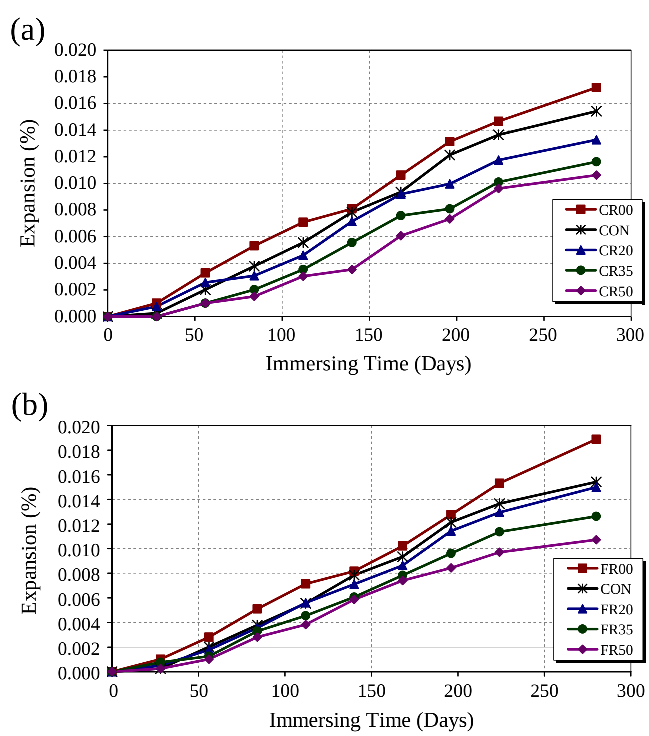

Fig. 8. Expansion of the concrete bars immersed in a 5% Na_2SO_4 solution for 9 months.

and the concretes using ground POFA expanded less than the CON concrete. At 9 months, the CR20, CR35, and CR50 concretes expanded by 0.013%, 0.012%, and 0.011%, respectively. The replacement of Portland cement by ground POFA reduced the amounts of $Ca(OH)_2$ and C_3A in the hardened concrete. The reductions in $Ca(OH)_2$ and C_3A reduced the gypsum formation and ettringite recrystallization [34,35]. Furthermore, the use of ground POFA with high fineness was also responsible for the pozzolanic reaction and refined the pore structure, resulting in a highly impermeable matrix [36,37]. This could clarify the reason for why the recycled aggregate concretes incorporating ground POFA had higher sulfate resistance than the CON concrete and recycled aggregate concretes without ground POFA.

When the concrete contained 100% CRA and 100% FRA (Fig. 8b), the FR20, FR35, and FR50 concretes expanded by 0.015%, 0.013%, and 0.011%, respectively. It should be noted that the expansions of the FR concretes were slightly lower than those of the CR concretes. This result confirmed that higher recycled aggregate contents in the concrete mixture resulted in lower concrete sulfate resistances. Furthermore, the expansions decreased with the increased of ground POFA replacement. Considering the expansions and compressive strength of the FR concretes mixed with ground POFA, the optimum replacement of ground POFA was 20% for increasing the resistance of sulfate attack and producing a compressive strength higher than that of the recycled aggregate concrete without ground POFA.

4. Conclusions

From the results of this experiment, the following conclusions can be drawn:

(1) The use of ground POFA with high fineness in recycled aggregate concrete could result in a higher compressive strength than that of recycled aggregate concrete without ground POFA. The compressive strength of concrete made from 100% CRA and 100% river sand was the same or slightly lower than that of the normal aggregate concrete when Portland cement was replaced by ground POFA at 20–35% by weight of binder.
(2) For concrete made from 100% CRA and 100% FRA, the addition of 10% of the binder content in recycled aggregate concrete could compensate for the reduction in the concrete's compressive strength due to the high amount of fine recycled aggregate. When 20% of the Portland cement was replaced by ground POFA, the compressive strength of the recycled aggregate concrete at 90 days was more than 90% of that of CON concrete.
(3) The modulus of elasticity of the recycled aggregate concrete with and without ground POFA was approximately 25% lower than that of the concrete made from normal aggregate for the same compressive strength. Furthermore, the use of ground POFA with high fineness did not change the characteristics of the modulus of elasticity of the recycled aggregate concrete, i.e., it still increased with the increased in the compressive strength of the concrete.
(4) The use of ground POFA with high fineness as a cement replacement in recycled aggregate concrete exhibited good results with respect to the concrete's water permeability, depending on the cement replacement level.
(5) After being immersed in a 5% Na_2SO_4 solution for 9 months, the use of ground POFA to replace Portland cement at all rates in concrete increased the sulfate resistance in terms of the expansion compared to the recycled aggregate concrete without ground POFA.

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Influence of Fly Ash on Slump Loss and Strength of Concrete Fully Incorporating Recycled Concrete Aggregates

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Abstract: This paper investigates the effects of fineness and replacement of fly ash on the fresh and hardened properties of recycled aggregate concrete. Two groups of recycled aggregate concretes were studied and compared with that of conventional concrete (CON) in which crushed limestone and local river sand were used as aggregates. The first group was prepared using 100% coarse recycled concrete aggregate and local river sand. For the second group, crushed limestone and local river sand were fully replaced by both coarse and fine recycled concrete aggregates. The results indicate that the slump loss of the recycled aggregate concrete with fly ash was reduced to lower than that of the recycled aggregate concrete without fly ash when the fineness of the fly ash was increased, which increased the slump loss of the fresh concrete. Fly ash can be used to increase the compressive strength of recycled aggregate concrete, depending on its fineness and the degree of fly ash replacement. The addition of fly ash with different fineness in recycled aggregate concrete had no significant effect on the splitting tensile strength and the modulus of elasticity of the recycled aggregate concrete, which are related to its compressive strength.
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CE Database subject headings: Compressive strength; Fly ash; Elasticity; Recycling; Concrete; Aggregates; Tensile strength.

Author keywords: Compressive strength; Fly ash; Fineness; Modulus of elasticity; Recycled concrete aggregate; Slump loss; Splitting tensile strength.

Introduction

Concrete is one of the most widely used construction materials in the world. Typically, concrete contains approximately 70 to 80% aggregates (coarse and fine) and 20 to 30% cement paste by mass. Therefore, aggregate is an essential component of concrete and has a significant effect on fresh and hardened concrete properties. In Thailand, recent statistics have shown that more than 180 million t of natural aggregates (Department of Primary Industry and Mines 2010) are used in the concrete industry each year; this value is showing a rapidly increasing trend due to industry expansion and economic growth, while the natural resources for producing aggregate are limited. At the same time, many old buildings and structures have reached their limit of use and need to be demolished. It is estimated that an average of 1.1 million t per year of demolition waste concrete is produced in Thailand (Kofoworola and Gheewala 2009), but its utilization is minimal and unmanaged. One application for using demolished concretes is as a low-value material for backfill in construction areas. Thus, almost all demolished concrete is dumped or disposed of as waste in landfills.

Over the last few decades, many researchers have studied the reuse of demolished concrete as recycled concrete aggregates in new concrete and have concluded that recycled concrete aggregates can be used as a new alternative source for producing aggregates in concrete (Ajdukiewicz and Kliszczewicz 2002; Rahal 2007; Tangchirpat et al. 2008). Topcu and Sengel (2004) reported that concrete incorporating more than 50% recycled concrete aggregate is especially problematic for the workability of fresh concrete. Poon et al. (2004) found that concrete should contain no more than 50% coarse recycled concrete aggregate in the air-dried state to yield recycled aggregate concrete of normal strength. In addition to reducing the compressive strength, recycled concrete aggregate also allows for high water absorption and results in low concrete workability. Chen et al. (2003) reported that the compressive strength of concrete containing 100% recycled coarse aggregate could be as low as 60% of the compressive strength of conventional aggregate.

Concretes made from recycled concrete aggregates have low workability and compressive strength. Moreover, most previous studies of recycled concrete aggregates in new concrete have focused on replacing either coarse or fine aggregates and have been limited to low replacement levels of recycled concrete aggregate. Therefore, all of the concrete used in this study was made from high amounts of recycled concrete aggregate, i.e., 100% recycled coarse aggregate and 100% of both coarse and fine recycled concrete aggregates. In addition, Class F fly ash was used to replace ordinary Type I portland cement in recycled aggregate concrete in order to increase its workability and improve the ultimate strength of the

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recycled aggregate concrete. The use of pozzolanic material in new concrete containing recycled concrete aggregates is one of several methods used to improve the hardened properties of recycled aggregate concrete in term of compressive strength. For instance, the compressive strength of recycled aggregate concrete could be improved by using silica fume, fly ash, and ground rice husk—bark ash (Kou et al. 2008; Gonzalez-Fonteboa and Martinez-Abella 2008; Tangchirapat et al. 2008). This method is more convenient than other methods such as removing old cement paste from the aggregate by using a ball mill (Montgomery 1998), treating the aggregate by ultrasonic cleaning (Katz 2004), or using a double-mixing method (Otsuki et al. 2003). In this study, the effects of fly ash replacement and fineness on the slump loss and mechanical properties such as compressive strength, splitting tensile strength, and the modulus of elasticity of recycled aggregate concretes were investigated, and these parameters were compared with those of conventional concrete.

The use of high levels of recycled concrete aggregate in new concrete would reduce the large quantity of demolished concrete, thereby helping the environment and conserving supplies of natural aggregates. Moreover, the use of fly ash may encourage other researchers to further study the use of fly ash in recycled aggregate concrete, resulting in a higher utilization of fly ash and a reduction in disposal waste from fly ash in landfills.

Experimental Program

Materials

Cement

Type I ordinary portland cement (OPC) used in both conventional concrete (CON) and recycled aggregate concretes had physical and chemical properties as shown in Tables 1 and 2, respectively.

Fly Ash

Lignite fly ash collected from the Mae Moh power plant in Thailand was used in this investigation. It is burnt by a pulverized coal combustion process at a temperature of 1,300–1,400°C. Original fly ash (OF) received directly from the power plant was ground by a grinding machine to reduce its size until the particles retained on a No. 325 sieve (45-μm opening) were 1.2% by weight; this was termed ground fly ash (GF). The physical properties of the fly ashes (OF and GF) are also reported in Table 1, while their chemical compositions are shown in Table 2. It was noted that the grinding process did not much change the chemical compositions of fly ash (Erdogdu and Turker 1998; Kiattikomol et al. 2001). The original and ground fly ashes were used as a pozzolanic material to partially replace OPC at replacement levels of 20, 35, and 50% by weight of binder for the recycled aggregate concrete.

Table 1. Physical Properties of Portland Cement Type I and Fly Ash

Sample	Specific gravity	Retained on a 45-μm sieve (No. 325) (%)	Median particle size, d_{50} (μm)
Cement	3.15	N/A	14.6
Original fly ash (OF)	2.19	42.5	27.1
Ground fly ash (GF)	2.72	1.2	7.7

Note: N/A = not applied.

Table 2. Chemical Compositions of Portland Cement Type I and Fly Ash

Chemical composition	Cement	Original fly ash (OF)	Ground fly ash (GF)
Silicon dioxide (SiO_2)	20.9	40.5	41.9
Aluminium oxide (Al_2O_3)	4.7	21.6	21.5
Iron oxide (Fe_2O_3)	3.4	12.3	12.7
Calcium oxide (CaO)	65.4	14.8	13.9
Magnesium oxide (MgO)	1.2	3.0	2.6
Sodium oxide (Na_2O)	0.2	0.9	2.7
Potassium oxide (K_2O)	0.3	3.0	2.5
Sulfur trioxide (SO_3)	2.7	1.8	0.6
Loss on ignition (LOI)	0.9	1.2	0.7

Natural Aggregates

In this experiment, local river sand with a fineness modulus of 3.04 and a specific gravity of 2.60 was used as a fine aggregate. Crushed limestone was used as a coarse aggregate, with a maximum size of 20 mm and a specific gravity of 2.67. The water absorptions of the coarse and fine aggregates were 0.46 and 0.94%, respectively.

Recycled Concrete Aggregates

In this investigation, cylinder concretes of 150×300 mm were obtained from various construction sites around Bangkok province in Thailand. These concretes were sent to the laboratory in order to determine the compressive strength. To avoid the difference of properties of recycled concrete aggregates caused by quality of the obtained concrete, the compressive strengths of concrete were controlled in the range of 25–40 MPa. After being tested for compressive strength, the tested concretes were crushed by swing hammer mills. The crushed concrete was then screened by sieving to separate coarse and fine recycled concrete aggregates, which were denoted as CRA and FRA, respectively. The physical properties of the recycled concrete aggregates (CRA and FRA) are reported in Table 3. Figs. 1(a and b) show the grading size of the recycled concrete aggregates compared with the ASTM C33 (2001a) requirements for fine and coarse aggregates, respectively. The CRA and FRA had a fineness modulus of 6.40 and 3.55, respectively. The fineness modulus of the CRA met the ASTM C33 (2001a) grading requirements, while the FRA had a fineness modulus slightly coarser than the limit specified by ASTM C33 (2001a).

The specific gravities of the CRA and FRA were 2.45 and 2.31, respectively, while the water absorption was 5.61 and 11.91%, respectively. These values conformed to the investigation reported by the Building Contractors Society of Japan (BCSJ) (1978) from which the specific gravity of coarse recycled concrete aggregate varied between 2.29 and 2.51, and fine recycled concrete aggregate between 2.19 and 2.32. The water absorption ranged from 3.6 to 8.0% for coarse recycled concrete aggregate and 8.3 to 12.1% for fine recycled concrete aggregate. The recycled concrete aggregates had a lower specific gravity and higher water absorption than the

Table 3. Physical Properties of Natural and Recycled Concrete Aggregates

Properties	Natural aggregates		Recycled concrete aggregates	
	River sand	Limestone	Fine	Coarse
Fineness modulus	3.04	6.79	3.55	6.40
Specific gravity (SSD)	2.60	2.67	2.31	2.45
Absorption (%)	0.94	0.46	11.91	5.61
Los Angeles abrasion loss (%)	N/A	21.70	N/A	33.08

Note: N/A = not applied.

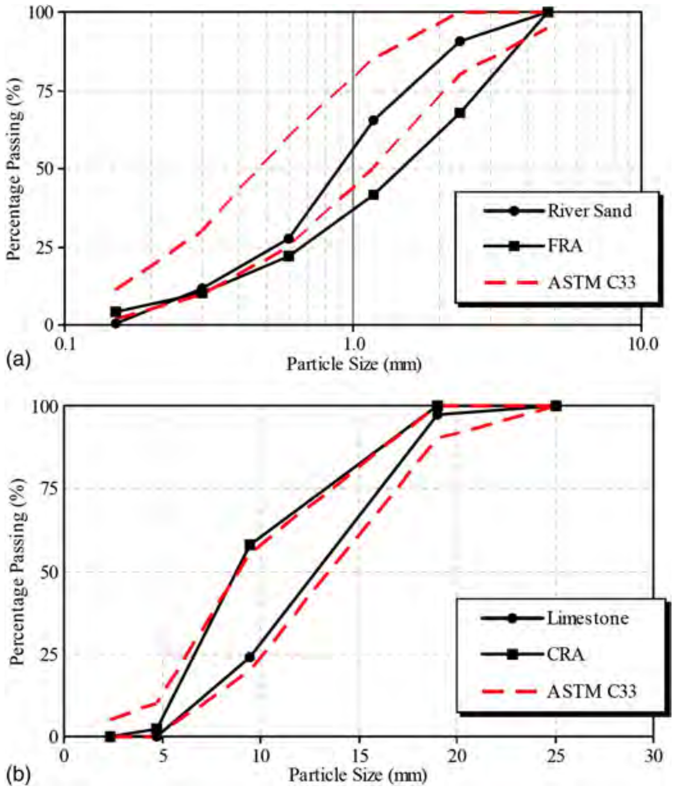

Fig. 1. Particle size distributions of river sand, limestone, and recycled concrete aggregates (FRA and CRA): (a) river sand and fine recycled concrete aggregate (FRA); (b) limestone and coarse recycled concrete aggregate (CRA)

natural aggregates. This was due to the residue from old mortar that adhered to the natural aggregate (Katz 2003; Rao et al. 2007). Moreover, the CRA had a Los Angeles abrasion of 33.08%, which was higher than that of the crushed limestone (21.70%). The high Los Angeles value of the CRA was caused by the adhering cement paste and mortar, which is usually weaker and has a lower density than natural aggregate (Shayan and Xu 2003).

Mixture Proportions

The mixture proportions of CON and recycled aggregate concretes are summarized in Table 4. It was noted that all natural aggregates and recycled concrete aggregates used in this experiment had the same condition, i.e., they were in the air-dried moisture state (as-received) and did not prewet or presoak prior batching. Generally, for the large-scale production of normal strength concrete, the optimal moisture condition is the air-dried moisture state. In addition, Barra de Oliveira and Vazquez (1996) and Poon et al. (2004) reported that the compressive strengths of recycled aggregate concretes prepared with air-dried and saturated surface dried aggregates were slightly different. A constant effective water to binder ratio (W/B) of 0.48 was used for all concrete mixtures. Because the recycled concrete aggregates had higher water absorption than the natural aggregates, this resulted in recycled aggregate concrete mixtures requiring more water to maintain the slump of fresh concrete between 50 and 100 mm. Therefore, the amount of mixing water was adjusted to compensate for the water absorbed by the recycled concrete aggregates.

All fresh concretes were prepared using a rotating drum mixer in the laboratory. The first step of mixing was to place fine and coarse aggregates into the mixer along with the water about one-half of effective water, and then mixed for 60 s. At this step, surface aggregates were wetted and absorbed some fractions of the water into aggregate particles. After that, the binder was being added, then with the remaining effective water, and the mixture was mixed for another 60 s. Finally, the remaining mixing water was gradually added and the mixing continued for the last 120 s in order to obtain the slump of fresh concrete between 50 and 100 mm.

In this study, the recycled aggregate concretes were divided into two groups. The first group was prepared by using 100% CRA and local river sand, denoted as the AF series of recycled aggregate concrete. For the other group, crushed limestone and local river sand were fully replaced by both CRA and FRA, denoted as the BF series of recycled aggregate concrete. In addition, original and ground fly ash was used to replace OPC at rates of 20, 35, and 50% by weight of binder. The properties of the recycled aggregate concretes were investigated and compared with that of conventional concrete in which crushed limestone and local river sand were used as aggregates.

Table 4. Mixture Proportions of Concretes

Mix	Mix proportion (kg/m^3)								W/B[c]	Slump (mm)
	Cement	Fly ash	Limestone	Sand	FRA[a]	CRA[b]	Mixing sater	Effective sater		
CON	380	—	1,006	800	—	—	191.0	182.4	0.48	60
AF	380	—	—	800	—	1,006	214.5	182.4	0.48	70
AOF20	304	76	—	790	—	994	214.0	182.4	0.48	80
AOF35	247	133	—	780	—	982	213.5	182.4	0.48	90
AOF50	190	190	—	770	—	970	213.0	182.4	0.48	100
AGF20	304	76	—	795	—	1,000	214.3	182.4	0.48	70
AGF35	247	133	—	790	—	994	214.0	182.4	0.48	80
AGF50	190	190	—	785	—	988	213.8	182.4	0.48	85
BF	380	—	—	—	800	1,006	256.5	182.4	0.48	50
BOF20	304	76	—	—	790	994	255.8	182.4	0.48	60
BOF35	247	133	—	—	780	982	254.9	182.4	0.48	70
BOF50	190	190	—	—	770	970	254.1	182.4	0.48	90
BGF20	304	76	—	—	795	1,000	256.2	182.4	0.48	60
BGF35	247	133	—	—	790	994	255.8	182.4	0.48	70
BGF50	190	190	—	—	785	988	255.4	182.4	0.48	80

[a]FRA = fine recycled concrete aggregate in air-dried condition.
[b]CRA = coarse recycled concrete aggregate in air-dried condition.
[c]W/B ratio was based on the saturated surface dry (SSD) condition of fine and coarse recycled concrete aggregates.

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Testing of Specimens

In this study, the slump loss of fresh concrete was measured using a standard slump test apparatus as described in ASTM C143 (2001c). The initial slump value was recorded immediately after mixing, and slump values were then measured every 15 min until the slump value of the fresh concrete was zero.

For compressive strength testing, cylindrical concrete samples 100 mm in diameter and 200 mm in height were cast and compacted by tamping. After casting, the specimens were allowed to set for 24 h; they were then removed from the molds and cured in water until the day of testing. The compressive strength of the specimens was determined at 7, 28, and 90 days. The splitting tensile strength and the modulus of elasticity of all concretes were also investigated at 28 days. The splitting tensile strength and modulus of elasticity of concrete were determined according to ASTM C496 (2001d) and C469 (2001e), respectively. At each testing age for the compressive strength, splitting tensile strength, and modulus of elasticity, the average of three concrete specimens was used to represent the mechanical properties of the concretes. The acceptable ranges of the tested results (average of the three specimens) were within 7.8% as specified by ASTM C39 (2001b).

Results and Discussion

Workability

The results of the initial slump and the amount of mixing water required for the recycled aggregate concrete mixtures are presented in Table 4. It was found that the recycled aggregate concretes required more mixing water than the CON concrete, particularly the concrete containing both coarse and fine recycled concrete aggregates. This was due to very high water absorption of the recycled concrete aggregates, which was approximately 12–13 times greater than those of the natural aggregates. In addition, the highly angular and rough surface of fine recycled concrete aggregate as compared with the river sand may be also recognized as a factor for more mixing water in BF concrete to achieve the same workability as fresh concrete.

The recycled aggregate concrete with original and ground fly ash required almost the same amount of mixing water as the recycled aggregate concrete without fly ash. However, the slump of fresh concrete made from the recycled concrete aggregate with fly ash seemed to increase slightly with increasing fly ash replacement. This result is due to the fact that fly ash with and without grinding has a much lower specific gravity than OPC, thus producing a greater volume of paste and leading to reduced aggregate particle interference and improved concrete workability.

Concerning the effects of the fly ash fineness on the fresh properties of the recycled aggregate concretes, it was found that the recycled aggregate concretes containing ground fly ash had an initial slump of fresh concrete that was slightly lower than that of the recycled aggregate concrete containing original fly ash at the same replacement levels. For example, the AOF20, AOF35, and AOF50 concretes had initial slumps of 80, 90, and 100 mm, respectively, while the AGF20, AGF35, and AGF50 concretes had initial slumps of 70, 80, and 85 mm, respectively. These lower initials slumps occur because the ground fly ash particles have a larger surface area than the original fly ash particles. The finer particle fly ash needed more water to coat the fly ash particles than the coarser one and led to reducing the amount of mixing water, resulting in a decrease in the workability of concrete. Additionally, most of the ground fly ash particles have irregular and angular shapes, resulting in increased friction between the aggregates.

Slump Loss

The slump losses of the CON concrete and recycled aggregate concretes are shown in Fig. 2. The slump loss of the CON concrete reached zero at approximately 105 min after mixing, while the AF and BF concretes had zero slump loss values at 90 and 60 min, respectively. The recycled aggregate concretes exhibited a faster slump loss than the CON concrete because of the high water absorption of the recycled concrete aggregate, which quickly reduced the amount of water in the mixture.

The slump loss of the fresh recycled aggregate concrete decreased when the fly ash replacement was increased. For example, the concrete samples made of 100% CRA, 100% river sand, and 0, 20, 35, or 50% original fly ash by weight of binder had slump loss to zero value at 90, 105, 120, and 150 min after mixing, respectively. Moreover, the slump loss for the AOF20 concrete was similar to that of the CON concrete, while the slump loss of the BOF50 concrete occurred more slowly than that of the CON concrete. This finding indicates that the use of fly ash can reduce the slump loss of recycled aggregate concrete and is similar to the results of Ravina (1984), who reported that fly ash can reduce slump loss when it is used to partially replace cement in conventional concrete. The slower slump loss may be due to two factors: first, the use of fly ash in concrete typically increases the setting

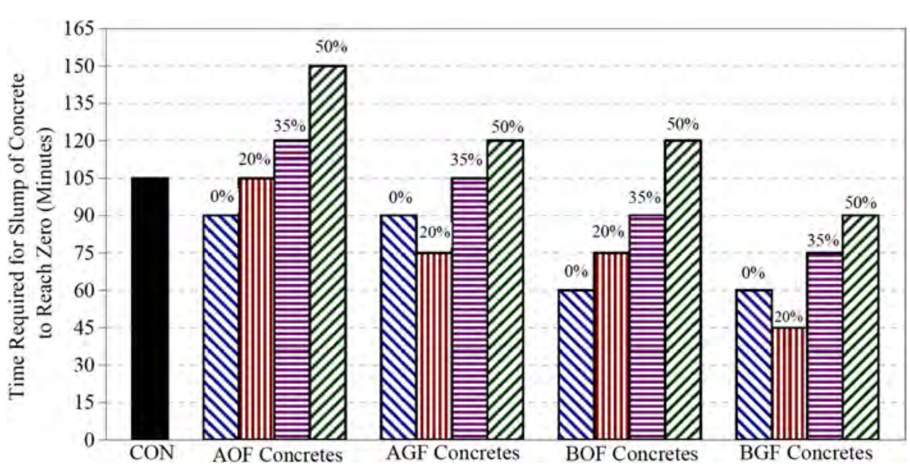

Fig. 2. Slump loss of concretes containing recycled concrete aggregates (values above the bars indicate the percentage of fly ash replacement)

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time of the concrete, and second, the cement content in the concrete mixture decreases due to the fly ash replacement (Kiattikomol et al. 2001).

After increasing the fineness of fly ash by grinding, the slump loss of the AF and BF series of recycled aggregate concretes varied from 75 to 120 and from 45 to 90 minutes, respectively. When the fineness of the fly ash was increased, the slump loss of the recycled aggregate concrete also increased because the fineness of the ground fly ash had a greater surface area for reacting with water. Additionally, the sample with 20% GF as a cement replacement exhibited the lowest slump loss of the recycled aggregate concretes, with times of 75 and 45 minutes for the AF and BF series of recycled aggregate concretes, respectively. With 35 and 50% GF replacement, however, the slump loss of the recycled aggregate concretes was increased and higher than that of the recycled aggregate concrete without fly ash.

Compressive Strength

The compressive strengths of the recycled aggregate concretes with and without fly ash as compared with that of the CON concrete are shown in Fig. 3. The compressive strength of the CON concrete at the age of 28 days was 47.0 MPa, while the AF concrete had a slightly lower compressive strength than the CON concrete, 44.1 MPa or 94% of the CON concrete strength at the same age. This indicated that the use of 100% CRA had not much effect on reducing the compressive strength of the concrete. The results agree with those of Gerardu and Hendriks (1985), who found that the compressive strength of concrete made with coarse recycled concrete aggregate and river sand was similar to or slightly lower than that of the conventional concrete. The results of compressive strength of concrete containing coarse recycled concrete aggregate obtained from this study were slightly lower than the conventional concrete, while the other studies showed that the compressive strength of that concrete was much lower (Chen et al. 2003) or slightly greater than the conventional concrete (Wade et al. 1997). This can be attributed to the difference of the original aggregate quality, crushing and mixing processes, and adhered mortar volume, which have large influences on the mechanical properties of the recycled aggregate concrete. Recycled concrete aggregates used in this experiment were in air-dried conditions and were not prewet prior batching, thus the additional mixing water reserved for aggregate absorption may not be fully absorbed by the aggregates in the period of mixing. Therefore, some of the additional mixing water still remained in the paste, resulting in an increasing of the W/B ratio of concrete. This manner may have an effect on reducing the compressive strength of the AF concrete.

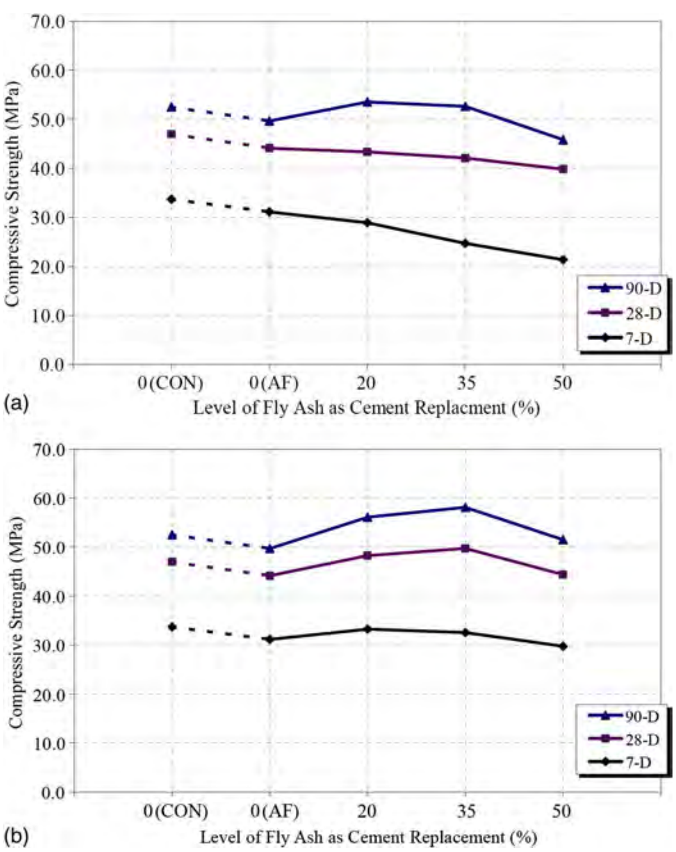

Fig. 3. Relationship between compressive strength and level of fly ash as cement replacement of concrete containing 100% CRA and 100% river sand (AF series): (a) AF series concretes with OF; (b) AF series concretes with GF

For the BF concrete, the compressive strength at 28 days was 35.9 MPa or 76% of that of the CON concrete. This result suggested that the use of both 100% coarse and fine recycled concrete aggregates had a strong effect on reducing the compressive strength of recycled aggregate concretes. Hansen and Narud (1983) and Topcu and Guncan (1995) observed a similar relationship for large quantities of concrete made from coarse and fine recycled concrete aggregates, which resulted in lower compressive strength as compared to the CON concrete. The results also found that the compressive strength at 28 days of AF concrete was only reduced 6% from CON concrete, while that of BF concrete was 24%. This result suggested that the use of fine recycled concrete aggregate had more effect on reducing the compressive strength of recycled aggregate concrete than the use of coarse recycled concrete aggregate. The lower compressive strength of BF concrete as compared with those of CON and AF concretes could be explained as having two reasons: (1) the mortar strength of BF concrete was reduced due to the lower strength of fine recycled concrete aggregate as compared with natural river sand (Chen et al. 2003), and (2) BF concrete required a high amount of mixing water due to high water absorption of fine recycled concrete aggregate leading to the lower of compressive strength.

Fig. 3(a) shows the relationship between the compressive strength and the level of fly ash replacement for concrete made from 100% CRA, 100% river sand, and OF. It was found that at 28 days, the AOF20, AOF35, and AOF50 concretes had compressive strengths of 43.4, 42.2, and 39.8 MPa, respectively. This finding implied that the higher the replacement of OF, the lower the compressive strength in the AOF concretes. At 90 days, however, the compressive strength of the AOF20 and AOF35 concretes increased to 53.6 and 52.7 MPa, respectively, which was 5–7% higher than that of the recycled aggregate concrete without OF.

Among recycled aggregate concrete containing ground fly ash (AGF concretes), as shown in Fig. 3(b), the AGF20 concrete had a compressive strength of 48.3 MPa at 28 days, which was higher than that of the AF concrete. The highest compressive strength of the AGF concretes was found for the AGF35 concrete, which was approximately 111% of the CON concrete at 90 days. The increased compressive strength of the recycled aggregate concrete mixed with ground fly ash could be attributed to the fineness of the ground fly ash particles, which filled the voids between the cement and the recycled concrete aggregates, and to the presence of SiO_2 and Al_2O_3 in the ground fly ash, which reacted with the $Ca(OH)_2$ generated by the hydration process to form additional calcium silicate hydrates (C-S-H), thus improving interfacial bonding

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between the recycled concrete aggregate and pastes (Poon et al. 2004; Li et al. 2009). These characteristics improved the compressive strength of the recycled aggregate concretes. In addition, the use of 50% GF in replacing the cement gave a compressive strength of 44.4 MPa at 28 days, which increased to 51.5 MPa at 90 days, corresponding to the strength of 94 and 98% of the CON concrete, respectively.

The results for concretes containing 100% CRA, 100% FRA, and OF at 20, 35, or 50% by weight of binder are shown in Fig. 4(a). It was found that the recycled aggregate concretes containing original fly ash had a lower compressive strength than the BF concrete at all tested ages, and that the compressive strength of the recycled aggregate concretes decreased with increasing OF replacement. This result revealed that the increase in compressive strength of the recycled aggregate concrete due to the pozzolanic reaction between the SiO_2 and Al_2O_3 in the OF and $Ca(OH)_2$ cannot compensate for the reduction in compressive strength of the recycled aggregate concrete caused by sand replacement by FRA.

After increasing the fineness of the fly ash by grinding, the compressive strength of the recycled aggregate concrete was increased [see Fig. 4(b)]. For example, the BGF20, BGF35, and BGF50 concretes had compressive strengths of 37.2, 38.8, and 35.8 MPa (79, 83, and 76% of CON concrete) at 28 days, respectively. Moreover, at 90 days, the compressive strength of the recycled aggregate concretes with 20–50% ground fly ash had compressive strengths higher than that of the BF concrete, which tended to increase over time. The higher compressive strength of the recycled aggregate concretes can be explained by the greater fineness of the ground fly ash, which promotes the pozzolanic reaction and fills the voids of the recycled aggregate concrete.

The previous results suggest that fly ash can be used to increase the ultimate compressive strength of concrete containing high amounts of recycled concrete aggregates, depending on the fly ash fineness and its degree of replacement. Concrete made from 100% CRA and river sand has an optimum cement replacement by original and ground fly ash of 20 and 35% by weight of binder, respectively. For this mixture proportion, the compressive strength of the recycled aggregate concrete at 90 days is expected to be as high as that of the CON concrete. For concrete made from both 100% CRA and FRA, the original fly ash did not show any significant improvement in the compressive strength of the recycled aggregate concrete. When the fly ash was processed to have high fineness, however, the compressive strength of the recycled aggregate concrete with ground fly ash was increased and could be higher than that of recycled aggregate concrete with original fly ash. Additionally, the replacement of cement by 35% ground fly ash resulted in a compressive strength of recycled aggregate concrete higher than 85% of that of the CON concrete.

Splitting Tensile Strength

The relationship between the splitting tensile strength and square root of compressive strength of the recycled aggregate concretes is shown in Fig. 5(a). Eq. (1) expresses the best-fit equation for splitting tensile strength based on data from this experiment. The splitting tensile strength of the recycled aggregate concretes

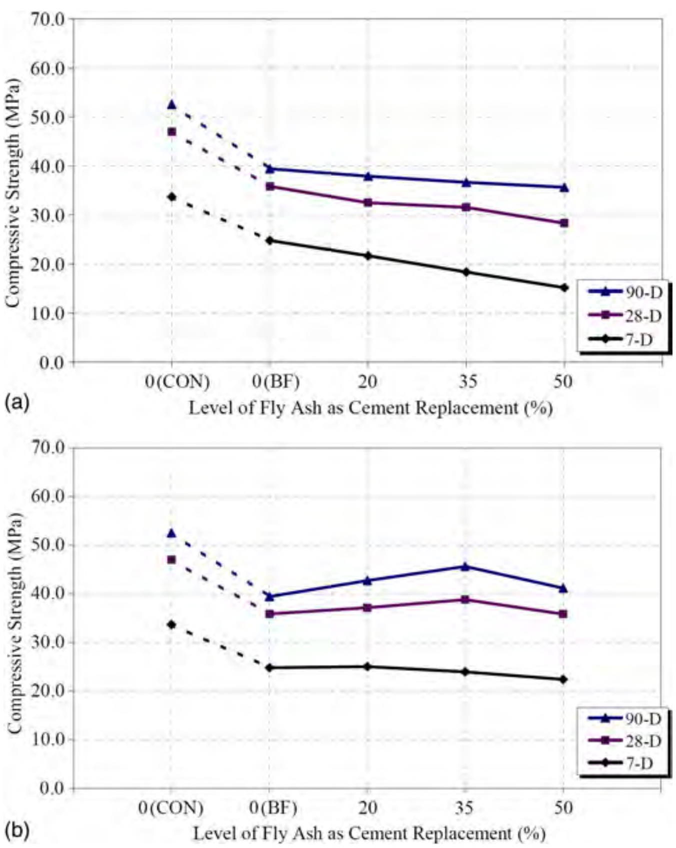

Fig. 4. Relationship between compressive strength and level of fly ash as cement replacement of concrete containing 100% CRA and 100% FRA (BF series): (a) BF series concretes with OF; (b) BF series concretes with GF

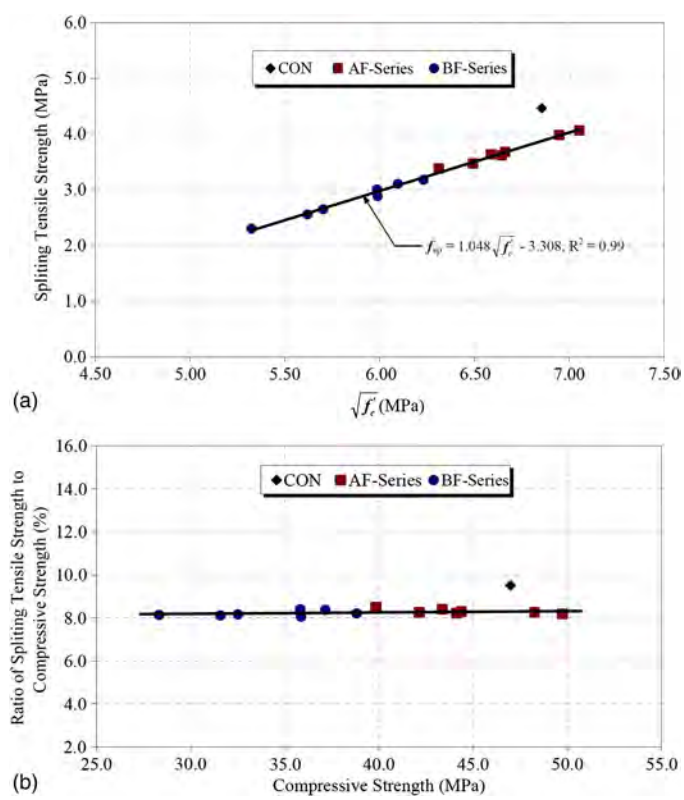

Fig. 5. Splitting tensile strength of concrete: (a) relationship between splitting tensile strength and square root of compressive strength of recycled aggregate concrete; (b) relationship between ratio of splitting tensile strength to compressive strength and compressive strength of recycled aggregate concrete

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with and without fly ash in the present experiment varied from 2.30 MPa in the BOF50 concrete to 4.07 MPa in the AGF35 concrete, while that of the CON concrete was 4.46 MPa. All of the recycled aggregate concretes had a lower splitting tensile strength than the concrete made from natural aggregate. In addition, the highest and lowest values of splitting tensile strength occurred in AGF35 and BOF50 concretes, respectively, which was similar to the result of compressive strength. Moreover, the splitting tensile strength of the recycled aggregate concretes tended to increase with increasing compressive strength.

$$f_{sp} = 1.048\sqrt{f_c'} - 3.308 \tag{1}$$

where f_{sp} = splitting tensile strength of recycled aggregate concrete (MPa); and f_c' = compressive strength of recycled aggregate concrete (MPa).

Fig. 5(b) shows the relationship between the ratio of the splitting tensile strength to the compressive strength and the compressive strength of the recycled aggregate concretes. The ratio of the splitting tensile strength to the compressive strength of the CON concrete was 9.5%, while those of the AF and BF concretes were 8.2 and 8.0%, respectively. It is noted that the splitting tensile strength of the recycled aggregate concrete seems to be slightly lower than that of the CON concrete. A similar result was obtained by Corinaldesi and Moriconi (2009), who found that the splitting tensile strength of recycled aggregate concrete is approximately 10% lower than that of conventional concrete because the adhered mortar in the recycled aggregate has a lower strength than natural aggregate, causing the concrete made from recycled concrete aggregate to be weaker. In addition, by visual inspection, as shown in Fig. 6, it was observed that the failure of the recycled aggregate concrete after the splitting tensile strength testing occurred through the old cement paste or mortar adhering to the recycled concrete aggregate.

Considering the effect of fly ash fineness and its replacement on the splitting tensile strength of recycled aggregate concrete, it was found that recycled aggregate concretes containing OF and GF exhibited maximum and minimum ratio values of splitting tensile strength to compressive strength of 8.1 and 8.5%, respectively, which was the same as those of recycled aggregate concretes without fly ash (AF and BF concretes). As found in this experiment, the incorporation of either original or ground fly ash did not have a great effect on the splitting tensile strength of the recycled aggregate concrete.

Modulus of Elasticity

The modulus of elasticity measured after 28 days of curing for the recycled aggregate concretes based on 100 mm diameter and 200 mm length cylindrical concrete is shown in Fig. 7. The AF and BF concretes had an average modulus of elasticity of 31.0 and 26.7 GPa, respectively, which is 11 and 24% lower than that of the CON concrete (34.9 GPa). This result indicates that the incorporation of recycled concrete aggregate into the new concrete decreased the modulus of elasticity, particularly when both coarse and fine recycled concrete aggregates were used. Hansen (1992) reported that due to the large amount of old mortar with a comparatively low modulus of elasticity adhering to the original aggregate particles in recycled concrete aggregates, the modulus of recycled aggregate concrete is always lower than that of conventional concrete. Furthermore, recycled concrete aggregate had high uncompacted void content, providing a low modulus of elasticity to the recycled aggregate concrete (Topcu and Sengel 2004). Neville (1997) and Evangelista and Brito (2007) concluded that the modulus of elasticity of concrete was strongly related to the stiffness of the coarse aggregates, the stiffness of the mortar, their porosity, and the bond of the mortar. Therefore, for BF concrete, it could be concluded that the lower stiffness and bond of the mortar as well as the porosity in fine recycled concrete aggregate were also significantly influenced to reduce the modulus of elasticity of concrete.

The recycled aggregate concretes mixed with original and ground fly ash had lower modulus of elasticity values than the CON concrete, even though some mixtures of recycled aggregate concretes had equivalent or greater compressive strengths than the CON concrete. For example, the modulus of elasticity of the AGF35 concrete was 32.4 GPa, with a corresponding compressive strength of 49.7 MPa, while that of the CON concrete was 34.9 GPa with a compressive strength of 47.0 MPa. This behavior occurs because the modulus of elasticity of typical concrete is usually related to the strength of the aggregate rather than the strength of the cement paste (Corinaldesi and Moriconi 2009; Neville 1997). In addition, the use of fly ash as a cement replacement slightly decreases the aggregate content of the concrete mixture when compared with that of the CON concrete, resulting in a decreased modulus of elasticity (Cetin and Carrasquillo 1998).

Eq. (2) was used to predict the modulus of elasticity values of the recycled aggregate concretes with and without fly ash having the compressive strength varied between 30 and 50 MPa. The coefficient of determination (R^2) was found using least-square linear-regression analysis for the best type of equation that fits the data. A very strong correlation was found for the relationship between

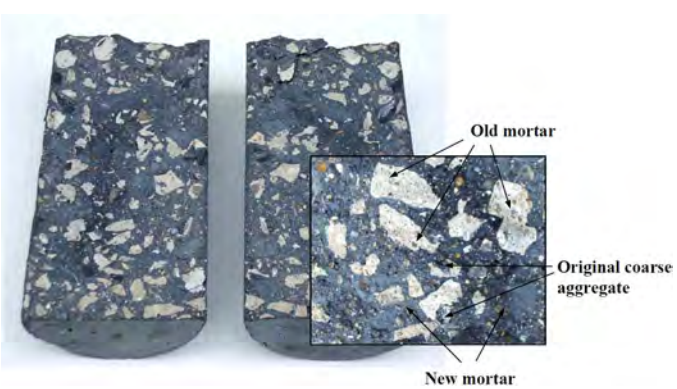

Fig. 6. Failure of recycled aggregate concrete sample after splitting tensile strength testing

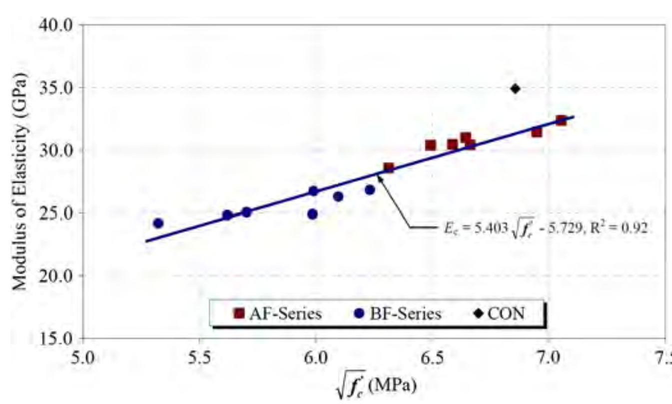

Fig. 7. Relationship between modulus of elasticity and square root of compressive strength of recycled aggregate concrete

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square root of compressive strength and modulus of elasticity of recycled aggregate concrete with and without fly ash ($R^2 = 0.92$). The results indicate that the modulus of elasticity values of the recycled aggregate concretes (with and without fly ash) are lower than that of the CON concrete by approximately 12% for the same compressive strength. This result agrees with Hansen and Boegh (1985), who reported that the modulus of elasticity of recycled aggregate concrete was reduced by approximately 14–28%, depending on the quality of the recycled concrete aggregate. Similar to the results of splitting tensile strength, the addition of original or ground fly ash did not have an effect on the modulus of elasticity of the concrete. The modulus of elasticity of the recycled aggregate concrete containing fly ash was still related to its compressive strength, i.e., it increases with the compressive strength.

$$E_c = 5.403\sqrt{f_c'} - 5.729 \tag{2}$$

where E_c = modulus of elasticity of recycled aggregate concrete (GPa); and f_c' = compressive strength of recycled aggregate concrete (MPa).

Conclusions

Based on the experimental results of this study, the following conclusions can be drawn:

- Concretes containing recycled concrete aggregates had slump loss faster than the conventional concrete, which was in the range of 15–45 min. However, use of fly ash in replacing Type I portland cement was effective to slow the slump loss of the recycled aggregate concrete, depending on the degree of fly ash replacement. The use of finer fly ash gave a slightly increased slump loss for the recycled aggregate concrete as compared to coarser fly ash. However, the slump loss of the recycled aggregate concrete containing 35% ground fly ash by weight of binder was slower than that of the recycled aggregate concrete without fly ash.
- Both OF and GF can be used to increase the compressive strength of recycled aggregate concrete, with strengths equal to or higher than that of concrete made from natural aggregate. In the case of concrete made of 100% CRA and FRA, the replacement of cement by 35% ground fly ash gave a desirable compressive strength of the recycled aggregate concrete at 85% of that of the CON concrete.
- The incorporation of original or ground fly ash did not alter the splitting tensile strength of the recycled aggregate concrete. The splitting tensile strength of the recycled aggregate concrete with or without fly ash ranged from 8.1 to 8.5% of its compressive strength, which was slightly lower than that of the conventional concrete (approximately 10%).
- The addition of fly ash in the recycled aggregate concrete did not have a significant effect on the modulus of elasticity values of the recycled aggregate concrete. The modulus of elasticity of the recycled aggregate concretes was still related to its compressive strength.

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