CHAPTER 4 RESULTS AND DISCUSSIONS

This chapter consists of the results and discussions of physical properties and chemical compositions of the calcium carbide residue and pozzolanic materials. Furthermore, setting times, compressive strength, modulus of elasticity, and splitting tensile strength of concrete using CR-pozzolans as a binder in concrete were reported and discussed. Moreover, Portland cement type I at 10% by weight of binder (CR-pozzolans) was used to improve properties of CR-pozzolans concrete. Concrete with W/B of 0.45, the water permeability were presented. For high-strength concrete (W/B = 0.25), the temperature rise result of high-strength concrete was discussed. In addition, the use of CR-pozzolans as a binder in concrete brick was also summarized.

4.1 Properties of Calcium Carbide Residue and Pozzolanic Materials

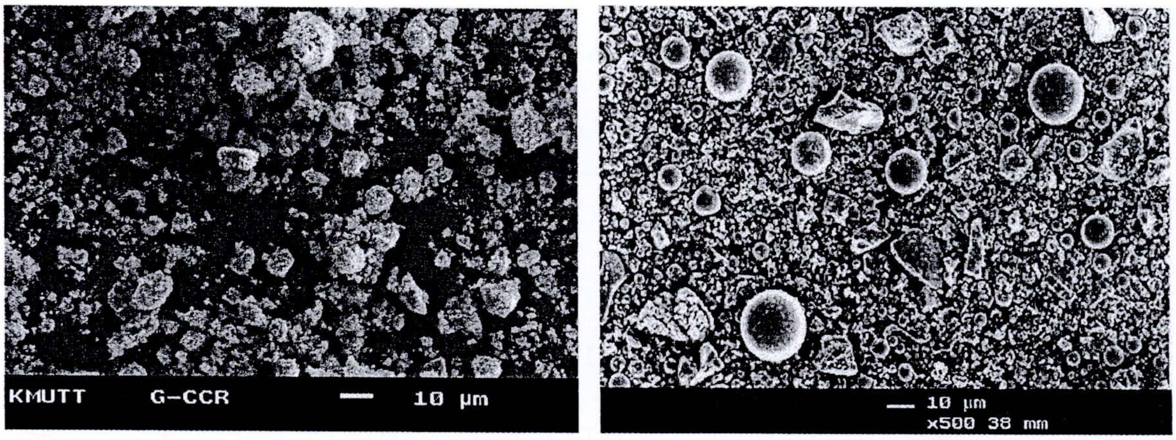
Figure 4.1 presents the particle morphologies of ground calcium carbide residue, ground pulverized coal combustion fly ash, ground fluidized bed combustion fly ash, ground palm oil fuel ash, and ground rice husk-bark ash from which the abbreviations were designed as CR, FM, FN, PA, and RA, respectively. Physical properties of CR, FM, FN, PA, RA and OPC are shown in Table 4.1. In addition, the particle size distributions of CR, FM, FN, PA, and RA obtained from a Mastersizers Malvern Instrument are shown in Figure 4.2.

4.1.1 Physical Properties

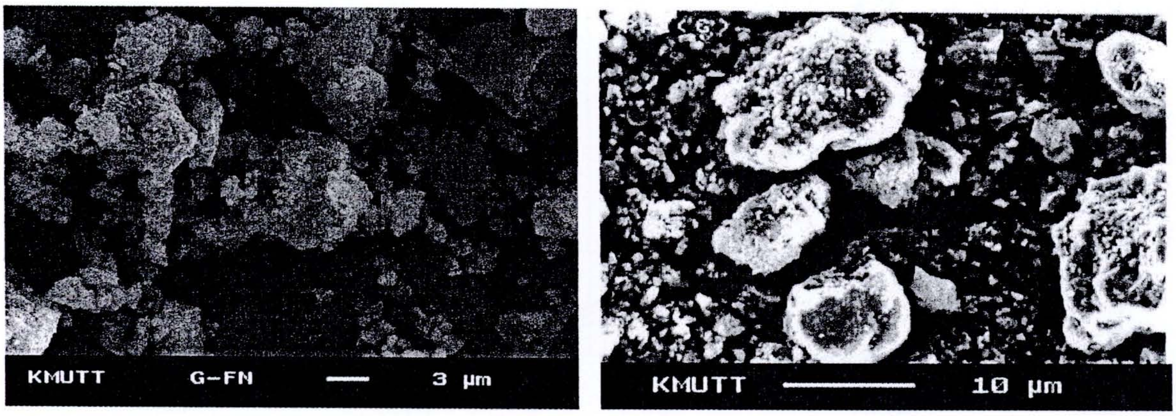
After grinding, the median particle size (d_{50}) of CR was 4.4 μm while the particles were retained on a 45-μm sieve were 2.3% by weight. CR had an irregular shape with spongy particles (see Figure 4.1(a)). The specific gravity of CR was 2.41, higher than the previous research reported by Jaturapitakkul and Roongreung (2003) and Krammart and Tangtermsirikul (2004), which were 2.21 and 2.26, respectively. The scanning electron microscope image of ground pulverized coal combustion fly ash (FM) showed that it was a mixture of crushed particles and spherical shapes (see Figure 4.1(b)). Figure 4.1(c) indicated that the ground fluidized bed combustion fly ash (FN) composed of crushed particles and irregular shapes.

The FM fly ash had a specific gravity of 2.72 while that of FN fly ash was 2.39. The particles retained on a 45-μm sieve of FM and FN were 1.0 and 1.3% by weight while the median particle sizes (d_{50}) were 6.0 and 5.4 μm, respectively. The result indicated that the specific gravity of FM was higher than that of FN although the median particle size of FM was closed to FN. This is because FM had solid particles while FN was porous particles.

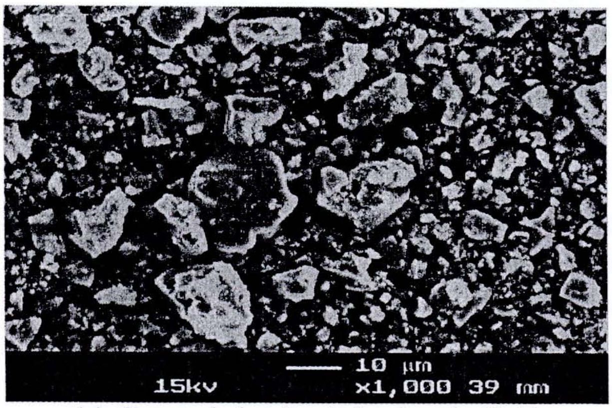
Ground palm oil fuel ash (PA) was in crushed shapes (see Figure 4.1(d)). The specific gravity of PA was 2.52. In addition, the particles by weight retained on a 45-μm sieve and its median particle sizes (d_{50}) were 1.4% and 6.2 μm, respectively. The specific gravity of ground rice husk-bark ash (RA) was 2.15. The median particle size (d_{50}) and the particles retained by weight on a 45-µm sieve of RA were 5.0 µm and 1.9%, respectively. Figure 4.1(e) shows the particle shapes of RA which had angular and irregular shapes.



(a) Ground calcium carbide residue (CR) (b) Ground pulverized coal fly ash (FM)



(c) Ground fluidized bed fly ash (FN) (d) Ground palm oil fuel ash (PA)



(e) Ground rice husk-bark ash (RA)

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Figure 4.1 Scanning electron microscope images of CR, FM, FN, PA, and RA

Table 4.1 Physical properties of CR, FM, FN, PA, RA, and OPC.

Physical properties	CR	FM	FN	PA	RA	OPC
Specific gravity	2.41	2.72	2.39	2.52	2.15	3.14
Retained on a 45-μm sieve (%)	2.3	1.0	1.3	1.4	1.9	N/A
Median particle size, d_{50} (micron)	4.4	6.0	5.4	6.2	5.0	14.7

Note: N/A means that it is not applied.

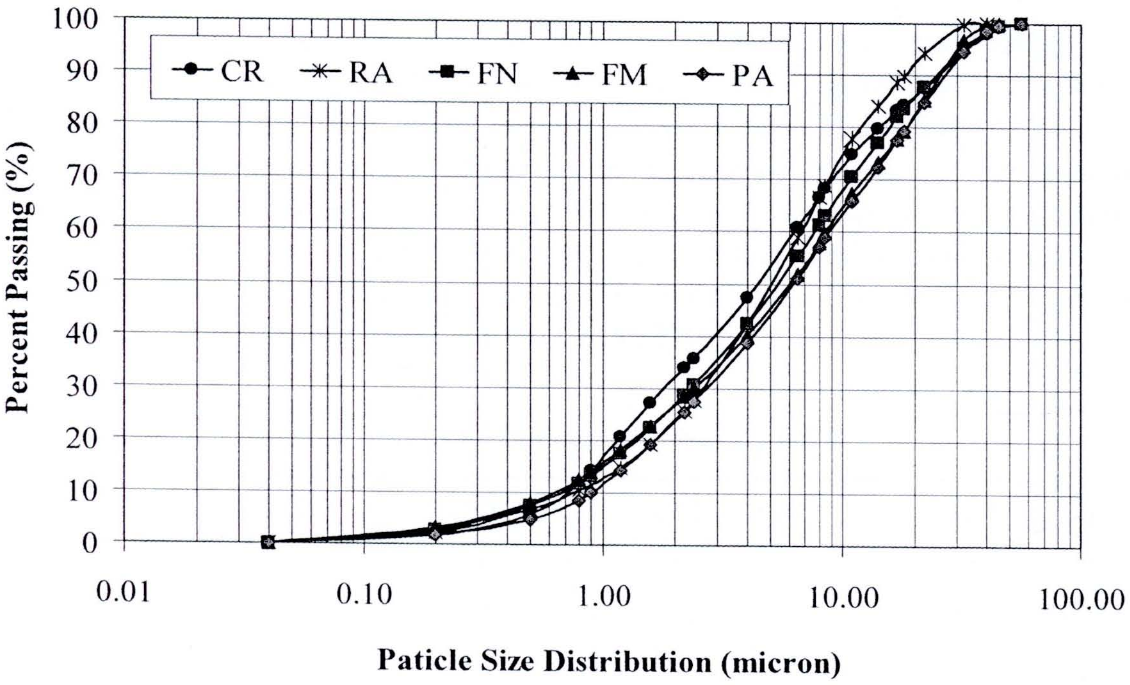

Figure 4.2 Particle size distributions of materials

4.1.2 Chemical Compositions

Table 4.2 shows the chemical compositions of calcium carbide residue and pozzolanic materials, determined by X-Ray Fluorescence analysis. It was found that CR had 51.9% of CaO as major chemical composition while the total of SiO_2, Fe_2O_3, and Al_2O_3 was only 6.3%. Moreover, CR had a high degree of loss on ignition (LOI): 41.7%. This LOI was particularly high because the LOI was determined at temperatures of 950 – 1000 °C while CR mainly consisting of $Ca(OH)_2$ decomposes into CaO and H_2O (gas) at temperature approximately 550 °C (Jaturapitakkul, et al., 2003). This high LOI value is similar to that reported by Krammart and Tangtermsirikul (2004): 31.7%. It should be noted that the CaO content of CR was 51.9% or about half of the total chemical composition and is not the same as that of CaO in Portland cement.

The sum of SiO_2, Fe_2O_3, and Al_2O_3 content of FM was 78.5% while that of FN was 71.7%. It was revealed that both fly ashes (FM and FN) had the 3 oxide contents higher than the minimum requirement of 70.0% as specified by ASTM C618 (2010) for fly ash Class F. In addition, the CaO, SO_3, and LOI values of FM and FN were 13.8, 1.2, 0.8 and 21.9, 4.1, 5.2%, respectively. Therefore, both fly ashes (FM and FN) could be classified as Class F fly ash according to ASTM C618.

Previous research from Tangchirapat, et al. (2007), palm oil fuel ash had total amount of SiO_2, Al_2O_3, and Fe_2O_3 lower than 70%. Furthermore, LOI value was 10.5% which was higher than 10%. However, PA of this study had the total oxide contents (SiO_2, Fe_2O_3, and Al_2O_3), LOI, and SO_3 of 70.3, 7.9, and 2.3%, respectively.

The major chemical composition of RA was 74.8% of SiO_2 which was not much different from that of rice husk ash (78.2% of SiO_2) studied by Jaturapitakkul and Roongreung (2003). The SO_3 and LOI were 0.5 and 11.2%, respectively. It was noted that the LOI of RA was slightly higher than the specified value from ASTM C618. At 7 and 28 days, however, results of Makaratat, et al. (2004) showed that the strength activity indices of rice husk-bark ash mortar were 87 and 92%, respectively which were higher than 75% of control mortar. The results suggested that the RA could be used as a pozzolanic material even though the chemical compositions of the RA could not be classified as a pozzolan according to ASTM C618 (2010).

Table 4.2 Chemical compositions of OPC, CR, FM, FN, PA, and RA

Chemical compositions (%)	OPC	CR	FM	FN	PA	RA
SiO_2	20.9	3.4	44.6	47.8	55.5	74.8
Al_2O_3	4.8	2.6	23.5	17.7	5.6	0.2
Fe_2O_3	3.4	0.3	10.4	6.2	9.2	0.8
CaO	65.4	51.9	13.8	21.9	12.4	5.9
MgO	1.3	0.5	3.3	1.3	4.6	0.6
Na_2O	0.3	0.0	0.1	0.0	0.3	0.2
K_2O	0.4	0.0	2.6	0.1	5.7	2.0
SO_3	2.7	0.2	1.2	4.1	2.3	0.5
Loss on ignition	1.0	41.7	0.8	5.2	7.9	11.2

4.2 Fresh Concrete Properties

Workability of fresh concrete shall be specified when concrete is placed in areas with high reinforcement congestion. In addition, the times for setting of fresh concrete are also important in concrete construction operations such as transporting, placing, compacting, and finishing of the concrete. This information is necessary issues when deciding whether or not to use retarding or accelerator admixture. Moreover, the heat in concrete is evolved due to the hydration reaction and the temperatures in mass concrete gradually increase. The result in a temperature difference in mass concrete, subsequently induce the internal restraint and the subsequent thermal contraction cracking in concrete. In this experiment, the requirement of superplasticizer, setting times, and heat evolution of fresh concrete were studied to evaluate the fresh concrete properties.

4.2.1 Requirement of Superplasticizer

The results of superplasticizer requirement and the slumps in all concrete mixtures are presented in Table 3.1. For normal-strength concrete (W/B = 0.65 and 0.45), the slump of fresh concrete was maintained between 50 and 100 mm by using naphthalene formaldehyde superplasticizer Type A&F while 150-200 mm of the slump was also maintained for high-strength concrete mixture (W/B = 0.25) with polymer-based high range water-reducing admixture Type F.

It was found that CR-FN(0.65) and CR-FN(0.45) concretes required 2.8 and 9.0 kg/m^3 of superplasticizer to maintain the slump of fresh concrete within the controlled range (50-100mm), respectively. This demonstrated that the superplasticizer dosage in the CR-pozzolan concrete is increased to maintain the same slump of the control concretes when the W/B ratio is decreased. It was noted that CR-FM(0.45) and CR-FM(0.45)10 concretes did not require superplasticizer while the other CR-pozzolan concretes had to use superplasticizer to maintain the slumps within the controlled range (50-100mm). This was because the spherical shapes and solid particles of FM fly ash resulted in increasing workability of fresh CR-FM(0.45) and CR-FM(0.45)10 concretes. This finding supports the result of Sata, et al. (2007) who reported that the spherical shapes of Mae Moh fly ash could reduce the friction between binder and aggregates, resulting in increased workability of concrete. CR-FN(0.45), CR-PA(0.45), and CR-RA(0.45) concretes required superplasticizer of 9.0, 2.9, and 10.1 kg/m^3, respectively. It was indicated that the high superplasticizer dosage was needed in CR-RA and CR-FN concrete mixtures. This is due to the high porosity within particles of RA and FN, thus increases the superplasticizer to maintain the same workability of the control concrete (Sata, et al., 2007; Tangchirapat, et al., 2008).

When 10% of OPC was used to replace in CR-FN, CR-PA, and CR-RA concrete binders, the concretes needed less superplasticizer than a concrete mixture without OPC. CR-FN(0.45)10, CR-PA(0.45)10, and CR-RA(0.45)10 concretes required 6.9, 2.8, and 6.0 kg/m^3 of superplasticizer, respectively. This finding was attributed that the replacement of OPC in concrete binder decreased the binder content (CR-pozzolan content) in concrete mixture because the specific gravity of the OPC (3.14) was higher than those of CR, FM, FN, PA, and RA. In addition, the porous particles of CR, FN, PA, and RA were also reduced, thus decreased the water requirement of the concrete mixture.

For high-strength concrete mixture, Portland cement concrete NC(0.25) required superplasticizer of 4.1 kg/m^3 while CR-FM(0.25) and CR-FM(0.45)10 concretes required superplasticizer of 3.9 and 4.4 kg/m^3, respectively. The result indicated that the CR-FM(0.25) concrete needed less superplasticizer than the Portland cement concrete NC(0.25). It was because spherical shapes of FM fly ash could enhance the workability of the CR-FM(0.25) concrete, resulting in reduced the superplasticizer requirement.

4.2.2 Setting Times of Concrete

The setting times of all concrete mixtures were tested by penetration resistance method (ASTM C403, 2010) under the same ambient condition, and the results are shown in Table 4.3. It was found that the setting times of CR-pozzolans concretes were longer than that of the Portland cement concretes when the same W/B ratio was considered. NC(0.65), NC(0.45), and NC(0.25) concretes had initial setting times of 4 h 10 min, 3 h 55 min, 5 h, and the final setting times of 6 h 30 min, 5 h 45 min, 7 h, respectively. Brooks, et al., (2000) reported that the setting times of Portland cement concrete depends on type and dosage of superplasticizer as well as the water to binder ratio and the cement content in the concrete mixture. In this study, the dosage of superplasticizer was not affected the setting times of CR-pozzolans concretes because it seems that most setting times of CR-pozzolans concretes depended on the reaction between CR and pozzolanic materials as well as the hydration reaction of OPC when it was used to replace binder in the concrete mixture.

For example, the initial setting times of CR-FN(0.65), CR-FM(0.45), CR-FN(0.45), CR-PA(0.45), and CR-RA(0.45) concretes were 15 h 10 min, 11 h 30 min, 11 h 40 min, 16 h 35 min, and 21 hr 40 min, and the final setting times were 33 h 5 min, 18 h 5 min, 29 h 10 min, 25 h 50 min, and 59 h 10 min, respectively. This showed that the setting times of CR-FM(0.45) concrete were close to CR-FN(0.45) concrete although both fly ashes obtained from different burning process. Furthermore, CR-PA(0.45) and CR-RA(0.45) concretes had initial and final setting times longer than those of the CR-fly ash concretes. Since the CR-FN(0.65), CR-FM(0.45), CR-FN(0.45), CR-PA(0.45), and CR-RA(0.45) concretes did not set by hydration reaction from Portland cement, the long delay in setting times of the concretes was expected. In addition, it was found that the setting times of CR-FN(0.65) concrete were longer than that of the CR-FN(0.45) concrete because the CR-FN(0.65) concrete used higher W/B, contained more free water present in the mixture than CR-FN(0.45) concrete (Andrade, et al., 2009). Moreover, Khedr and Abou-Zeid (1994) reported that the pozzolanic reaction is much slower than the hydration reaction from Portland cement by nature. It was noted that the longest setting times of CR-pozzolans concrete was occurred in CR-RA mixture, for initial and final setting times, about 5.2 and 9.1 times greater than that of the NC(0.65) concrete. This indicated that the long delay in setting times of CR-pozzolans concrete should be considered before it was used in construction work. Therefore, one possible application where longer setting times may be desirable is in mass concrete. However, if the long delay in setting times of the CR-pozzolans concretes is an issue, Portland cement may be used as an admixture to accelerate the setting times as well as the early compressive strength of the concrete.

Due to the above results, 10% of OPC by weight of binder was used in concrete mixtures, and found that OPC significantly affected the setting times of CR-pozzolans concrete. The initial and final setting times of CR-FN(0.65)10, CR-FM(0.45)10, CR-FN(0.45)10, CR-PA(0.45)10, and CR-RA(0.45)10 concretes were much lower than those of CR-pozzolans concretes without OPC. The initial setting times of CR-FN(0.65)10, CR-FM(0.45)10, CR-FN(0.45)10, CR-PA(0.45)10, and CR-RA(0.45)10 concretes were 6 h 30 min, 6 h 50 min, 4 h 5 min, 7 h 25 min, and 5 h 40 min, about 2.3, 1.7, 2.9, 2.2, and 3.8 times shorter than those of CR-FN(0.65), CR-FM(0.45), CR-FN(0.45), CR-PA(0.45), and CR-RA(0.45) concretes, respectively. The final setting times of those concretes were 14 h 10 min, 10 h 15 min, 9 h 10 min, 14 h 20 min, and 14 h 40 min or about 2.3, 1.8, 3.2, 1.8, and 4.0 times shorter than those of the concretes without OPC, respectively. The results showed that the replacement of 10% OPC in CR-pozzolans binder could reduce the setting times of CR-pozzolans concretes since the hydration reaction of OPC accelerated the setting times. It was also noted that the initial setting times of CR-FN(0.45)10 and CR-RA(0.45)10 concretes were closed to the NC(0.65) concrete (used OPC 300 kg/m^3) even though the mixtures contained OPC of 45 kg/m^3. As a result, it was concluded that the long delay in setting times of CR-pozzolans concrete could be solved by using OPC to accelerate the setting times of the CR-pozzolans concretes.

Table 4.3 Setting times of concretes

Concretes	Initial setting times (h:min)	Final setting times (h:min)
CR-FN(0.65)	15:10	33:05
CR-FN(0.65)10	6:30	14:10
CR-FM(0.45)	11:30	18:05
CR-FM(0.45)10	6:50	10:15
CR-FN(0.45)	11:40	29:10
CR-FN(0.45)10	4:05	9:10
CR-PA(0.45)	16:35	25:50
CR-PA(0.45)10	7:25	14:20
CR-RA(0.45)	21:40	59:10
CR-RA(0.45)10	5:40	14:40
CR-FM(0.25)	4:35	7:10
CR-FM(0.25)10	2:55	5:10
NC(0.65)	4:10	6:30
NC(0.45)	3:55	5:45
NC(0.25)	5:00	7:00

For high-strength concrete, CR-FM(0.25) and CR-FM(0.25)10 concretes had initial setting times of 4 h 35 min and 2 h 55 min, and final setting times of 7 h 10 min and 5 h 10 min, respectively. It was indicated that the initial and final setting times of CR-FM(0.25) and CR-FM(0.25)10 concretes were closed to the Portland cement concrete NC(0.25) (used OPC 550 kg/m^3). This may be due to CR-FM(0.25) and CR-FM(0.25)10 concretes used a low W/B ratio (W/B = 0.25), resulted in significantly accelerated the pozzolanic reaction between CR and FM fly ash as well as the hydration reaction from OPC.

4.2.3 Heat Evolution of Concrete

The results of heat evolution in term of the highest temperature rise, the reduction in the temperature rise compared to the Portland cement concrete NC(0.25), and the time to obtain the highest temperature after casting of high-strength concretes are shown in Table 4.4. Figure 4.3 shows the relationship between temperature rise of the high-strength concretes and time after casting.

It was observed that CR-FM(0.25) concrete had the highest temperature rise of 11°C while that of NC(0.25) was 42°C or was lower than that of NC(0.25) concrete of 31°C. The result showed that the heat evolution of CR-FM(0.25) concrete was much lower than that of NC(0.25) concrete. This was because the temperature rise of the CR-FM(0.25) concrete occurred from only the pozzolanic reaction between CR and FM, which was much lower than the hydration reaction of Portland cement. In addition, CR-FM(0.25)10 concrete had the highest temperature rise of 15°C which was slightly higher than that of CR-FM(0.25) concrete. This indicated that the temperature of CR-FM(0.25)10 concrete slightly increased due to the hydration reaction from OPC. Moreover, the highest temperature rise of CR-FM(0.25)10 concrete was lower than that of the NC(0.25) concrete of 27°C. In addition, the time to obtain the highest temperature rise of CR-FM(0.25) and CR-FM(0.25)10 concretes did not much difference from the NC(0.25) concrete because the highest temperatures of CR-FM(0.25), CR-FM(0.25)10, and NC(0.25) concretes occurred at 16, 20 and 18 hours after casting, respectively.

Table 4.4 Heat evolution of concretes

Concretes	Max. Temp. (°C)	Highest Temp. Rise (°C)	Time of Highest Temp. Rise after Casting (Hours)	Reduce Temp. (°C)	Reduce Temp. (%)	Highest Temp. Rise (°C/100kg of Binder
CR-FM(0.25)	40	11	16	31	26	2.0
CR-FM(0.25)10	44	15	20	27	35	2.7
NC(0.25)	71	42	18	-	100	7.6

Note: The ambient temperature is 29°C.

The temperature rises in concrete per 100 kg of binder are also shown in Table 4.4. CR-FM(0.25) and CR-FM(0.25)10 concretes had temperature rises of 2.0 and 2.7°C/100 kg of binder while the NC(0.25) concrete had 7.6°C/100 kg of binder, respectively. The result indicated that the temperature rises per 100 kg of CR-fly ash binder were much lower than that of Portland cement concrete NC(0.25) and also lower than those results of plain concretes containing pozzolanic materials, reported by Sata, et al., (2004) and Chusilp, et al., (2009). Sata, et al., (2004) reported that use of silica fume and ground palm oil fuel ash to replace Portland cement at rate of 30% by weight of binder in high-strength concrete had temperature rises of 7.9 and 7.1°C/100 kg of binder, respectively. Further, Chusilp, et al., (2009) showed that the plain concrete containing 30% of ground bagasse ash had temperature rise of 5.7°C/100 kg of binder which was higher than 2 times of the concrete using CR-fly ash as a binder.

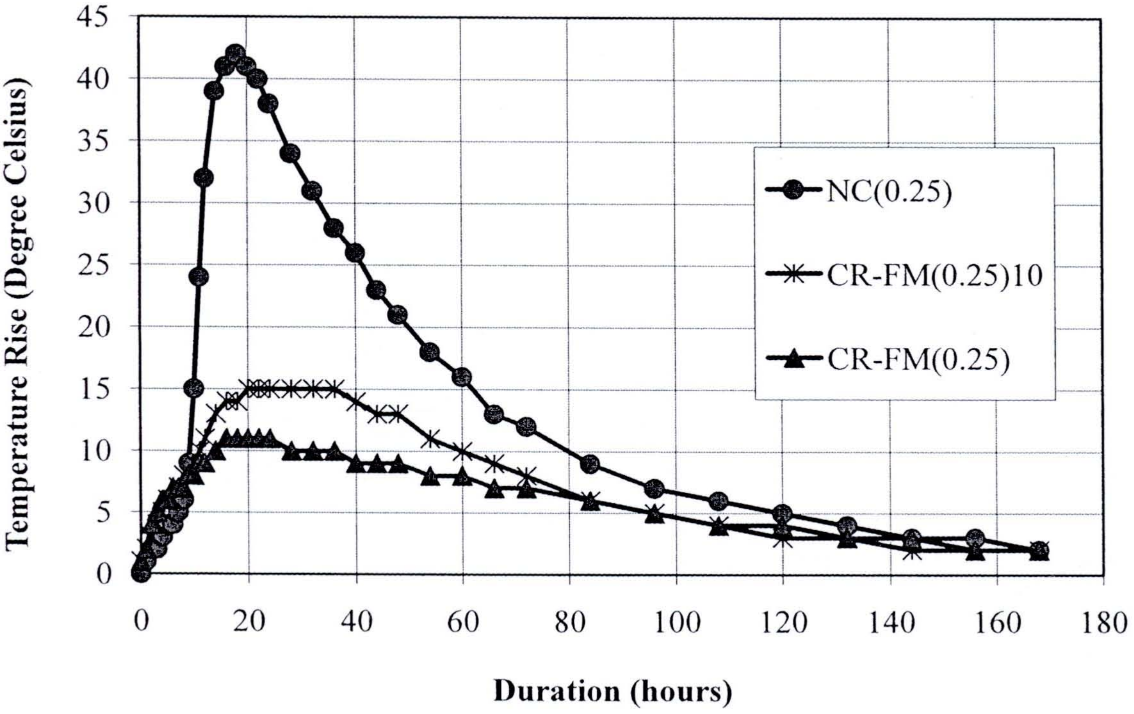

Figure 4.3 Relationship between temperature rise and duration time after casting

From the temperature measurements of fresh concrete in high-strength CR-fly ash mixtures, the maximum temperature of CR-FM(0.25) and CR-FM(0.25)10 concretes were 40 and 44°C, respectively which were lower than that of Portland cement concrete NC(0.25) (71°C). This result indicated that the highest temperature rise of CR-FM(0.25) and CR-FM(0.25)10 concretes was about 0.26 and 0.36 times that of the NC(0.25) concrete, respectively. In addition, the highest differential temperature between CR-fly ash mixtures and the ambient temperature was found to be 11 and 15°C for CR-FM(0.25) and CR-FM(0.25)10 concretes, respectively. According to ACI 207 (2003) for mass concrete, the maximum allowable differential temperature which control cracking is specified to be 20°C. As a result, the CR-fly ash mixtures with and without OPC are excellent binder for low-heat cementitious material of mass concrete.

4.3 Mechanical Properties of Concrete

This section, mechanical properties of concrete such as compressive strength and splitting tensile strength were determined from cylindrical 100 x 200 mm concrete specimen. In addition, the modulus of elasticity of the concrete was also determined. The results are described in below topics as follows:

4.3.1 Compressive Strength of Concrete

At each testing date, the average values of three concrete specimens were used for the compressive strength and the results are tabulated in Table 4.5. Figures 4.4, 4.5, and 4.6 present relationship between compressive strength of concretes and ages at W/B ratios of 0.65, 0.45, and 0.25, respectively.

Table 4.5 Compressive strength and elastic modulus of concretes

Concretes	Compressive strength (MPa)					Elastic modulus (GPa)	
	7 days	28 days	60 days	90 days	180 days	28 days	90 days
CR-FN(0.65)	8.4	10.4	13.6	13.7	14.2	18.6	21.9
CR-FN(0.65)10	10.4	15.3	22.5	24.6	25.9	19.2	21.3
CR-FM(0.45)	7.3	12.5	16.4	19.9	22.5	17.3	20.9
CR-FM(0.45)10	11.7	17.6	24.6	28.2	29.2	20.2	25.5
CR-FN(0.45)	11.0	29.0	32.3	34.3	35.0	27.9	33.6
CR-FN(0.45)10	17.3	31.5	36.5	38.5	42.7	28.8	36.2
CR-PA(0.45)	6.8	12.5	14.9	16.1	18.9	11.2	15.3
CR-PA(0.45)10	13.4	20.7	22.4	24.1	27.9	21.5	28.9
CR-RA(0.45)	4.8	11.5	11.6	12.5	14.1	14.8	15.1
CR-RA(0.45)10	9.2	19.4	26.8	28.6	32.5	20.3	23.4
CR-FM(0.25)	21.9	33.5	45.9	51.2	56.1	24.9	29.2
CR-FM(0.25)10	25.9	42.3	57.0	65.5	72.4	29.8	33.2
NC(0.65)	23.5	31.9	36.2	37.5	38.9	28.3	35.5
NC(0.45)	29.9	50.0	52.6	53.8	54.5	31.9	35.3
NC(0.25)	51.9	72.6	81.8	88.4	99.5	34.3	40.7

It was found that the compressive strengths of CR-FM, CR-FN, CR-PA, and CR-RA concretes which contained no OPC ranged from 10.4 to 33.5 MPa at 28 days and increased to be 14.2 to 56.1 MPa at 180 days depending on the W/B ratio and the types of pozzolan. Portland cement concretes in which OPC was used as a binder, NC(0.65), NC(0.45), and NC(0.25) concretes had compressive strengths at 28 and 180 days of 31.9, 50.0, 72.6 and 38.9, 54.5, 99.5 MPa, respectively. The result showed that NC(0.45) and NC(0.65) concretes were high-strength concrete while NC(0.65) concrete was normal-strength concrete according to ACI C363 (2003). The compressive strength of CR-pozzolans concretes increased with curing age although the binder did not contain OPC. For example, CR-FN(0.65) and CR-FN(0.45) concretes had compressive strengths of 8.4 and 11.0 MPa at 7 days, and increased to be 10.4 and 29.0 at 28 days, respectively. At the later ages of 60, 90 and 180 days, CR-FN(0.65) and CR-FN(0.45) concretes had compressive strengths of 13.6, 13.7, and 14.2 and 32.3, 34.3, and 35.0 MPa, respectively. The results suggested that most of the compressive strengths of CR-pozzolans concretes developed within 28 days and then increased moderately afterwards.

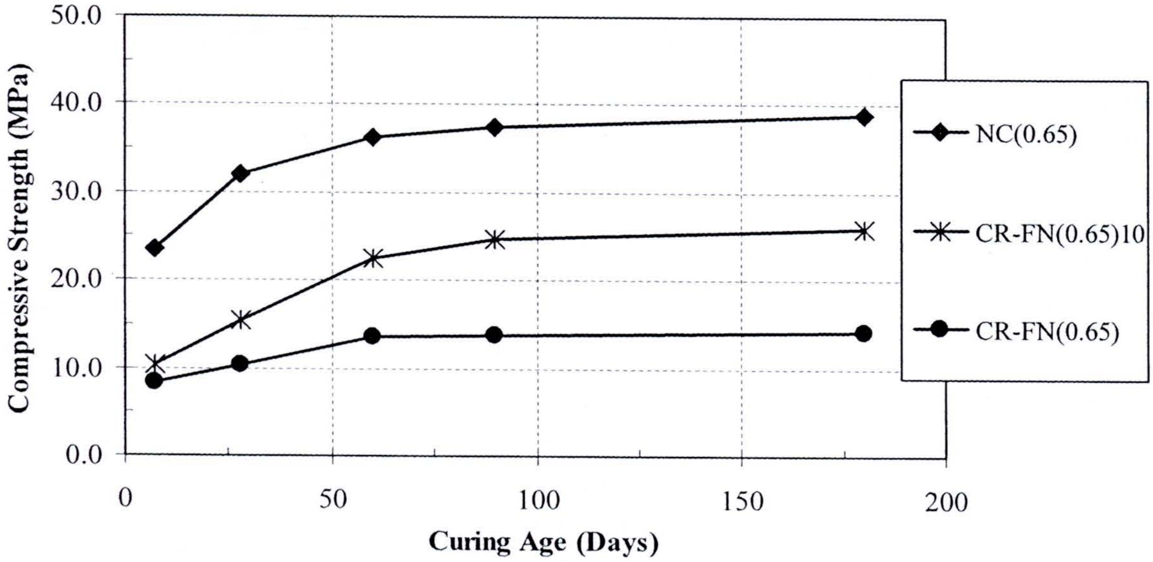

Figure 4.4 Compressive strengths of concretes at W/B ratio of 0.65

In addition, W/B ratio had a pronounced effect on the compressive strength of CR-pozzolans concretes: lower W/B ratios corresponded to higher compressive strength development. The compressive strengths of CR-FM(0.45) concrete (W/B = 0.45) were 7.3, 12.5, 16.4, 19.9, and 22.5 MPa while that of CR-FM(0.25) concrete (W/B = 0.25) were 21.9, 33.5, 45.9, 51.2, and 56.1 MPa at 7, 28, 60, 90, and 180 days, respectively. The compressive strength of CR-FM(0.25) concrete were about 3.0, 2.7, 2.8, 2.6, and 3.9 times greater than those of CR-FM(0.45) concrete at the same age, respectively.

For CR-pozzolans concretes without OPC at W/B ratio of 0.45, CR-FM(0.45) and CR-FN(0.45) concretes gave the compressive strength higher than those of CR-PA(0.45), and CR-RA(0.45) concretes. At 7 and 28 days, CR-FM(0.45) and CR-FN(0.45) concretes had compressive strengths of 7.3, 11.0 and 12.5, 29.0 MPa, respectively. At later age of 60, 90, and 180 days, the compressive strengths of the CR-FM(0.45) and CR-FN(0.45) concretes were 16.4, 19.9, and 22.5 and 32.3, 34.3, and 35.0 MPa, respectively. It was noted that the compressive strengths of CR-FN(0.45) concrete were higher than that of CR-FM(0.45) concrete at all ages, and were about 90% of the NC(0.65) concrete (used OPC of 300 kg/m^3) at 28 to 180 days although the CR-FN(0.45) concrete did not contain OPC. This is probably due to the porous particles of FN fly ash absorbed more free water in concrete mixture resulted in enhancing compressive strength of concrete. At 7 and 28 days, CR-PA(0.45) and CR-RA(0.45) concretes had compressive strengths of 6.8, 4.8 and 12.5, 11.5 MPa, respectively. At later ages of 60, 90, and 180 days, the compressive strengths of CR-PA(0.45) and CR-RA(0.45) concretes increased to be 14.9, 16.1, and 18.9 and 11.6, 12.5, and 14.1 MPa, respectively. The result showed that CR-PA(0.45) and CR-RA(0.45) concretes developed compressive strength similar to CR-FN(0.45) and CR-FM(0.45) concretes, but their compressive strengths were lower than those of CR-fly ash concretes when the same W/B ratio was used.

The result of using 10% of OPC to replace in CR-pozzolans binder indicated that the use of OPC had significantly effect on increasing compressive strength of the CR-pozzolans concrete. Furthermore, CR-pozzolans concretes containing OPC had compressive strength higher than those of CR-pozzolans concretes without OPC when the same W/B ratio was considered. CR-FN(0.45)10 concrete had compressive strengths of 17.3, 31.5, 36.5, 38.5, and 42.7 MPa at 7, 28, 60, 90, and 180 days, respectively. It was noteworthy that at 28 days, CR-FN(0.45)10 concrete had compressive strength about 99% of NC(0.65) concrete (used OPC of 300 kg/m^3), and then its compressive strengths were higher than that of the NC(0.65) concrete at later ages even though CR-FN(0.45)10 concrete used OPC of 45 kg/m^3, about 6.7 times lower than that of the NC(0.65) concrete. At early age of 7 days, the compressive strength of CR-PA(0.45)10 concrete was higher than that of CR-FM(0.45)10 concrete while at later ages of 28 to 180 days, the compressive strengths of CR-PA(0.45)10 and CR-FM(0.45)10 concretes were not much different. The compressive strengths of CR-PA(0.45)10 concrete were 13.4, 20.7, 22.4, 24.1, and 27.9 MPa at 7, 28, 60, 90, and 180 days, respectively.

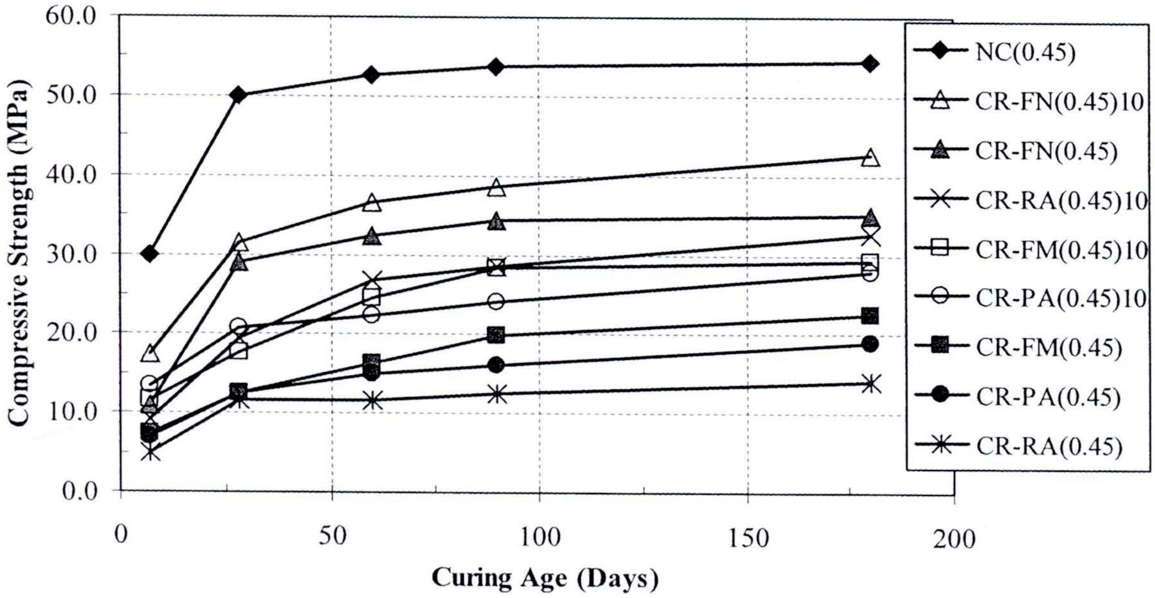

Figure 4.5 Compressive strengths of concretes at W/B ratio of 0.45

Moreover, it was found that the use of OPC in CR-RA mixture resulted in effectively enhanced compressive strength of CR-RA(045)10 concrete. For example, at 7 and 28 days, CR-RA(045)10 concrete had compressive strengths of 9.2 and 19.4 MPa, about 1.9 and 1.7 times higher than that of CR-RA(0.45) concrete (4.8 and 11.5 MPa), and the compressive strengths of CR-RA(0.45)10 increased to 26.8, 28.6, and 32.5 MPa or about 2.3 times higher than that of CR-RA(0.45) concrete at 60, 90, and 180 days, respectively. In addition, at 28 to 180 days, the compressive strengths of CR-RA(0.45)10 concrete were higher than those of CR-FM(0.45)10 and CR-PA(0.45)10 concretes although CR-RA mixture without OPC gave the lowest compressive strength as compared to CR-FN(0.45), CR-FM(0.45), and CR-PA(0.45) concretes.

The highest compressive strength was occurred in CR-FM(0.25)10 concrete with a W/B ratio of 0.25. The CR-FM(0.25)10 concrete had compressive strengths of 25.9 and 42.3 MPa at 7 and 28 days, respectively. At 60 days, the CR-FM(0.25)10 concrete had a compressive strength of 57.0 MPa (about 2.3 times greater than that of CR-FM(0.45)10 concrete), and then gradually increased to 72.4 MPa at 180 days or about 46.5 MPa gain from its compressive strength at 7 days although the mixture contained small amount of Portland cement (used OPC of 55 kg/m^3).

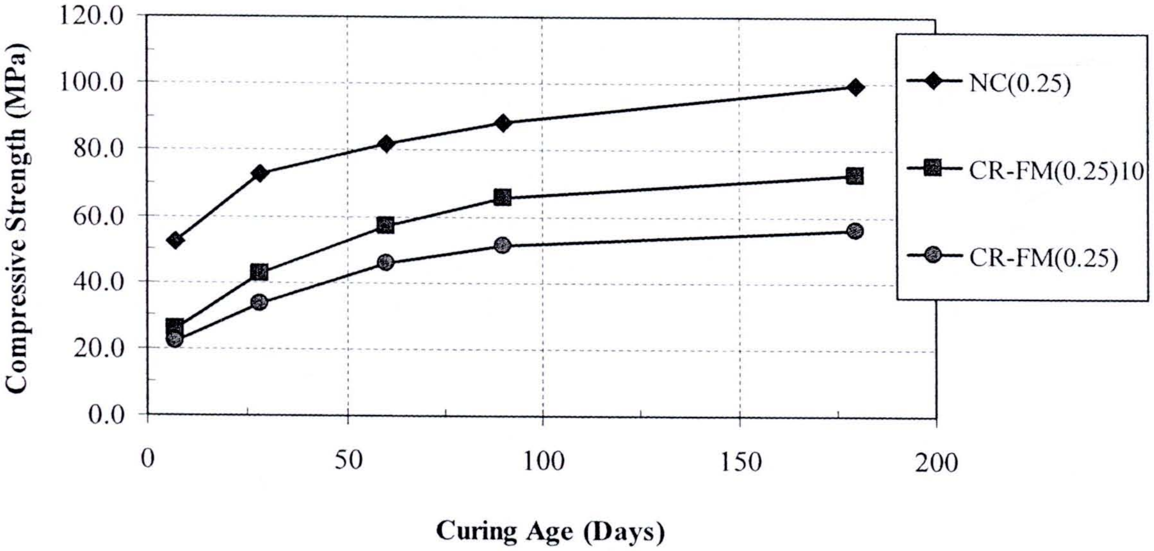

Figure 4.6 Compressive strengths of concretes at W/B ratio of 0.25

From the above results, it was concluded that CR-fly ash concretes without OPC gave compressive strength higher than those of CR-PA and CR-RA concretes. Furthermore, use of FN fly ash and CR together as a binder gave compressive strength of concrete higher than that use of FM fly ash and CR binder when the same W/B ratio was considered. The OPC could be used in concrete binder to enhance compressive strength of CR-pozzolans concretes when 10% of OPC was used to replace CR-pozzolan binder. In addition, the use of OPC in CR-PA(0.45)10 and CR-RA(0.45)10 concretes resulted in significantly increased their compressive strength. The compressive strengths of CR-PA(0.45)10 concrete were not much different from CR-FM(0.45)10 concrete while the compressive strengths of CR-RA(0.45)10 concrete were higher than those of CR-FM(0.45)10 and CR-PA(0.45)10 concretes. CR-FM mixture could be used as a binder for high-strength concrete with compressive strength at 90 days of 51.2 MPa although the mixture contained no OPC.

4.3.2 Modulus of Elasticity of Concrete

For modulus of elasticity of concrete, the average test results for each of the three concrete specimens are also shown in Table 4.5. The relationships between the modulus of elasticity and square root of the compressive strength of concrete are shown in Figure 4.7. The results were compared with those obtained from Portland cement concretes. The Portland cement concretes; NC(0.65), NC(0.45), and NC(0.25) had modulus of elasticity values of 28.3, 31.9, and 34.3 GPa at 28 days, and increased to be 35.5, 35.3, and 40.7 GPa at 90 days, respectively.

For normal-strength concrete, the elastic modulus of CR-pozzolans concrete without OPC increased with age and ranged from 11.2 to 27.9 GPa and 15.1 to 33.6 GPa at 28 and 90 days, respectively depending on the compressive strength of concrete. Furthermore, the elastic modulus values of CR-pozzolans concretes containing OPC were higher than those of CR-pozzolans concretes without OPC which followed the same trend as the compressive strength. For example, CR-FN(0.45), CR-FN(0.45)10, CR-RA(0.45), and CR-RA(0.45)10 concretes had modulus of elasticity values at 28 days of 27.9, 28.8, 14.8, and 20.3 GPa, and their compressive strengths were 29.0, 31.5, 11.5, and 19.4 MPa, respectively. For high-strength concrete, the same result also applied: the modulus of elasticity of CR-fly ash concretes increased with the compressive strength. For example, at 28 and 90 days, CR-FM(0.25) and CR-FM(0.25)10 concretes had elastic modulus values of 24.9, 29.8 and 29.2, 33.2 GPa, and their compressive strengths were 33.5, 42.3 and 51.2, 65.5 MPa, respectively. Thus, the modulus of elasticity of CR-pozzolans concretes was related to its compressive strength which supported those results for plain concrete researches of Cetin and Carrasquillo, (1998), Abdelgader and Gorski, (2003), and Nassif, et al., (2005).

The modulus of elasticity of CR-pozzolans concrete can be predicted by using Eq. (4.1) as follow:

$$E_{CR-pozzolan} = 4.74\sqrt{f'_c} \qquad (4.1)$$

where $E_{CR-pozzolan}$ and $f'c$ are expressed in GPa and MPa, respectively.

As a result, the modulus of elasticity of CR-pozzolans concrete is similar to Portland cement concrete: it increases with the increasing of compressive strength and can be predicted as suggested by ACI 318 (2003).

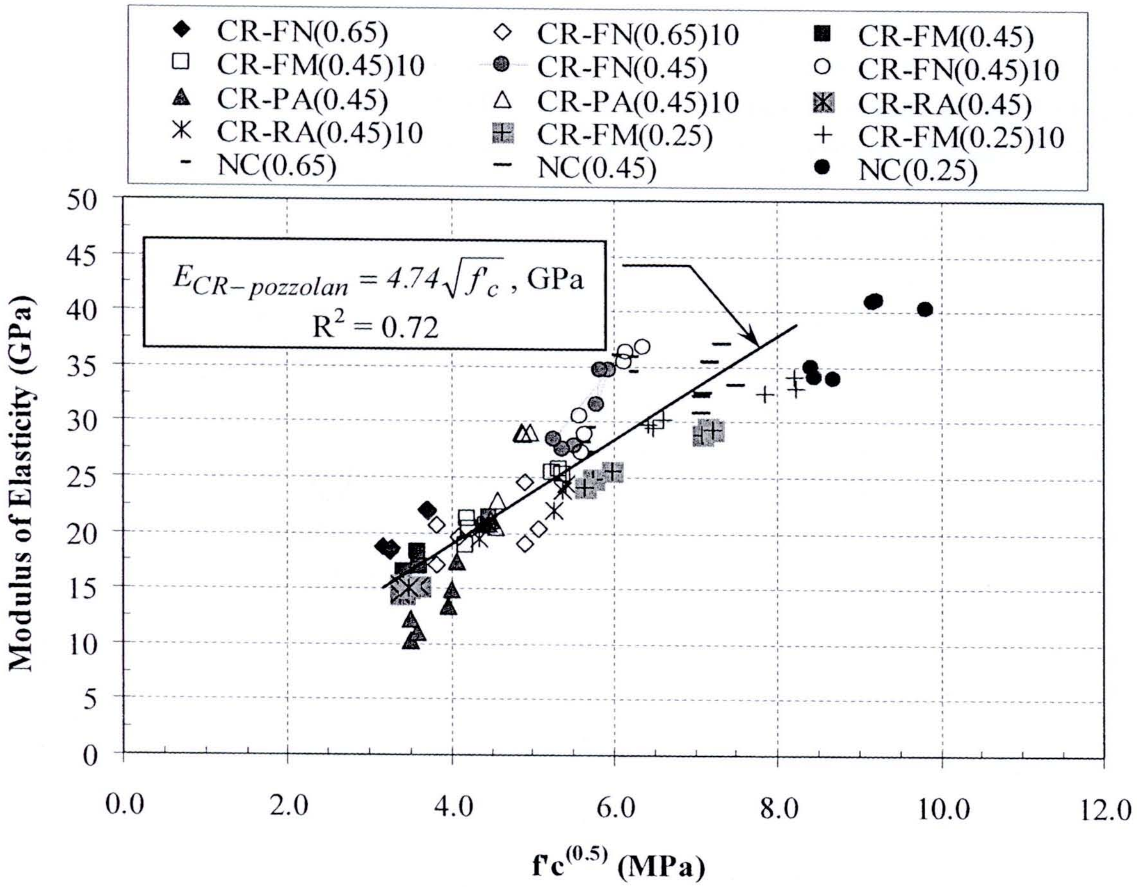

Figure 4.7 Relationship between modulus of elasticity and square root of compressive strength of concrete

4.3.3 Splitting Tensile Strength of Concrete

The splitting tensile strengths, determined according to ASTM C496 (2010) procedure, and the ratios of splitting tensile strength to its compressive strength are tabulated in Table 4.6. The relationship between splitting tensile strength and square root of compressive strength for each concrete is shown in Figure 4.8. It was observed that the splitting tensile strengths of CR-pozzolans concretes tended to increase with increasing of compressive strength. At 28 days, CR-FN(0.65) and CR-FN(0.45) concretes had splitting tensile strengths of 1.65 and 3.50 MPa, and their compressive strengths were 10.4 and 29.0 MPa, respectively. At 90 days, the splitting tensile strengths of CR-FN(0.65) and CR-FN(0.45) concretes increased to 2.12 and 4.15 MPa, respectively. In addition, the splitting tensile strengths of CR-FN(0.45) concrete were higher than those of CR-FM(0.45), CR-PA(0.45), and CR-RA(0.45) concretes. At 28 and 90 days, the splitting tensile strengths of CR-FM(0.45), CR-PA(0.45), and CR-RA(0.45) were 2.01, 1.37, and 1.44 and 2.28, 1.61, and 1.61 MPa, respectively. This result revealed that the splitting tensile strength of CR-pozzolans concrete is also related to its compressive strength. The result is the same as Portland cement concrete including those plain concretes reported by Swamy (1990) and Abdelgader and Elgalhud (2008).

CR-pozzolans concrete with low W/B ratio can increase the splitting tensile strength. It can be seen from high-strength concrete, CR-FM(0.25) concrete. It had the splitting tensile strengths of 3.16 and 3.61 MPa which were higher than that of CR-FM(0.65) concrete (W/B = 0.65), at 28 and 90 days, respectively. Furthermore, the use of OPC as an strength accelerator in CR-pozzolans concrete resulted in increased splitting tensile strength as well as compressive strength. CR-FM(0.25)10 concrete had splitting tensile strengths of 4.80 and 5.25 MPa, and their compressive strength were 42.3 and 65.5 MPa, at 28 and 90 days, respectively. The results also showed that the splitting tensile strengths of CR-FM(0.25) and CR-FM(0.25)10 concretes ranged from 7% to 11% of their compressive strengths, similar to the splitting tensile strength ratios of Portland cement concretes, NC(0.45) and NC(0.25), 9% to 11%. For normal-strength concrete, the splitting tensile strengths of CR-pozzolans concretes at 28 days ranged from 9% to 16% of their compressive strengths, which were close to the splitting tensile strength ratios of Portland cement concrete NC(0.65) (11% to 14%). This result supports previous researches of plain concrete, which indicated that the splitting tensile strength of plain concrete is about 10% of its compressive strength (Yazici, 2008; Siddique, et al., 2009).

Table 4.6 Splitting tensile strength of concretes

Concretes	Splitting tensile strength (MPa)		***Ratio of splitting tensile strength to compressive strength (%)***	
	28 days	90 days	28 days	90 days
CR-FN(0.65)	1.65	2.12	***16***	***15***
CR-FN(0.65)10	2.04	2.63	***13***	***11***
CR-FM(0.45)	2.01	2.28	***16***	***11***
CR-FM(0.45)10	2.15	2.45	***12***	***9***
CR-FN(0.45)	3.50	4.15	***12***	***12***
CR-FN(0.45)10	3.55	4.30	***11***	***11***
CR-PA(0.45)	1.37	1.61	***11***	***10***
CR-PA(0.45)10	2.41	3.27	***12***	***14***
CR-RA(0.45)	1.44	1.61	***12***	***13***
CR-RA(0.45)10	2.50	3.10	***13***	***11***
CR-FM(0.25)	3.16	3.61	***9***	***7***
CR-FM(0.25)10	4.80	5.25	***11***	***8***
NC(0.65)	3.60	5.16	***11***	***14***
NC(0.45)	5.03	5.67	***10***	***11***
NC(0.25)	7.23	7.94	***10***	***9***

The results of splitting tensile strengths of CR-pozzolans concretes were also compared to those Portland cement concretes as shown in Figure 4.8. Although CR-pozzolans concrete without OPC or used small amount of OPC, the splitting tensile strength trend of CR-pozzolans concrete is similar to that of Portland cement concrete. Furthermore, the prediction of splitting tensile strength of CR-pozzolans concrete are expressed in Eq. (4.2) which is the same as recommended by ACI 363 (2003) and is higher than that of ACI 224 (2003) recommendation. The splitting tensile strengths of normal weight concrete as recommended by ACI 224 and ACI 363 are shown in Eq. (4.3) and (4.4), respectively.

$$f_{sp(CR-pozzolans)} = 0.58\sqrt{f'_c} \quad \text{MPa} \tag{4.2}$$

$$f'_{t(ACI\ 224)} = 0.33\sqrt{f'_c} \quad \text{MPa} \tag{4.3}$$

$$f_{sp(ACI\ 363)} = 0.59\sqrt{f'_c} \quad \text{MPa} \tag{4.4}$$

for 21 MPa < $f'c$ < 83 MPa

Therefore, the concrete made from CR-pozzolans mixture as a binder had the mechanical properties such as compressive strength, modulus of elasticity, and splitting tensile strength similar to Portland cement concrete although the binder had no OPC or had OPC only 10% by weight of binder.

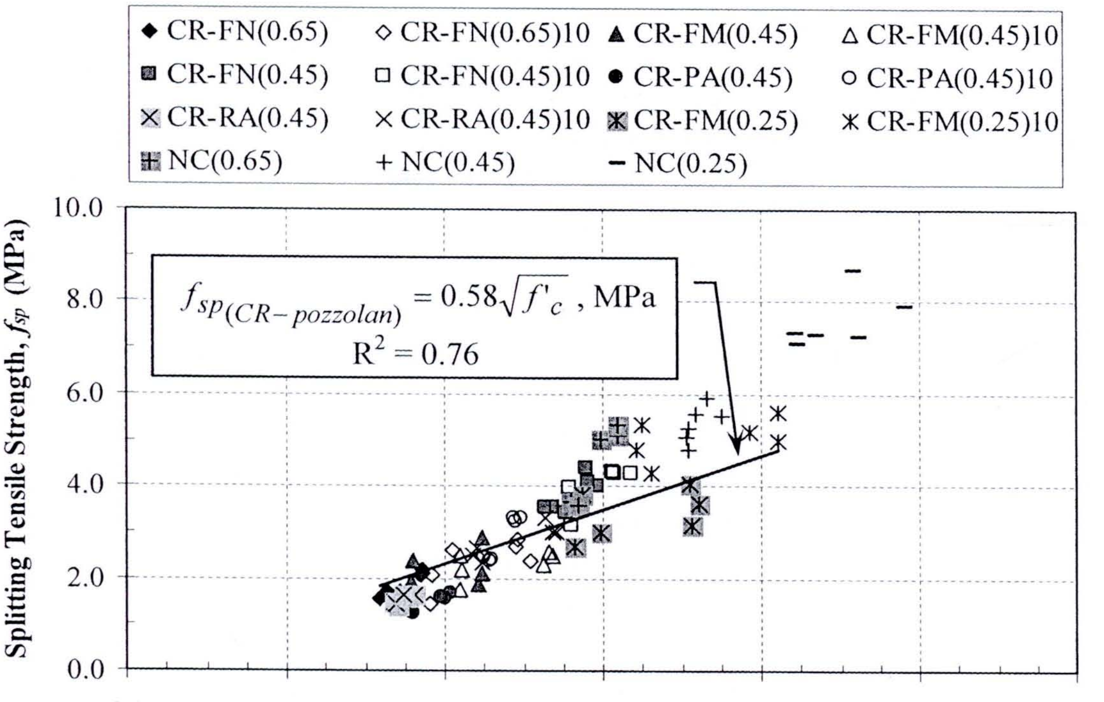

Figure 4.8 Relationship between splitting tensile strength and square root of compressive strength of concrete

4.4 Water Permeability of Concrete

Water permeability and the ratio of water permeability of CR-pozzolans concretes at W/B ratio of 0.45 are given in Table 4.7. The water permeability ratio was defined as the water permeability of CR-pozzolans concrete divided by the water permeability of the Portland cement concrete NC(0.65) (W/B ratio of 0.65). The water permeability values of CR-pozzolans concretes were compared to the Portland cement concrete NC(0.65) because at 28 and 90 days, the compressive strengths of NC(0.65) concrete were closed to CR-pozzolans concretes, especially CR-FN(0.45) and CR-FN(0.45)10 concretes. NC(0.65) concrete had water permeability values of 1.89×10^{-12} and 0.59×10^{-12} m/s at 28 and 90 days, respectively which corresponded to the previous result of Chindaprasirt, et al., (2007) (2.89×10^{-12} and 2.05×10^{-12} m/s at 28 and 90 days). The relationship between compressive strength and water permeability of CR-pozzolans concretes and Portland cement concretes is shown in Figure 4.9. The results are compared with other results of Portland cement concretes. Water permeability values of NC(0.45) concrete at 28 and 90 days were 4.82×10^{-13} and 1.27×10^{-12}, respectively.

It was found that the water permeability values of CR-pozzolans concretes without OPC varied from 0.65×10^{-12} to 81.92×10^{-12} m/s at 28 days depending on their compressive strengths. For example, CR-FM(0.45) and CR-FN(0.45) concretes had water permeability values of 4.77×10^{-12} and 0.65×10^{-12} m/s while their compressive strengths were 12.5 and 29.0 MPa at 28 days, respectively. It was noted that at 28 days, CR-FN(0.45) concrete had water permeability value lower than that of NC(0.65) concrete and had water permeability ratio of 0.34 even though the compressive strength of CR-FN(0.45) concrete was lower. At 90 days, the water permeability values were 2.26×10^{-12}, 0.34×10^{-12}, 9.88×10^{-12}, and 63.20×10^{-12} m/s for CR-FM(0.45), CR-FN(0.45), CR-PA(0.45), and CR-RA(0.45) concretes while their compressive strengths were 19.9, 34.3, 16.1, and 12.5 Mpa at 90 days, respectively. The results indicated that the water permeability of CR-pozzolans concretes reduced with the increasing of compressive strength. This result supported the result of plain concrete reported by Tangchirapat, et al. (2010). In addition, the water permeability of CR-pozzolans concrete reduced with curing age, similar to plain concrete (Chindaprasirt, et al., 2007; Chusilp, et al., 2009; Tangchirapat, et al., 2009) even though the CR-pozzolans concretes contained no Portland cement. This was because the pozzolanic reaction between CR and pozzoalanic materials was increased with the curing time. Moreover, it should be noted that CR-RA(0.45) concrete had very high value of water permeability (81.92×10^{-12} and 63.20×10^{-12} m/s at 28 and 90 days) when compared to the other CR-pozzolans concretes. At 28 and 90 days, CR-RA(0.45) concrete had water permeability ratios of 43.33 and 108.03, respectively. This is due to the compressive strengths of CR-RA(0.45) concrete were too low (11.5 and 12.5 Mpa at 28 and 90 days).

CR-pozzolans concretes containing OPC had water permeability lower than those of CR-pozzolans concretes without OPC. For example, at 28 days, CR-FM(0.45)10, CR-FN(0.45)10, CR-PA(0.45)10, and CR-RA(0.45)10 concretes had water permeability values of 3.74×10^{-12}, 0.25×10^{-12}, 0.63×10^{-12}, and 0.14×10^{-12} m/s corresponding to water permeability ratios of 1.98, 0.13, 0.33, and 0.07, respectively. The result indicated that the water permeability of CR-FN(0.45)10, CR-PA(0.45)10, and CR-RA(0.45)10 concretes were lower than that of NC(0.65) concrete. Subsequently, at 90 days, the water permeability of CR-FM(0.45)10, CR-FN(0.45)10, CR-PA(0.45)10, and CR-RA(0.45)10 concretes reduced to $0.30x10^{-12}$, $0.14x10^{-12}$, $0.42x10^{-12}$, and $0.09x10^{-12}$ m/s or had the water permeability ratios of 0.51, 0.24, 0.72, and 0.17, respectively. Thus, most of the water permeability values of CR-pozzolans concretes containing OPC were lower than those of the NC(0.65) concrete although the compressive strengths of the CR-pozzlans concretes were lower. This finding was attributed that the porosity within the CR-pozzolans concrete was lower than that of the NC(0.65) concrete and the CR-pozzolans concretes used W/B ratio of 0.45 which was lower than that of NC(0.65) concrete (W/B ratio = 0.65).

Table 4.7 Water permeability of concretes

Concretes	Compressive Strength (Mpa)		Water Permeability $Kx10^{-12}$ (m/sec)		***Water Permeability Ratio*** ***$K/K_{NC(0.65)}$***	
	28 days	90 days	28 days	90 days	28 days	90 days
CR-FM(0.45)	12.5	19.9	4.77	2.26	***2.52***	***3.75***
CR-FM(0.45)10	17.6	28.2	3.74	0.30	***1.98***	***0.51***
CR-FN(0.45)	29.0	34.3	0.65	0.34	***0.34***	***0.57***
CR-FN(0.45)10	31.5	38.5	0.25	0.14	***0.13***	***0.24***
CR-PA(0.45)	12.5	16.1	11.41	9.88	***6.03***	***16.89***
CR-PA(0.45)10	20.7	24.1	0.63	0.42	***0.33***	***0.72***
CR-RA(0.45)	11.5	12.5	81.92	63.20	***43.33***	***108.03***
CR-RA(0.45)10	19.4	28.6	0.14	0.09	***0.07***	***0.17***
NC(0.65)	31.9	37.5	1.89	0.59	***1.00***	***1.00***
NC(0.45)	50.0	53.8	0.48	0.12	***0.26***	***0.22***

Moreover, at 28 and 90 days, the water permeability values of CR-RA(0.45)10 concrete were $0.14x10^{-12}$ and $0.09x10^{-12}$ m/s, which were lower than that of the NC(0.65) concrete (water permeability ratios of 0.07 and 0.17, respectively), and about 585 and 702 times lower than that of the CR-RA(0.45) concrete, respectively. This result showed that the use of OPC in CR-pozzolans concrete was effectively increasing the impermeability as well as the compressive strength of the CR-pozzolans concrete, especially the CR-RA binder.

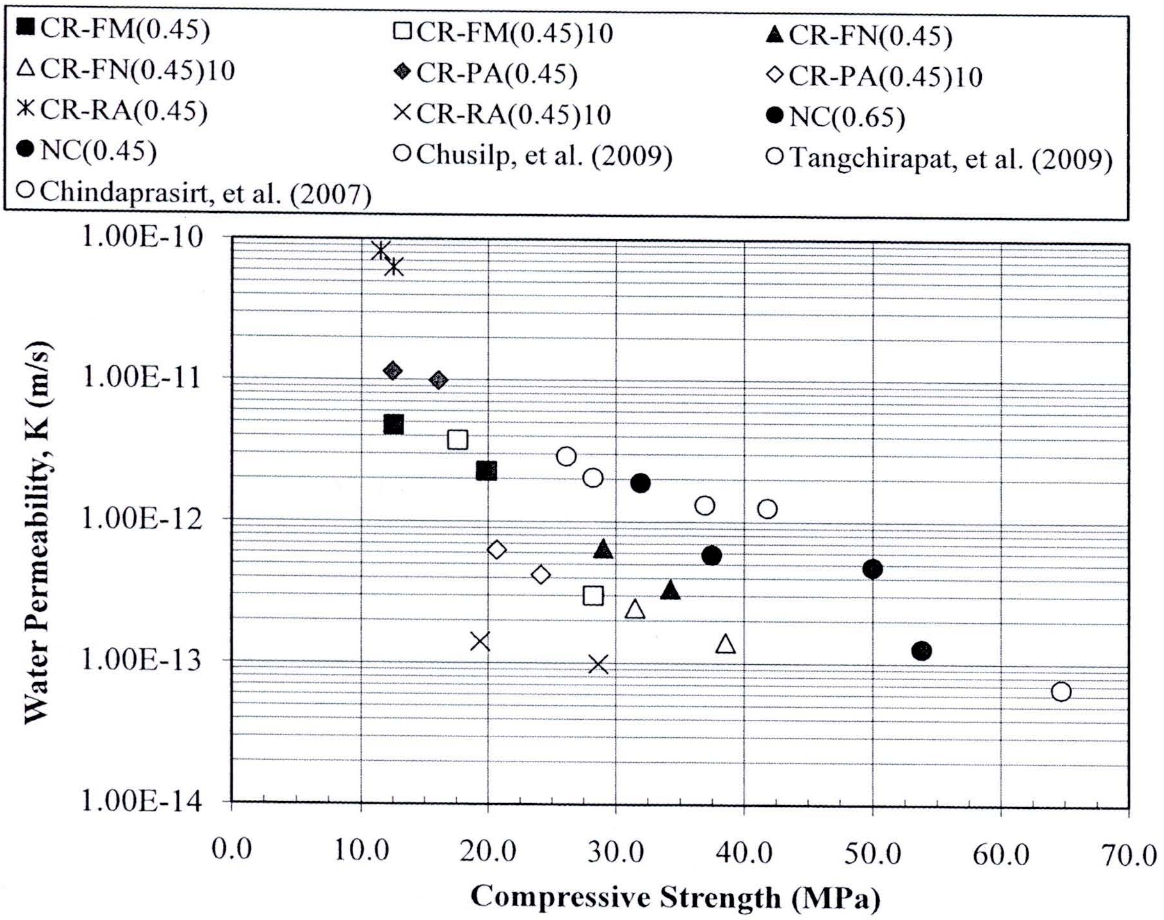

Figure 4.9 Relationship between water permeability and compressive strength of concrete

From the results and discussions as mentioned earlier, the mechanical properties and water permeability of CR-pozzolans concrete were similar to Portland cement concrete even though the CR-pozzolans concrete contained no Portland cement or had OPC of 45 kg/m^3 (about 6.7 times lower than that of the NC(0.65) concrete). The mixture of calcium carbide residue and pozzolanic materials could not only be used as a new binder for concrete, but could also help reduce the environmental problems due to reducing the production of Portland cement and disposal of calcium carbide residue and pozzolanic materials.

4.5 Use of CR-Pozzolans Binder for Concrete Brick

4.5.1 Compressive Strength of Concrete Brick

At each testing date, the average values of the three concrete brick specimens were used for the compressive strength and the results are tabulated in Table 4.8. The relationships between compressive strengths of concrete bricks and curing age are shown in Figure 4.10. The compressive strengths of CR-FM, CR-FN, CR-PA and CR-RA concrete bricks ranged from 8.1 to 15.5 MPa at 3 days, and increased to be 13.7 to 33.9 MPa at 90 days depending on type of pozzolan. A Portland cement concrete brick NB had compressive strengths of 27.3, 28.5, 31.6, 35.3, and 35.9 MPa at 3, 7, 28, 60, and 90 days, respectively.

The compressive strengths of CR-FM, CR-FN, CR-PA and CR-RA concrete bricks increased with curing age although the binder contained no OPC. At early ages, CR-FM and CR-FN concrete bricks had compressive strengths of 12.6 and 10.1 MPa at 3 days and 18.0 and 15.8 MPa at 7 days, respectively. At 28 days, the compressive strength of CR-FM and CR-FN concrete bricks was 26.5 and 20.5 MPa, respectively. At the later ages the compressive strength of CR-FM and CR-FN concrete bricks were increased continuously. For example, at 60 and 90 days, CR-FM and CR-FN concrete bricks had compressive strengths of 32.3, 33.9 and 24.5, 29.8 MPa, respectively. The results indicated that the compressive strength of CR-FM and CR-FN concrete bricks developed very fast at early ages (up to 28 days) and then increased gradually. This is similar to compressive strength development in the Portland cement concrete brick (NB) from which Portland cement is used as a binder.

CR-PA and CR-RA concrete bricks developed compressive strength in a similar way to CR-FM and CR-FN concrete bricks. At 3 and 7 days, CR-PA concrete brick had compressive strengths of 15.5 and 19.1 MPa, and increased to be 27.4 MPa at 28 days, respectively. At later ages of 60 and 90 days, CR-PA concrete brick had compressive strengths of 30.0 and 32.6 MPa, respectively. The highest compressive strength of concrete brick was occurred in CR-FM binder. In addition, the compressive strengths of CR-FM and CR-PA concrete bricks were about 84% and 87% at 28 days, and increased to 94% and 91% of the NB concrete brick at 90 days, respectively although the CR-FM and CR-PA concrete bricks contained no OPC. It should be noted that the CR-RA concrete brick gave the lowest compressive strength as compared to the others CR-pozzolans. The same result was obtained from the compressive strength result of CR-RA(0.45) concrete.

Table 4.8 Compressive strengths of concrete bricks

Concrete brick	Compressive strength (MPa) – ***Normalized compressive strength (%)***				
	3 days	7 days	28 days	60 days	90 days
CR-FM	12.6 - ***46***	18.0 - ***63***	26.5 - ***84***	32.3 - ***92***	33.9 - ***94***
CR-FN	10.1 - ***37***	15.8 - ***55***	20.5 - ***65***	24.5 - ***69***	29.8 - ***83***
CR-PA	15.5 - ***57***	19.1 - ***67***	27.4 - ***87***	30.0 - ***85***	32.6 - ***91***
CR-RA	8.1 - ***30***	8.5 - ***30***	9.3 - ***29***	11.1 - ***32***	13.7 - ***38***
NB	27.3 - ***100***	28.5 - ***100***	31.6 - ***100***	35.3 - ***100***	35.9 - ***100***

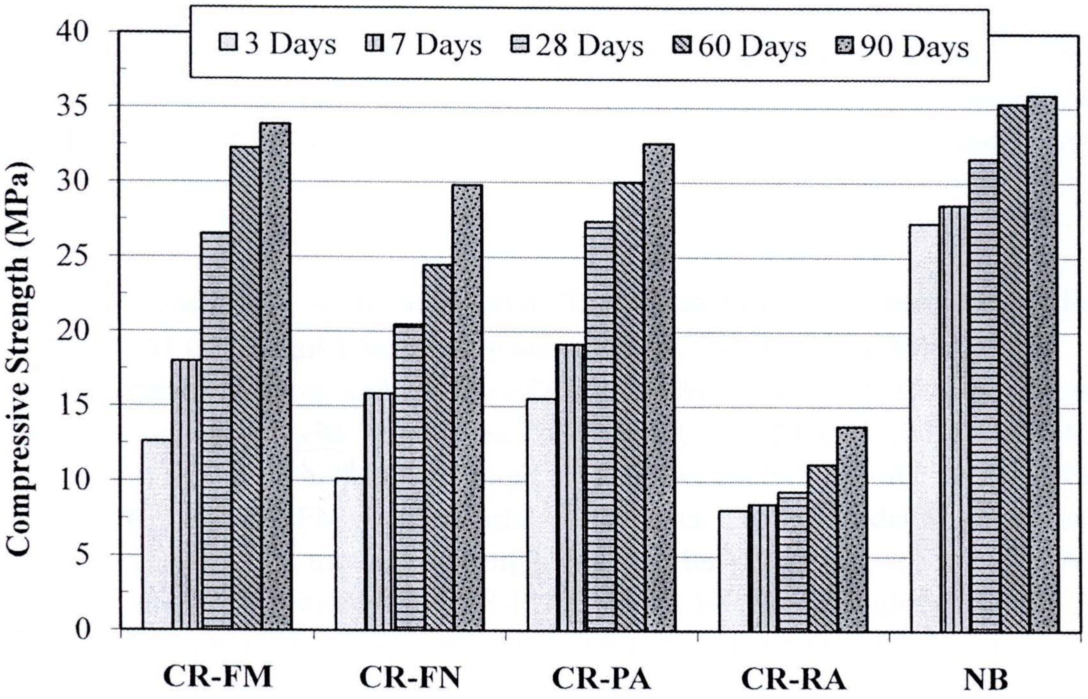

Figure 4.10 Compressive strengths of concrete bricks

4.5.2 Density and Water Absorption of Concrete Brick

The physical properties of concrete bricks at 28 days are shown in Table 4.9. The densities of CR-FM, CR-FN, CR-PA, and CR-RA concrete bricks were 2293, 2137, 2239, and 2096 kg/m^3, respectively which were lower than that of Portland cement concrete brick NB (2365 kg/m^3). This is due to the specific gravity of CR-pozzolans binder (2.39-2.72) is lower than that of Portland cement (3.14). The oven-dry densities of CR-FM, CR-FN, CR-PA, CR-RA, NB concrete bricks were 2256, 2102, 2155, 2014, and 2310 kg/m^3, respectively.

Table 4.9 Physical properties of concrete bricks at 28 days

Concrete bricks	Density (kg/m^3)	Oven-Dry Density (kg/m^3)	Absorption /Volume (kg/m^3)	Water absorption (%)
CR-FM	2293	2256	32.57	1.4
CR-FN	2137	2102	64.98	3.1
CR-PA	2239	2155	80.45	3.7
CR-RA	2096	2014	105.48	5.2
NB	2365	2310	41.66	1.8

The lowest water absorption value of concrete brick was occurred in CR-FM binder, which was 32.57 kg/m^3 or about 1.4% corresponding to its density. CR-FN, CR-PA, and CR-RA binders had water absorption values of 64.98, 80.45, and 105.48 kg/m^3 or about 3.1, 3.7, and 5.2%, respectively. It was noted that the water absorption of CR-FM concrete brick was also lower than that of the Portland cement concrete brick NB although the compressive strength of CR-FM concrete brick was lower. This was due to the solid particles of FM required less free water penetration when other pozzolans and OPC were compared.

4.5.3 Comparison with Standard Specifications for Concrete Building Brick (ASTM C55) and Concrete Facing Brick (ASTM C1634)

Strength, water absorption, and density of CR-pozzolans and Portland cement concrete bricks were compared with the values specified by ASTM C55 (2010) and ASTM C1634 (2010) as shown in Table 4.10 and 4.11, respectively. From the above results, it was concluded that CR-FN concrete brick made from CR-FN binder without Portland cement was classified as moderate-strength concrete building brick according to ASTM C55. The compressive strength of CR-FN concrete brick was higher than 17.2 MPa while the water absorption was lower than 208 kg/m^3 as specified by ASTM C55 for normal weight classification of concrete building brick. It was noted that CR-RA concrete brick could not meet the standard specified by ASTM C55 and ASTM C1634 because the compressive strength of CR-RA concrete brick was lower than those of ASTM C55 and ASTM C1634 specifications.

Table 4.10 Comparison with concrete building brick (ASTM C55, 2010) for normal weight

Concrete brick	Oven-Dry Density, kg/m^3	Water Absorption, kg/m^3		Compressive Strength, MPa		ASTM C55 Classification
	Average of 3 Units	Specific Limit	Actual Value	Specific Limit	Actual Value	
CR-FM	2256	208	32.57	17.2	26.5	Included
CR-FN	2102	208	64.98	17.2	20.5	Included
CR-PA	2155	208	80.45	17.2	27.4	Included
CR-RA	2014	208	105.48	17.2	9.3	No Included
NB	2310	208	41.66	17.2	31.6	Included

Moreover, CR-FM and CR-PA mixtures without Portland cement could be used as a binder for high-strength and high resistance to moisture penetration of concrete facing brick according to ASTM C1634 (2010) because CR-FM and CR-PA concrete bricks had the compressive strength more than 24.1 MPa and had the water absorption less than 160 kg/m^3 as specified by ASTM C1634 (2010) for normal weight classification of concrete facing brick. The Portland cement concrete brick NB was also classified as high-strength concrete facing brick.

Table 4.11 Comparison with concrete facing brick (ASTM C1634, 2010) for normal weight

Concrete brick	Oven-Dry Density, kg/m^3	Water Absorption, kg/m^3		Compressive Strength, MPa		ASTM C1634 Classification
	Average of 3 Units	Specific Limit	Actual Value	Specific Limit	Actual Value	
CR-FM	2256	160	32.57	24.1	26.5	Included
CR-FN	2102	160	64.98	24.1	20.5	Not Included
CR-PA	2155	160	80.45	24.1	27.4	Included
CR-RA	2014	160	105.48	24.1	9.3	Not Included
NB	2310	160	41.66	24.1	31.6	Included

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