Vol.7 No.2 July-December 2019

Journal of Thailand Concrete Association
วารสารวิชาการสมาคมคอนกรีตแห่งประเทศไทย

INFLUENCE OF HIGH VOLUME TERNARY BLEND FROM FLY ASH AND GROUND GRANULATED BLAST FURNACE SLAG ON CONCRETE PROPERTIES

Nattapong Makaratat [1] Punnaman Norrarat [2] Chai Jaturapitakkul [3] Smith Songpiriyakij [4]

[1]Assistant Professor, Department of Civil and Environmental Engineering Technology, College of Industrial Technology, King Mongkut's University of Technology North Bangkok, Bangkok, Thailand
[2]Ph.D., Concrete Testing Manager, Siam Research and Innovation Company Limited, Saraburi, Thailand
[3] Professor, Department of Civil Engineering, Faculty of Engineering, King Mongkut's University of Technology Thonburi, Bangkok, Thailand
[4]Associate Professor, Department of Civil and Environmental Engineering Technology, College of Industrial Technology, King Mongkut's University of Technology North Bangkok, Bangkok, Thailand

ARTICLE INFO:

Received: July 30, 2019
Received Revised Form: October 15, 2019
Accepted: October 25, 2019

**Corresponding Author,*
Email address: natmakaratat.kmutnb@gmail.com

ABSTRACT:

This paper presents the properties of concrete containing high volume of fly ash and ground granulated blast furnace slag (HVFGS). The fly ash (FA) and ground granulated blast furnace slag (GS) were used to replace Portland cement at 40 to 80% by weight of the binder as ternary blends. Many series of test, namely setting times, compressive strength, water permeability, rapid chloride permeability, total shrinkage, and abrasion resistance were evaluated, and compared to those of OPC concrete and fly ash concrete, in which 30% of FA was replacement in binder. The results revealed that HVFGS concrete produced excellent strength and durability properties. The HVFGS binder effectively reduced water permeability, chloride ion penetration, and drying shrinkage of concrete. In addition, HVFGS binder provided good abrasion resistance for the concrete, although the HVFGS concrete contained low Portland cement.

KEYWORDS: Fly ash; Ground granulated blast furnace slag; High volume; Ternary

1. Introduction

At present, supplementary cementitious materials (SCMs), such as fly ash, ground granulated blast furnace slag, silica fume, metakaolin, limestone powder, and natural pozzolans are used in concrete around the world. Benefits of these materials (when used as partial replacements in cement) are improved workability, enhanced long-term compressive strength and durability of the concrete [1-3]. In addition, cost of the concrete is reduced and environmental problems due to the reduction of Portland cement production and disposal of these minerals are mitigated [4-7].

Fly ash and ground granulated blast furnace slag are by-products of industries. In 2010, worldwide fly ash production was approximately 500 million tons [8]. More than 3.0 million tons of fly ash is produced annually in Thailand, with approximately 1.5 million tons/year is used in concrete production [9]. Ground granulated blast furnace slag is a by-product from blast furnace production of pig iron [10]. Annually, worldwide production of ground granulated blast furnace slag is approximately 250 million tons, with approximately 90 million tons is used in concrete production [11]. Ground granulated blast furnace slag is seldom used in Thailand while the fly ash is usually used in ready mixed concrete to produce more than million cubic meters of concrete annually. Thus, the excess fly ash and ground granulated blast furnace slag is routinely disposed of in landfills, causing many environmental problems.

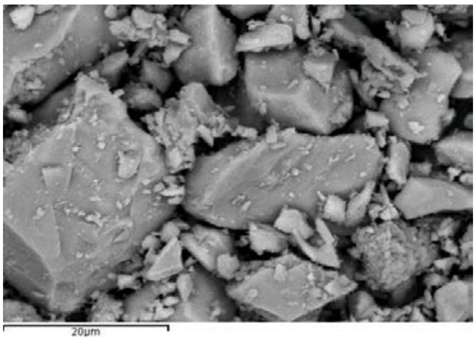
Many studies, Thomas et al. [3], Guneyisi and Gesoglu [12], Guneyisi et al. [13], and Nehdi et al. [14] reported that the production of Portland cement concrete incorporating a high replacement volume of ternary or quaternary SCMs resulted in enhanced fresh and hardened concrete properties superior to binary blended cement concrete. Furthermore, the replacement of Portland cement with an optimal dosage of highly refined SCM can reduce the pore structure and porosity of concrete, resulting in dramatically decreased penetration of aggressive chloride ions into concrete [15-17]. Permeability is also a very important factor affecting the durability of concrete structures. The permeability properties control the deterioration of a concrete structure in severe environments such as sulfate attacks and steel corrosion under chloride attacks [18, 19]. To achieve durability, the concrete must have low water to binder ratio, low permeability, and high resistance to chloride penetration. Reports of Elahi et al. [18] and Seleem et al. [19] also indicated that the use of SCMs could increase the durability properties and service life of a concrete structure.

This research aims to study the influence of large amounts of ternary blends from HVFGS binder on strength and durability properties of concrete. The results of setting times, compressive strength, water permeability, rapid chloride permeability, drying shrinkage, and abrasion resistance of the HVFGS concrete were evaluated. Consequently, this research leads to a better understanding of the factors affecting the strength and durability properties of the concrete containing high volume ternary blends from fly ash and ground granulated blast furnace slag. Moreover, the results of this study may be helpful for cement and concrete industries in selecting suitable dosage of fly ash and ground granulated blast furnace slag to replace of Portland cement as ternary blend.

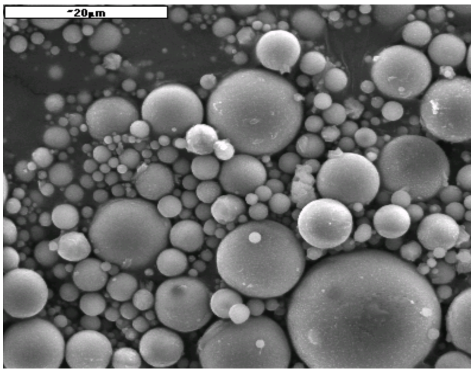
2. Experimental program

2.1. Materials

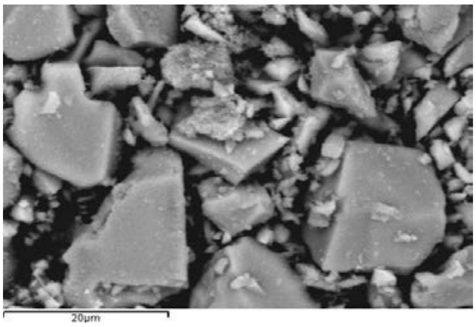
The materials used in this research were Portland cement type I (OPC), class F fly ash (FA), ground granulated blast furnace slag (GS), river sand, crushed limestone, water, and superplasticizer (SP). The particle morphologies of the materials (OPC, FA, and GS) were determined with a scanning electron microscope (SEM) and are shown in Figure. 1. Table 1 shows their physical properties, including specific gravity, surface area (via an air permeability method), and median particle sizes (by means of a Mastersizers Malvern Instrument). Table 2 shows the chemical compositions of the materials determined through X-Ray fluorescence analysis.



(1a) OPC



(1b) FA



(1c) GS

Figure 1 SEM Images of Portland cement type I (OPC), fly ash (FA), and ground granulated blast furnace slag (GS): (1a) OPC; (1b) FA; (1c) GS.

Table 1 Physical properties of Portland cement type I (OPC), fly ash (FA), and ground granulated blast-furnace slag (GS).

Materials	Specific gravity	Retained on a 45-μm sieve (No.325) (%)	Specific surface area (cm^2/g)	Median particle size, d_{50} (μm)
OPC	3.15	16.0	3400	17.0
FA	2.15	31.3	2500	26.4
GS	2.91	3.12	4110	14.2

Table 2 Chemical compositions of ordinary Portland cement type I (OPC), fly ash (FA), and ground granulated blast-furnace slag (GS).

Oxides (%)	OPC	FA	GS
SiO_2	20.2	40.9	33.8
Al_2O_3	5.1	22.4	15.2
Fe_2O_3	3.7	13.6	0.4
CaO	64.9	13.6	42.2
SO_3	2.1	1.9	1.9
Na_2O	0.0	0.9	0.0
K_2O	0.5	2.4	0.3
MgO	1.0	2.9	5.5
LOI	2.3	0.8	0.0

OPC has a specific gravity of 3.15. In addition, it has a specific surface area and median particle size (d50) of 3,400 cm2/g and 17.0 μm, respectively. Figure. 1(a) shows that OPC has an irregular shape with solid particles. FA was collected from the pulverized coal combustion process of the Mae Moh power plant in northern part of Thailand. Figure. 1(b) shows that FA, as received, has a smooth surface and spherically shaped particles. FA has a specific gravity of 2.15, which is lower than that of the OPC. The median particle size (d50) of FA is 26.4 μm, while 31.3% of FA particles (by weight) are retained on a 45-μm sieve. The test results of the Mae Moh fly ash are similar to those of Chindaprasirt et al. [16] and Jaturapitakkul et al. [20].

As for chemical composition, FA consists of an amorphous or glass content of 87.6%, as determined through quantitative X-ray diffraction analysis. The oxide content (SiO2, Fe2O3, and Al2O3) of the FA is 76.9%, higher than the minimum requirement of 70.0% according to ASTM C618-12a [21] for Class F fly ash. In addition, the CaO, SO3, and LOI values of the FA were 13.6%, 1.9%, and 0.8%, respectively.

The GS consists of an amorphous or glass content of 98.9% and can be classified as grade 100 according to ASTM C989-12a [22]. Figure. 1(c) shows that the GS has solid particles with some rough surfaces, similar to OPC particles. The specific gravity of the GS is 2.91. The median particle size (d50) and the weight of the particles retained on a 45-μm sieve of the GS are 14.2 μm and 3.12%, respectively. Furthermore, the GS has a specific surface area of 4,110 cm2/g, which is higher than both the OPC and FA. The results also indicate that GS has higher fineness than both the OPC and FA.

Natural river sand with a fineness modulus of 3.20 and a specific gravity of 2.6 was used as a fine aggregate. Crushed limestone was used as a coarse aggregate; it had a maximum size of 19 mm, a fineness modulus of 6.90, and a specific gravity of 2.7. Water absorptions of the fine and coarse aggregates were 0.71% and 0.52%, respectively. An ASTM C 494-12 [23] type F superplasticizer with a density of 1.10 g/cm3 and a total solid content of 41.6% was also used to maintain constant slump of the tested fresh concrete at 200 ± 20 mm.

2.2. Concrete mixture proportions

All concrete mixture proportions and the workability of the fresh concretes are summarized in Table 3. Five concrete mixtures were assessed to evaluate the properties of the HVFGS concrete. In addition, the Portland cement concrete (OPC concrete) and the fly ash concrete (30FA) were also prepared for comparison purposes. All of the concrete mixtures had a binder content of 450 kg/m3 and a water-to-binder (W/B) ratio of 0.40. The OPC concrete only contained OPC as a binder. Fly ash (FA) was used to replace OPC at a rate of 30% (by weight) of binder to cast concrete and was designated as 30FA concrete. For HVFGS, ternary blends (OPC+FA+GS) containing both FA and GS at replacement percentages of 40, 50, 60, 70, and 80% (by weight) of binder were prepared to cast HVFGS concrete specimens and were designated as 30FA10GS, 30FA20GS, 30FA30GS, 30FA40GS, and 30FA50GS concretes, respectively.

2.3. Concrete mixture proportions

2.3.1 Slump, setting times, and compressive strength of concrete

The amount of SP required to maintain the same degree of slump (200 ± 20 mm) of fresh concrete was measured in all of the concrete mixtures according to ASTM C143-12 [24]. The initial and final setting times of the fresh concretes were determined according to ASTM C403-08 [25] procedures. Cube concrete specimens (100x100x100 mm) were cast for compressive strength tests. After casting, the concretes were de-molded at 24 hours, and then cured in tap water until the testing dates. The compressive strengths of the concretes were determined at 1, 7, 28, 60, and 90 days.

2.3.2 Coefficient of water permeability

The depth of water penetration was determined according to DIN 1048 Part 5 [26], and the water permeability test setup is shown in Figure 2. This procedure is suitable for concrete with very low permeability as recommended by Khatri and Sirivivatnanon [27], who measured the depth of penetration and converted it to a coefficient of water permeability. Concrete specimens of 150x150x125 mm. were cast and cured in water for 28 days and then air dried for 7 days. The specimens were then installed in a permeability housing cell, and a water pressure of 5 bars (0.5 MPa) was applied to the top surface of the samples for 3 days. Afterwards, each sample was split and the maximum depth of water penetration was measured. The coefficient of water permeability (Kp) was calculated by using Dacy's law and continuity equation, as shown in Equation 1.

$$Kp = d^2v/2Th \quad (1)$$

where Kp is the coefficient of water permeability (m/sec), d is the average depth of water penetration (mm.), T is the time to penetrate up to depth d (sec), h is the pressure head (m.), and v is the volume of permeable pore space (%) as obtained from ASTM C642-06 [28] procedures.

Figure 2 Water permeability setup for testing concrete

2.3.3 Rapid chloride permeability

The chloride ion penetration was determined by using a rapid chloride permeability test according to ASTM C1202-12 [29] as shown in Figure 3. Cylindrical concrete specimens (100 mm. in diameter and 200 mm. in height) were used to evaluate the ability of the concrete to resist chloride penetration. After curing for 28 days, a 50 mm. thick slice of each sample was taken from the mid-height of the concrete cylinder. They were immersed in distilled water for 24 hours. The samples were then placed between two cells; a 0.3 N sodium hydroxide solution and a 3.0% sodium chloride solution (by mass). A potential difference of 60 ± 0.1 voltage DC was maintained across the specimens for 6 hours. The total charge passing (in coulombs) was measured and related to the chloride ion penetration resistance of the concrete.

Figure 3 Apparatus for testing rapid chloride permeability

2.3.4 Total shrinkage

Prismatic concrete specimens with a cross-section of 75 x 75 mm^2 and a length of 285 mm. were cast and used to determine the total shrinkage. Stainless steel studs were fitted at both ends of each concrete specimen. The specimens were removed from the molds after 1 day and the initial lengths of the concrete specimens were measured with a standard length change comparator. The specimens were placed in an air storage cabinet with a controlled temperature of 23 ± 2 °C and a relative humidity of 50% ± 4% according to ASTM C157-08 [30] during the test period. The total shrinkage of all concrete specimens was measured for 180 days.

2.3.5 Abrasion resistance

The abrasion resistance of the concrete was determined according to ASTM C944-12 [31]. Concrete specimen cubes (100x100x100 mm.) were cast, and were tested at 28 days of curing age. The abrasion with a normal weight was continued to rotate at a surface of the specimen for 2 minutes. The three separate surface areas were tested in the same conduct for a concrete specimen. After testing, the weight loss of the specimen was monitored at each instance with a balance with an accuracy of 0.1 gram. The average weight loss value (in grams) of three concrete specimens was reported and compared to those of the OPC and 30FA concretes.

3. Results and Discussions

3.1 Requirement of superplasticizer

Table 3 shows the superplasticizer (SP) requirements of the OPC, 30FA, and HVFGS concretes to maintain the same slump (between 200 ± 20 mm). It was shown that OPC concrete required a SP of 0.52% by weight of binder, while 30FA concrete required a lower SP content than that of the OPC concrete to achieve the same slump or 0.28% by weight of binder. The 30FA concrete required less SP than the OPC concrete because the spherical shapes and smooth surface of the FA particles resulted in an enhanced workability of the fresh concrete. This result supports the findings of Chindaprasirt et al. [32], Kiattikomol et al. [33], and Angsuwattana et al. [34] who reported that the spherical shapes and round surface of FA could improve the workability of fresh concrete.

For the HVFGS concretes, the SP dosages were even lower than those of the OPC and 30FA concretes. Furthermore, the levels reduced with the increased GS content in the concrete. For example, the 30FA10GS, 30FA20GS, 30FA30GS, 30FA40GS, and 30FA50GS concretes required SP dosages of 0.20, 0.20, 0.15, 0.10, and 0.10% by weight of binder, respectively. This result confirms the reported results of Guneyisi et al. [13], Gesoglu et al. [35], and Gesoglu et al. [36] for binary and ternary blends of OPC, FA and GS. Moreover, it was observed that the FA and GS particles enhanced the workability of the HVFGS concretes because of favorable particle characteristics, good particle dispersion, and increased paste volume [10, 37].

Table 3 Concrete mix proportions.

Concretes	Mix proportions (kg/m^3)						SP*	W/B	Slump
	OPC	FA	GS	Sand	Rock	Water	(%)		(mm)
OPC	450	0	0	680	1080	180	0.52	0.40	200
30FA	315	135	0	650	1067	180	0.28	0.40	210
30FA10GS	270	135	45	650	1060	180	0.20	0.40	205
30FA20GS	225	135	90	647	1052	180	0.20	0.40	210
30FA30GS	180	135	135	646	1040	180	0.15	0.40	205
30FA40GS	135	135	180	644	1038	180	0.10	0.40	210
30FA50GS	90	135	225	642	1037	180	0.10	0.40	205

*Percentage by weight of binder.

Table 4 Setting times of concretes.

Concretes	Times of setting (hr:min)	
	Initial setting times	Final setting times
OPC	3:41	4:59
30FA	3:41	5:02
30FA10GS	3:42	5:09
30FA20GS	3:51	5:16
30FA30GS	4:01	5:20
30FA40GS	4:23	6:13
30FA50GS	4:53	7:36

3.2 Setting times of concrete

Table 4 shows the results from the evaluation of concrete setting times for all mixtures. It was found that the initial setting times of OPC and 30FA concretes were equal at 3 hr 41 min while the final setting times were 4 hr 59 min and 5 hr 2 min, respectively.

For the HVFGS concrete, the setting times did not have much difference than that of OPC concrete although they had lower Portland cement content than that of the OPC concrete. The initial setting times of 30FA10GS, 30FA20GS, and 30FA30GS concretes were 3 hr 42 min, 3 hr 51 min, and 4 hr 1 min while the final setting times were 5 hr 9 min, 5 hr 16 min, and 5 hr 20 min, respectively. Several researchers have shown that the use of a high pozzolan content in binary blended cements create long delays in the setting times of concrete [38, 39] because binders containing high amounts of pozzolan have a low hydration reaction from the Portland cement. However, Gesoglu et al. [35] reported that the long delay in the setting times of concrete containing 60% replacement of GS in Portland cement could be solved by using ternary blends of 30% FA and 30% GS in concrete. This was because the GS could react with OPC and water to create the same products as those of the hydration process. Subsequently, the GS can react with $Ca(OH)_2$ from the hydration process to form CSH [40].

As a result, it was found that when the level of GS was increased in ternary blends, the setting times of HVFGS concretes were longer than that of the OPC concrete because they had a lower hydration reaction from the Portland cement. For example, at a high volume replacement (70 and 80% of Portland cement), the initial setting times of 30FA40GS and 30FA50GS concretes were 4 hr 23 min and 4 hr 53 min, and the final setting times were 6 hr 13 min and 7 hr 36 min, respectively. The 30FA40GS and 30FA50GS concretes had a Portland cement content of only 135 and 90 kg/m3 in mixtures, approximately 3.3 and 5.0 times lower than that of the OPC concrete (cement content of 450 kg/m^3), respectively.

3.3 Compressive strength of concrete

At each testing date, the average compressive strength of three concrete specimens was used; the results of the compressive strength and the percentage of compressive strength of the 30FA and HVFGS concretes (as compared to the OPC concrete) are tabulated in Table 5. The results show that the OPC concrete had compressive strengths of 35.0, 55.3, 61.7, 64.2, and 65.1 MPa at 1, 7, 28, 60, and 90 days, respectively. At the early ages of 1 and 7 days, the 30FA concrete had compressive strengths of 21.1 and 40.3 MPa, or approximately 60% and 73% of the OPC concrete, respectively. The low compressive strength of the concrete containing fly ash was expected at early ages, and this result is consistent with the results of Sata et al. [41] and Duran-Herrera et al. [42]. This is because the 30FA concrete has low cement hydration reaction. The compressive strength increased at later ages due to the pozzolanic reaction. At 28 days, the compressive strength of the 30FA concrete was 53.3 MPa (86% of the OPC concrete) and increased to 62.3 and 64.7 MPa (97% and 99% of OPC concrete) at 60 and 90 days, respectively. It is noted that the compressive strength of the 30FA concrete develops to be the same as OPC concrete after 90 days or more.

Table 5 Compressive strength and percentage compressive strength of concretes.

Concretes	Compressive Strength (MPa) - ***Percentage compressive strength (%)***				
	1 day	7 days	28 days	60 days	90 days
OPC	35.0 - ***100***	55.3 - ***100***	61.7 - ***100***	64.2 - ***100***	65.1 - ***100***
30FA	21.1 - ***60***	40.3 - ***73***	53.3 - ***86***	62.3 - ***97***	64.7 - ***99***
30FA10GS	19.3 - ***55***	43.3 - ***78***	56.0 - ***91***	64.9 - ***101***	65.8 - ***101***
30FA20GS	16.3 - ***47***	41.8 - ***76***	56.8 - ***92***	61.3 - ***95***	62.3 - ***96***
30FA30GS	12.7 - ***36***	38.7 - ***70***	53.7 - ***87***	61.4 - ***96***	62.3 - ***96***
30FA40GS	9.8 - ***28***	35.0 - ***63***	48.8 - ***79***	55.7 - ***87***	59.3 - ***91***
30FA50GS	8.7 - ***25***	34.0 - ***61***	46.0 - ***75***	50.1 - ***78***	52.3 - ***80***

Similar results of low compressive strengths at early ages were also found in HVFGS concrete. At 1 day, the compressive strengths of the HVFGS concretes ranged from 8.7 to 19.3 MPa and were much lower than those of the 30FA and OPC concretes (25% to 55% of the OPC concrete). At 7 days, the compressive strengths of the HVFGS concretes ranged from 34.0 to 43.3 MPa or 61% to 78% of the OPC concrete. It was indicated that the compressive strength of the HVFGS concretes decreased with increased GS replacement. At early ages, the strength development of the HVFGS concretes was lower than that of the OPC concrete because the cement content was replaced with high amounts of FA and GS mixtures (40% to 80% replacement rates of cement). Moreover, at 1 and 7 days, the pozzolanic reaction from the FA and GS is little and much slower than the hydration of cement. Both FA and GS require calcium hydroxide ($Ca(OH)_2$) from the hydration of the cement to increase the pozzolanic reaction rate [10, 37, 43].

At 28 days, the compressive strengths of the 30FA10GS, 30FA20GS, 30FA30GS, 30FA40GS, and 30FA50GS concretes were 56.0, 56.8, 53.7, 48.8, and 46.0 MPa, or approximately 91%, 92%, 87%, 79%, and 75% of the OPC concrete, respectively. The results indicate that the 30FA10GS and 30FA20GS concretes had higher compressive strengths than that of the 30FA concrete, even though the cement contents of the 30FA10GS and 30FA20GS concretes were lower (40% and 50% replacement rate of cement).

At later ages of 60 to 90 days, the compressive strengths of the concretes increased and ranged from 50.1 to 64.9 MPa and 52.3 to 65.8 MPa, respectively. At 60 days, the 30FA10GS, 30FA20GS, 30FA30GS, and 30FA40GS concretes had compressive strengths of 64.9, 61.3, 61.4, and 55.7 MPa, or 101%, 95%, 96% and 87% of the OPC concrete, respectively. At 90 days, the compressive strengths of the 30FA10GS, 30FA20GS, 30FA30GS, and 30FA40GS concretes increased to 65.8, 62.3, 62.3, and 59.3 MPa, or 101%, 96%, 96%, and 91% of OPC concrete, respectively. It should be noted that the 30FA10GS, 30FA20GS, and 30FA30GS concretes had the compressive strengths similar to OPC concrete at later ages of 60 and 90 days (40% to 60% replacement rates of Portland cement). Moreover, it was found that the compressive strength of the 30FA10GS, 30FA20GS, 30FA30GS, and 30FA40GS concretes was also higher than 55 MPa, which was considered high strength concrete according to ACI 363R-10 [44].

The highest compressive strength of HVFGS concrete occurred in 30FA10GS concrete, with the compressive strength of 65.8 MPa (101% of OPC concrete) at 90 days. Moreover, it was also noted that 30FA50GS concrete provided a compressive strength of 52.3 MPa (80% of OPC concrete at 90 days), although the concrete contained only 90 kg/m^3 of OPC. The results indicate that the compressive strength of HVFGS concrete increased with curing ages, even though the binder contained low amounts of cement. This is due to the SiO2, and Al2O3 of the FA and GS reacting with $Ca(OH)_2$ (from the hydration of the cement) to form calcium silicate hydrates (CSH) and calcium aluminate hydrates (CAH), thus creating the compressive strength of the HVFGS concrete [10, 37]. In addition, lime in the GS can produce CSH from its hydration reaction similar to Portland cement, but at a lower hydration. Moreover, GS can also react with sodium and potassium alkalis to create additional CSH, leading to increased compressive strengths at later ages [10, 45].

3.4 Coefficient of water permeability of concrete

Table 6 shows the water penetration depth values (d) and coefficients of water permeability (Kp) at 28 days. It was found that the water penetration depth of OPC concrete was higher than those of 30FA and HVFGS concretes. The OPC and 30FA concretes had water penetration depths of 18.0 and 9.0 mm, respectively, while the water penetration depths of HVFGS concretes ranged from 8.5 to 3.5 mm, which were lower than that of the 30FA concrete. The results showed that the water penetration depths of the HVFGS concretes decreased with the increased GS content, although the compressive strengths of the HVFGS concretes were lower. The water penetration depths of the 30FA10GS, 30FA20GS, 30FA30GS, 30FA40GS, and 30FA50GS concretes were 8.5, 7.0, 6.5, 5.0, and 3.5 mm, respectively.

The water permeability coefficient (Kp) of the OPC concrete was 13.8x10-13 m/s, which conforms to the previous results of normal concrete studied by Chindaprasirt et al. [46] (28.9x10-13 and 20.5x10-13 m/s at 28 and 90 days, respectively). The 30FA concrete had a Kp of 3.3x10-13 m/s, which was lower than that of the OPC concrete. For the 30FA10GS, 30FA20GS, 30FA30GS, 30FA40GS, and 30FA50GS concretes, the Kp values were 2.9x10-13, 1.8x10-13, 1.5x10-13, 0.9x10-13, and 0.4x10-13 m/s, respectively. It can be observed that the HVFGS concretes had lower Kp values than those of both the OPC and 30FA concretes. In addition, the results also indicate that Kp reduced when the replacement of GS was increased in HVFGS concrete.

The volume of permeable pore space in the hardened concrete was tested at 28 days and the results are also tabulated in Table 6. It was revealed that the volume of permeable pore space in the OPC concrete was 11.0%, while the volume in the 30FA concrete was 10.5%. The HVFGS concretes had lower volumes of permeable pore space than those of both OPC and 30FA concretes and decreased with increasing of GS replacement. The 30FA10GS, 30FA20GS, 30FA30GS, 30FA40GS, and 30FA50GS concretes had volumes of permeable pore space of 10.4, 9.7, 9.5, 9.4, and 8.9%, respectively. These results revealed that the volume of permeable pore space decreased as the GS was increased. Furthermore, the Kp and volume of permeable pore space were reduced with the increasing GS replacement as ternary blends. This was because the pozzolanic reaction from the FA and GS refined the pore structures, resulting in reduced porosity and impermeable property within the HVFGS concrete [47]. Similar results for fly ash and GS concretes were also reported by Keck [45], Jiang et al. [48], and Berndt [49], who reported that use of FA and GS to replace cement in concrete resulted in low permeability of concrete.

The relationship between the water permeability coefficient and the volume of permeable pore space at 28 days is illustrated in Figure 4. This suggests that the results of the water permeability coefficient are consistent with the volume of permeable pore space. Figure. 4 clearly indicates that the water permeability coefficient of the HVFGS concrete decreased as the volume of permeable pore space decreased. It was shown that the HVFGS concrete had a good resistance to the water penetration, although the HVFGS concrete contained low Portland cement.

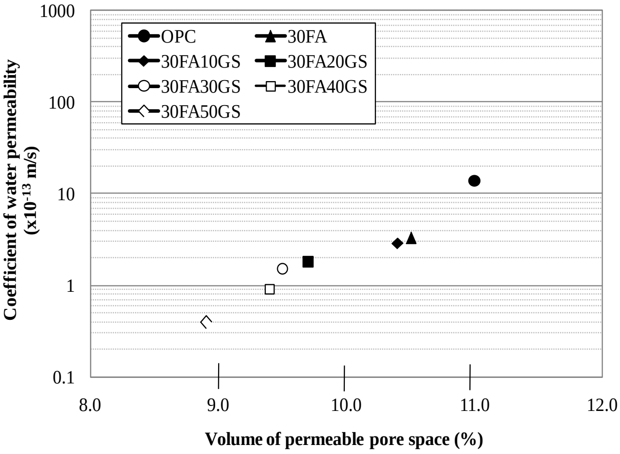


Figure 4 Relationship between coefficient of water permerability and volume of permeable pore space

3.5 Rapid chloride permeability

Table 6 presents the results of rapid chloride penetration of the concrete at 28 days. It was found that the total charge passed through the OPC concrete was 3,720 coulombs, which was classified as moderate chloride ion penetration according to ASTM C1202-12 [29]. This result was similar to the rapid chloride penetration results of plain concrete that was reported by Ahmad et al. [50]. The 30FA concrete had a total charge passed of 1,089 coulombs, which was much lower than that of the OPC concrete and classified as low chloride ion penetration according to ASTM C1202-12 [29]. In addition, the total charge passed of the HVFGS concretes was lower than those of both the OPC and 30FA concretes. Moreover, the total charge passed of the HVFGS concretes reduced with the increased GS content, although their compressive strengths decreased.

Table 6 Depth of penetration, volume of permeable pore space, and water permeability coefficient of concretes at 28 days.

Mixes	Depth of penetration, d (mm)	Volume of permeability pore space, v (%)	Coefficient of permeability, Kp ($x10^{-13}$ m/sec)	Chloride ion penetration (Coulombs)	Chloride ion permeability (ASTM C1202)
OPC	18.0	11.0	13.8	3720	Moderate
30FA	9.0	10.5	3.3	1089	Low
30FA10GS	8.5	10.4	2.9	914	Very Low
30FA20GS	7.0	9.7	1.8	763	Very Low
30FA30GS	6.5	9.5	1.5	674	Very Low
30FA40GS	5.0	9.4	0.9	486	Very Low
30FA50GS	3.5	8.9	0.4	428	Very Low

The total charge passed of the 30FA10GS, 30FA20GS, 30FA30GS, 30FA40GS, and 30FA50GS concretes was 914, 763, 674, 486, and 428 coulombs, respectively. The results of chloride ion penetration of the HVFGS concretes were classified as very low (less than 1,000 coulombs). As a result, the low OPC concrete incorporating the HVFGS binder significantly increased chloride penetration resistance. Furthermore, the result of chloride penetration resistance is consistent with the water permeability coefficient of the concrete: it decreased with the increasing of GS content in ternary blends. This was attributed to the pozzolanic reaction of the FA and GS, resulting in the refinement of pore structures and leading to a dense paste matrix and lower permeability [10, 47]. Furthermore, the increase of FA and GS in the concrete also increased the amount of Al2O3 content, resulting in the enhanced chloride penetration resistance of the concrete [3, 47]. Thomas et al. [3] also reported that the incorporating of FA and GS as ternary blends at 60% and 80% replacement rates in concrete with a W/B ratio of 0.4 could reduce chloride penetration, the chloride diffusion coefficient, and the chloride charge passed in coulombs after 25 years of exposure in a marine environment tidal zone.

3.6 Total shrinkage

Figure 5 illustrates the relationship between the total shrinkage of concretes and age. It was seen that the shrinkage strains of all concretes significantly increased at an early age of 1 month and then slowly increased afterwards. OPC concrete had the highest shrinkage strain value of 536 $x10^{-6}$ at 180 days. However, the total shrinkage of concrete was slightly decreased when fly ash was used to replace cement as a binary blend (30FA concrete) to 516 $x10^{-6}$ at 180 days.

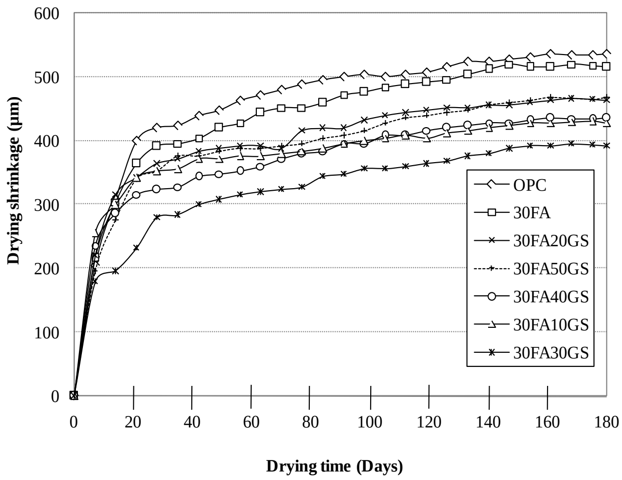


Figure 5 Total shrinkage of concretes

For the HVFGS concretes, the ternary blend of concrete had a total shrinkage lower than those of both OPC and 30FA concretes. It was observed at 180 days that the total shrinkage strains of the 30FA10GS, 30FA20GS, 30FA30GS, 30FA40GS, and 30FA50GS concretes were 428x10-6, 464x10-6, 392x10-6, 436x10-6, and 464x10-6, or 20%, 13%, 27%, 19%, and 13% lower than that of the OPC concrete, respectively. It was noted that the lowest total shrinkage strain occurred in a ternary blend of 30FA30GS concrete. Furthermore, the 30FA30GS concrete had higher the compressive strengths than those of 30FA40GS, and 30FA50GS concretes.

According to the volume of permeable pore space in the HVFGS concretes, it can also be explained that the pore refinement from the pozzolanic and hydration reactions of the ternary blends resulted in reducing the drying shrinkage strain. This is due to the drying shrinkage associated with the water held in the concrete pores [51]. Tangchirapat et al. [52] also reported that the refinement of large pores into fine pores reduced water loss, and thus reduced the drying shrinkage of the concrete. Similar results were also reported by Guneyisi et al. [13] and Gesoglu et al. [36], who noted that the ternary blends of FA and GS (30% of FA+30% of GS) with a W/B ratio of 0.44 had a low drying shrinkage of less than 400 x10^{-6} at 56 days.

3.7 Abrasion resistance

The abrasion resistance of all concretes as reported in weight loss tests at 28 days are tabulated in Table 7. The OPC concrete had a weight loss of 3.1 g, while the 30FA concrete had a slightly higher weight loss at 3.2 g. In general, the abrasion resistance of concrete is related to its compressive strength [45, 53]. However, the studied results showed that the weight loss of 30FA concrete was not much different from OPC concrete, even though its compressive strength was lower. The compressive strengths of OPC and 30FA concrete at 28 days were 61.7 and 53.3 MPa, respectively.

For the HVFGS concretes, the weight losses of the 30FA10GS, 30FA20GS, 30FA30GS, and 30FA40GS concretes were 3.1, 2.9, 2.8, and 2.7 g, respectively. The result also showed that the weight losses of the HVFGS concretes were lower than those of both the OPC and 30FA concretes at 40-70% replacement rates with ternary mixtures. Furthermore, it was observed that the weight losses of the 30FA10GS, 30FA20GS, 30FA30GS, and 30FA40GS concretes were lower than that of the OPC concrete, even though their compressive strengths were lower. The results indicate that concretes containing HVFGS at 40-70% replacement rates provided good abrasion resistance. This is probably due to the hydration reactions from the limes in the cement and GS and the pozzolanic reaction created a strong hardened paste that resulted in high abrasion resistance for the HVFGS concretes [54]. However, it was noted that at the 80% replacement rate, the 30FA50GS concrete had weight loss of 4.1 g, which was higher than both the OPC and 30FA concretes. The compressive strengths of the OPC and 30FA concrete were 61.7 and 53.3 MPa, while that of the 30FA50GS was 46 MPa at 28 days, respectively.

Table 7 Abrasion resistance of concretes at 28 days.

Concretes	Abrasion resistance (Weight loss) Grams
OPC	3.1
30FA	3.2
30FA10GS	3.1
30FA20GS	2.9
30FA30GS	2.8
30FA40GS	2.7
30FA50GS	4.1

4. Conclusions

The following conclusions can be drawn from the experimental results of this study:

1. The use of HVFGS could reduce the amount of superplasticizer required in the concrete mixture compared to the OPC and 30FA concretes when the same slump of fresh concrete was maintained. The setting times of the HVFGS concretes were not different from those of the OPC and FA concretes, although the HVFGS concretes contained low cement content.
2. The highest compressive strength of HVFGS concrete occurred in the 30FA10GS concrete, with compressive strengths of 56.0 and 65.8 MPa (91% and 101% of OPC concrete) at 28 and 90 days, respectively. Moreover, the 30FA50GS concrete provided the compressive strengths of 46.0 and 52.3 MPa at 28 and 90 days, although the concrete contained only 90 kg/m^3 of Portland cement.
3. The HVFGS concretes had lower water permeability and drying shrinkages than those of the OPC and 30FA concretes. At 40-70% replacement rates, although the compressive strengths of HVFGS concretes were lower, the HVFGS concretes had good resistance for chloride ion penetration and higher abrasion resistance than the OPC and 30FA concretes.
4. The use of HVFGS binder enhanced the durability properties of the concrete to a greater degree than those using OPC and fly ash. It was observed that the durability properties of the HVFGS concrete increased when the GS was increased in the concrete as a ternary mixture up to 70% replacement.

5. Acknowledgement

The authors gratefully acknowledge the financial supports of the Thailand Research Fund (TRF) under the TRF Senior Research Scholar Grant No. RTA5380002, as well as the National Research University (NRU) from King Mongkut's University of

Technology Thonburi. We also wish to thank the Siam Research and Innovation Co., Ltd. for supporting the laboratory facilities and equipment used in this study.

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