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Use of ground coarse fly ash as a replacement of condensed silica fume in producing high-strength concrete

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Abstract

This paper presents a method of improving coarse fly ash in order to replace condensed silica fume in making high-strength concrete. The coarse fly ash, having the average median diameter about 90–100 μm, yields a very low pozzolanic reaction and should not be used in concrete. In order to improve its quality, the coarse fly ash was ground until the average particle size was reduced to 3.8 μm. Then, it was used to replace Portland cement type I by weights of 0%, 15%, 25%, 35%, and 50% to produce high-strength concrete. It was found that concrete containing the ground coarse fly ash (FAG) replacement between 15% and 50% can produce high-strength concrete and 25% cement replacement gave the highest compressive strength. In addition, the concrete containing FAG of 15–35% as cement replacement exhibited equal or higher compressive strengths after 60 days than those of condensed silica fume concretes. The results, therefore, suggest that the FAG with high fineness is suitable to use to replace condensed silica fume in producing high-strength concrete.

Keywords: Coarse fly ash; Condensed silica fume; Fly ash; Grinding; High-strength concrete

1. Introduction

In recent years, high-strength concrete has increasingly been used in civil engineering work because it has an advantage of reducing the sizes of beams and columns, which are essential in high-rise building. According to ACI 363 [1], concrete having a 28-day compressive strength higher than 41 MPa can be considered as high-strength concrete. Generally, high-strength concrete is achieved by using superplasticizer to reduce the water–binder ratio and by using supplementary cementing materials such as silica fume, natural pozzolan, or fly ash in order to create extra strength by pozzolanic reaction. Furthermore, Shannag [2] used natural pozzolan and silica fume to produce high-strength concrete, and it was found that the combination of the two can be used in producing high-strength concrete in the range of 69 to 85 MPa at 28 days, with medium workability.

Silica fume is a powder by-product resulting from the manufacture of ferrosilicon and silicon metal. It has a high content of glassy of silicon dioxide (SiO_2) and consists of very small spherical particles. Because of this, it has been a popular mineral admixture to use in high-strength concrete. However, silica fume is expensive compared to Portland cement type I or fly ash.

Fly ash is a by-product of coal-burning power plants. It is widely used as a cementitious material and a pozzolanic

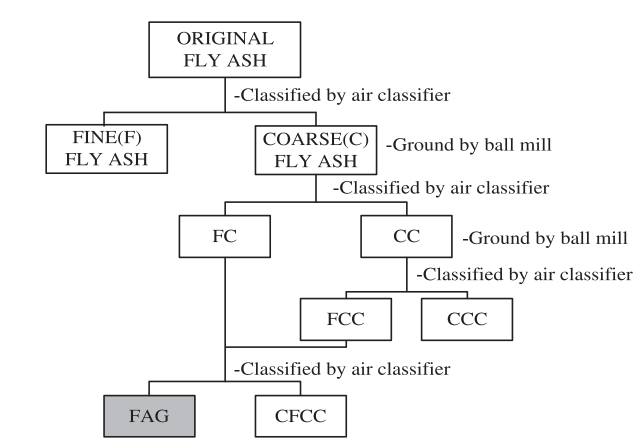

Fig. 1. Schematic process of FAG.

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Table 1
Concrete mix proportions

Mix No.	Symbol	Mix proportion (kg/m^3)								W/C	Slump (mm)
		Cement	SFI	SFII	FAG	Fine aggregate	Coarse aggregate	Water	Superplasticizer		
1	Control	554	–	–	–	780	976	146.3	5.5	0.27	190
2	SFI05	526	28	–	–	780	976	142.4	12.0	0.27	205
3	SFI10	499	55	–	–	780	976	140.4	15.2	0.27	190
4	SFI15	471	83	–	–	780	976	138.5	18.5	0.27	185
5	SFII05	526	–	28	–	780	976	142.7	11.5	0.27	210
6	SFII10	499	–	55	–	780	976	140.7	15.2	0.27	200
7	SFII15	471	–	83	–	780	976	138.8	18.0	0.27	195
8	FAG15	471	–	–	83	780	976	146.0	6.0	0.27	210
9	FAG25	416	–	–	138	780	976	146.4	5.3	0.27	205
10	FAG35	360	–	–	194	780	976	147.1	4.2	0.27	200
11	FAG50	277	–	–	277	780	976	147.6	3.2	0.27	190

ingredient in concrete. The use of fly ash in concrete is constantly increasing because it improves the properties of concrete, namely workability, durability, and strength in hardened concrete. Many researchers [3–6] concluded that classified fly ash with a high degree of fineness was an important factor in producing high-strength concrete. However, Berry et al. [7] suggested that coarse fly ash exhibited low pozzolanic activity since it contained a high proportion of crystalline phases, and thus should not be used in concrete. It is shown that the classified fly ash is suitable for use in concrete, but the residue from the classifying process (coarse fly ash) has to be disposed of [3,4]. However, Kiattikomol et al. [8], Songpiriyakij and Jaturapitakkul [9], and Paya et al. [10,11] found that by grinding the coarse fly ash into a high degree of fineness the compressive strength of concrete can be improved. Cornelissen et al. [12] also investigated the micronised fly ash and found that the use of ground fly ash can produce concrete with excellent strength.

2. Objective

The objective of this study is to investigate the use of ground coarse fly ash (FAG) in making high-strength concrete and to compare the results to those made from condensed silica fume.

Table 2
Physical properties of Portland cement type I, original fly ash, coarse fly ash, FAG, and condensed silica fumes (SFI and SFII)

Property	Portland cement	Original fly ash	Coarse fly ash	FAG	SFI	SFII
Specific gravity	3.14	2.02	1.81	2.63	2.22	2.19
Retained on sieve No. 325 (%)	4.7	37.4	92.0	0.6	1.6	2.8
Blaine fineness (cm^2/g)	3230	2370	940	8800	–	–
Median particle size, d_{50} (μm)	12.0	28.5	100.0	3.8	89.0	105.0

3. Experimental program

3.1. Materials

Materials used in this study consisted of Portland cement type I, fine and coarse aggregates, fly ash, condensed silica fume, superplasticizer, and water.

The coarse aggregate used was crushed limestone with 12 mm maximum size. The fine aggregate was natural river sand, having a fineness modulus of 3.02. The coarse and fine aggregates had a specific gravity of 2.67 and 2.61, and water absorption of 0.3% and 0.8%, respectively.

The original fly ash from silo of Mae Moh power plant in the northern part of Thailand was classified into different particle sizes. It is known that fly ash with high fineness is an excellent pozzolanic material to make high-strength concrete [4]. However, this is not true for fly ash having a large particle size. The mortar made from coarse fly ash, having the average particle size of about 90–100 μm, exhibited a strength activity index of 59% and 63% at the ages of 7 and 28 days, respectively [3], which was very low and did not conform to ASTM C 618. In this investigation, the coarse fly ash (Sample C as shown in Fig. 1) was ground by ball mill and reclassified. The ground fly ash, having an

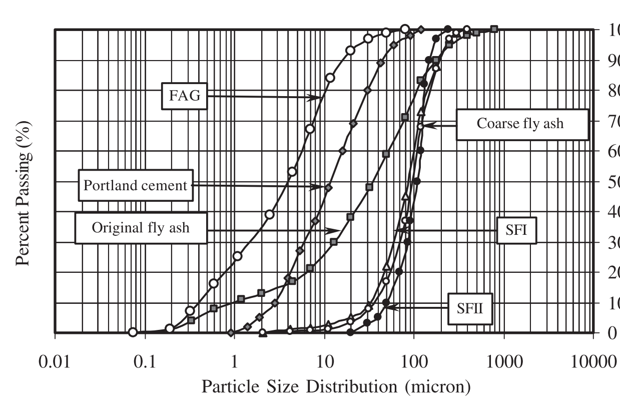

Fig. 2. Particle size distribution of cementitious materials.

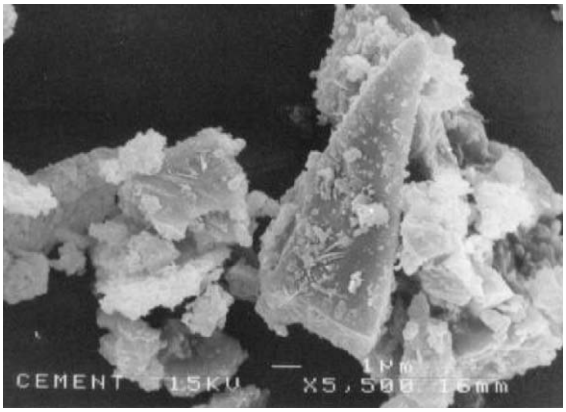

Fig. 3. Scanning electron microscopy of Portland cement type I.

average particle size of about 3.8 μm, was identified as FAG. The refinement and separation process is shown in Fig. 1.

Two imported brands of condensed silica fume, namely SFI and SFII, in powder form were used in this experimental program. Sulphonated naphthalene formaldehyde superplasticizer was used in all concrete mixtures and tap water was used throughout the experimental program.

3.2. Mix proportions

All mix proportions had the same cementitious materials of 554 kg/m^3, and the ratio of fine to coarse aggregate was 45:55 by volume. The water to cementitious materials ratio (w/c) was 0.27 and superplasticizer was employed in all concrete mixtures in order to maintain the slump of fresh concrete between 175 and 225 mm.

Three mix proportions of high-strength concrete were used in the current study. The first mix was control concrete (control) containing only Portland cement type I as cementitious materials. The second mix contained the replacement of Portland cement type I by two different brands of condensed silica fume (SFI, SFII) and named as SFI05, SFI10, SFI15, SFII05, SFII10, and SFII15. The numbers 05, 10, and 15 represent the percentage of the replacement of Portland cement type I by condensed silica fume at 5%, 10%, and 15% by weight of cementitious materials, respectively. The third mix contained the replacement of Portland cement type I by FAG and the mixtures named as FAG15, FAG25, FAG35, and FAG50. These had a FAG at 15%, 25%, 35%, and 50% by weight of cementitious materials, respectively. The concrete mix proportions are given in Table 1. The size of the cylindrical mold used to cast all the concrete samples was 100 mm in diameter and 200 mm in height. After 24 h, the concrete samples were removed from the molds and cured in water at room temperature. They were tested to determine their compressive strengths at the ages of 7, 28, 60, 90, and 180 days.

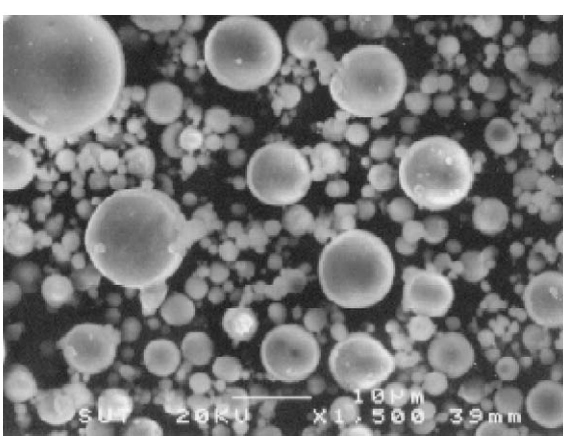

Fig. 4. Scanning electron microscopy of original fly ash.

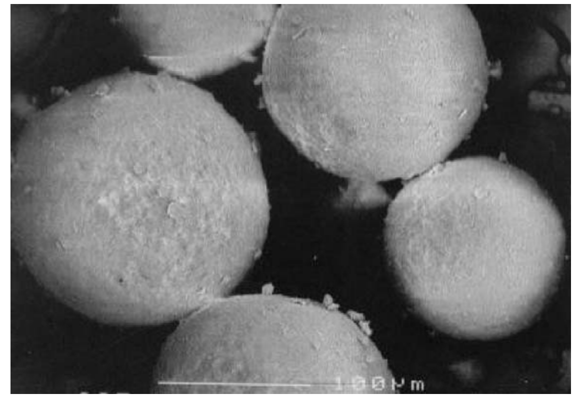

Fig. 5. Scanning electron microscopy of condensed silica fume SFI.

4. Results and discussion

4.1. Fineness and particle shape of materials

Table 2 shows the physical properties of Portland cement type I, original fly ash, coarse fly ash, FAG, and condensed silica fumes (SFI and SFII). Particle size distribution curves of the materials were obtained by using Mastersizers Mal-

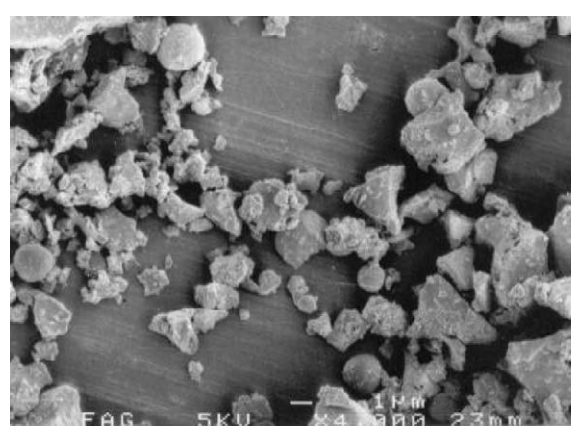

Fig. 6. Scanning electron microscopy of FAG.

Table 3
Chemical compositions of Portland cement type I, original fly ash, coarse fly ash, FAG, and condensed silica fumes (SFI and SFII)

Chemical compositions	Portland cement	Original fly ash	Coarse fly ash	FAG	SFI	SFII
SiO_2	21.16	46.25	45.20	50.77	93.80	94.09
Al_2O_3	6.04	26.43	20.52	27.15	0.21	0.17
Fe_2O_3	3.15	10.71	11.99	8.35	0.09	0.07
SO_3	2.88	1.85	0.55	0.85	–	–
CaO	63.96	7.61	12.51	9.09	0.12	0.18
MgO	0.87	2.21	2.30	2.70	0.33	0.34
Na_2O	0.05	1.11	1.14	0.06	–	–
K_2O	0.54	3.07	2.72	2.84	0.38	0.35
LOI (%)	1.39	0.23	0.08	2.09	4.89	4.65

vern Instruments and the results are shown in Fig. 2. It should be noted that, after coarse fly ash had been ground, the median particle size was reduced from about 100 to 3.8 μm, while the specific gravity was increased from 1.81 to 2.63. This is due to the hollow or porous particles of coarse fly ash have been crushed to be fine particles [9,10]. About 80% of the particle size of FAG varied between 0.4 and 15 μm. Blaine's fineness of Portland cement type I, original fly ash, coarse fly ash, and FAG were 3230, 2370, 940, and 8800 cm^2/g, respectively. Figs. 3–6 sequentially show SEM of Portland cement type I, original fly ash, condensed silica fume (SFI), and FAG. It reveals that the FAG and Portland cement type I have irregular and crushed shaped particles, whereas the original fly ash and condensed silica fumes have spherically shaped particles.

4.2. Chemical compositions of materials

Chemical compositions of Portland cement type I, original fly ash, coarse fly ash, FAG, and condensed silica fumes are given in Table 3. According to the chemical composition, the original fly ash, coarse fly ash, and FAG are the fly ash of Class F as prescribed by ASTM C 618 since the sum of the components SiO_2, Al_2O_3, and Fe_2O_3 are higher than 70%, and the loss on ignition (LOI) and SO_3 is not higher than 6% and 5%, respectively. It was found that the grinding process did not have much effect on

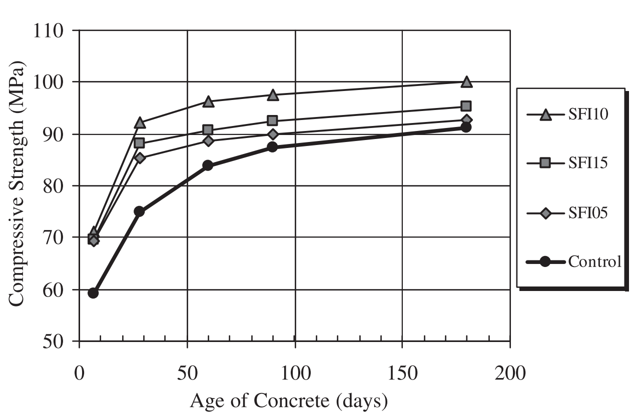

Fig. 7. Relationship between compressive strength of SFI concrete and age.

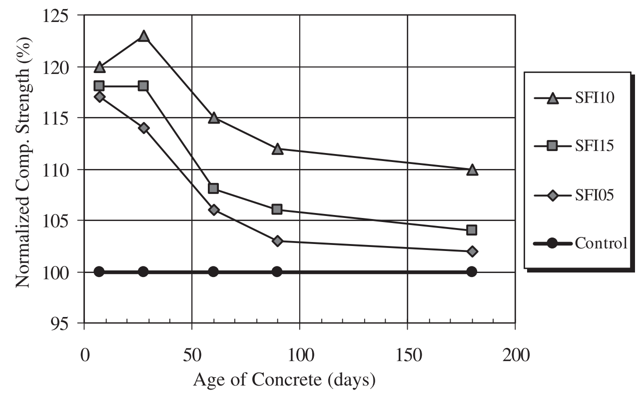

Fig. 8. Relationship between normalized compressive strength of SFI concrete and age.

the chemical composition of fly ash. LOI for FAG (2.09%) was higher than LOI for original fly ash (0.23%) and coarse fly ash (0.08%) since the very high fine fineness of FAG by grinding process can cause easy in burning and the result conformed to the previous research [9]. The SFI and SFII consist of high-SiO_2 content at 93.80% and 94.09%, with LOI of 4.89% and 4.65%, respectively. Their chemical compositions conformed to ASTM C 1240 since the component of SiO_2 is higher than 85% and the LOI is less than 6%.

4.3. Compressive strength

Compressive strengths and normalized compressive strengths of concrete are shown in Figs. 7–12. They show that all concretes in this study are high-strength concrete and the 28-day compressive strengths varied between 74.9 and 92.2 MPa.

4.3.1. Effect of condensed silica fume on compressive strength

The compressive strength of concrete using condensed silica fumes (SFI or SFII) of 5%, 10%, and 15% is presented

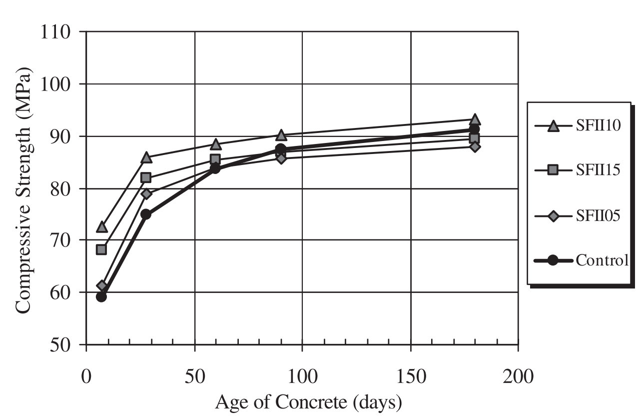

Fig. 9. Relationship between compressive strength of SFII concrete and age.

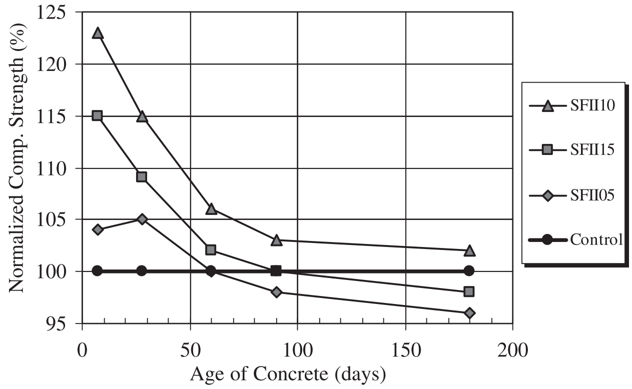

Fig. 10. Relationship between normalized compressive strength of SFII concrete and age.

in Figs. 7 and 9, respectively. At an early age up to 7 days, the compressive strengths varied from 61.4 MPa in sample SFII05 to 72.5 MPa in sample SFII10 corresponding to the normalized compressive strengths of 104% and 123%, respectively. The silica fume concretes producing higher compressive strength than control concrete were due to the hydration and pozzolanic reactions as well as the filler effects of high fineness silica fume, which caused the improvement of concrete pore structure [13,14].

The compressive strengths of sample SFI10 varied from 71.0 MPa at 7 days to 92.2 MPa at 28 days or increased the strength from 7 days about 30%. However, the compressive strengths of sample SFI10 increased from 92.2 MPa at 28 days to 96.2 MPa at 60 days or increased the strength from the 28 days about 5%. This means that the effect of condensed silica fumes on the improvement of the compressive strength is not significant after 28 days. As shown in Figs. 7 and 9, using 10% of condensed silica fume in concrete can cause larger improvement in compressive strength than that caused by using 5% and 15% of condensed silica fume at all curing ages. This result confirms that of Savva [13]. At 180 days, the normalized compressive strengths of silica fume concrete varied between 96% and 110% of the control concrete as shown in Figs. 8 and 10.

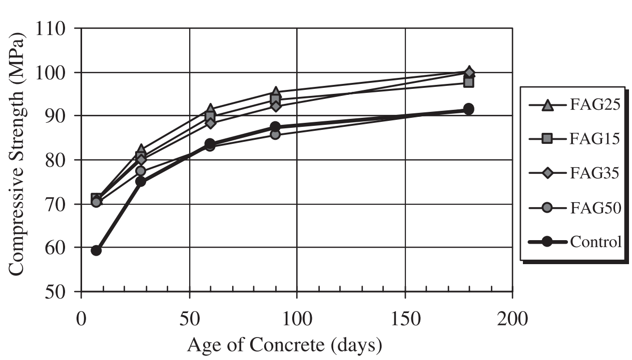

Fig. 11. Relationship between compressive strength of FAG concrete and age.

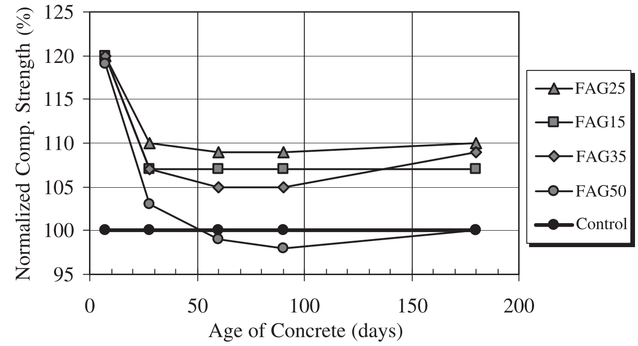

Fig. 12. Relationship between normalized compressive strength of FAG concrete and age.

4.3.2. Effect of FAG on compressive strength

A strength development of concrete containing FAG as a cement replacement of 15%, 25%, and 35% was faster than that of the 50% cement replacement, while 25% cement replacement gave the highest compressive strength at all ages as shown in Fig. 11. At 15–35% content replacements, the compressive strengths were higher than that of control concrete at all ages up to 180 days. For example, the 7-day compressive strengths of FAG15, FAG25, and FAG35 were 71.0, 71.2, and 70.8 MPa or about 120% of the control concrete (see Fig. 12). At 28 days, the compressive strength tended to increase with the curing age for all mixtures and varied from 77.3 MPa in sample FAG50 to 82.5 MPa in sample FAG25. This is due to the extreme fineness of fly ash that exhibits pozzolanic properties and packing effect. These characteristics tend to improve concrete strength as well as its density [4]. The results also confirm those of Kiattikomol et al. [8] that the fineness of fly ash was the major factor affecting the compressive strength of FAG–cement mortar. In addition, no significant difference in compressive strength was observed between mortars containing classified fly ash and FAG of similar median particle size. The sample FAG50, which contained 50% of FAG as a cement replacement, had compressive strength at 7 days of 70.3 MPa or 119% of control concrete. Thereafter, the

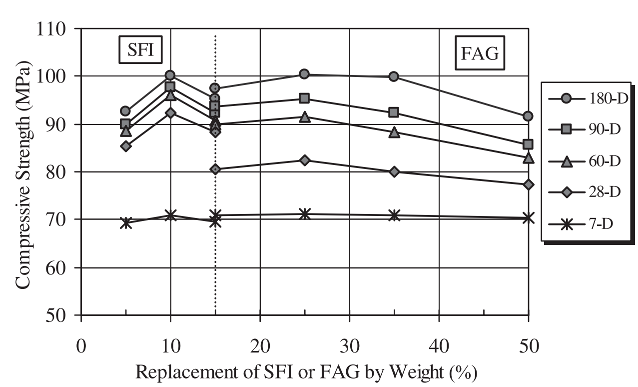

Fig. 13. Comparison of compressive strength of concrete mixed with SFI or FAG.

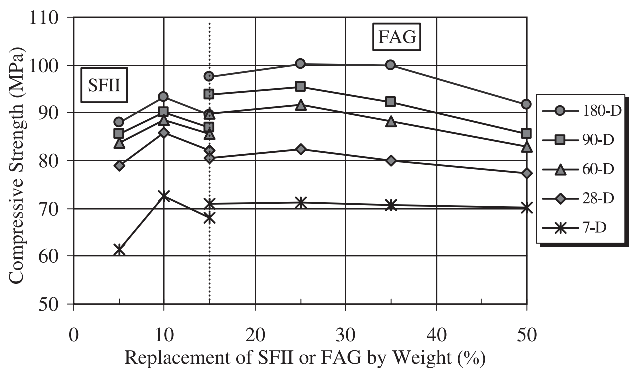

Fig. 14. Comparison of compressive strength of concrete mixed with SFII or FAG.

compressive strength of FAG50 was almost the same as that of control concrete as shown in Fig. 12.

4.3.3. Comparison between condensed silica fume and FAG

Comparisons between the compressive strength of concrete mixed with condensed silica fumes (SFI and SFII) and that of FAG at all ages are presented in Figs. 13 and 14. At the age of 7 days, the compressive strengths of concretes mixed with 10% condensed silica fume and concretes mixed with FAG regardless of percentage replacement were almost the same. After 7 days, the compressive strengths of FAG concretes constantly increased with curing ages, while the SFI and SFII concretes tended to have an initially high rate of strength increase, which slowed down after 28 days. At 180 days, the highest compressive strength of concrete with FAG was FAG25 (100.3 MPa), while that of concrete with condensed silica fume was SFI10 (100.2 MPa). The results also indicated that the concrete replaced by FAG of 15%, 25%, and 35% gave equal or higher compressive strength than those of condensed silica fume concretes. These results led to the conclusion that the FAG concretes gave the same compressive strengths as those of condensed silica fume.

4.4. Economic consideration

Classified fly ash with high fineness is suitable to use as a cement replacement in concrete [3–7]. However, the coarse fly ash residue from the classifying process has to be disposed mostly to a landfill, which is expensive and is a major threat to the environment. The grinding of coarse fly ash to obtain a high fineness can improve the pozzolanic activity and can be used as a cement replacement.

Silica fume has widely been used to produce high-strength concrete. However, in Thailand, silica fume is imported and expensive. Its cost is about 10 times higher than Portland cement type I and much more expensive than fly ash. Each year, more than 3.5 million tons of fly ash are produced in Thailand and the amount is increasing every year. Moreover, more than 70% of fly ash has been disposed to landfill. Since the fly ash used in high-strength concrete must have high fineness, the major cost of the fly ash or FAG depends on the process of reducing its particle size to an effective size. The cost of Mae Moh fly ash is very cheap and is about US$1.6 /ton. In this study, the cost of FAG with grinding, classifying, and transportation, except for the grinding machine, is much cheaper than imported condensed silica fumes. According to the study [15], the use of FAG in producing high-strength concrete is cheaper than condensed silica fume by about 13–55% depending on the amount of FAG replacement to Portland cement type I.

5. Conclusions

According to the experimental results, conclusions can be drawn as follows:

1. The replacement of Portland cement type I with 15%, 25%, 35%, and 50% of FAG ($d_{50}=3.8$ μm) produces high-strength concrete and 25% cement replacement by FAG gives the highest compressive strength.
2. Concrete mixed with FAG between 15% and 35% or condensed silica fume between 5% and 15% cement replacement gives almost the same compressive strength at the curing ages after 60 days.
3. The FAG with high fineness is a suitable pozzolanic material to replace condensed silica fume in producing a cheaper high-strength concrete that is more environment friendly.

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