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Review

Strength development of mortar and concrete containing fly ash: A review

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Among the construction materials; concrete, steel, timber and glass, concrete has gained popularity all over the world due to its durable properties in normal environment and easiest construction procedure. Compare to others constituent, cement performs a vital role for the production of concrete. Due to continuous increasing demand and the cost of cement, recently, the utilization of supplementary cementing materials such as industrial by-product (fly ash, silica fume and slag) and agricultural wastes (rice husk ash, palm oil fuel ash, bagasse ash and ash from timber) has become an important issue for the researchers in concrete industry. Fly ash (FA), one of these valuable industrial wastes, is generated as by-product from power generating industry. The production of FA increases every year, it is disposed for landfills without any commercial gain and now becomes a trouble. It contains a non-crystalline silicon dioxide with high specific surface area and high pozzolanic reactivity. Huge researches have been carried out for the use of pozzolans, mainly waste pozzolans such as FA, slag and rice husk ash, as a supplement of ordinary portland cement (OPC). Test results of compressive strength and durability of concrete from those previous researches ensured the use of FA as a pozzolanic material for cement replacement in concrete. In this paper, a critical review on the strength development of concrete as influenced by the use of FA as a supplement of cement in concrete has been presented on the basis of available information in the published literatures of utilization of FA in blended cement and concrete. The compressive strength of mortar and concrete as varied by the percent replacement and fineness of FA is discussed here. Physical and chemical properties, pozzolanic activity, normal consistency and setting time, strength activity index, advantages and disadvantages of using FA in concrete are also pointed out. Proper consumption of FA as pozzolanic material in concrete would be a useful step for the production of cost effective and more durable concrete. Besides, utilization of FA in cement and concrete could reduce negative environmental effect, and also would be the appropriate solution for the disposal of this waste.

Key words: Fly ash, mortar, concrete, compressive strength.

INTRODUCTION

Nowadays, the growing energy demand causes higher consumption of coal and lignite and, accordingly, the fly ash production increases. According to the study of ACAA (2009), US power plants produce more than 63 million tons of fly ash per year and used only 39.2%. In Asia, more than 100 million tons of fly ash is produced in China per year, with about 40% being recycled. The production feature of fly ash in Europe exceeds 50 million tons per year. These production figures of FA indicate that the recycling of this ash is an urgent issue that needs to be addressed. Besides, it is seen that some of the produced fly ash has been reused beneficially in a variety of ways, but most of it is still dumped as a waste in ponds or landfills (Kim and Prezzi, 2008). Besides, a large number of researches have been carried out towards the utilization of these waste materials at present decades.

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The development and use of blended cements is growing rapidly in the concrete industry due to their technical and financial benefits. Lai (2009) investigated the properties of blended cement, 34% type II OPC with 66% slag, rice husk ash (RHA), palm oil fuel ash (POFA) and ash from timer, and found better performance of concrete in terms of strength and durability. Industrial and agricultural by-products such as FA and RHA are now widely used as pozzolans in concrete since their uses generally improve the properties of the blended cement concrete (Bouzoubaa et al., 2001), reduce production cost and eliminate environmental pollutions (Chindaprasirt and Rukzon, 2008).

According to the report of the Fly Ash Utilisation Programme (FAUP), only about 35% of the huge quantity of fly ashes produced are used in commercial applications: lightweight aggregate, mass concrete, asphalt paving filler, stabilizer to road bases, raw material for concrete, construction of bricks, additives to soil, mining stowing, etc. The remaining amount of ashes are dumped as waste in a large area used for disposal purposes. However, a huge financial loss to power plants was also made and at the same time causing an ecological imbalance, as well as environmental pollutions. Approximately 50 million ton of fly ash is produced in the United States; about 10 to 12% of the total production is utilized in the production of concrete and concrete products (ACI Committee 232).

Not only FA but also by-products from agricultural process such as rice husk ash (Zain et al., 2010; Safiuddin et al., 2010; Mahmud et al., 2009) and palm oil fuel ash (Sata et al., 2010; Tangchirapat et al., 2007; Basri et al., 1999) have been used as pozzolan to improve the properties of cement paste and mortar. FA is one of the most common pozzolan and is being used quite extensively. Nowadays, the utilization of fly ash in concrete has increased rapidly because it contains high amount siliceous and aluminous compounds and has high potential to be used as a raw material to produce pozzolan cement or fine aggregate, especially it was used as pozzolanic material to partially replace cement in concrete (Bijen, 1983; Ravina, 1997; Sarkar et al., 1995). Depending on the location of each power plant, the unused fly ash is disposed at the ponds, lagoons or landfills (Iyer, 2002). When unused fly ash and bottom ash is disposed from coal combustion power plants, it makes major negative environment effects such as air pollution and groundwater quality problem due to leaching of metals from the ashes, specially unused fly ash which has very small particle size (Iyer, 2002; Janos et al., 2002). The cement content in concrete mixture can be reduced by using FA as a replacement of cement, inconsequence, decreasing both energy and CO_2 from the production of cement. This CO_2 is a major contributor to the greenhouse effect as well as being responsible for global warming of the planet (Ferreira et al., 2003; Tietenberg, 2003); cement is responsible for approximately 7% of the world's CO_2 emissions (Mehta, 1999).

The supplementary cementing materials, such as FA, ground granulated blast furnace slag and condensed silica fume are most often used in the production of high strength concrete. These waste materials exhibit either pozzolanic or both pozzolanic and self-cementitious property to a certain degree. It is well known that most of these materials are industrial by-products, so their utilization in concrete not only contributes to produce superior concrete but also preserves and enhances the environment (Haque and Kayali, 1998). These materials are applied to almost all kinds of concrete structures, while it is the exclusive material for structures in marine environments (Bijen, 1996). In fact, fly ash offers benefits with respect to the production costs of concrete, because this raw material is produced as by-product or waste material from power generating industries and can be replaced as Portland clinker. Fewer primary energy and raw materials are required in producing concrete with FA as compared to OPC concrete, although the durability of structures is improved. It is observed from literatures that there is no reduction of strength of concrete up to a certain limit. Utilization of FA in both cement and concrete is one of the solutions to fulfill the demand of cement as well as to solve/manage the disposal problem. Therefore, the aim of this paper is to summarize physical and chemical properties of FA, pozzolanic activity and strength activity index of FA, effect of fineness and replacement level of FA on strengths of mortar and concrete, benefits of supplementary use of FA to encourage researchers as well as developers for more consumption of FA in concrete construction.

PHYSICAL AND CHEMICAL PROPERTIES OF FA

Fly ash, a by-product of the coal power generation industries, is widely used as a cementitious and pozzolanic ingredient in OPC concrete. According to the definition of ACI 116, fly ash is the finely divided residue resulting from the combustion of ground or powdered coal and which is transported from the firebox through the boiler by flue gases, known in UK as pulverized-fuel ash. FA is a complex material consisting of heterogeneous combination of amorphous (glassy) and crystalline phases. Modern coal-fired power plants that burn coal from a consistent source generally produce uniform fly ash. However, the FA particles vary in size, chemical composition and density. Sizes may vary from less than 1 μm to more than 80 μm and density of individual particles from less than 1 Mg/m^3 (62.5lb/ft^3) hollow spheres to more than 3 Mg/m^3 (ACI Committee 232). The main chemical composition includes SiO_2 and Al_2O_3, which are regarded as pozzolanic addition. There is a small amount of crystalline minerals, such as quartz, mullite, mica, etc., in the FA, but the amorphous glass is the main

Table 1. Chemical and physical properties of FA (Wt%).

Chemical properties of FA									Reference
SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Na_2O_3	K_2O	LOI	
41.1	21.60	11.3	14.4	3.30	2.2	1.1	2.6	2.50	(Chindaprasirt and Ruzkan, 2008)
39.9	26.4	24.1	2.59	1.89	2.12	0.83	2.26	-	(Kim and Prezzi, 2008)
62.6	20.9	4.5	5.8	1.5	0.1	2.5	1.7	0.30	(Bouzoubaa et al., 2001)
58.64	25.94	6.55	2.78	1.16	0.40	0.24	2.46	-	(Toutanji et al., 2004)
44.92	18.47	7.90	14.87	2.22	3.89	0.77	1.71	-	(Papadakis and Tsimas, 2002)
Chemical properties of OPC									
20.9	4.8	3.4	65.4	1.3	2.7	0.2	0.4	0.90	(Chindaprasirt and Ruzkan, 2008)
20.6	4.0	3.1	62.8	2.6	3.1	0.8	-	-	(Toutanji et al., 2004)
20.9	4.76	3.41	65.41	1.25	2.71	-	-	0.96	(Chusilp et al., 2009)

Physical properties of FA			
Material specific gravity (gm/cm^3)	Mean particle size (μm)	Fineness (Blaine)	Reference
2.45	4.9	5700 (cm^2/gm)	(Chindaprasirt and Ruzkan, 2008)
2.01	21.2	2120 (cm^2/gm)	(Bouzoubaa et al. 2001)
2.62	-	400 (m^2/kg)	(Toutanji et al., 2004)
Physical properties of OPC			
3.14	15.0	3600 (cm^2/gm)	(Chindaprasirt and Ruzkan, 2008)
3.15	-	388 (m^2/kg)	(Toutanji et al., 2004)
3.10	22.5	326 (m^2/kg)	(Ganesan et. al., 2008)
3.11	-	3250 (cm^2/gm)	(Chatveera and Lertwattanaruk, 2009)

component. It consists of mainly oxides of SiO_2, Al_2O_3, Fe_2O_3 and CaO, and some impurities. According to ASTM C618, when the sum of the percent of SiO_2, Al_2O_3 and Fe_2O_3 exceeds 70, the ash belongs to class F; if this oxide percent ranges between 50 to 70, then the ash is classified as C. Class C fly ash is normally generated from burning of sub-bituminous or lignite coals, alternatively burning of bituminous or anthracite coals produces class F fly ash. Generally, it is seen that class F fly ashes contains a low content of CaO (that is, ≤ 10% CaO) and exhibit pozzolanic properties; on the other hand, class C fly ashes have up to 20% CaO and possesses cementitious properties.

Low-calcium fly ash can be produced by burning anthracite or bituminous coal, whereas high-calcium fly ash is produced by burning lignite or sub-bituminous coal. The low-calcium FA has been classified as a normal pozzolan, a material consisting of silicate glass modified with aluminum and iron (Qian et al., 2001; Papadakis, 1999). Class C fly ashes usually have loss on ignition (LOI) values less than 1%, but class F fly ashes have ranges from this low level to a value as high as 20% (ACI Committee, 232). Fly ash used in concrete typically has less than 6% LOI; however, ASTM 618 recommends the use of class F fly ash with up to 12.0% LOI if either acceptable performance records or laboratory test results are made. The chemical and physical properties of FA and OPC are shown in Table 1. It is demonstrated from this table that FA contains a large amount of silica having ranges from 40 to 60%, alumina 18 to 26% and lower loss of ignition values; specific gravity 2.0 to 2.6 and high specific surface area. Due to its high fineness and silica content, it plays an important role as a pozzolanic material in making concrete; and hence, improves the properties of concrete in terms of strength and durability.

It is generally documented that loss on ignition, fineness, particle distribution, shape morphology and smoothness surface of FA particles influence decisively on rheological behavior, flowability and workability of fly ash cement mixtures (Paya et al., 1996a). Since FA consists largely of multi-sized solid and hollow particles of spherical shape, the following opinions are observed in different literatures: the incorporation of FA in cement mixtures improves their workability and water-demand

Table 2. Influence of fineness on strength of blended cement (Fu et al., 2002).

FA (%)	Clinker (%)	Slag (%)	Gypsum (%)	Specific surface area (m^2/kg)	Flexural strength (MPa)			Compressive strength (MPa)		
					7 (days)	28 (days)	90 (days)	7 (days)	28 (days)	90 (days)
64.8	20	7.2	8	322	2.0	6.3	8.2	6.5	21.7	36.0
64.8	20	7.2	8	386	2.3	7.2	8.7	7.6	24.9	38.9
64.8	20	7.2	8	461	2.6	7.9	9.1	8.3	28.6	40.8

due to ball-bearing effect, dispersion effect in cement particles, hydrophilic character and improved packing density of the solid material. However, from different study, Paya et al. (1996b) stated that the behavior of fly ashes can be adjusted by several procedures: (a) chemical treatments finally produce a modification of chemical surface composition and texture; (b) physical treatments, such as air separation, flotation, sieving, modifying essentially fineness and granulometric distribution; (c) thermal treatments, such as slow or rapid cooling, producing changes in the vitreous/crystalline ratio and (d) mechanical treatments, such as grinding, where particles are crushed and samples present differences in fineness and shape morphology of particles. Then, a combination of these treatments can be carried out again.

FINENESS EFFECT OF FA ON STRENGTH OF MORTAR AND CONCRETE

The fineness or particle size of FA is an important factor in developing the strength of mortar and concrete. According to the ASTM C 618, the fly as it is suitable for use in concrete when not more than 34% of the particle is retained on the sieve number 325 (45 μm). Li and Wu (2005) found that fly ash and its mean particle size play a very significant role on the strength of masonry mortars. Fineness of ground disposed fly ash plays very important role on compressive strength of mortar. However, the ground disposed fly ashes which have particle sizes retained on sieve number 325 less than 5% by weight can be used as good pozzolanic material (Cheerarot and Jaturapitakkul, 2004). The particle size smaller than 9 μm was used in a research and the strength activity index achieved was over 100% of that of the control within 28 days. The mortar with finer fly ashes gained greater strength than that of coarser ones. These results confirmed that the fineness of fly ash, not the chemical composition, is the major factor affecting the strength activity index of ground coarse fly-ash cement mortar (Kiattikomol et al., 2001). Although, ACI Committee 232 reported that strength characteristics of fly ash vary widely depending on the physical and chemical properties of the ash. Slanicka (1991) and Paya et al. (1995) separated fly ash into various finenesses and observed that the concrete with finer fraction of fly ash gained a better compressive strength than that without fly ash and the coarser fly ash reduced the compressive strength of concrete. Mehta (1985) investigated 11 fly ashes from different sources in the United States and observed that the calcium content and particle size distribution is the most important factor governing the strength development rate. However, Erdogdu and Turker (1998) claimed that fly ashes do not have the same properties for different size fractions. They also mentioned that the effect of a fly ash on mortar strength is a combined effect of its size fractions.

The activity of the grain can be improved by increasing the specific surface area of the blended cement to increase the surface energy of the cement particles. Alternatively, increasing the contact surface between clinker grain and fly ash promoted the hydration between the calcium hydroxide and silicon oxide or aluminum oxide in the fly ash, thus improved the activity of the fly ash (Fu et al., 2002). They investigated the effect of the fineness on the strength of the mortars made with blended cements with high fly ash content: the blended cements were ground for different durations to achieve different finenesses. These experimental results are shown in Table 2; it is observed from this table that the strengths of the mortars increased at all ages with increased specific surface area. Kiattikomol et al. (2001) determined the compressive strength of FA mortar with different particle size; the results are presented in Figure 1. It is apparent from this table and figure that the mortar with small particle size (larger surface area) of FA achieved greater strength than that of larger one. They also observed that FA has Blaine fineness of 7720 cm^2/gm while it retained 45.9% on sieve number 325 and the median particle size was 44.2 μm. They concluded that only Blaine fineness may not be sufficient to indicate the fineness of FA especially for FA with spongy shape (irregular and porous). Chindaprasirt et al. (2005) used two types of class F fly ash in a research with different fineness: original fly ash (19.1 μm) and classified fly ash (6.4 μm); test results show that the mortar containing classified fly ash achieved greater strength than that of original one. Felekoglu et al. (2009) recommended that highest compressive strength of fly ash substituted mortars primarily depends on the fineness of fly ash incorporation. If any other type of fly ash with different

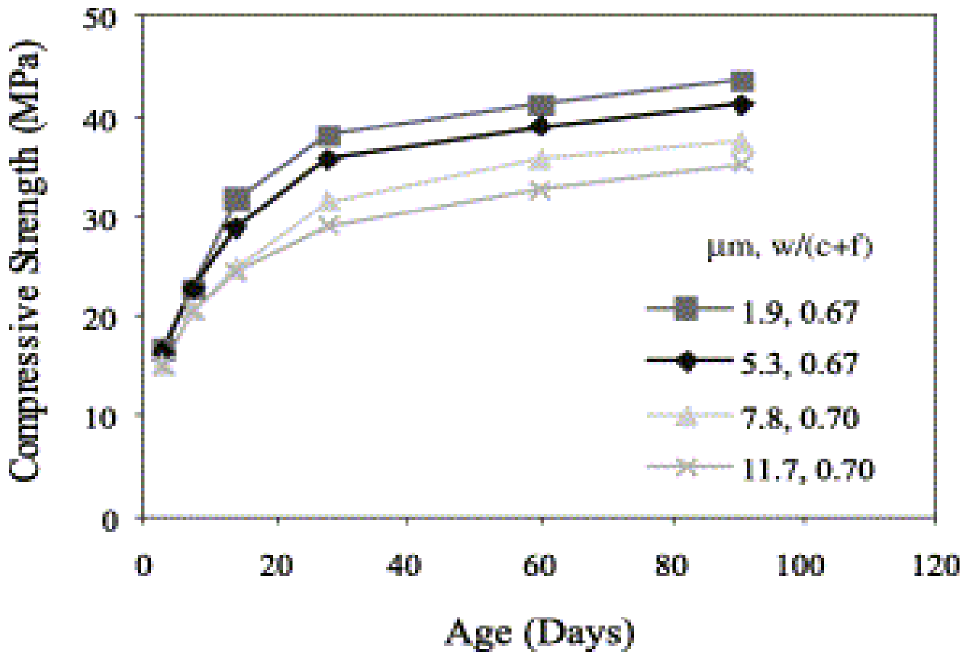

Figure 1. Compressive strength of mortars with the same water binder ratio and different particle size (Kiattikomol et al., 2001).

fineness is considered, they also stated that it is possible to find the optimum fineness of fly ash to reach maximum compressive strengths.

Dhir et al. (1998) suggested that strength development of concrete is influenced by FA fineness with a gradual reduction with decreasing fineness, as percentage retained on a 45 µm sieve. Similar results were observed by Tangpagasit et al. (2005), for all tested ages, fly ash mortar with the smaller particle size has higher compressive strength than that of mortar with the larger particle size. For example, the compressive strengths of mortars with FA median particle sizes (2.7, 16, 19 and 160 µm) at the ages of 3 and 90 days are 20.6, 18.4, 17.4 and 15.0, and 46.2, 40.9, 36.0 and 26.8 MPa, respectively. In consequence, they recommended that FA with large particle size is not suitable to be used as a pozzolanic material. Therefore, it is concluded that, like OPC, fineness of FA is very important and is an essential parameter for the development of strength mortar and concrete.

POZZOLANIC ACTIVITY OF FA

The American society for testing and materials (ASTM) defines pozzolan as a siliceous or alumino-siliceous material that itself has little or no cementitious property, but that in finely divided form and in the presence of moisture, it will chemically react with alkali and alkaline earth hydroxides at ordinary temperatures to form compounds that possess cementitious properties (ASTM, 1995). The crystalline mineral of FA has no properties such as hydration and hardening under normal temperature. The amorphous glass reacts with the $Ca(OH)_2$ which is released from the hydration of clinker to form calcium silicate hydrate and calcium aluminate hydrate, etc. Thus, the activity of fly ash depends on the proportion of vitreous and crystalline mineral. For the same chemical composition, the activity of fly ash is greater due to the higher proportion of vitreous matter (Fu et al., 2002). The siliceous glass is the primary contributor from the fly ash to pozzolanic reaction in concrete since it is the amorphous silica that combines with free lime and water from calcium silicate hydrate (C-S-H), the binder in concrete (ACI Committee, 232). Pozzolanic reaction of the mineral admixtures are formed by the following mechanism: after addition of pozzolanic materials, calcium hydroxide $Ca(OH)_2$ is transformed into secondary calcium silicate hydrate (C–S–H) gel, causing the transformation of larger pores into finer pores. The hydrated cement paste contains about 70% C–S–H, 20% $Ca(OH)_2$, 7% sulpho-aluminate and 3% of secondary phases. The $Ca(OH)_2$ is produced during the hydration, which affects the quality of the concrete negatively by forming cavities due to its solubility in water and low strength. Besides, the utilization of mineral admixtures has a positive effect on the quality of the concrete by binding the $Ca(OH)_2$ (Papadakis and Tsimas, 2002; Memon et al., 2002; Mehta, 1983).

Cement hydration: Cement (C_3S; C_2S) + H_2O → CSH - gel + $Ca(OH)_2$

Table 3. The strength activity index of FA mortar.

Type of FA	Median particle size (μm)	Strength activity index							References
		1-day	3-day	7-day	14-day	28-day	60-day	90-day	
Standard	13.0	-	100	100	100	100	100	100	(Kiattikomol et al., 2001)
Original	28.5	-	75	80	86	87	91	91	
Large	9.0	-	81	83	97	99	100	102	
Medium	5.3	-	91	96	105	112	114	115	
Small	1.9	-	93	97	116	119	120	121	
Control	16.0	100	100	100	100	100	100	100	(Jaturapitakkul et al., 1999)*
O	40.0	52	77	82	82	85	94	95	
F	18.0	111	100	107	113	117	123	130	
CC	50.0	52	68	97	98	109	104	105	
CFA	19.5	106	110	118	108	118	111	111	
CFF	5.0	113	125	125	114	103	122	125	
Control	11.0	-	100	100	100	100	100	100	(Tangpagasit et al., 2005)
Small	2.7	-	91	94	102	108	114	117	
Medium	16.0	-	81	82	87	93	100	104	
Original	19.0	-	77	77	79	81	86	91	
Large	160	-	66	66	67	66	67	68	

*Original fly ash (O) was firstly classified by air classifier into fine (F) and coarse (C) fractions. The coarse fraction of fly ash (C) was ground into smaller particle size and then classified by air classifier again. The coarse outcome from air classifier was collected and denoted as CC (coarse and coarse). Again, the fine fraction (CF-coarse and fine) was classified into two parts denoted as CFC (coarse, fine, and coarse) and CFF (coarse, fine, and fine), respectively.

Pozzolanic reaction: $Ca(OH)_2 + SiO_2 \rightarrow$ CSH - gel

It is generally accepted that addition of pozzolan reduces the calcium hydroxide in cement paste and improves the permeability of concrete. This facilitates to increase the resistance of concrete to the attack of sulfate and other harmful solutions. Moreover, it is well known that incorporation of pozzolanic materials as a partial replacement to Portland cement in concrete is an effective technique for improving the properties of concrete (Chindaprasirt et al., 2008; Tay, 1990). It is observed that the calcium hydroxide produced by cement hydration reacts with pozzolan and in consequence generates additional calcium silicate hydrate (CSH) gel, blocking existing pores and altering the pore structure. Shi and Stegemann (2000) observed that the dissolution of $Ca(OH)_2$ and calcium sulfoaluminates, and the decalcification of CSH with a high C/S ratio in hardened portland cement paste resulted in a very porous layer whereas the decalcification of the low C/S CSH resulted in a protective layer of silica gel. Chindaprasirt et al. (2007) concluded that C/S ratio of CSH would have been lower for the case of FA blended cement as a result of the pozzolanic reaction. FA mortars thus show better resistance to the sulfate attack in comparison to Portland cement mortar.

STRENGTH ACTIVITY INDEX OF FA

According to ASTM C 311, the strength activity index is defined as the ratio (in %) between the compressive strength of mortar containing substituting materials 20% by weight of binder and that of the control mortar at the same ages. The strength activity index of FA can be improved by grinding or increasing their fineness. Kiattikomol et al. (2001) investigated the strength activity index for FA with the different particle sizes that are shown in Table 3. It can be observed from this table that strength activity index for original FA is lower than 75%, the rest values are higher and which satisfies the ASTM C 618 standard, that strength activity index must be higher than 75% at the age of 7 and 28 days. For the small particle size, they obtained the strength activity value of 121% at the age of 90 days. Similar results were observed from a study of Jaturapitakkul et al. (1999); with increasing fineness of particle, strength activity index is increased up to 125 for the particle size of 5.0 micron; and Tangpagasit et al. (2005) found strength activity index as 117% for the particle size of 2.7 micron. Kiattikomol et al. (2001) also proposed a relationship between strength activity index and median particle size for FA as shown in Figure 2. It is clear from this figure that strength activity index gradually increases with

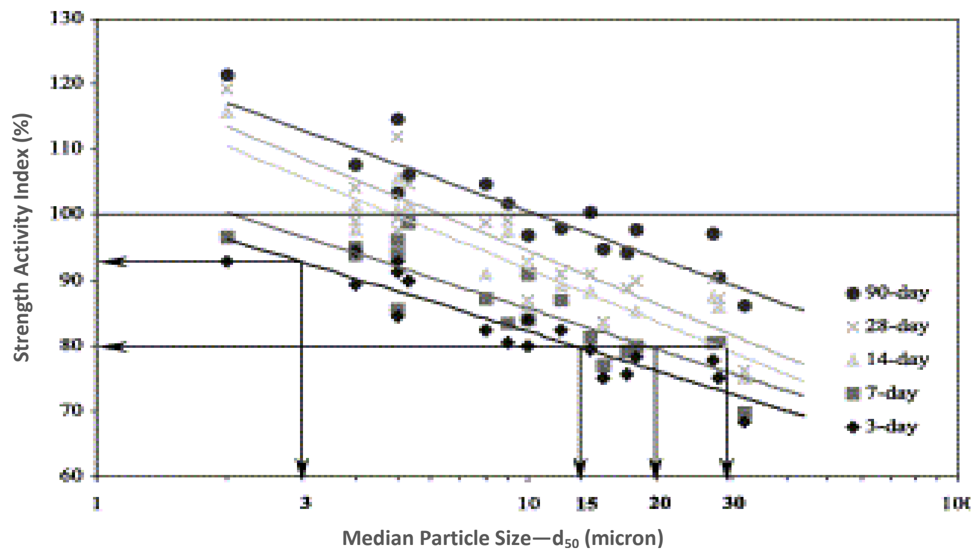

Figure 2. Relationship between median particle size and strength activity index (Kiattikomol et al., 2001).

increasing fineness of FA and vice-versa.

Strength activity index of coarse fly ash can be improved by grinding, and when coarse fly ash is not in crystalline phase. For a good quality of fly ash, the important factor is its fineness and it can be improved by classifying or grinding. Fly ash having small particle size could increase ultimate strength as well as rate of strength gain of fly ash cement mortar (Jaturapitakkul et al., 1999).

However, Qian et al. (2001) concluded that addition of Na_2SO_4 can increase the strength of FA paste very significantly; the grinding of FA can also increase the activity of FA, they added. The strength activity indices of the three fly ashes were investigated by Bouzoubaa et al. (1997) and found that it increased with increasing grinding time. They recommended that the optimum grinding time of approximately 4 h for the fly ashes is beyond which the water requirement increased, and the strength activity indices either decreased or did not increase significantly. Tangpagasit et al. (2005) investigated that the strength activity index of fly ash mortar depends on the median particle size of fly ash and curing ages of mortar samples. They also agreed that, at early ages, the strength activity index of fly ash mortar due to packing effect is higher than that due to pozzolanic reaction. Thereafter, it can be understood that fineness of FA influences significantly the strength activity index.

SUPPLEMENTARY USE OF FA

Since many mineral admixtures are by-products of different industries, these waste by-products can be used in construction to reduce the amount of cement requirement, in consequence, in some cases reducing the production cost of the concrete. Mineral admixtures, such as silica fume, fly ash and ground granulated blast furnace slag should be studied in research works in order to understand their ability to enhance the properties of concrete. All of these supplementary materials have different properties and reacts differently in the presence of water (Toutanji et al., 2004). Detailed laboratory investigations were carried out by Singh et al. (2008) on cement stabilized fly ash (GBFS) mixes in order to find out its possibility and suitability for use in the road embankments and for base and sub-base courses of highway pavements. Test results in terms of maximum dry density and California bearing ratio indicate its better performances and suitability for use in base and sub-base courses in highway pavements with proper combinations of raw materials. Fly ash is useful to almost all types of concrete structures; however, it possesses the exclusive role as construction material for structures in marine environments (Bijen, 1996).

Class F fine fly ash with a fineness of 99% passing a 45 μm sieve was used in a research of Haque and Kayali (1998) to produce workable high-strength concrete. Test results represent 20% increase in strength as compared to the corresponding concrete without fine FA; the water penetrability was about 28% less than the corresponding plain concretes. Depending on these results, they concluded that, by proper utilization of the fine FA, it can be able to produce both high strength and high performance concrete. The fly ash has been used as a construction material in place of soil in a study (Kim and Prezzi, 2008). The mechanical response of class F fly ash, including the compaction response, compressibility, collapsibility and shear strength, were investigated thoroughly. Various geotechnical tests, such as standard compaction, one-dimensional compression, direct shear

Table 4. Normal consistency and setting time of FA mixed paste.

FA : OPC (by weight)	Normal consistency (%)	Initial setting time (h:min)	Final setting time (h:min)	References
00 : 100	26.8	1:27	2:45	(Cheerarot and Jaturapitakkul, 2004)
10 : 90	27.8	1:44	3:00	
20 : 80	27.8	1:56	3:15	
30 : 70	28.1	2:07	3:30	
20 : 80	25.5	2:42	4:32	(Fu et al., 2002)
44 : 45*	31.0	6:22	13:41	
51 : 38*	31.5	4:42	11:52	
65 : 23*	33.0	5:44	25:54	
00 : 100	24.7	1:47	2:55	(Kiattikomol et al., 2001)
20 : 80[a]	23.4	1:59	3:30	
20 : 80[b]	25.1	1:57	2:15	
20 : 80[c]	25.2	1:55	2:15	
20 : 80[d]	24.4	1:45	2:10	

*Mentioned FA with clinker plus 4% slag and the rest amount is gypsum. [a, b, c, d]fly ash with median particle size 28.5, 9.0, 5.3 and 1.9 μm respectively.

and consolidated-drained triaxial compression were performed on class F fly ash. Based on these test results, they recommended that: fly ash exhibits shear strength comparable to that of sandy soils; the values of the maximum compacted dry density of fly ash were lower than those of typical compacted soils.

A study on the mechanical properties and durability of concrete, made with a high-volume fly ash (HVFA) blended cement using a coarse fly ash that does not meet the fineness requirement of ASTM C 618 was performed (Bouzoubaa et al., 2001). The properties of the fresh concrete determined are the slump, air content, slump loss, stability of air content, bleeding and setting time; those of the hardened concrete investigated were the compressive strength, flexural and splitting-tensile strengths, Young's modulus of elasticity, drying shrinkage, resistance to abrasion, chloride-ion penetration, freezing and thawing cycling and to deicing salt scaling. These test results show that, the mechanical properties and the durability of concrete made with this blended cement were superior to the concrete of unground fly ash and the cement, except for the resistance of the concrete to the deicing salt scaling. Ordinary Portland cement containing available pozzolans namely, fly ash and ground rice husk ash (RHA) was studied (Chindaprasirt et al., 2007). Class F lignite fly ash and RHA were used at replacement dosages of 20 and 40% by weight of cement. It is summarized that FA could perform an imperative role as a supplementary/ alternative of cementing material in concrete construction. Ferreira et al. (2003) investigated and then recommended the possible applications: construction materials (cement, concrete, ceramics, glass and glass-ceramics); geotechnical applications (road pavement, embankments); "agriculture" (soil amendment) and miscellaneous (sorbent, sludge conditioning). Successful application of this waste will have great advantages in waste minimization as well as resources conservation, they also mentioned.

CONSISTENCY, SETTING TIME AND FLOW OF FA MIXED PASTE

Consistency for any given cement is the water content which will produce a paste of standard consistency. Setting time is the term to describe the stiffening of cement paste; setting time refers to a change from liquid to rigid state (Neville and Brooks, 2003). These two properties are also essential for proper mixing and construction of concrete for any type of structures. Cheerarot and Jaturapitakkul (2004) obtained that normal consistency of OPC paste was 26.8% while those of original disposed FA cement pastes were between 27.8 and 29.0% (Table 4). It is seen from this table that the normal consistency of original disposed FA cement pastes increases with the increasing percent of FA in the mixture. They concluded that this happens due to the high porous of some particles in disposed FA, which absorbs water and results in higher water consumption.

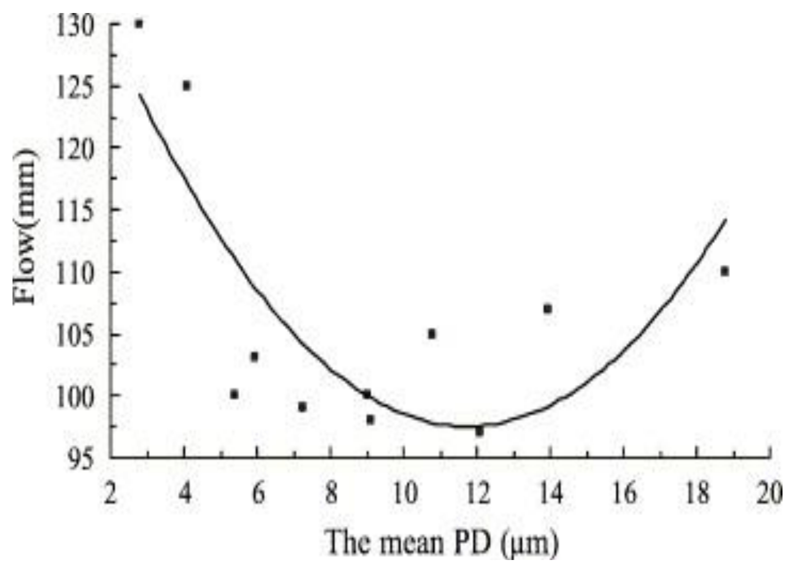

Figure 3. Influence of mean particle size (PD) on the flow properties of mortar (Li and Wu, 2005).

They also investigated that the grinding process can reduce the porosity of disposed fly ash thus, decreases the normal consistency of the paste. However, Felekoglu et al. (2009) concluded that increasing the fineness may result in higher mixing water demand due to the increase in surface area of fly ash particles; optimum fly ash fineness is the function of mixing water content for a constant workability. They also mentioned that another important parameter is the initial particle shape characteristics of raw fly ashes which control the water requirement of mortars prepared.

The use of fly ash may extend the time of setting of concrete if the OPC is reduced (ACI 232). Cheerarot and Jaturapitakkul (2004) found that the initial and final setting times of the cement paste are 87 and 165 min while those of original disposed fly ash cement pastes are between 104 to 128 and 180 to 210 min, respectively. They mentioned that the pastes with the disposed fly ash have longer setting times than the cement paste because tricalciumsilicate (C_3S) which gives the hardening and compressive strength of paste at early age in blended pastes is reduced.

From the study of Li and Wu (2005), the flow measurements for those modified composite mortars with different particle size were plotted against the mean particle size (PD) of fly ash (Figure 3). It can be observed from this figure that as the mean PD of fly ash particles increases, the flow decreases to a certain value and then gradually increases; the highest flow is obtained at a mean PD of 2.8 μm, this value corresponds again to ultra fine FA. The result also appears that the lowest flow is reached at a mean PD of about 9 ± 3 μm; these values correspond again to FA. This consequence seems to indicate an optimum and a minimum PD, with the optimum at 2.8 μm and the lowest at 9 ± 3 μm.

STRENGTH DEVELOPMENT OF MORTAR WITH FA

The mechanical strength of hardened cement is the property of the material that is perhaps most obviously required for structural use. The strength of mortar depends on the cohesion of the cement paste, on its adhesion to the aggregate particle, and to a certain extent on the strength of aggregate itself (Neville, 1995). In this regard, strength development of FA mixed mortar was investigated in different literatures. OPC was partially replaced by 20 and 40% with ground palm oil fuel ash, ground rice husk ash and classified fine fly in a research (Chindaprasirt and Rukzon, 2009). They found that the compressive strengths of cement pastes similar for 20% replacement of pozzolan but in the case of 40% dosage, a significant strength decreasing trend were observed with an increment in the replacement of pozzolans at the age of 7 days. But, at the age of 28 days, the strengths of pastes containing pozzolans were approximately the same as that of OPC paste. Different results were found at 90 days, the strengths of pastes containing pozzolans were slightly higher than that of OPC paste by up to 6 MPa. This greater strength development character at later age exhibits the characteristic of pozzolanic materials. It is seen from these result that the compressive strengths of FA pastes were slightly higher than those of POA and RHA pastes with comparison among FA, POA and RHA pastes at the same age. Based on their study, Paya et al. (1996a) and Isaia et al. (2003) explained that FA consists largely of spherical shape particles and due to its contribution in cement mixtures, improves workability for the ball-bearing effect, and it also advances the dispersion of cement particles and increases packing density of the solid material. A better dispersion of cement grains and development of more gel phases are largely responsible for the strengthening effect (Xu and Sarkar, 1994).

The effects of fly ash is strongly dependent on the amount of replacement used (Bijen, 1996). A research was performed by Cheerarot and Jaturapitakkul (2004) on the disposed fly ash as cement replacement material. They concluded that at 20% replacement, the ground disposed fly ash mortar has gained compressive strengths higher than 75% of the standard mortar at the ages of 7 and 28 days; but 100% higher than that of the standard mortar after 60 days. The ternary blends of OPC, ground rice husk ash (RHA), and classified fly ash (fine FA) was used in mortar; test results such as compressive strength, porosity and accelerated corrosion with impressed voltage show that the use of ternary blend of OPC, RHA and FA produces mortars with improved strengths at the low replacement level with RHA and FA, and at the later age in comparison to that of OPC mortar (Chindaprasirt and Rukzon, 2008).

Mortars were prepared with ternary blends of OPC, ground palm oil fuel ash (POFA) and classified FA in a study (Rukzon and Chindaprasirt, 2009). The mortar mixtures were made with OPC type I containing 0 to 40 wt% FA and POFA. These samples were prepared with 1to 3 wt% retained on a sieve number 325. The test results (that is, compressive strength and rapid chloride penetration depth of mortars) reveal that the use of ternary blended cements produces good strength mortars. The blend of FA and POFA with OPC also produces high strength mortars and excellent resistance to chloride penetration due to the synergic effect of FA and POFA. Depending on their test results, they concluded that strength development of mortar containing FA and POFA are approximately equal at early dates but at later age (more than 28 days), FA contributes to achieve greater strength than that of POFA. Bouzoubaa et al. (2001) investigated that the 3 and 7 day compressive strength of the mortar made with the blended cement (55% FA and cement) was 13.1 and 18.0 MPa; this was higher than the minimum strength of 10 and 17 MPa at 3 and 7 days, respectively, as specified in ASTM C 1157-8a.

Mortar test results obtained from the previous different researches are presented in Table 5. It is examined from this table that no significant reduction in strength of mortar up to 20% replacement is observed at the early and longer ages; on the other hand, for the case of 40% replacement, slower strength gaining rate is observed at early age but greater strength achievement is seen at later age. The improvements in strength of mortar are due to dispersing effect of FA and synergic effect of the blend of fine pozzolans (Chindaprasirt et al., 2008). These results encourage the use of FA as a pozzolanic material for cement replacement in concrete. As shown in Table 5, the introduction of fly ash resulted in a reduction of 7-day compressive strength. At 28 days, the use of FA and high level of replacement of 40% also resulted in reduction in the strength as compared to that of PC mortar. The reduction of early strength is typical of the FA mixes. Compressive strength development of fly ash incorporated mortars with different fineness of FA is presented in Figure 4. It is seen from this figure that strength development trend of fly ashes are slow as compared to OPC at earlier age while greater strength is achieved by the mortar with larger fineness.

Fu et al. (2002) investigated that at a higher contents of fly ash in blended cement, the strength of the mortar was relatively lower (Table 5). In order to overcome this phenomenon, they introduced the coarse aggregate (CA) in the experiment. Comparing the results of these two procedures, it is observed that the strengths were significantly improved at 28 and 90 days when 1.15% CA was added to the blended cement. They found that the 28 and 90 days compressive strengths of mortar with CA were 50% higher than that of only mortar, respectively. But the increase of strengths was lower at 7 days, indicating that the activation was poor at this age. In this regard, they concluded that after 7 days, the vitreous matter of fly ash reacted with OH^- and Na+ ions under CA function, and the bonds of O-Al and O-Si were destroyed to form $[SiO_4]^{4--}$, $[AlO_4]^{5--}$ anion mass, resulting in the reduced degree of polymerization of the aluminosilicate vitreous matter of fly ash. And finally, the anion mass reacted with $Ca(OH)_2$ to produce calcium aluminate hydrate and calcium silicate hydrate and resulted in enhancement of the strength of the mortars at 28 and 90 days. However, Toutanji et al. (2004) concluded that the combination of different supplementary materials increased compressive strength. They investigated combination of 10% silica fume, 25% slag, 15% fly ash, and 50% cement, found an increase in strength of about 22% over the control mix at early age of 14 days.

Magnetic and non-magnetic fly ash fractions of aqueous-fly ash suspensions were produced by the magnetic extractions in a study (Paya et al., 1996b). Several fractions were obtained from an original fly ash (TO), from TO and further grinding, and from a ground fly ash (T60). For 15, 30, 45 and 60% replacement of (TO) FA, they obtained mortar strength of 46.96, 35.47, 30.88 and 20.73 MPa, respectively, whereas, plain cement mortar yielded 45.05 MPa compressive strength (R_0) at age 28 days. They also suggested that compressive strength gain (SG) can be calculated for mortars containing fly ashes as follows:

$$SG_i = R_i - R_o \frac{w_c}{w_c + w_{fa}}$$

where R_i is the compressive strength for fly ash-containing mortar, w_c is the weight of cement and w_{fa} is

Table 5. Compressive strength of FA mixed mortar.

FA:OPC	W/B ratio	Compressive strength (MPa) of FA mixed mortar at days:							References
		3	7	14	28	60	90	180	
00:100	0.5	-	43.5	-	57.0	-	60.0	-	(Chindaprasirt and Rukzon, 2008)
10:90		-	45.0	-	59.2	-	62.7	-	
20:80		-	44.5	-	59.5	-	63.5	-	
40:60		-	33.0	-	56.5	-	62.0	-	
00:100	0.5	-	44.0	-	58.0	-	62.0	-	(Rukzon and Chindaprasirt, 2009)
10:90		-	46.0	-	60.2	-	63.7	-	
20:80		-	45.5	-	60.5	-	64.5	-	
40:60		-	34.0	-	57.5	-	63.0	-	
00:100	0.68	18.0	23.5	27.3	31.8	34.1	35.8		(Kiattikomol et al., 2001)
20:80a	0.67	13.5	18.9	23.4	27.7	30.9	32.4	-	
20:80b	0.68	14.5	19.6	26.6	31.5	34.2	36.4	-	
20:80c	0.67	16.4	22.6	28.8	35.6	38.8	41.0	-	
20:80d	0.67	16.7	22.7	31.6	37.9	41.0	43.5	-	
00:100	0.55	-	44.0	-	51.0	-	57.0	60.0	(Chindaprasirt et al., 2007)
20:80	0.53	-	32.0	-	45.0	-	57.0	57.0	
40:60	0.51	-	29.0	-	46.0	-	62.0	77.0	
69.3:15	According to Normal consistency	-	5.5	-	13.5	-	18.3	-	*(Fu et al., 2002)
64.8:20		-	7.3	-	16.3	-	23.9	-	
60.3:25		-	9.8	-	20.1	-	25.8	-	
55.8:30		-	11.3	-	24.8	-	31.7	-	
51.0:35		-	13.0	-	28.3	-	35.8	-	
46.5:40			14.9	-	32.5	-	39.3	-	
42.0:45		-	16.7	-	36.0	-	43.8	-	
00:100	0.500	20.0	31.5	-	48.5	-	52.0	-	(Chindaprasirt et al., 2004)**
40:60	0.458	11.5	20.5	-	30.5	-	41.5	-	
40:60	0.420	15.5	19.0	-	38.5	-	53.5	-	
40:60	0.430	20.0	25.5	-	42.5	-	56.0	-	
40:60	0.439	25.0	31.0	-	53.5	-	61.5	-	
40:60	0.453	16.5	22.0	-	37.0	-	52.0	-	
40:60	0.572	8.5	13.5	-	23.0	-	29.0	-	

[a, b, c, d]fly ash with median particle sizes 28.5, 9.0, 5.3 and 1.9 μm respectively. *Used the mentioned FA and clinker with 8% gypsum and the rest amount is slag. **Used the mentioned FA and OPC with different fineness of the FA.

the weight of fly ash. In this way, contribution to compressive strength can be estimated for each fly ash and each replacing percentage.

COMPRESSIVE STRENGTH OF CONCRETE WITH FA

Compressive strength is the most important design parameter for any type of concrete structures. This critical parameter drives the design process and can influence the cost of a structure, as well as a project. Through the use of certain mineral admixtures, the cost of concrete can be reduced. These admixtures also enhance the properties of mortar or concrete. In some cases, a boost in early strength becomes apparent, while in others, an increase in late strength occurs (Toutanji et al., 2004). The ACI Committee, 232 reported that the properties of freshly mixed, unhardened concrete and the strength of hardened concrete are influenced by the shape, fineness, particle size distribution and density of fly ash particle. Not only FA but also silica fume, ground granulated blast furnace slag, metakaolin and rice-husk ash can be used

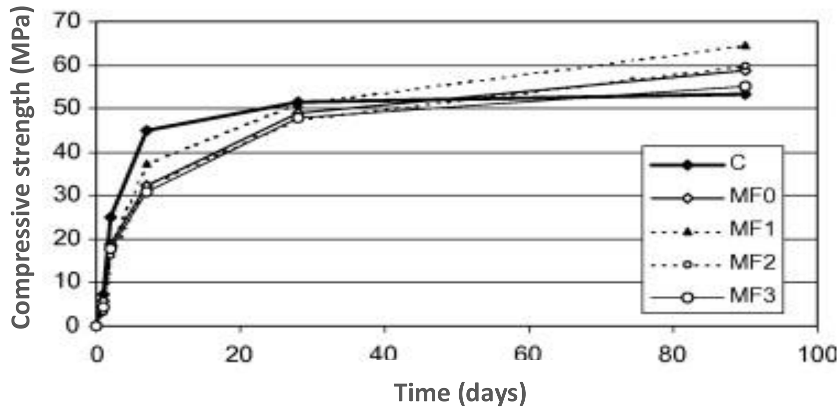

Figure 4. Compressive strength development of fly ash incorporated mortars (Felekoglu et al., 2009). C denoted cement, original fly ash MF0; fly ashes were grounded to revolutions of 1000, 2000 and 3000 times and named as MF1, MF2 and MF3, respectively.

in concrete as supplementary cementing materials. With help of these pozzolan, less permeability and a denser calcium silicate hydrate (C-S-H), concrete can be obtained when compared with Portland cement (Oner et al., 2005).

The percent of calcium content is an influencing factor for the strength achievement of concrete. Papadakis (1999, 2000) investigated low-calcium and high-calcium fly ash in Portland cement systems in two different research works. He concluded that higher strengths are observed after 14 days when aggregates are replaced by low-calcium fly ash; whereas in cement replacement, higher strengths are observed after 91 days. On the other hand, if aggregates are replaced by high-calcium FA, significantly higher strengths are observed at the earlier stage of the hydration, including higher water binding and significantly lower porosity. The strength remained unchanged in the case of high calcium FA replacement of cement. The final strength gain is roughly proportional to the content of active silica in the mortar volume. With the increased cement content in the concrete mixture, hydration product $Ca(OH)_2$ will also increase and inconsequence the amount of $Ca(OH)_2$ with which the FA will enter into reaction will increase, as a result, amount of C-S-H would be increased finally (Oner et al., 2005).

The efficiency factor of FA in concrete, considering the strength to water/cement ratio relations, age and percentage of replacement was investigated (Ganesh Babu and Rao, 1993). They reported that the overall cementing efficiency (k) of FA was established through a general efficiency factor (ke) and percentage efficiency factor (kp). The ke and kp depend on the age and percentage of replacement, respectively. Higher early strength and excellent strength development over time were exhibited in the concretes with 10% fine FA. The optimum level of cement replacement was found to be 10%. Rapid reduction in the workability of the concrete was observed at 15% cement replacement (Haque and Kayali, 1998).

The test results of compressive strength of FA mixed concrete, as mentioned in different literatures, are presented in Table 6. It is evident from this table that strength development of FA mixed concrete is slow at earlier stage but equal or more than that of OPC concrete. Up to 40% replacement, Chindaprasirt and Rukzon (2008) obtained greater result as compared to OPC concrete at the age of 90 days. In the study of Bouzoubaa et al. (2001), a similar trend was observed. However, Haque and Kayali (1998) found a greater result for 15% replacement at the age of 56 days. Therefore, FA replacement in concrete would be remarkable cement saving as well as cost minimizing steps for the construction of concrete structures without sacrificing the strength of concrete. The effects of mineral and chemical admixtures (fly ash, ground granulated blast furnace slag, silica fume and superplasticizers) on the porosity, pore size distribution and compressive strength development of high-strength concrete were investigated (Memon et al., 2002). In the study, for a total cement replacement of 30 and 70% by weight, 25% FA were substituted. For the water/binder ratio of 0.4, all the mixes produced greater strength than that of OPC concrete after 28 days.

Neville (1995) proposed the following empirical equation for the prediction of compressive strength of control concrete. In order to estimate the k-values, the following procedure can be followed. The compressive strength fc (MPa) of a Portland cement concrete can be estimated by the following empirical equation:

$$f_c = K\left(\frac{1}{W/C} - a\right)$$

where W is the water content in the initial concrete mix (kg/m^3), C is the cement content in the concrete (kg/m^3), K is a parameter depending on the cement type (MPa)

Table 6. Compressive strength of FA mixed concrete.

FA:OPC	W/B ratio	Compressive strength (MPa) of FA mixed concrete at days:							References
		1	7	14	28	56	90	364	
00:100	0.5	-	43.5	-	57.0	-	60.0	-	(Chindaprasirt and Rukzon, 2008)
10:90		-	45.0	-	59.2	-	62.7	-	
20:80		-	44.5	-	59.5	-	63.5	-	
40:60		-	33.0	-	56.5	-	62.0	-	
00:100[a]	0.42	30.5	39.1	41.0	46.3	-	50.4	-	(Bouzoubaa et al., 2001)
00:100[b]	0.42	21.4	32.5	34.4	38.6	-	43.4	-	
55:45[c]	0.32	7.7	15.9	19.6	24.0	-	32.7	-	
55:45[d]	0.32	13.1	30.5	37.5	43.8	-	53.7	-	
00:100	0.38	-	62.0	70.5	77.5	-	-	-	(Haque and Kayali, 1998)
	0.37		69.0	75.0	92.5	106.0			
10:90	0.35	-	70.0	77.5	94.0	99.5	-	-	
	0.25		84.0	93.5	111.0	121.5			
15:85	0.36	-	58.0	65.0	73.5	-	-	-	
	0.28		75.5	89.0	102.0	113.5			
00:100	0.40	-	-	-	54	-	-	59	(Memon et al., 2002)
25:70[e]		-	-	-	63	-	-	72	
25:30[f]		-	-	-	63	-	-	74	

[a]OPC type III cement; [b]Laboratory made OPC cement; [c]FA added to the concrete mix and ; [d]FA added blended cement; [e]Rest 5% amount is silica fume; [f]Rest amount 5% silica fume and 40% slag.

and *a* is a parameter depending mainly on time and curing. However, the efficiency factor (k-value) is defined as the part of the SCM in an SCM concrete, which can be considered as equivalent to Portland cement. In the case of supplementary cementing material (SCM) in concrete, the following expression has been proposed by Papadakis and Tsimas (2002) for calculating compressive strength:

$$f_c = K\left(\frac{1}{W/(C+kP)} - \mathrm{a}\right)$$

where P is the SCM content in the concrete (kg/m^3). Using this equation, they have the measured values of the compressive strength of concrete and compared between the measured and the calculated compressive strengths, and an excellent agreement was observed. For fly ashes, the k-values are around unity (K=1) at early ages and they exceed it as time proceeds. This means that up to a certain level, these specific pulverized fly ashes can substitute, equivalently, for Portland cement. The k-values calculated in their study are in good agreement with those calculated in their earlier study.

FLEXURAL AND SPLITTING TENSILE STRENGTH OF FA CONCRETE

The determination of flexural tensile strength is essential to estimate the load at which the concrete members may crack; this test is useful in the design of pavement slabs and airfield runways (Gambhir, 1993). The ratio of tensile/compressive strength of concrete depends on the general level of compressive strength; for higher compressive strength this ratio will be lower. Bouzoubaa et al. (2001) investigated that the 28-day flexural strengths of the control concrete made with the laboratory produced cement (LPC) and the commercially available ASTM (Type III) cement were 6.3 and 6.7 MPa, respectively; the corresponding strengths of the concrete made with the LPC in which fly ash had been batched separately, and that of the blended cement using fly ash were 4.0 and 5.1 MPa, respectively. They also reported that the 28-day splitting tensile strength for all the

Table 7. The flexural and splitting tensile strengths of the FA concrete.

FA:OPC	W/B ratio	Flexural strength (MPa)			Splitting tensile strength (MPa)		References
		7 (days)	14 (days)	28 (days)	14 (days)	90 (days)	
00:100a	0.42	-	6.5	6.7	3.4	-	(Bouzoubaa et al., 2001)
00:100b	0.40	-	5.6	6.3	3.3	-	
55:45c	0.32	-	3.2	4.0	2.2	-	
55:45d	0.32	-	3.9	5.1	3.2	-	
69.3:15	According to normal consistency	0.9	-	2.8	-	3.4	*(Fu et al., 2002)
64.8:20		1.4	-	3.7	-	4.6	
60.3:25		1.9	-	4.1	-	5.0	
55.8:30		2.3	-	4.7	-	5.6	
51.0:35		2.8	-	5.1	-	6.0	
46.5:40		3.3	-	5.6	-	6.5	
42.0:45		3.6	-	6.1	-	7.0	

[a]OPC type III cement; [b]Laboratory made OPC cement; [c]FA added to the concrete mix and; [d]FA added blended cement. *Used the mentioned FA and clinker with 8% gypsum and the rest amount is slag.

concretes were approximately 3 MPa except for a mixture (2.2 MPa). The aforementioned results show that the use of high volume FA blended cement improves the flexural and splitting tensile strength of concrete, and this increase was due to an increase in the fineness of the fly ash and the LPC in the blended cement resulting from the intergrinding of the two components. Haque and Kayali (1998) obtained a greater indirect tensile strength of FA concrete than that of ordinary one. The flexural and splitting tensile strengths of the concrete obtained from different literatures are given in Table 7. As seen from this table, that blended cement with FA achieves greater tensile strength than that of ordinary cement. Hence, FA could be used in cement to improve the tensile strength of concrete.

ADVANTAGES OF USING FA IN CEMENT AND CONCRETE

When supplementary cementing materials (SCM) including FA substitute aggregates, strengths higher than the controls are achieved. When SCMs replace cement, the strength is reduced at first, but as time proceeds, this gap is gradually eliminated and the strength becomes higher than that of the control for these SCMs with higher active silica content in comparison with the cement (Papadakis and Tsimas, 2002). Fly ash is now used in concrete for many reasons, such as reduced cost, improvements in workability of fresh concrete, reduction in temperature rise during initial hydration, improved resistance to sulfates, reduced expansion due to alkali-silica reaction and contribution to the durability to the hardened concrete (ACI Committee, 232); all of these benefits are also mentioned in different literatures. Besides these, fly ash has some major beneficial effects on the performance of reinforced concrete structures that are mentioned as follows:

1. Strength increases (Cheerarot and Jaturapitakkul, 2004; Memon et al., 2002) with increasing amount of fly ash up to an optimum value of 40% of cement (Oner et al., 2005);
2. It can be used as a zero-cost raw material, the conservation of natural resources and the elimination of waste (Ferreira et al., 2003);
3. It reduces the rate of penetration of chloride ions into concrete and increases the critical chloride concentration concerning chloride-induced corrosion (Bijen, 1996);
4. It possesses the ability to produce both high strength and high performance concrete, increases in both the indirect tensile strength and the modulus of elasticity values and reduces water penetrability (Haque and Kayali, 1998);
5. FA blended cement improves the compressive and tensile strengths of concrete (Bouzoubaa et al., 2001);
6. Fly ash has a role to play in the development of high performance concretes through the use of multi-binder combinations (McCarthy and Dhir, 1999);
7. Increases strength of mortar and exhibits excellent resistance to chloride attack (Rukzon and Chindaprasirt, 2009; Chindaprasirt et al., 2008);
8. It has remarkable resistance against sulphate attack and the inertness with respect to alkalisilica reactive expansion (Bijin, 1996);
9. Combination of silica fume with FA (20 to 30%) is very

effective against alkalisilika reaction and possesses high level of sulfate resistance (Thomas et al., 1999);
10. The porosity of mortar containing pozzolan (like FA) reduces with the low replacement level of up to 20%, but increases with the 40% replacement level and improves the corrosion resistance (Chindaprasirt and Rukzon 2008);
11. Combination of FA with slag shows good strength and durability of concrete (Toutanji et al., 2004);
12. Increases workability (Beycioglu et al., 2011) and bond strength of concrete (ACI Committee 232);
13. FA reduces cost of cement and environmental effects (Rukzon and Chindaprasirt, 2009), and it is significant in economic contribution of concrete production (Esen, 2010);
14. Reduces amount of superplasticizer to maintain the flow in concrete (Chindaprasirt et al., 2008);
15. PFA cement shows better strength and durability performance than OPC cement in peat bricks (Deboucha and Hashim, 2010);
16. Its utilization is not only a policy of resource conservation but also a promising alternative to traditional disposal solutions (Kim and Prezzi, 2008);
17. The mechanical properties and the durability of concrete made with FA blended cement were superior to the concrete with the unground fly ash and the cement (Bouzoubaa et al., 2001);
18. Up to 40% of Portland cement could be replaced with FA in making blended cement with good sulfate resistance; this would reduce the amount of Portland cement use and the greenhouse gas, CO_2 (Chindaprasirt et al., 2005);
19. The concrete incorporating SCM including FA, whether used as partial replacement for aggregate or cement, exhibited significantly lower total chloride content; the use of SCM as an addition to Portland cement mixtures, should therefore significantly enhance the chloride-induced corrosion initiation stage (Papadakis and Tsimas, 2002).

DISADVANTAGES OF FA

Utilization of FA in concrete production possesses financial and environmental benefits. In most of the cases, the contribution of FA either in cement or concrete enhances the properties of concrete. There are some disadvantages certainly, mentioned as follows, but these can be overcome by taking measures well known in concrete technology:

1. The low compressive strengths were observed from original disposed fly ash mortars (Cheerarot and Jaturapitakkul, 2004);
2. It possesses slower strength achievement character at early dates (Cheerarot and Jaturapitakkul, 2004; Chindaprasirt et al., 2004);
3. The hydration of concretes with fly ash is slower than that of OPC concrete; therefore, curing time must be extended as compare to OPC concrete (Bijen, 1996);
4. Increases carbonation of concrete (Bijen, 1996);
5. The original fly ash increases total porosity of cement paste; the effect is reduced using smaller particle size of ash (Chindaprasirt et al., 2005);
6. Increases setting time of the paste (Fu et al., 2002);
7. Requires more curing time (Toutanji et al., 2004).

CONCLUSIONS AND RECOMMENDATIONS

A huge amount of FA is produced as by-product from power generating industries, mainly from developed countries, which are disposed to ponds or lagoons as landfills. Due to the deficiency in proper consumption strategy, all of these fly ashes are dumped into environment without any significant come back. Besides these, it requires a lot of handling cost; also many of the land area become ineffective and productivity of soil is reduced. On the other hand, during OPC production, clinker is burnt at a high temperature, which is accountable for the emission of large quantity of green house gas (CO_2) to the atmosphere. Also huge fuel energy is consumed for the cement production. So, if the utilization of FA in cement or concrete is increased, then it would be able to make a role to reduce the demand of OPC; in consequence CO_2 emission would be reduced; also fuel energy would be saved. All of these mentioned multidimensional problems can be solved or minimized by properly utilizing the FA in the production of cement or concrete.

Having large amount of silica, FA exhibits excellent pozzolanic property. In reality, incorporation of FA both in cement and concrete contributes to perform dual roles: fulfills the demand of cement in concrete industry and improves the durability properties of concrete. Based on the past research results, it is concluded that the strength development of concrete containing a particular level of FA replacement is the same or higher as compared to OPC concrete at later age. For about 20 to 40% replacement of FA, no remarkable reduction in strength of concrete is observed at 7 days, and eventually, greater strength gaining characteristic also appeared. The better performances of ashes and their pozzolanic activity are usually related with the more spherical shape and smooth texture of fly ash as compared to cement particles. It is very important to note that the test results for specimens cured for a short period of time; these results might have been completely different if the curing period was much longer. Information from different studies indicate that in order to fully benefit from the addition of these supplementary cementitious materials to concrete, a long curing period is necessary (Toutanji et al., 2004). Furthermore, a valuable cement and energy saving concern could be executed by effective consumption of

FA in the production of cement or concrete; it will also be favorable for the present demand of concrete industry. Waste disposal, global warming due to green house gas emission and sustainable concrete production are the present vital issues for concrete industry in the world; all of these issues could be managed by appropriate operation of waste including FA in cement or concrete. Finally, proper utilization of FA in cement or concrete could reduce the cost of cement, environmental pollution and required land area for disposal of these wastes. The addition of FA to the cement or concrete is now environmental, technical, economical and energy conservation demand to save the planet for the present and future population.

It is observed from the cited literatures and documents that most of the researches have been performed based on supplementary use of FA as binary blend with OPC in mortar and concrete. Thus, a ternary blend of FA with rice husk ash, palm oil fuel ash and slag or other natural pozzolans could be recommended for future investigation as a partial replacement or full replacement of OPC by inclusion of several chemical activators, such as calcium hydroxide, sodium hydroxide, potassium hydroxide, calcium silicate, calcium carbonate and so on. In this regard, the mechanical activation process (improvement of fineness by grinding) could also be considered.

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