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COMPRESSIVE STRENGTH AND THERMAL CONDUCTIVITY OF WATER AND AIR CURED PORTLAND CEMENT-FLY ASH-SILICA FUME MORTARS

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Abstract

This paper investigated the compressive strength and thermal conductivity of water and air cured Portland cement-fly ash-silica fume mortars. The results showed that density, compressive strength and thermal conductivity of blended cement mortars with fly ash were lower than Portland cement control. However, blended cement mortars that contained silica fume as replacement cement both in binary and ternary phase were higher than fly ash mixes and tends to increase with increase silica fume used as cement replacement due to increased C-S-H phase formation from pozzolanic reaction and its filler effect. In ternary phase, compressive strength and thermal conductivity of 10FA5SF and 5FA10SF mixes had values higher than Portland cement control while 20FA10SF mixes had values similar to Portland cement control. The density, compressive strength and thermal conductivity of blended cement mortars those cured in saturated lime water were higher than air cured specimens. Moreover, relationships between compressive strength and thermal conductivity as well as density and thermal conductivity were compared. X-ray diffraction traces show that intensity of C-S-H phase increased while intensity of $Ca(OH)_2$ decreased with increased silica fume content due to the increased pozzolanic reaction when compared to the reference FA mix.

Key words: cement, compressive strength, fly ash, silica fume, thermal conductivity

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1. Introduction

Nowadays, global warming and climate change are significant problems in the world. The total annual global production of concrete exceeded 2.5 billion metric tons (Kalina et al., 2012).

Every year, the cement industrial expects approximately 5% of global human activity CO_2 (Damtoft et al., 2008). Therefore, reduction of cement consumption is a suitable solution by using Portland cement (PC) replacement materials. Pozzolanic materials are widely used to replace part of Portland cement as binary or ternary cements such as fly ash and silica fume.

Fly ash (FA) is produced as a by-product from coal-fired electric power plants (Goga et al., 2013; Malhotra and Metha, 1996). FA is widely used as a replacement material for PC because it is cost efficient and is widely available. Moreover, FA is friendlier to environment than PC (Haque et al., 1984). It is known that FA needed $Ca(OH)_2$ to form strength developing products (pozzolanic reaction), and therefore is used in combining with PC, since $Ca(OH)_2$ is one of PC hydration products (Baert et al., 2008; Vessalas et al.,

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2009). It lowers the heat of hydration and improves durability when FA is used as cement replacement. FA also contributes to strength by pozzolanic reaction and filler effect (Helmuth, 1987; Poon et al., 2001).

Silica fume (SF) is produced as a by-product from the ferrosilicon manufacturing in which SiO_2 vapors are produced, oxidized and dense in extremely fine amorphous silica particles (Malhotra and Metha, 1996). Using SF in sub-micron size is known to improve mechanical properties of PC (Gleize et al., 2003; Nochaiya et al., 2010; Shih et al., 2006). SF has high content of amorphous silica dioxide (more than 80%) and very fine particle (100 nm average diameter) are significant reasons for its high pozzolanic reaction (Malhotra and Metha, 1996). Previous literatures reported that SF with FA can increase properties when compared to FA alone (Chaipanich et al., 2010; Demirboga, 2007; Shehata and Thomas, 2002; Yazici, 2008). In additional, the FA content with SF improved the early strength of concrete (Barbhuiya et al., 2009).

Material ability to conduct heat is called thermal conductivity (Othuman Mydin, 2013). The chemical constituent, humidity and temperature all of which has an effect on the thermal conductivity which also relates to the density and specific heat. The high thermal conductivity concrete is convenient for reducing temperature difference in building while the low thermal conductivity concrete is satisfactory for the building insulation. The consequence from temperature difference is thermal stresses might generate mechanical properties depreciation (Yunsheng and Chung, 2000). Previous literatures reported that the thermal conductivity increased with increasing density (Johnson Alengaram, 2013). Demirboga et al. (2007) also reported that mixture of 50, 60 and 70 % FA by weight of PC decreased thermal conductivity to 32 %, 33 % and 39 %, respectively (compared with 0 % FA mixture). Kizilkanat et al. (2013) demonstrated that SF had cause a slight increase of thermal conductivity of concretes by approximately 5–8%.

Curing is an important process of cement specimens after set for their strength and durability development. This process is to keep specimens saturated, in order to prevent loss of moisture which affects the hydration reaction of cement, strength development and other properties. However, it is questionable that sufficient water curing scheme on cement is implemented in real life construction site practices. Due to diversity of reason, in earlier period after mixing and casting, it is in general the cement structure to expose air curing condition (Lai, 2008). With different curing practices different properties are obtained. For this reason, suitable curing methods can enhance properties of blended cement at early age.

The purpose of this work was to investigate the compressive strength and the thermal conductivity, and to compare their relationship of blended cement mortars containing FA and SF. Curing methods such as air cured and water cured at laboratory temperature were used in this study.

2. Material and methods

In this research, primary binding materials was Portland cement type I (63.62% CaO, 20.64% SiO_2, 4.848% Al_2O_3), fly ash (10.43% CaO, 45.37% SiO_2, 20.65% Al_2O_3) provided from Mae Moh power plant, Thailand was used. The undensified silica fume type 920-U (93.549% SiO_2) received from Elkem, Norway was used as partial replacement materials for cement. Their full compositions can be seen in the authors' previous other work (Wongkeo et al., 2012). River sand was used as fine aggregate according with standard of ASTM C33 (ASTM C33-02, 2002). Modified polycarboxylate superplasticizer from Sika, Thailand was used in this research. The mix proportions of mortars were given in Table 1. In this study, FA and SF were utilized as replacement materials for PC. Free water to binder ratio of mixture was kept constant at 0.475. The fine aggregate to binder ratio was 2.5 for PC.

Mortars (50×50×50 mm^3) were cast and demoulded using the same method as Wongkeo et al. (2013). Mortars were cured for 28 days in standard lime water (23±2°C) and air at ambient temperature (relative humidity of the laboratory was ≈65±5 %). After curing, the density of specimen was determined. The compressive strength test was carried out at 28 days. At 28 days, thermal conductivity test specimens were dried at 110 °C for 24 h and then the specimens were cooled down for 12 h before testing. Thermal conductivity test was carried out by using Decagon KD2 pro thermal properties analyzer in accordance with ASTM D5334-00 (ASTM D5334-00, 2000). Moreover, the identification phases of the sample were investigated using X-ray diffractometer (Rigaku MiniFlex, Japan).

3. Results and discussion

3.1. Microstructure

The microstructure of blended cement mortar can be seen from scanning electron microscope (SEM). Fig. 1 shows SEM micrographs of PC and 10FA5SF cured at 28 days. C-S-H and ettringite phase can be found. PC and 10FA5SF in water cured specimens (Fig. 1b) can be seen to be denser than air cured specimens (Fig. 1a). This is due to water curing aid the hydration and pozzolanic reaction by keeping the specimens saturated and prevent moisture loss.

3.2. Density

From this research, the density of blended cement mortar with FA (15FA and 30FA mixes) were lower than PC control (Fig. 2). However, the density of blended cement mortar that contained SF replacement was higher than 15FA and 30FA mixes and tends to increase with increase SF replacement due to C-S-H phase formation from hydration product and pozzolanic materials behaving as filler and/or pozzolanic reaction.

Table 1. Mix proportions

Mix	*PC*	*FA*	*SF*	*PC*	*FA*	*SF*	*Free w/b ratio*	*Total water*	*Sand*	*Super plasticizer*
	%	%	%	kg/m^3	kg/m^3	kg/m^3		kg/m^3	kg/m^3	%
PC	100	-	-	576	-	-	0.475	288	1440	0.12
5SF	95	-	5	547	-	29	0.475	288	1430	0.17
10SF	90	-	10	518	-	58	0.475	288	1420	0.33
5FA10SF	85	5	10	490	29	58	0.475	288	1407	0.3
10FA5SF	85	10	5	490	58	29	0.475	288	1406	0.17
15FA	85	15	-	490	86	-	0.475	288	1404	-
20FA10SF	70	20	10	403	115	60	0.475	288	1371	0.25
25FA5SF	70	25	5	403	144	30	0.475	288	1369	0.15
30FA	70	30	-	403	173	-	0.475	288	1368	control

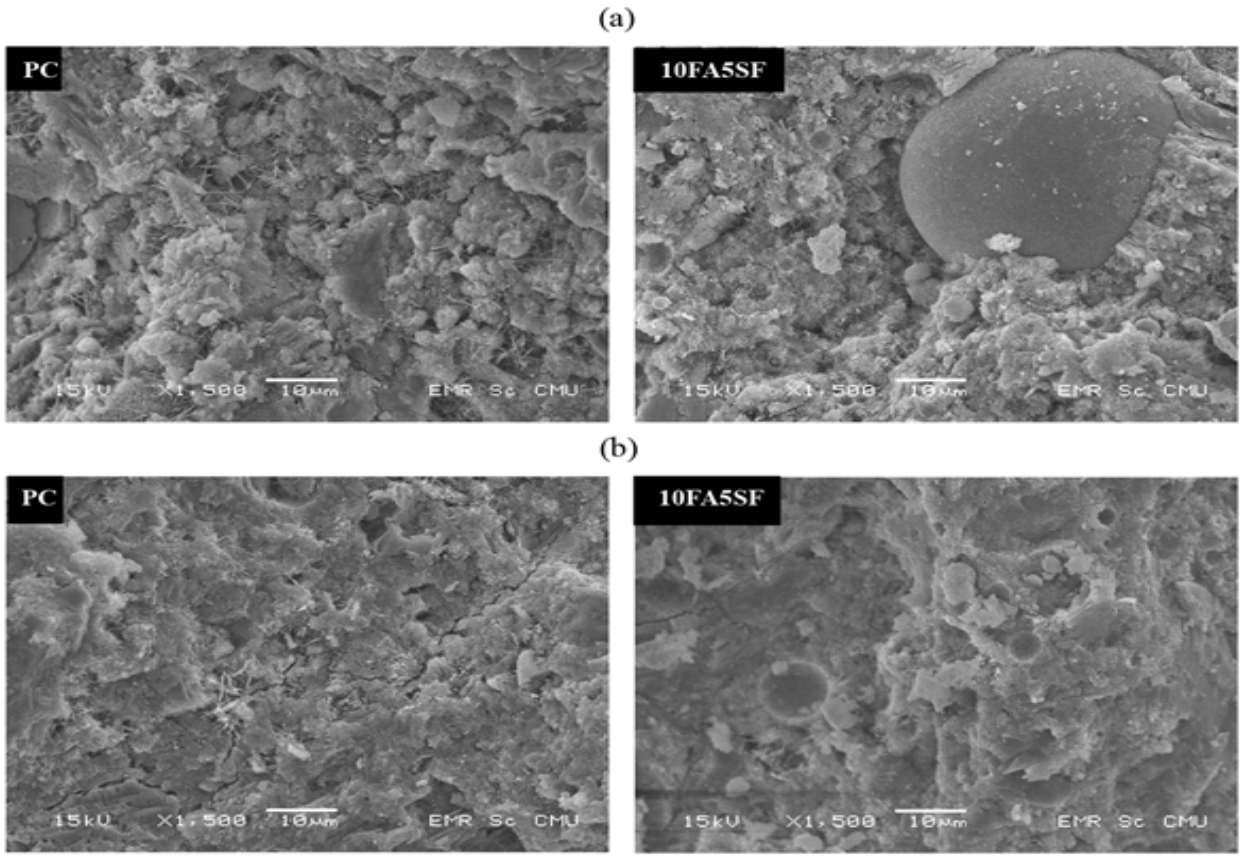

Fig. 1. SEM micrographs of PC and 10FA5SF cured at 28 days a) air cured and b) water cured

FA particles are able to fill the regions between PC particles while SF particles are able to fill the voids between FA particles which lead to optimum density values (Chen and Kwan, 2013). The density of blended cement mortars that cured in saturated lime water was higher than air cured specimens. The density results agree with compressive strength and thermal conductivity that increase with an increase SF content.

3.3. Compressive strength

Fig. 3 shows the compressive strength of PC-FA-SF mortars at 28 days. The results indicated that PC blended with FA mixes had lower compressive strength than PC control mix. This was resulted from the slow degree of pozzolanic reaction of FA (Wongkeo and Chaipanich, 2010). The compressive strength can be increased when adding SF as cement replacement both in binary and ternary. Water cured samples of 10FA5SF and 5FA10SF mixes had compressive strength values higher than PC control while 20FA10SF mixes had compressive strength values similar to PC control at 28 days.

Therefore, the benefit of SF is seen in all compressive strength results of mortars. Due to SF particles are much finer and has greater pozzolanic reaction than FA particles. Moreover, the internal voids of cement microstructure was filled by SF and SiO_2 in SF reacted with $Ca(OH)_2$ from hydration reaction to provide C-S-H creation to enhance the bonding strength (Shih et al., 2006). Compressive strength of air cured samples are noticeably lower than water cured samples, especially in binary and ternary

mixes showing important effect of water curing for pozzolanic materials.

According to the XRD patterns (Fig. 4) of typical binary and ternary mixes from Portland cement-fly ash pastes with and without SF, the dominant peak was $Ca(OH)_2$ and can be seen in all mixes. This gives concept of hydration and pozzolanic reaction of each mixes. In X-ray diffraction traces, the intensity of $Ca(OH)_2$ of blended cement paste with FA and SF is lower than blend cement paste with only FA (at same PC replacement level). This indicate that SiO_2 from pozzolanic materials reacted with $Ca(OH)_2$ (Alonso and Wesche, 1992; Baert et al., 2008; Vessalas et al., 2009) has occurred, therefore $Ca(OH)_2$ was evidently used by SiO_2. Mehta and Monteiro (1993) reported that using FA with SF can reduce $Ca(OH)_2$ content in the cement.

This is due to increase in C-S-H phase while intensity of $Ca(OH)_2$ decreased with increased SF content from the pozzolanic reaction. Similar reaction was found in bottom ash-silica fume mixes by Wongkeo et al. (2008). Therefore, SF and FA have ability to increase and develop compressive strength in blended cement mortars (Nochaiya et al., 2010).

3.4. Thermal conductivity

The thermal conductivity results of water and air cured Portland cement-fly ash-silica fume mortars are shown in Fig. 5. Due to thermal conductivity depends on density of concrete, structure of pore from aggregates and cement paste matrix (Cornaldesi et al., 2011; Topcu and Uygunoglu, 2007). Thus, one of the most important factors that affected the thermal conductivity development in this study is density. Relationship between thermal conductivity and density of blended cement mortars under saturated lime water curing and air curing at 28 days are shown in Fig. 6.

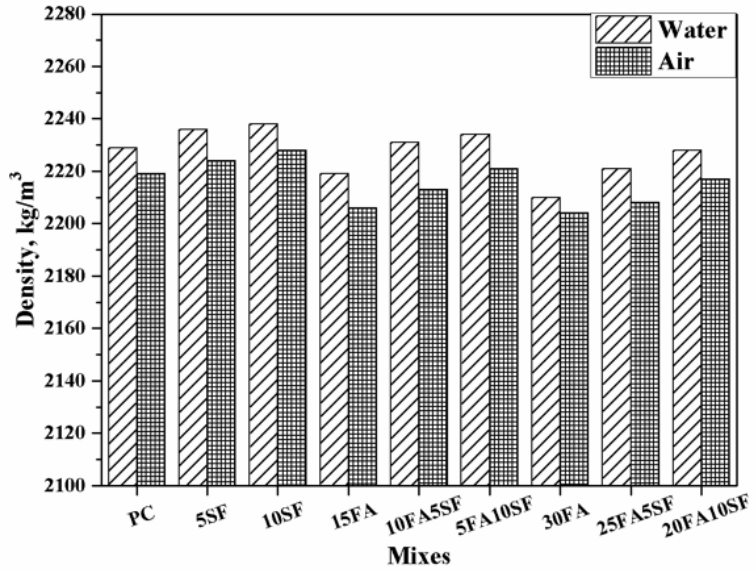

Fig. 2. Density of blended cement mortars under saturated lime water curing and air curing at 28 days

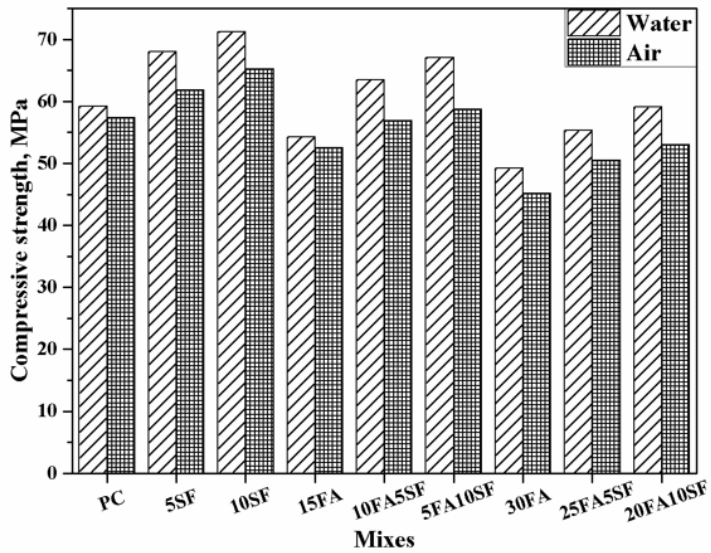

Fig. 3. Compressive strength of blended cement mortars under saturated lime water curing and air curing at 28 days

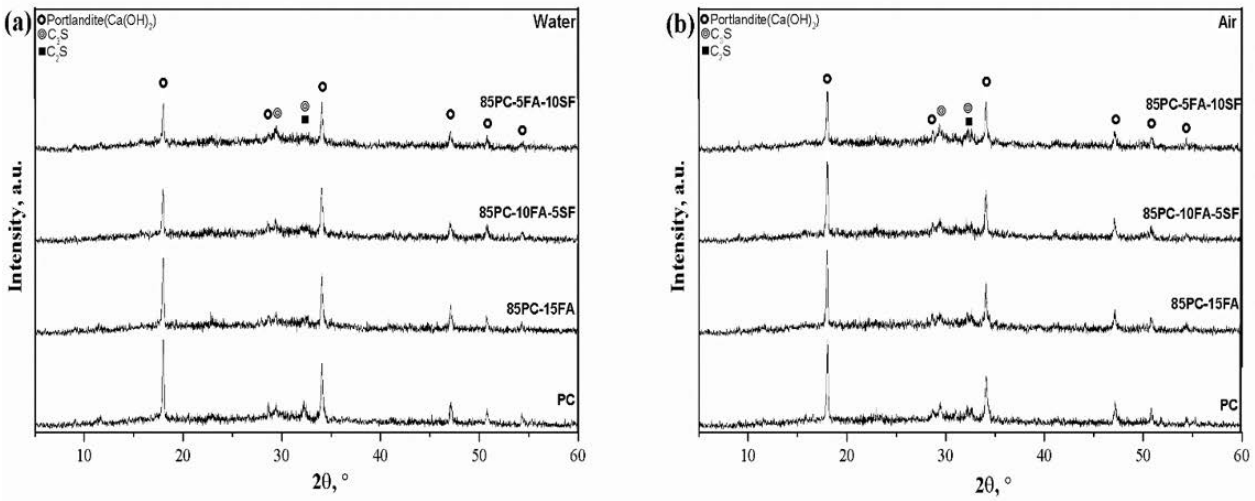

Fig. 4. XRD pattern of blended cement pastes at 28 days: (a) water cured and (b) air cured

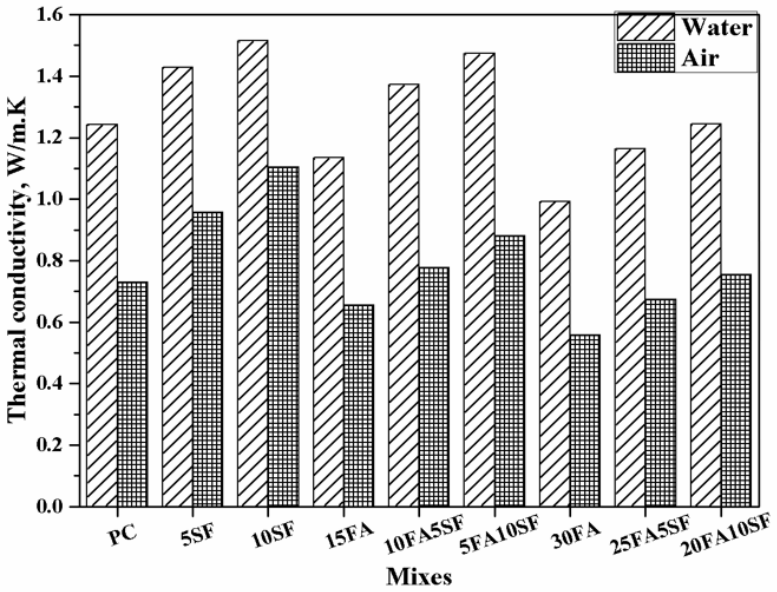

Fig. 5. Thermal conductivity of blended cement mortars under saturated lime water curing and air curing at 28 days

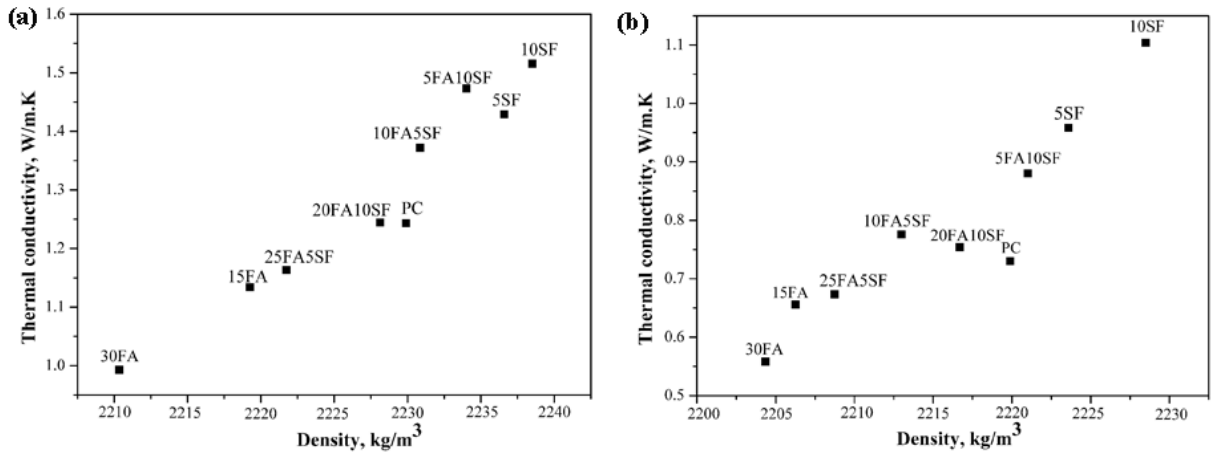

Fig. 6. Relationship between thermal conductivity and density of blended cement mortars at 28 days: (a) water cured and (b) air cured

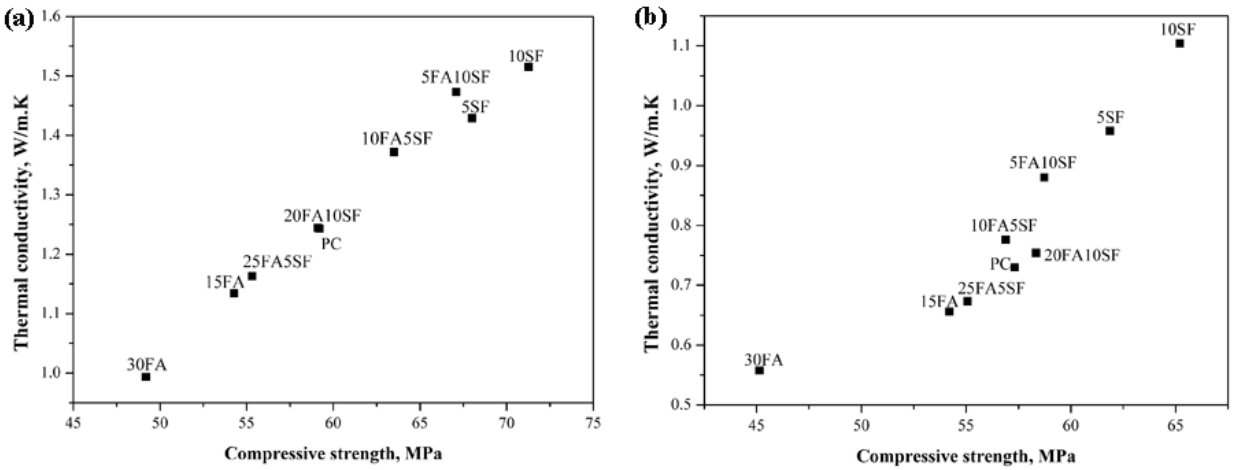

Fig. 7. Relationship between thermal conductivity and compressive strength of blended cement mortars at 28 days: a) water cured and b) air cured

The relationship between thermal conductivity and compressive strength of blended cement mortars under saturated lime water curing and air curing at 28 days are shown in Fig. 7. A direct relationship between thermal conductivity and density can be seen where the thermal conductivity linearly increased as density of samples increased. Thermal conductivity and compressive strength can also be seen to have a good direct linear relationship. The thermal conductivity of mortar samples increased with increased compressive strength.

Albayrak et al. (2007) reported that the decrease in density would cause a reduction in thermal conductivity and compressive strength values. Blanco et al. (2000), Demirboga (2003, 2007) and Demirboga and Gul (2003) also reported that decrease in the density of concrete result in decreased thermal conductivity. Thus, thermal conductivity is known to increase with increase in density. From this research, the thermal conductivity of blended cement mortar with 30FA, 15FA are lower than PC control. For the mixes tested, the lowest thermal conductivity value is therefore found in 30FA in both curing in saturated lime water and air curing. These results agree with results reported by Turgut (2010) where increasing FA content decreased the thermal conductivity. But the thermal conductivity were increased when added SF as replacement both in binary and ternary phase (10FA5SF and 5FA10SF). The thermal conductivity values of 10FA5SF and 5FA10SF mixes are higher than PC control while 20FA10SF mixes had thermal conductivity values similar to PC control.

These results relate to density of blended cement mortars. It can be seen that the thermal conductivity tend to increase due to increase in density with increase SF. Wongkeo and Chaipanich (2010) reported in densified microstructure of cement paste can be enhanced by SF. Demirboga (2003) reported that thermal conductivity and density increased when replacing FA with SF. This was due to SF decreased the open porosity and lead to increase of the thermal conductivity (Demir and Serhat Baspinar, 2007). The hydration rate increases due to SF perform as nucleation site (Mohamed Heikal, 2013). Thermal conductivity values that cured in saturated water are noticeably higher than when air cured samples due to water curing had sufficient necessary moisture to complete the hydration reaction (Mindess et al., 2003).

Over all, it was found that FA can be mixed with SF to increase the compressive strength at early ages and at 28 days. The inclusion of SF results in a denser microstructure from the reduction of $Ca(OH)_2$ and increase in C-S-H. Moreover, thermal conductivity of ternary blended cement mortars (at similar strength to PC mortar) is similar to that of PC control mortar. The results found show that thermal conductivity is directly related to the density of the specimens.

4. Conclusions

The results of this work showed that the thermal conductivity and compressive strength of FA mortars were lower than the PC control. However, Portland-FA-SF mortars obtained higher thermal conductivity and compressive strength than FA mixes when SF was used. Thermal conductivity of air and water cured samples were found to be closely related to density and compressive strength of all mortars tested.

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References

Albayrak M., Yorukoglu A., Karahan S., Atlihan S., Aruntas H.Y., Girgin I., (2007), Influence of zeolite additive on properties of autoclaved aerated concrete, *Building and Environment*, **42**, 3161-3165.

Alonso J.L., Wesche K., (1992), *Characterization of Fly Ash*, In: *Fly Ash in Concrete. Properties and Performance*, RILEM Report, Wesche K. (Ed.), E. & F.N. SPON, 3-23.

ASTM C33-02, (2002), *Standard Specification for Concrete Aggregates*, American Society for Testing and Materials, Philadelphia.

ASTM D 5334-00, (2000), *Standard Test Method for Determination of Thermal Conductivity of Soil and Soft Rock by Thermal Needle Probe Procedure*, American Society for Testing and Materials.

Baert G., Horste S., Schutter G., Belie N., (2008), Reactivity of fly ash in cement paste studied by means of thermogravimetry and isothermal calorimetry, *Journal of Thermal Analysis and Calorimetry*, **94**, 485-492.

Barbhuiya S.A., Gbagbo J.K., Russell M.I., Basheer P.A.M., (2009), Properties of fly ash concrete modified with hydrated lime and silica fume, *Construction and Building Materials*, **23**, 3233-3239.

Blanco F., Garcia P., Mareos P., Ayala J., (2000), Characteristic and properties of lightweight concrete manufactured with cenosphere, *Cement and Concrete Research*, **30**, 1715-1722.

Chaipanich A., Nochaiya T., (2010), Thermal analysis and microstructure of Portland cement-fly ash-silica fume paste, *Journal of Thermal Analysis and Calorimetry*, **99**, 487-493.

Chen J.J., Kwan A.K.H., (2013), Triple blending with fly ash microsphere and condensed silica fume to improve performance of cement paste, *Journal of Materials in Civil Engineering*, **25**, 618-626.

Cornaldesi V., Mazzoli A., Moriconi G., (2011), Mechanical behavior and thermal conductivity of mortar containing waste rubber particles, *Materials and Design*, **32**,1645-1650.

Damtoft J.S., Lukasik J., Herfort D., Sorrentino D., Gartner E.M., (2008), Sustainable development and climate change initiatives, *Cement and Concrete Research*, **38**, 115-127.

Demir I., Serhat Baspinar M., (2008), Effect of silica fume and expanded perlite addition on the technical properties of fly ash-lime-gypsum mixture, *Construction and Building Materials*, **22**, 1299-1304.

Demirboga R., (2003), Influence of mineral admixtures on thermal conductivity and compressive strength of mortar, *Energy and Building*, **35**, 189-192.

Demirboga R., Gul R., (2003), The effect of expanded perlite aggregate, silica fume, fly ash on thermal conductivity of lightweight concrete, *Cement and Concrete Research*, **33**, 723-727.

Demirboga R., Turkmen I., Burhan Karakoc M., (2007), Thermo-mechanical properties of concrete containing high-volume mineral admixtures, *Building and Environment*, **42**, 349-354.

Demirboga R., (2007), Thermal conductivity and compressive strength of concrete incorporation with mineral admixtures, *Building and Environment*, **42**, 2467-2471.

Gleize P.J.P., Muller A., Roman H.R., (2003), Microstructural investigation of silica fume-cement-lime mortar, *Cement and Concrete Composites*, **25**, 171-175.

Goga F., Dudric R., Cormos C., Imre F., Bizo L., Misca R., (2013), Fly ash from thermal power plant, raw materials for glass ceramics, *Environmental Engineering and Management Journal*, **12**, 337-342.

Haque M., Langan B., Ward M., (1984), High fly ash concrete, *ACI Journal Proceedings*, **81**, 54-60.

Heikal M., El-Didamony H., Sokkary T.M., Ahmed I.A., (2013), Behavior of composite cement pastes containing microsilica and fly ash at elevated temperature, *Construction and Building Materials*, **38**, 1180-1190.

Helmuth R., (1987), Fly ash in cement and concrete, Portland Cement Association, *Journal of Cement and Concrete Research*, **30**, 201-204.

Johnson Alengaram U., Al Muhit B.A., bin Jumaat M.Z., Jing M.L.Y., (2013), A comparison of the thermal conductivity of oil palm shell foamed concrete with conventional materials, *Materials and Design*, **51**, 522-529.

Kalina L., Koplik J., Soukal F., Masilko J., Jaskowiecova L., (2012), Potential uses of geopolymers to immobilize toxic metals from by-products materials, *Environmental Engineering and Management Journal*, **11**, 579-584.

Kizilkanat A.B., Yuzer N., Kabay N., (2013), Thermo-physical properties of concrete exposed to high temperature, *Construction and Building Materials*, **45**, 157-161.

Lai W.L., Tsang W.F., (2008), Characterization of pore systems of air/water-cured concrete using ground penetrating radar (GPR) through continuous water injection, *Construction and Building Materials*, **22**, 250-256.

Malhotra V.M., Metha P.K., (1996), *Pozzolanic and Cementitious Materials*, In: *Advances in Concrete Technology*, vol. 1, Gordon and Breach Publisher, Amsterdam, The Netherlands.

Mehta P.K., Monteiro P.J.M., (1993), *Concrete: Microstructure, Properties and Materials*, 2nd Edition, McGraw-Hill (Ed.), New York.

Mindess S., Young J.F., Darwin D., (2002), *Concrete*, 2nd Edition, Pearson Education, New Jersey.

Nochaiya T., Wongkeo W., Chaipanich A., (2010), Utilization of fly ash with silica fume and properties of Portland cement-fly ash-silica fume concrete, *Fuel*, **89**, 768-774.

Othuman Mydin M.A., (2013), An experimental investigation on thermal conductivity of lightweight foamcrete for thermal insulation, *Jurnal Teknologi*, **63**, 43-49.

Poon C.S., Kou S.C., Lam L., Lin Z.S., (2001), Activation of fly ash/cement systems using calcium sulphate anhydrite ($CaSO_4$), *Cement and Concrete Research*, **31**, 873-881.

Shehata M.H., Thomas M.D.A., (2002), Use of ternary blends containing silica fume and fly ash to suppress expansion due to alkali-silica reaction in concrete, *Cement and Concrete Research*, **32**, 341-349.

Shih J.Y., Chang T.P., Hsiao T.C., (2006), Effect of nanosilica on characterization of portland cement composite, *Materials Science and Engineering A*, **424**, 266-274.

Topcu I.B., Uygunoglu T., (2007), Properties of autoclave lightweight aggregate concrete, *Building and Environment*, **42**, 4108-4116.

Turgut P., (2010), Mansonry composite material made of limestone powder and fly ash, *Powder Technology*, **204**, 42-47.

Vessalas K., Thomas P.S., Ray A.S., Guerbois J.P., Joyce P., Haggman J., (2009), Pozzolanic reactivity of the supplementary cementitious materials pitchstone fines by thermogravimetric analysis, *Journal of Thermal Analysis and Calorimetry*, **97**, 71-76.

Wongkeo W., Thawornson W., Chaipanich A., (2008), Microstructure and characterizations of Portland-bottom ash-silica fume cement pastes, *Advance Materials Research*, **55-57**, 629-632.

Wongkeo W., Chaipanich A., (2010), Compressive, microstructure and thermal analysis of autoclave and air cured structural lightweight concrete made with coal

bottom ash and silica fume, *Materials Science and Engineering A*, **567**, 3676-3684.

Wongkeo W., Thongsanitgarn P., Chaipanich A., (2012), Compressive strength and drying shrinkage of fly ash-bottom ash-silica fume multi-blended cement mortars, *Materials and Design*, **36**, 655-662.

Wongkeo W., Thongsanitgarn P., Chindaprasirt P., Chaipanich A., (2013), Thermogravimetry of ternary cement blends effect of different curing methods, *Journal of Thermal Analysis and Calorimetry*, **113**, 1079-1090.

Yazici H., (2008), The effect of silica fume and high-volume class C fly ash on mechanical properties, chloride penetration and freez-thaw resistance of self-compact concrete, *Construction and Building Materials*, **22**, 456-462.

Yunsheng X., Chung D.D.L., (2000), Cement of high specific heat and high thermal conductivity, obtained by using silane and silica fume as admixtures, *Cement and Concrete Research*, **30**, 1175-1178.