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Packing effect and pozzolanic reaction of fly ash in mortar

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Abstract

This research is to study the effect of particle size of fly ash on packing effect and pozzolanic reaction of mortar when 20% of fly ash is used to replace Portland cement type I. Both effects can be determined by using fly ash and insoluble material which have almost the same particle size to replace Portland cement type I. Normally, the compressive strength of fly ash mortar is contributed from hydration reaction, packing effect, and pozzolanic reaction. For mortar mixed with insoluble material, the compressive strength is due to hydration reaction and packing effect. Thus, compressive strength due to pozzolanic reaction can be determined from the difference in compressive strength between fly ash mortar and insoluble material mortar. The results show that the strength activity index of fly ash mortar depends on the median particle size of fly ash and curing ages of mortar samples. At early ages, the strength activity index of fly ash mortar due to packing effect is higher than that due to pozzolanic reaction. At the ages of 3 to 90 days, the difference in strength activity index due to packing effect of fly ashes with median particle size of 2.7 and 160 μm is almost constant about 22% of the strength of standard mortar (STD). The differences in strength activity index due to pozzolanic reaction of fly ashes with median particle size of 2.7 and 160 μm are 3%, 20%, and 27%, respectively, at the ages of 3, 28, and 90 days.

Keywords: Fly ash; Mortar; Packing effect; Pozzolan

1. Introduction

ASTM C 618 [1] specifies that fly ash (class F or class C) mortar should have strength activity index at least 75% of the standard mortar (STD) at the ages of 7 or 28 days when fly ash is used to replace Portland cement at the rate of 20% by weight of cementitious materials. Compressive strength of fly ash mortar or fly ash concrete is contributed by hydration reaction, packing effect, and pozzolanic reaction. Hydration and pozzolanic reactions are the chemical reaction between Portland cement and water and Portland cement plus fly ash and water, respectively, but packing effect is a proper arrangement of small particles which fill the voids and contribute to the increment of compressive strength without any chemical reaction [2–4]. The smaller particle size of pozzolanic material tends to produce higher compressive strength than the coarser one [5,6]. However, ASTM standard does not distinguish the compressive strength of mortar contributed by packing effect and pozzolanic reaction. If the packing effect and pozzolanic reaction of fly ash are distinguished, the strength activity index of fly ash with different particle sizes can be predicted. This concept will help the concrete technologist to select a suitable fly ash for use in concrete.

To determine the packing effect and pozzolanic reaction, three types of mortar, namely, standard mortar with Portland cement type I, insoluble material mortar, and fly ash mortar, were prepared and tested according to ASTM C 109 [7]. For insoluble material mortar and fly ash mortar, Portland cement type I was replaced by 20% of insoluble material or fly ash by weight of binder, respectively. The packing effect is determined by the difference in compressive strength between the standard and insoluble material mortars having the same curing age. For the pozzolanic reaction, it can be

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calculated by the difference in compressive strength at the same curing age between insoluble material and fly ash mortars having approximately the same particle sizes of insoluble material and fly ash.

Using fly ash with small and spherical shape in mortar or concrete will reduce water demand of the mixtures [8,9]. Therefore, to avoid effects due to water to binder ratio on compressive strength, all mortars in this investigation are controlled water to binder ratio at constant of 0.485 instead of using constant flow.

The objective of this study is to investigate the compressive strength of fly ash mortar due to packing effect and pozzolanic reaction when fly ash with different particle sizes is used to replace Portland cement type I at the rate of 20% by weight of cementitious materials.

2. Experimental program

2.1. Materials

Materials used in this investigation consisted of Portland cement type I, river sand which passed through sieve No. 16 and retained on sieve No. 100, and fly ash from the Mae Moh power plant in Thailand.

Fly ash from silo designated as original size (OF) was classified by air classifier into three different sizes: small (SF), medium (MF), and large (LF). To prepare insoluble material, river sand was washed by water and sun-dried for 2–3 days to reduce its moisture content to be less than 0.1%. Then, it was ground by ball mill to reduce its size into three different sizes, as in the case of classified fly ashes. After that, the process according to ASTM C 114 [10] was applied to obtain the insoluble material from ground river sand. The ground river sand was mixed with cold water and dissolved in hydrochloric acid followed after filtration by further digestion in sodium hydroxide and then washed in ammonium nitrate solution. The final residue was the insoluble material. This process insures that the insoluble material will not be dissolved in acid or basic solution which implies that the insoluble material will not react with $Ca(OH)_2$ [4]. Three particle sizes of insoluble material, namely, small, medium, and large, were designated as SI, MI, and LI, respectively.

2.2. Parameter investigated

Chemical composition, specific gravity, fineness, median particle size, and particle size distribution of Portland cement type I, fly ashes, and insoluble materials were investigated.

2.3. Detail of mortars

A constant ratio of cementitious materials (Portland cement plus fly ash or insoluble material) to sand was set at 1 to 2.75 by weight, and water to cementitious materials ratio was maintained at 0.485. Portland cement type I was replaced by fly ash or insoluble material at the rate of 20% by weight of cementitious materials. All mortars were cast in 50×50×50-mm standard molds and removed from the molds after casting for 24 h and then cured in saturated limewater. Compressive strengths of mortars were determined at the ages of 3, 7, 14, 28, 60, and 90 days.

3. Results and discussion

3.1. Physical properties of materials

Table 1 compares the physical properties of Portland cement type I, fly ashes, and insoluble materials. It is seen that Portland cement type I has particles retained on a sieve No. 325 of 13%, while the specific gravity and median particle size are 3.15 and 11 μm, respectively.

The weight retained on sieve No. 325 of original fly ash (OF) is 29%, while those of classified fly ashes SF, MF, and LF are 0%, 12%, and 83%, respectively. Median particle sizes of fly ashes SF, MF, OF, and LF are 2.7, 16, 19, and 160 μm, and their specific gravities are 2.60, 2.22, 2.12, and 1.91, respectively. It was observed that the specific gravity of fly ash depended on its fineness and conformed to the former researches [11,12]. For insoluble materials SI, MI, and LI, the weights retained on a sieve No. 325 were 0%, 23%, and 85%, and corresponding median particle sizes were 3.3, 19, and 200 μm, respectively. It should be noted that the classified fly ash and insoluble material for each pair (SF&SI, MF&MI, and LF&LI) have approximately the same median particle size.

Fig. 1a–d shows the particle size distributions of Portland cement type I and original fly ash, classified fly ash, and insoluble material of large, medium, and small sizes, respectively. It is noted that particle size distributions of fly ash and insoluble material for each pair are slightly different.

3.2. Chemical composition of materials

Chemical compositions of Portland cement type I, fly ashes, and insoluble materials are shown in Table 2. The

Table 1
Physical properties of materials

Type of sample		Specific gravity	Retained on sieve no. 325 (%)	Median particle size, d_{50} (μm)
Cement		3.15	13	11
Fly ash	OF	2.12	29	19
	SF	2.60	0	2.7
	MF	2.22	12	16
	LF	1.91	83	160
Insoluble material	SI	2.61	0	3.3
	MI	2.60	23	19
	LI	2.59	85	200

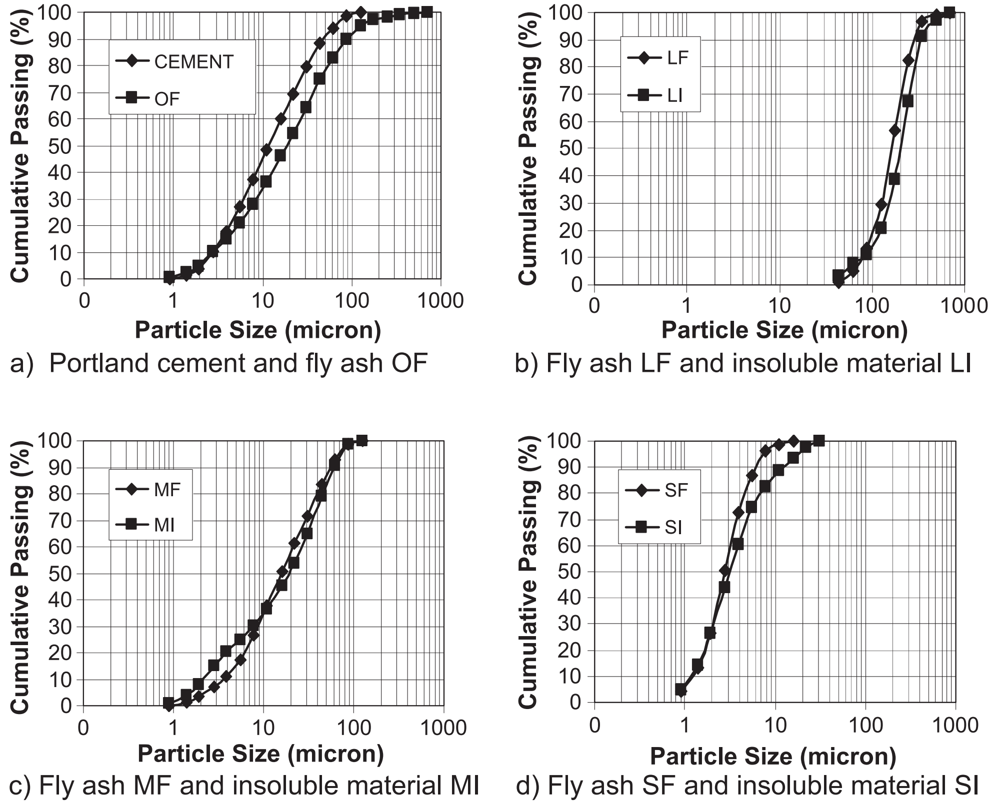

Fig. 1. Particle size distribution of materials.

chemical compositions of original fly ash and classified fly ashes are similar, and their SiO_2+Al_2O_3+Fe_2O_3 are in the range of 70.5% to 76.8%, and therefore meet the ASTM C 618 [1] chemical composition requirement for class F fly ash. For insoluble material, the major chemical composition is SiO_2, which is approximately 92%. The results in Table 2 show that the grinding and air classifying processes have slight effect on chemical composition of the materials, which is in line with previous published data [6,11,12].

3.3. Compressive strength of mortar

Table 3 shows compressive strength and strength activity index of mortar. Strength activity index as determined by ASTM C 311 [13] is defined as a ratio (in percent) of the compressive strength of mortar mixed with fly ash (or insoluble material in this study) at the rate of 20% by weight of cementitious materials to that of standard mortar. It is found that the compressive strengths of standard mortar (STD) at the ages of 3, 7, 14, 28, 60, and 90 days are 22.7, 28.9, 33.0, 36.5, 38.9, and 39.5 MPa, respectively.

Strength activity indices of mortar OFM (made with fly ash OF) at the ages of 7 and 28 days are 77% and 81%, respectively. According to ASTM C 618 [1], original fly ash from Mae Moh power plant can be used as pozzolanic material because it produces strength activity indices higher than 75% at the ages of 7 or 28 days. For all tested ages, it was observed that fly ash mortar with the smaller particle size

Table 2
Chemical composition of materials

Chemical composition (%)	Type of sample							
	Cement	Fly ash				Insoluble material		
		OF	SF	MF	LF	SI	MI	LI
SiO_2	20.2	40.0	38.2	42.1	43.2	91.3	91.8	91.7
Al_2O_3	5.4	20.9	20.7	21.2	21.5	5.8	7.4	4.7
Fe_2O_3	2.9	11.8	11.6	11.8	12.1	1.8	0.0	1.4
CaO	63.8	12.7	14.0	13.2	13.4	0.9	0.2	0.2
MgO	1.5	2.4	2.2	2.5	2.7	0.1	0.1	0.1
Na_2O	2.7	1.4	1.2	1.3	1.8	0.2	0.3	0.2
K_2O	0.3	2.8	2.7	2.9	2.6	2.9	3.8	2.4
SO_3	2.3	2.3	5.0	1.9	0.4	–	–	–
LOI	2.9	2.3	4.5	1.4	2.3	1.8	0.5	0.6

Table 3
Compressive strength and strength activity index of mortar

Sample	Compressive strength (MPa)–(Strength activity index)					
	3 days	7 days	14 days	28 days	60 days	90 days
STD	22.7–(100)	28.9–(100)	33.0–(100)	36.5–(100)	38.9–(100)	39.5–(100)
SFM	20.6–(91)	27.1–(94)	33.6–(102)	39.4–(108)	44.5–(114)	46.2–(117)
MFM	18.4–(81)	23.9–(82)	28.6–(87)	33.9–(93)	38.9–(100)	40.9–(104)
OFM	17.4–(77)	22.2–(77)	26.2–(79)	29.6–(81)	33.4–(86)	36.0–(91)
LFM	15.0–(66)	19.0–(66)	22.0–(67)	24.1–(66)	26.2–(67)	26.8–(68)
SIM	19.5–(86)	24.8–(86)	28.6–(87)	32.6–(89)	34.3–(87)	34.4–(87)
MIM	17.6–(78)	22.3–(77)	25.5–(77)	28.5–(78)	30.1–(77)	31.0–(78)
LIM	14.8–(65)	18.1–(63)	21.5–(65)	23.8–(65)	25.4–(65)	25.9–(66)

has higher compressive strength than that of mortar with the larger particle size. For example, the compressive strengths of mortars SFM, MFM, OFM, and LFM 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. Fly ash with higher fineness can produce higher compressive strength of mortar due to faster pozzolanic reaction of fly ash [12,14–17], and small particle of fly ash contributes extra compressive strength to mortar by packing effect. This compressive strength is higher than that of fly ash with the coarser one. However, the compressive strength of mortar due to pozzolanic reaction or packing effect cannot be distinguished.

Fig. 2 shows the relationship between strength activity index of insoluble material mortars SIM, MIM, and LIM and curing ages. The curves are nearly straight lines and parallel to the axis of curing ages. For example, the strength activity indices of mortar SIM at the ages of 3, 7, 14, 28, 60, and 90 days are 86%, 86%, 87%, 89%, 87%, and 87% of the strength of standard mortar, respectively. The average strength activity indices of mortars SIM, MIM, and LIM at all tested ages are about 87.0%, 77.5%, and 64.8%, respectively, which correspond to the median particle sizes of 3.3, 19, and 200 μm of the insoluble materials, respectively. This suggests that the strength activity index of insoluble material mortar does not depend on the curing ages but rather on the particle size of insoluble material. It is also observed that the mortars with the smaller particle size of insoluble material has higher strength activity index than the one with the larger particle size, which confirms the packing effect of the material.

From Fig. 3, it is found that the strength activity index of fly ash mortar increases with curing age and differs from the case of insoluble material mortar. For example, the strength activity indices of mortars MFM and SFM at the ages of 7 and 90 days are 82%, 94% and 104%, 117%, respectively. However, when large particle size of fly ash is used in the mortar, the strength activity index is almost constant, that is, the strength activity indices of mortar LFM at the ages of 3, 7, 14, 28, 60, and 90 days were 66%, 66%, 67%, 66%, 67%, and 68%, respectively. The results confirm that the compressive strength of fly ash mortar depends on the fly ash fineness [12,16,18].

3.4. Strength activity index of mortar due to packing effect

Fig. 4 shows the relationship between strength activity index of mortar at given ages and the median particle size of insoluble material, and it can be expressed in Eq. (1) as follows:

$$\mathrm{SHP}(\%) = -5.408 \times \ln(d_{50}) + 93.445 \qquad (1)$$

where SHP is the strength activity index of mortar contributed by hydration reaction plus packing effect, and d_{50} is the median particle size of insoluble material or fly ash (μm).

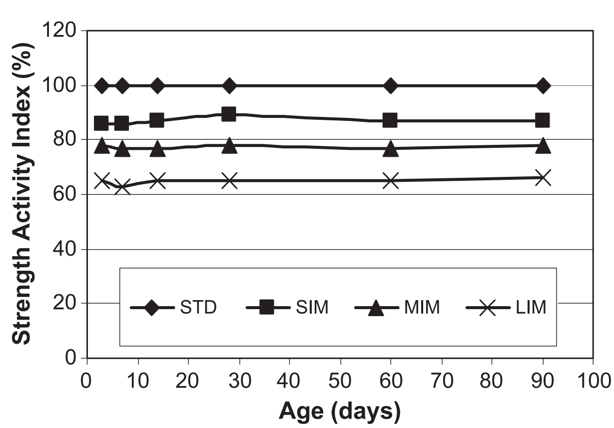

Fig. 2. Relationship between strength activity index of insoluble material mortar and curing age.

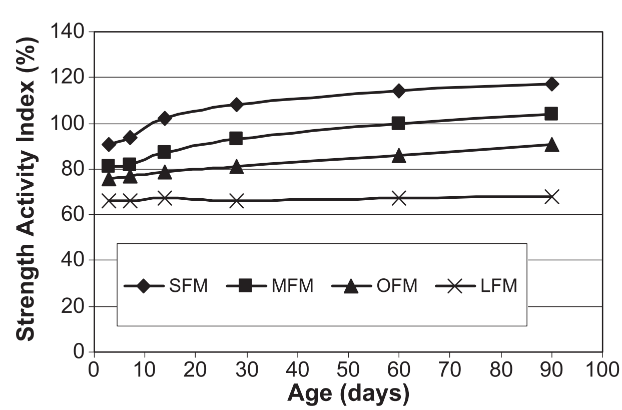

Fig. 3. Relationship between strength activity index of fly ash mortar and curing age.

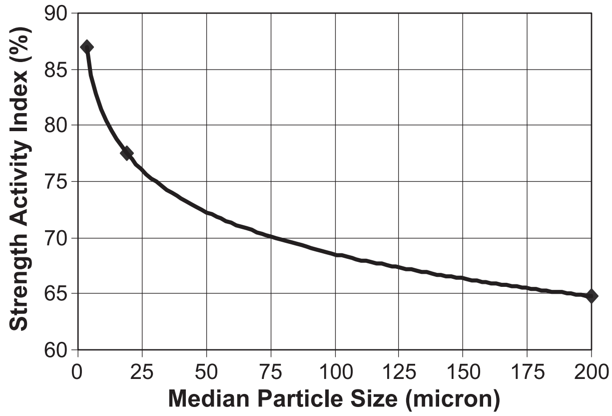

Fig. 4. Relationship between strength activity index of insoluble material mortar and median particle size.

From Fig. 4, it can be seen that the mortar made with insoluble material with median particle size less than 30 μm can produce strength activity index more than 75%, although it contains insoluble material (inert material). When fly ashes SF and LF with median particle sizes of 2.7 and 160 μm, respectively, were used in Eq. (1), it was found that the strength activity indices due to hydration reaction plus packing effect of mortars SFM and LFM are 88% and 66%, respectively (see Table 4). The difference in strength activity index of mortars SFM and LFM is 22%, and this represent the strength percentage due to packing effect only. In the same manner, one can calculate the differences in strength activity index due to packing effect of fly ash mortar with fly ash median particle sizes of SFM&MFM, SFM&OFM, MFM&OFM, MFM&LFM, and OFM&LFM, and they are 9.5%, 8.5%, 1.0%, 12.5%, and 11.5% of the strength of standard mortar, respectively.

For standard mortar, if it is assumed that 20% of the cementitious materials is the inert material (and has Portland cement 80%) of total and the same median particle size of Portland cement about 11 μm is used to substitute in Eq. (1), then the strength activity index is calculated to be 80.5%. It presents that the strength activity index due to hydration reaction will decrease 19.5% of the strength of standard mortar. Therefore, the strength activity index of fly ash mortar when replacing Portland cement type I at the rate of 20% by weight of cementitious materials at an early age decreases about 19.5% (due to hydration reaction). However, for packing effect, the strength activity index of mortar may decrease or increase depending on the fineness (or median particle size) of fly ash.

From Fig. 4, it can be observed that the fineness of insoluble material plays an important role on strength activity index of mortar because the strength activity index increases when the fineness of insoluble material increases. The difference in strength activity index of insoluble material mortar with different fineness is the compressive strength of mortar contributed by packing effect. For example, the strength activity indices of insoluble material mortars SIM (d_{50} of 3.3 μm) and LIM (d_{50} of 200 μm) as calculated by Eq. (1) are 87.0% and 64.8%, respectively. Thus, the difference in strength activity index of the two specimens is 22.2%. This means that the strength activity index of mortar due to packing effect is 22.2%, although Portland cement type I is replaced by insoluble material at the same replacement (20% by weight of cementitious materials). This result suggests that packing of particles has a significant effect on the compressive strength of mortar, and the results confirm the previous researches [2,3].

3.5. Strength activity index of mortar due to pozzolanic reaction

For mortar with constant replacement of fly ash, the difference in compressive strength of fly ash mortars containing different particle sizes of fly ash is due to the pozzolanic reaction and packing effect. The strength activity indices of fly ash mortar due to packing effect and pozzolanic reaction can be shown in Table 4. The strength activity indices of fly ash mortar due to packing effect plus hydration reaction can be calculated from Eq. (1), and that due to pozzolanic reaction can be calculated from the difference of the strength activity index of fly ash mortar tested and presented in Table 3 and that calculated from Eq. (1). It is observed from Table 4 that the strength activity index due to pozzolanic reaction of fly ash mortar increases with fineness of fly ash and curing ages.

Fly ash having particle size larger than that of Portland cement type I not only decreases the compressive strength of mortar due to pozzolanic reaction but also decreases the

Table 4
Strength activity index of fly ash mortar due to pozzolanic reaction and hydration reaction plus packing effect

Sample	Median particle size of fly ash (μm)	Strength activity index (%)						
		From pozzolanic reaction[a]						From P+H[b]
		3 days	7 days	14 days	28 days	60 days	90 days	
SFM	2.7	3	6	14	20	26	29	88
MFM	16	2.5	3.5	8.5	14.5	21.5	25.5	78.5
OFM	19	−0.5	−0.5	1.5	3.5	8.5	13.5	77.5
LFM	160	0	0	1	0	1	2	66

P—packing effect, H—hydration reaction.
[a] Calculated by using strength activity index at a given age (in Table 3) minus the value from Eq. (1).
[b] Calculated from Eq. (1).

compressive strength of mortar due to packing effect. For example, the strength activity index of mortar LFM at the age of 3 days is 66% (see Table 3), therefore the strength activity index of mortar reduces equal to 100% minus 66% or 34% from the strength of standard mortar. The reduction of the strength activity index can be calculated as 19.5% from hydration reaction (Portland cement type I is replaced by fly ash) and 14.5% from packing effect since the particle size of fly ash LF (d_{50} of 160 μm) is larger than that of Portland cement type I (d_{50} of 11 μm).

Considering original fly ash mortar OFM (median particle size of 19 μm), the strength activity index of mortar due to packing effect and hydration reaction from Eq. (1) is equal to 77.5% (see Table 4) and is close to the tested compressive strength of mortar OFM in Table 3, which is 77% at the age of 3 days. It is suggested that the strength activity index of mortar OFM decreases 23% from the strength of standard mortar. This can be calculated that the reduction of strength activity index of 19.5% due to hydration reaction and 3.5% (from 23%−19.5%) due to packing effect. At the age of 90 days, the increment of compressive strength of mortar OFM due to pozzolanic reaction is 13.5% of the strength of standard mortar, thus giving the strength activity index of mortar OFM of 91% (as shown in Table 3).

For fly ash MF and SF, it is found that the strength activity indices due to pozzolanic reaction of mortars MFM and SFM at the ages of 3, 7, 14, 28, 60, and 90 days are 2.5%, 3.5%, 8.5%, 14.5%, 21.5%, 25.5% and 3%, 6%, 14%, 20%, 26%, 29%, respectively. From Eq. (1) and Table 4, the packing effect between mortars SFM and MFM is calculated as 9.5% (88%−78.5%) and means that the strength activity indices of fly ash mortar at the early ages (between 3 to 7 days) is more pronounced from packing effect than that of pozzolanic reaction. However, at the later ages (after 28 days), the pozzolanic reaction has more effect on the strength activity index than that of packing effect.

In Table 3, at the age of 90 days, the strength activity indices of fly ash mortars SFM and LFM with particle sizes of 2.7 and 160 μm are 117% and 68%, respectively. The difference of strength activity index is 49%. Table 4 shows that 22% (88%−66%) is due to packing effect and 27% (29%−2%) is due to pozzolanic reaction. It should be noted that the strength activity index from pozzolanic reaction of fly ash LF is very low and in the range of 0–2% at ages of 3 to 90 days (see Table 4). This is quite different from that of fly ash SF, which is 3% at 3 days and increases to 29% at 90 days. This result suggests that fly ash with median particle size larger than 160 μm is not an active pozzolan and unsuitable to use as a substitute material for cement in mortar or concrete.

4. Conclusions

From the results of using fly ash with median particle sizes of 2.7, 16, 19, and 160 μm and insoluble material with median particle sizes of 3.3, 19, and 200 μm to replace Portland cement type I at 20% by weight of cementitious materials in mortar, the following conclusions can be drawn:

(1) At the early ages (between 3 to 28 days), the strength activity index of fly ash mortar due to packing effect is higher than that due to pozzolanic reaction.
(2) The differences in strength activity index due to packing effect of fly ash mortar with median particle sizes of fly ash of 2.7 and 160 μm at all tested ages are about 22% of the strength of standard mortar.
(3) The difference in strength activity index due to pozzolanic reaction of fly ashes with median particle size of 2.7 and 160 μm is 3% at the age of 3 days and increases to be 20% and 27%, respectively, at the ages of 28 and 90 days.
(4) At the age of 90 days, fly ash with median particle size of 160 μm has strength activity index due to pozzolanic reaction of 2% which is very low. This means that fly ash with large particle size is not suitable to be used as a pozzolanic material.

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