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目　次　CONTENTS

【土木構造・材料論文集 第 30 号 2014 年 12 月】

An Experimental Study on Mitigating ASR Using Fly Ash and Silica Fume

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The ASR suppression effect of fly ash, silica fume and the combination of them was evaluated by both concrete prism test and mortar bar test. Concrete prism bars were made based on RILEM AAR-3, meanwhile mortar prism bars were made according to JIS A 1146. Both prism specimens were stored in 40°C 100% R.H. controlled room. Two aggregates were used in this experiment; one was classified as alkali silica reactive (andesite) and the other was classified as non-reactive (limestone).

The present study investigated the combination of fly ash (FA) and silica fume (SF) in order to reduce expansion due to ASR, and some concrete and mortar mixtures have been made in pessimum proportion. The results indicated that the combination of FA and SF showed smaller expansion compared to FA.

1. Introduction

Concrete damage due to alkali silica reaction (ASR) is a phenomenon that was recognized around 75 years ago in the U.S.A., and has been observed in many countries. Crack caused by ASR occurs during service life of structures, and gives early warnings of damage. Among some problems in durability, researches on ASR mitigation has been carried out as described in many papers by a number of experts[1,2].

Some ways of mitigation and some test methods are continuously developed to findmore effective way of suppressing expansion and detecting reactive and non reactive aggregate. Other countermeasures such as limitation of alkali under 3.0 kg/m^3, use of blended cement, and use of innocuousaggregate[3] have been applied. Some recommendations have been proposed: Class F fly ash or Class N Pozzolan (25 to 40% by weight), or ground granulated blast-furnace slag (GGBFS) (40 to 50% by weight) or combination of both[2].

In Japan, the use of FA at the level of 15% to 25% are considered to be sufficient in mitigating concrete expansion[4,5]. Based on this reason, the study focused on FA levels at 15% and 25%. These FA levels are determined to combine FA and SF. Futhermore, these levels are also compared to mixture with FA only.

Silica Fume is defined by the American Concrete Institute (ACI) as a ‘‘very fine non-crystallinesilica produced in electric arc furnaces as a by-product of production of elemental silicon or alloys containing silicon’’. Silica Fume also referred to as condensed silica fumeor microsilica that is used as a pozzolan. Its color usually gray powder, somewhat similar to Portland cement or FA. Fundamental performance properties of SF are pozzolanic reaction and micro filler effect, and they lead to improve durability of concrete. The aim of this study was to investigate the combination effect fly ash with silica fume at certain level of fly ash. Therefore, a study on ASR by combining FA and SF are needed to be conducted.

In this study, the combination of fly ash with silica fume was investigated in order to reduce expansion. As a result, some concrete prisms and mortar bars have been made. Concrete prisms were made based on RILEM AAR-3, and mortar bars were made based on JIS A 1146. Concrete specimens were stored under 40°C, and R.H. 100%, except compressive strength specimens were cured in 20°C, R.H.

60%. Meanwhile, mortar specimens for expansion measurement were also treated under 40°C, and R.H. 100%.

2. Material and Mixture Proportions

Material and mixture proportions are described below:

(1)Material

Three types of binder were used in this study, namely: Ordinary Portland Cement (OPC), Fly ash (FA), and Silica fume (SF). OPC, FA and SF meet the requirements of JIS R 5202 and JIS A6201, and JIS A 6207, respectively. Chemical composition of OPC, FA and SF are depicted in Table 1, meanwhile the physical properties of material are presented in Table 2.

Table 1: Chemical compositions of cement, fly ash and silicafume

Constituents	OPC	FA	SF
MgO, %	0.92	1.30	0.56
SiO_2, %	20.89	54.96	95.5
SO_3, %	2.02	0.49	0.18
Na_2O, %	0.35	1.07	-
K_2O, %	0.36	1.30	-
LoI	1.87	2.37	1.22

Table 2: Physical properties of materials

Material	Discription
Cement, OPC	Density = 3.16 g/cm^3, Specific Surface Area = 3330 cm^2/g
Flyash,(Type II)	Density = 2.26g/cm^3, Specific Surface Area = 3970 cm^2/g
Silica fume	Density = 2.35g/cm^3, Specific Surface Area = 18 m^2/g
Fine aggregate (Limestone)	Density (SSD) = 2.70 g/cm^3, Water absorption = 0.61%, Rc = 8 mmol/l, Sc = 1 mmol/l
Coarse aggregate (1):(Andesite)	Density (SSD) = 2.60 g/cm^3, Water absorption = 2.75%, Rc = 185 mmol/l, Sc = 620 mmol/l
Coarse aggregate (2): (Limestone)	Density (SSD) = 2.70 g/cm^3, Water absorption =0.55%, Rc = 8 mmol/l, Sc = 1 mmol/l

(2) Mixture proportion

This paper presents an experimental study carried out on some concrete and mortar mixtures. Mortar bars have been made based on JIS A 1146. Andesite coarse aggregate was crushed into fine aggregate that matches requirement of particle size distribution in JIS A1146. Aggregate combination (in ratio 30:70) between reactive and non-reactive were prepared in mortar and concrete. Previous study showed maximum expansion was happened when aggregate ratio was used in this ratio[7]. Expansion at 6 months of mortars varying aggregate combinations ratio in previous study is shown in Fig.1. Water to cement ratio of mortar was adjusted 0.50 and alkali content was set such that Na_2Oeq of cement 1.2 wt% by adding NaOH solution to mixing water. Meanwhile, concrete prisms have been made based on RILEM AAR-3. Material and mixture proportions of concrete are shown in Table 2 and Table 3. Mixture 1 was made for control; Mixture 2 and 3 used FA at level 15% and 25%. Mixture 4 and 5 used SF at level 5% and 10%. Furthermore, to investigate incorporation effect of FA and SF, Mixture 6 (FA10%, SF5%) and Mixture 7 (FA15%, SF10%) were made.

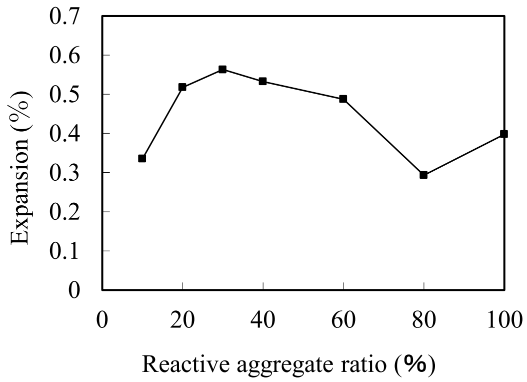


Fig.1: Expansion at 6 months of mortar bars with different reactive aggregate ratio

Table 3: Mixture proportions of concrete

Mixtures	Mixture 1 (Control)	Mixture 2 (FA15)	Mixture 3 (FA25)	Mixture 4 (SF5)	Mixture 5 (SF10)	Mixture 6 (FA10SF5)	Mixture 7 (FA15SF10)
w/b,%	50	50	50	50	50	50	50
s/a,%	45	45	45	45	45	45	45
Water, kg/m^3	160	160	160	160	160	160	160
OPC, kg/m^3	320	272	240	304	288	272	240
FA, kg/m^3	-	48	80	-	-	32	48
SF, kg/m^3	-	-	-	16	32	16	32
Sand, kg/m^3	843	836	831	841	838	824	813
Gravel (1), kg/m^3	298	295	293	297	296	291	287
Gravel (2), kg/m^3	694	689	685	693	691	679	670
NaOH, kg/m^3	1.856	2.499	2.928	2.07	2.285	2.192	2.314
(AE+WR), gr/m^3	1000	1000	1000	1000	1000	880	880
AE, gr/m^3	12.80	9.60	16.00	12.80	12.80	12.80	12.80
Temp, °C	19	23	22	22	21	21	21
Slump, mm	80	150	180	70	60	125	125
Air content, %	5.0	4.0	2.8	3.8	3.5	4.5	3.1

WRA= water reducing and air entraining agent (WR+AE), AE= air entraining agent

(a) wrapped with wet paper (b) wrapped with thin plastic sheet (c) completion of wrapping

(d) polyethylene container (e) container in maintained room (f) length measurement

Fig.2:Procedure of concrete prism test RILEM AAR-3

Seven concrete mixtures with water binder ratio 0.5 were prepared, by using tap water and total alkali in concrete of 6 kg/m^3. In the author's view, by enlarging alkali content in concrete up to 6 kg/m^3, the expansion will be also high. So, it will be easy to observe and study the expansion behavior. Concrete mixtures were designed according to Japan Society of Civil Engineers Standards[6)].

3.Testing Methods

(1) Compressive strength and elastic modulus tests

Concrete cylinders were demoulded after 24 hours of casting then be cured by wrapping with cloth and plastic sheet in a room maintained at 20^{o}C and 60% R.H. Furthermore, tests were conducted after 28 days of curing in accordance with JIS A1108 and JIS A1149. The average values of compressive and elastic modulus were determined from three specimens for each concrete mixture.

(2) Porosity test

Concrete cylinder specimens were cut into 5mm-thick slice samples after curing for 28 and 91 days.Then, acetone was used for washing and immersing the fragments for 15 minutes to stop cement hydration. Moreover, keep the sliced samples for two days in freeze drying to remove all remaining water in the pores. Micromeritics auto pore III (Pore analyzer) was used to test the porosity or total pore volume of concrete specimens. The range of measured radius of pore size distributions are: 6.6-20, 20-50, 50-100, 100-200, 200-10μ, and more than 10μ. The pore system in cement-based materials consists of: gel pores (micro pores, size 0.5-10 nm), capillary pores (mesopores, 5-5000 nm), macro pores due to deliberately entrained air and macro pores due to inadequate compaction. The gel pores (size 1.5-2.0 nm) do not influence the strength of concrete adversely through its porosity. Capillary pores and other larger pores are responsible for reduction in strength and elasticity.

(3) Ultrasonic pulse velocity (UPV) test

This test was intended to assess the quality of concrete by ultrasonic pulse velocity method.The basic principle of this test was by measuring the time of travel of an ultrasonic pulse passing through the concrete being tested.

It is possible to determine average pulse velocity, if the distance is known. Higher velocity was obtained when concrete quality was good in terms of density, uniformity, homogeneity etc.

(4) Expansion test

(a) Mortar test

Mortar specimens were also observedassociated with JIS A 1146.The size of mortar was 40x40x160 mm. Samples were wrapped with wet paper and placed vertically in stainless container, then were stored in a 40^{o}C and 100% R.H. controlled room. To observe expansion behavior of mortar, measuring were conducted at 1 day, 2 weeks, 1 month, 2 months, 3 months and 6 months.

(b) Concrete test

Prism specimens treatment are shown in Fig.2. Specimens were wrapped by wet paper and thin plastic sheet as shown in Fig.2(a), and 2(b). Then, specimens were placed in polyethylene container (d) with water in the bottom and the water was adjusted to a constant level. After completing the measurement, specimens were maintained in controlled room (e).To observe the concrete expansion, prism specimens were made based on RILEM Standards (AAR-3).The size of specimen was 75x75x250 mm.

An important issue for concrete prisms is moisture control. Specimens were wrapped with wet paper, and covered with thin plastic sheet. One piece of unwoven paper (KimTex, size: 355 x 425 mm) was used for each specimen. Then, specimens for each experiment were placed vertically in a polyethylene container and were stored in a 40°C and 100% R.H. of controlled room for the whole period of observation. The length of concrete was measured periodically for every two weeks. Before measuring, container was moved to 20°C room to cool specimens for 24 hours. The observation for concrete expansion was taken in 6 months.

3. Results and discussion

(1) Expansion test

Expansion behavior of mortar is shown at Fig.3. In the case of mortar without mineral admixtures, expansion was also large and fast from the beginning until the end of this period. It can be observed that there are expansion reduction due to usage of FA and SF. The expansion rate of mortar with FA25% was lower compared to mortar expansion with FA15%. Mortar expansion by using SF showed expansion reduction compared to mortar expansion without mineral admixtures.

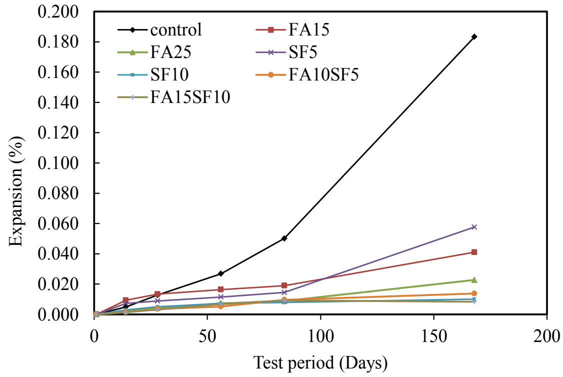


Fig.3: Test results of mortar bar test JIS A 1146

The expansion rate of mortar with level SF5% was moderate whereas mortar with level SF10% was lower. Both mortar expansion reduction by using incorporation of FA and SF are under 0.1% which are classified as innocuous.

Next, Figure 4 shows expansion behavior of concrete by using limestone as fine aggregate and combines coarse aggregate between limestoneand andesite.In the case of concrete without mineral admixtures, expansion was large and fast from the beginning until 182 days of this period.

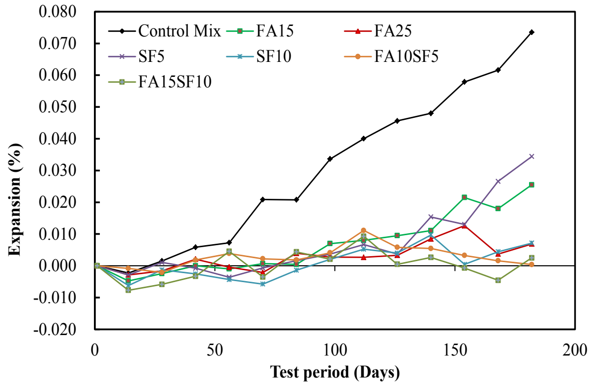
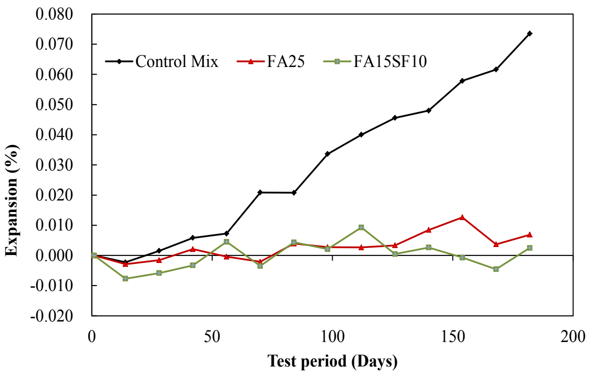
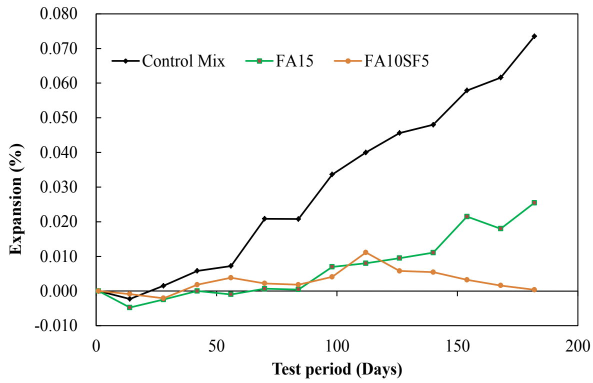


Fig.4: Concrete expansion



(a) Concrete expansion for FA15, and FA10SF5



(b) Concrete expansion for FA25, and FA15SF10

Fig. 5: Concrete expansion for control and combination of FA with SF

It can be observed that there is expansion reduction due to usage of FA. The expansion rate of concrete with FA25% was lower compared to concrete with FA15%. Concrete expansion by using silica fume showed expansion reduction compared to concrete expansion without mineral admixtures.The expansion rate of concrete with level SF5% was moderate whereas concrete with level SF10% was lower.

Based on Fig.5, concrete expansion by using incorporation of fly ash and silica fume showed expansion reduction compared to concrete expansion without mineral admixtures.The comparison of concrete expansion between concrete with FA15 to concrete with FA10SF5, and compare concrete expansion between concrete with FA25 to concrete with FA15SF10. Concrete with FA and SF incorporation showed that concrete expansion with incorporation of fly ash and silica fume concrete was lower compared to concrete with FA only. The effect of FA and SF combination of Alkali-Silica Reaction are stronger than FA.

Both expansion reduction by using incorporation of FA and SF are under 0.05% which are classified as non-reactive. FA reduces expansion by lowering alkali concentration and hydroxide ion in the pore solution. This is one of the mechanisms behind mineral admixtures to suppress expansion. The addition of an appropriate amount of mineral admixtures, lead to the formation of C-S-H gel with low Ca/Si ratio, resulting in lower alkali concentrations and hydroxide ion[4,5]. FA combines with alkalis from cement thatreact with silica from aggregate, thereby preventing expansion.

The replacement of cement by FA leads to an increase in the total alkali content of blended cement. However, alkalis are not released from FA particles; alkalis seem to be kept in a hydrated product resulting from the pozzolanic reaction. N Tenoutasse’s conclusion mentioned that: FA has the ability to react chemically with the alkali hydroxide in Portland cement paste and absorb alkalis, thus making them unavailable for reaction with silica in certain aggregates. Meanwhile, finer pozzolans are also sufficient in reducing ASR expansion, such as SF with particle size of approximately 0.1 μm is also very effective in preventing ASR[12]. SF is a reactive pozzolanic material because of its finesses and high amorphous silicon dioxide content. SF reacts with calcium hydroxide ($Ca(OH)_2$) to form additional Calcium Silica Hydrate (C-S-H), which is similar to the calcium hydrate formed from the Portland cement. The product of pozzolanic reaction (secondary C-S-H) can incorporate alkali metal ions into their structure and reduce the alkalinity of the pore solution. At the same time, the secondary C-S-H hydrates fill the adjacent pores and reduce the permeability of concrete, consequently, reducing the free movement of alkali ions[8].

(2) Compressive strength and elastic modulus

The results of compressive strength test at 28 days are shown in Fig.6. It can be seen that the usage of minerals could influence the compressive strength values. The compressive strength of concrete with FA 15% and 25% are smaller than strength of control concrete. FA reduced compressive strength of the concrete. The strength reduction decrease because of the increasing of FA replacement level. The compressive strength reduction is related to the properties of FA that declines the heat of concrete hydration. As a result FA slows the rate of hardening and reduces the compressive strength[15].

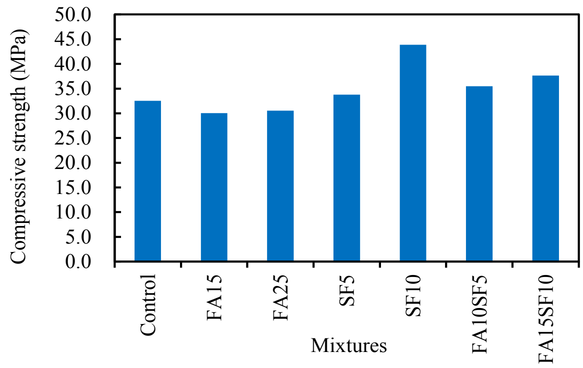


Fig.6: Compressive Strength of concrete at 28 days

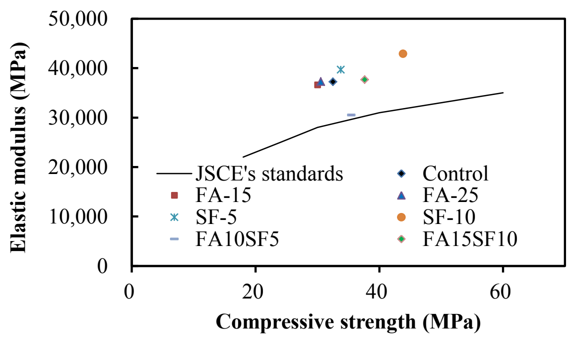


Fig.7: Relationship between compressive strength and elastic modulus

On the other hand, the usage of SF and the combination of FA and SF enhance the compressive strength. The highest strength is achieved on concrete with SF 10%. The relationship between compressive strength and elastic modulus at 28 days are shown in Fig.7. It was observed that the higher compressive strength, the higher elastic modulus is. Most of the relation between compressive strength (f'_c) and modulus elasticity (E_c) are above JSCE standard given by following equations. However, a good linear correlation between compressive strength and elastic modulus is acquired.

$$E_c = \left(2.2 + \frac{f'_c - 18}{20}\right) X10^4 \; f'_c < 30 \; N/mm^2 \; (1)$$

$$E_c = \left(2.8 + \frac{f'_c - 30}{33}\right) X10^4 \; 40 \leq f'_c < 70 \; N/mm^2 \; (2)$$

$$E_c = \left(3.1 + \frac{f'_c - 40}{50}\right) X10^4 \; 40 \leq f'_c < 70 \; N/mm^2 (3)$$

$$E_c = \left(3.7 + \frac{f'_c - 70}{100}\right) X10^4 \; 70 \leq f'_c < 80 \; N/mm^2 \; (4)$$

(3) Porosity test

Porosity is a measure of the proportion of the total volume of concrete occupied by pores. The pore of the structure of this material is complex. So some assumptions are made such as: the pores are interconnected and distribution size is not affected by the loss of water upon drying. Porosity or total pore volume can be measured by mercury intrusion. Porosity or total pore volume measurement is usually expressed in percent. Mercury intrusion test results of concrete at age of 28 and 91 days are depicted in Fig.8 and Fig.9.

In case of concrete with additional alkali, it seems that there are no significant effects of FA, and SF or incorporation of FA and SF towards porosity. Porosity values increase at control mixture, but not dramatically enlarge at FA15 and FA25 mixtures. However, at 28 days, small effect of silica fume at level 10% can reduce porosity compare to silica fume at level 5%.Furthermore, at 91 days, the effect of silica fume at level 5% can be seen to reduce porosity. Also the combination of FA and SF can reduce porosity at 91 days.

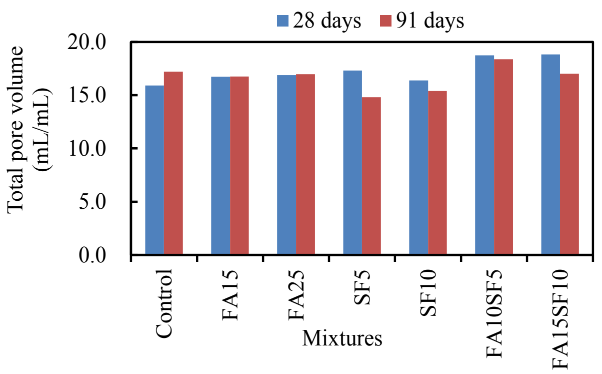
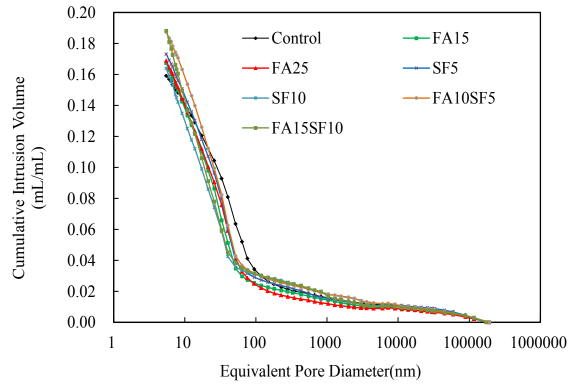
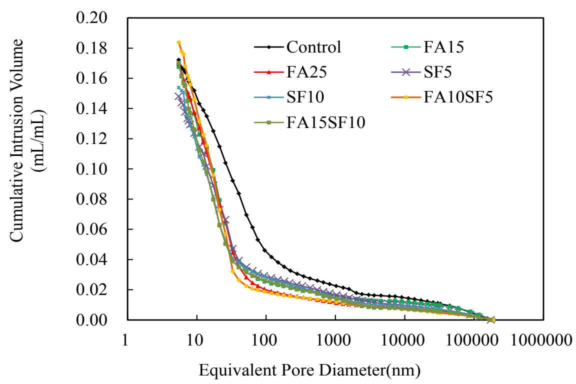


Fig.8: Total pore volume at age of 28 and 91 days

The study of pozzolanic activity of SF blended cement showed the beneficial influence of SF in reducing the porosity, and hence the permeability of the cement pastes[12]. Adding SF to concrete mixture would bring very small particles to fill in the spaces between cement grains. It would affect toward significant improvement of the concrete. Thus, this micro filling greatly reduces permeability and improves the paste to aggregate bond. The highest compressive strength was at SF 10% which has smallest total pore volume or porosity compared to among the concrete with mineral admixtures, as shown at Fig.6 and Fig.8.



(a) At 28 days



(b) At 91 days

Fig.9: Pore size distributions of concrete

(4) Ultrasonic pulse velocity (UPV) test

Test results of UPV at 28 and 91 days are depicted in Fig.10. The values are in range of 3.9 km/s to 4.2 km/s. The results indicate that the concrete quality is good. All values were higher than 3.7 km/s. Comparison of UPV results among concrete with mineral to concrete control, it seems that mineral admixture and also combination of FA and SF contribute to improve the concrete quality at all ages. Moreover, there are reduction of UPV results at age 91 days compare to UPV results at 28 days, except concrete with SF10%, and combination of FA with SF.

Comparison of porosity results at 28 days with 91 days as shown at Fig.8 and UPV results as shown at Fig.10, it can be observed that if porosity values are increased, the UPV results are low (control concrete, concrete with FA15 and FA25). Furthermore, if porosity results are reduced (concrete with SF5, SF10 and combination of FA with SF), the UPV values are increased (except concrete with SF5%) at age 91 days.

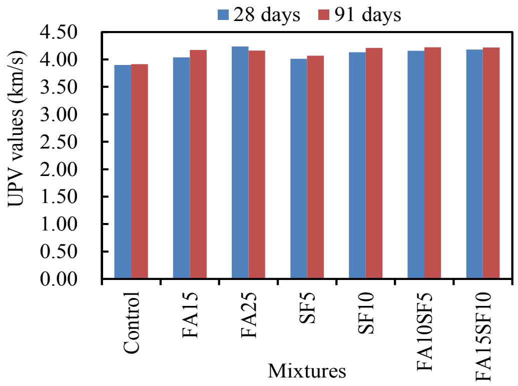


Fig.10: UPV results of concrete at 28 and 91 days

4. Conclusion

In order to investigate the combination of fly ash with silica fume at certain levels of fly ash, concrete prism and mortar bar have been tested, and cured at 40°C. The following conclusions are obtained based on the results of investigations:

1) The incorporation of FA and SF reduced expansion more effective compared to FA itself at the same levels of mineral investigated.

2) The effect of FA15% is lower compare to SF5%, meanwhile the effect of FA25% is same with the effect of SF10% to reduce expansion.

3) In the case of fresh concrete workmanship, degree of difficulty of concrete with silica fume is higher than concrete with a combination of silica fume and fly ash. Then concrete with fly ash is the easiest.

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