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Permeation properties of concretes incorporating fly ash and silica fume

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Abstract. This paper conveys the effects of fly ash and silica fume incorporated in concrete at various replacement ratios on the durability properties of concretes. It is quite well known that concrete durability is as much important as strength and permeability is the key to durability. Permeability is closely associated with the voids system of concrete. Concrete, with less and disconnected voids, is assumed to be impermeable. The void system in concrete is straightly related to the mix proportions, placing, compaction, and curing procedures of concrete. Reinforced concrete structures, particularly those of subjected to water, are at the risk of various harmful agents such as chlorides and sulfate since the ingress of such agents through concrete becomes easy and accelerates as the permeability of concrete increases. Eventually, both strength and durability of concrete reduce as the time moves on, in turn; the service life of the concrete structures shortens. Mineral additives have been proven to be very effective in reducing permeability.

The tests performed to accomplish the aim of the study are the rapid chloride permeability test, pressurized water depth test, capillarity test and compressive strength test. The results derived from these tests indicated that the durability properties of concretes incorporated fly ash and silica fume have improved substantially compared to that of without mineral additives regardless of the binder content used. Overall, the improvement becomes more evident as the replacement ratio of fly ash and silica fume have increased. With regard to permeability, silica fume is found to be superior to fly ash. Moreover, at least a 30% fly ash replacement and/or a replacement ratio of 5% to 10% silica fume have been found to be highly beneficial as far as sustainability is concerned, particularly for concretes subjected to chloride bearing environments.

Keywords: rapid chloride permeability; water depth; capillarity; mineral additives; durability

1. Introduction

Concrete is one of the most commonly used materials in construction sector as it is relatively low cost, readily available and can be produced in any desired shape, and as it is sufficiently resistant to aggressive environments compared to its companions.

Concrete is an alkaline material with a high pH between 12.5 and 13.5. Therefore, concrete generally deteriorates in acidic environments due to the chemical reactions taking place.

Permeability is the main controlling factor for the durability of concrete exposed to detrimental conditions (Mehta and Monteiro 2006, Wang 2015). As the permeability of concrete decreases, its durability properties, in terms of physico-chemical degradation, gets better. So, the permeability of concrete is considered to be one of the most crucial parameters in determining the durability of concrete (Khan 2003). Permeability of concrete can be reduced by decreasing the water to binder ratio, by using mineral additives like fly ash, blast furnace slag and silica fume, and by paying much attention to placing, compacting and curing processes of concrete. By incorporating mineral additives in concrete, it is possible to save a considerable amount of energy and therefore reduce CO_2 emission in addition to produce concrete with low permeability (Mehta and Monteiro 2006, Li 2011). It has been reported that the amount of CO_2 emission is approximately 1 kg per 1 kg of cement production (Reiner 2007).

Durability indicators are regarded as direct when they measure the type of attack involved chlorides and carbonation and indirect when they measure transport-related parameters such as water absorption, permeability, porosity, and electrical resistivity. Both are directly associated with the pore structure of concrete (Medina *et al*. 2016).

Fly ash is a byproduct from burning pulverized coal in electric power generating plants (Sata *et al.* 2016). Many studies have shown that incorporation of fly ash in concrete improves workability and the durability of concrete, reduces water demand and hydration heat, and helps long term flexural and compressive strengths development (Garcés *et al.* 2010, Ghafoori *et al.* 2015, Ghais *et al.* 2014, Kouloumbi and Batis 1992, Papadakis 2000). Fly ash also fills up the gaps in concrete in addition to its perfect pozzolanic activity (Fraay *et al*. 1989).

In a study performed using 30% and 40% fly ash

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Table 1 Particle density, water absorption, and moisture content of aggregates

Aggregate	Particle density, Mg/m^3	Water absorption, %	Moisture content, %
Coarse aggregate (Crushed stone)	2.74	1.00	0.25
Crushed sand	2.64	2.60	1.60

replacements, it has been seen that both strength and durability of concrete increased as the replacement ratio of fly ash was increased and chloride permeability was also decreased depending on the amount of binder used and the duration of curing time (Nath and Sarker 2011).

Silica fume has been known one of the most efficient supplementary cementitious materials since it contributes to the durability of concrete via the pozzolanic reaction with the calcium hydroxide to constitute calcium silicate hydrates (C-S-H), to pore size and matrix structure as well as aggregate-cement paste interfacial improvement (Diamond and Sahu 2006). Silica fume is highly reactive due to the high portion of non-crystalline SiO_2 and the large surface area (Khan and Siddique 2011). It is stated out in many studies that it is possible to reduce permeability of concrete considerably and increase its strength by using silica fume with Portland cement (Bagheri *et al.* 2012, Gesoğlu *et al.* 2009, Gleize *et al.* 2003, Nochaiya and Wongkeo 2010, Ramezanianpour 1995, Shih *et al.* 2007, Siddique 2011, Wongkeo 2010). In one study (Ramezanianpour 1995), it is stated that concrete with a water/cement ratio of 0.50 and 10% silica fume substitution yielded a compressive strength 25% higher with regard to concrete without silica fume at the end of 28 days of standard curing. Based on the results of rapid chloride permeability test carried out on the same concrete, regard to that of without silica fume, a reduction of approximately 80% in chloride permeability was obtained.

Chloride ingress in concrete is undesirable due to its electrochemical reaction with reinforcing steel in concrete and the eventual harmful effects on the durability of reinforced concrete structures (Sideris and Savva 2005, Vu and Stewart 2000). Corrosion of rebar in concrete can take place in the presence of chloride and sulfate ions and may cause structural damage to the reinforced concrete structures (Martys and Ferraris 1997). The money spent annually is approximately 5 billion Euros to compensate for the damage to reinforced concrete structures in Europe (Frølund *et al.* 2000).

2. Experimental setup

2.1 Materials used

The aggregate used was a mixture of calcareous crushed aggregate with a maximum size of 16 mm and crushed sand. The particle density at SSD state, water absorption and the moisture content of the aggregates are given in Table 1. The gradation of the aggregate mixture along with the reference curves is given in Fig. 1.

The cement used in the experimental program was CEM I 42.5 R type, manufactured by Aşkale Trabzon Cement Factory. The chemical composition of the cement, along with its some physical and mechanical properties is given in Table 2.

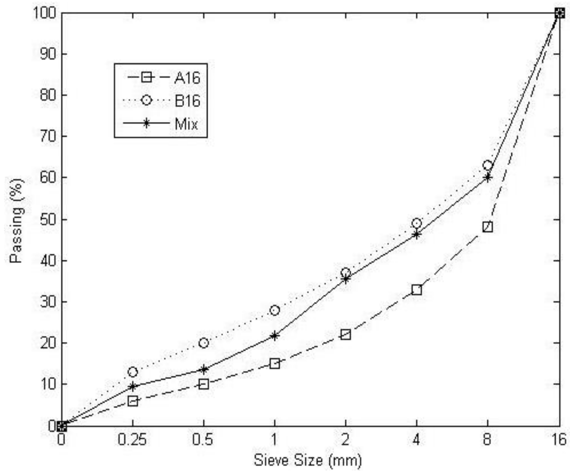

Fig. 1 The gradation of the aggregate mix and the reference curves

Table 2 Chemical composition, physical and mechanical properties of cement

Chemical Composition		Physical and Mechanical Properties		
Components	(%)	Retained on sieve 45 μm (%)		9.8
SiO_2	19.46	Retained on sieve 90 μm (%)		1.0
Al_2O_3	5.11	Specific surface (Blaine) (m^2/kg)		412.6
Fe_2O_3	3.31	Specific gravity		3.12
CaO	60.23	Setting Times (Vicat) (min.)	Initial	140
MgO	2.08		Final	200
SO_3	3.05	Water Demand (%)		29.2
Na_2O	0.27	Soundness (mm)		1.0
K_2O	0.69	Compressive Strength (MPa)	2 days	28.0
Cl^-	0.02		7 days	40.4
Loss on ignition	3.00		28 days	51.5

The fly ash was provided by Zonguldak-Çatalağzı power generation plant and the silica fume was provided by a private company. The chemical composition of the fly ash and silica fume, along with their densities is given in Table 3. A superplasticizer type chemical admixture was also used in the production of the mixes.

2.2 Mixture proportions

The mix proportions of the concretes are given in Table 4. The water/binder ratio was kept constant as 0.50 for all mixes. Four 150 mm cube, two 100 mm cube, one 100 mm diameter and 200 mm height cylinder specimens were prepared for each batch. Two 150 mm cubes were used for compressive test while the other two were used for water ingress test. The two cube specimens of 100 mm were used for determining capillarity coefficient. The cylinder specimen was used for rapid chloride permeability test. All tests were performed on concretes cured for 28 days in

Table 3 Chemical composition of fly ash and silica fume

	Fly ash	Silica fume
Density (g/cm^3)	2.34	2.20
Specific surface area, Blaine (cm^2/g)	2920	-
SiO_2 (%)	61.57	93.00
Al_2O_3 (%)	20.25	0.58
Fe_2O_3 (%)	7.00	2.79
CaO (%)	1.54	0.60
MgO (%)	-	1.00
Na_2O (%)	-	1.00
K_2O (%)	-	0.10
SO_3 (%)	-	0.50
Moisture content	-	0.10
Loss on ignition	-	0.50

Table 4 Mix proportions of the concretes produced

Designation for the mixes	Type of mineral additive	Replacement ratio for the mineral additives, %	Amount of constituent materials, kg/m^3				Chemical admixture, %
			Cement	Water	Aggregate	Mineral additive	
290PC	-	0	290		1994.5	0	1.92
290FA10		10	261		1985.8	29	1.81
290FA20	Fly ash	20	232		1977.0	58	1.69
290FA30		30	203	145	1968.3	87	1.26
290SF5		5	275.5		1989.4	14.5	2.34
290SF10	Silica fume	10	261		1984.2	29	2.48
290SF15		15	246.5		1979.1	43.5	2.76
340PC	-	0	340		1883.9	0	1.10
340FA10		10	306		1873.6	34	1.05
340FA20	Fly ash	20	272		1863.3	68	0.86
340FA30		30	238	170	1853.1	102	0.73
340SF5		5	323		1877.8	17	1.38
340SF10	Silica fume	10	306		1871.8	34	1.47
340SF15		15	289		1865.8	51	1.68

Fig. 2 Set up for rapid chloride permeability test

Table 5 Chloride ion permeability classification according to ASTM C1202

Electrical Charge Passing (Coulomb)	Chloride Ion Permeability
>4000	High
2000-4000	Moderate
1000-2000	Low
100-1000	Very low
<100	Negligible

Fig. 3 Set up for water ingress

Fig. 4 Marked depth of water ingress

standard curing condition. Chloride permeability test was also performed on concretes cured for 90 days in standard curing condition in addition to those of cured 28 days of standard cured ones. The amounts of chemical admixture used for the mixtures are provided in the last column of Table 4 as the proportion to the amount of binder used.

2.3 Methods

2.3.1 Rapid chloride permeability test

The rapid chloride permeability test was performed in accordance with the procedures prescribed in ASTM C1202. Initially, 25-mm slices were cut off from the two ends of the 100-mm cylinder specimens and then 50-mm sliced specimens were prepared from the remaining part of each specimen for the test. Prior to the testing, the concrete specimen was initially water saturated. The specimen was then placed in the test set up shown in Fig. 2 to have one face of the specimen in contact with a 3% NaCl solution and the other face with a 0.3 N NaOH solution. The cylindrical faces of the specimen not in conduct with the solution were isolated using a silicone agent to prevent water leakage. The charge that passed through the specimen within 6 hours under 60 V potential difference was measured in Coulombs (C).

Due to the charge passed, chloride ion permeability may be classified in accordance with ASTM C1202 as given in Table 5.

2.3.2 Water permeability test

Water permeation test was carried out in compliance with the procedures given in TS EN 12390-8. The specimens were exposed to a water pressure of 5 bars for 72 hours and then they were split perpendicular to the face of the specimen subjected to water ingress to determine water permeation. The apparatus used for the test is shown in Fig. 3. The maximum depth of water ingress on the split face

Table 6 Criteria for water permeation in concrete

Maximum Water Permeation, mm	Classification
> 50	Pervious Concrete
< 50	Impervious Concrete
< 30	Impervious Concrete to Aggressive Environments

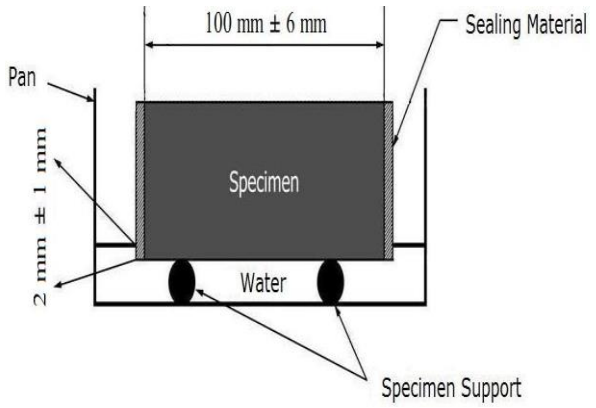

Fig. 5 Set up for the capillary test (ASTM C1585)

was specified by marking the water profile as indicated in Fig. 4.

The evaluation regarding the maximum depth of water permeation measured on concrete specimens in accordance with TS EN 12390-8 is given in Table 6.

2.3.3 Capillary test

Cube specimens of 100-mm were prepared for capillary testing. The test was performed in accordance with the procedures in ASTM C1585. Concrete specimens were initially kept in an oven at 70℃ for two days and then were left in laboratory condition for cooling. Following the cooling process, the specimens were placed in the set up shown schematically in Fig. 5 to have the bottom 2 mm±1 mm of specimens submerged in water. The side faces of the specimens were sealed to prevent water ingress. The amount of water absorbed with time due to capillary suction was measured and recorded at time intervals of 0, 5, 10, 20, 30, 45, 60, 120 and 1440 minutes. The capillarity coefficients in mm/s$^{1/2}$ were then calculated using those measurements.

2.3.4 Compression strength test

Compressive strengths were determined on 150 mm cube specimens. The test was performed in accordance with to TS EN 12390-3.

3. Results and discussion

3.1 Workability

A slump range between 50 and 100 mm was aimed for all mixes. However, it wasn't easy to adjust the exact amount of admixture to obtain the aimed slump since even a small amount of chemical additive had a considerable effect on the slump value. Hence, although measures were usually fluctuating, equal slumps have been obtained for some mixtures. The slumps measured for each mix are given in Fig. 6.

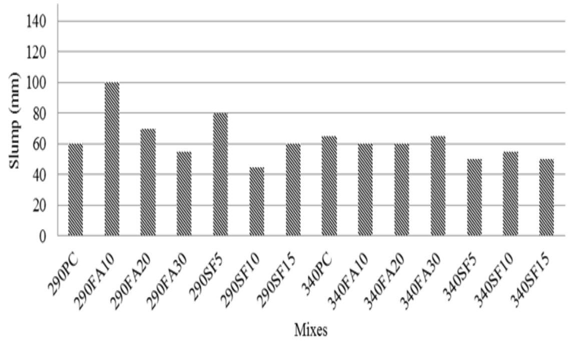

Fig. 6 Slumps of the concrete mixes

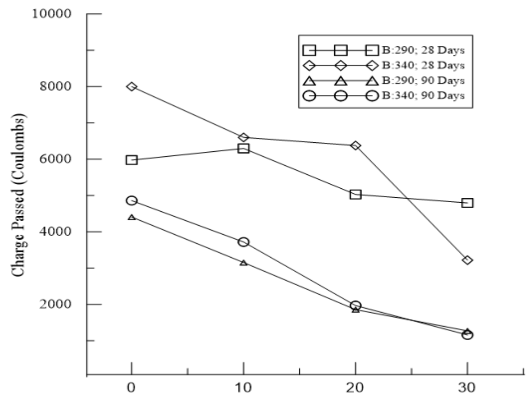

Fig. 7 Rapid chloride permeability for concretes containing fly ash

3.2 Rapid chloride permeability

The rapid chloride permeability measurements obtained in accordance with ASTM C 1202 at the end of 28 days and 90 days of standard curing are illustrated in Figs. 7-8. Fig. 7 shows the rapid chloride permeability measurements for concretes incorporated fly ash at replacement ratios of 0%, 10%, 20%, and 30%. Similarly, Fig. 8 shows the rapid chloride permeability measurements for concretes incorporated silica fume at replacement ratios of 0%, 5%, 10%, and 15%. Evaluation is done for concretes containing total cementing materials of 290 kg/m^3 and 340 kg/m^3.

As seen from Fig. 7, a significant reduction in chloride permeability is observed as the replacement ratio of the fly ash increases. This trend becomes more pronounced as the total binder content increases. In a study (Nath and Sarker 2011) performed for determining the chloride permeability of concretes containing a cement content of 335 kg/m^3 and 30% fly ash replacement indicated that concretes containing 30% fly ash yielded chloride permeability 40% smaller compared to those of without fly ash at the end of 28 days. The reduction in chloride permeability in this study is approximately 60% for concretes containing total binder contents of 340 kg/m^3 with a 30% fly ash replacement.

Fig. 8 indicates that a noticeable decrease in the chloride

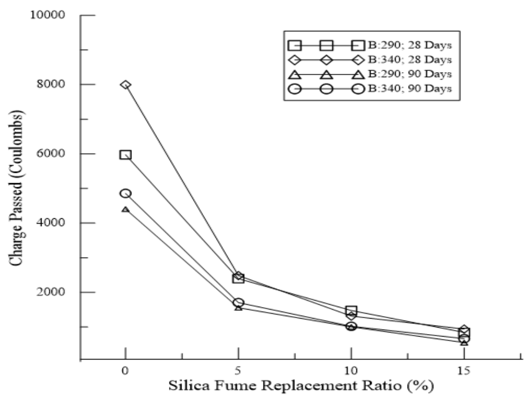

Fig. 8 Rapid chloride permeability for concretes containing silica fume

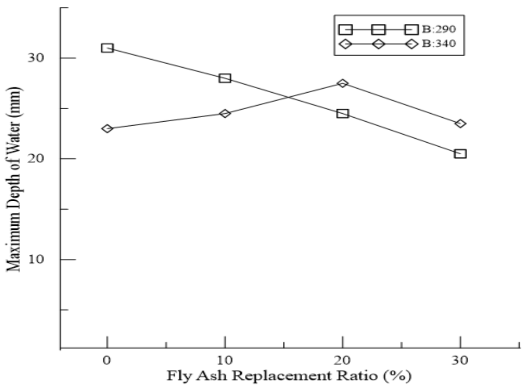

Fig. 9 The maximum depths of water ingress for concretes containing fly ash

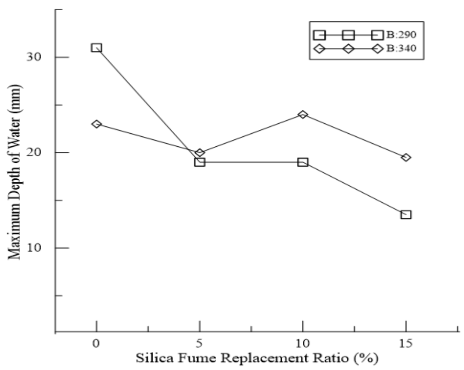

Fig. 10 The maximum depths of water ingress for concretes containing silica fume

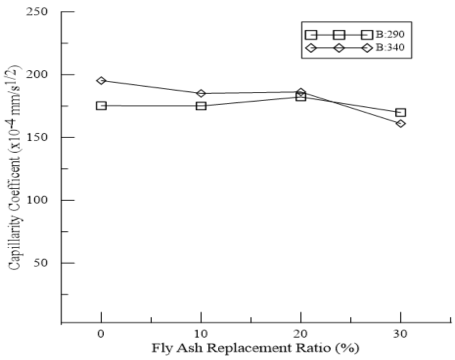

Fig. 11 Capillarity coefficients for concretes containing fly ash

permeability of concretes is possible as the silica fume replacement ratio increases. In a study (Ramezanianpour 1995), a reduction of 81% in rapid chloride permeability has been reported for concretes with a total cementing materials content of 372 kg/m^3 and a silica fume replacement ratio of 10%. In this study, 77% and 79% reductions were obtained for concretes containing total cementing materials of 290 kg/m^3 and 340 kg/m^3, respectively.

3.3 Water permeation

Figs. 9-10 demonstrate the variation of the maximum depth of water ingress for concretes produced with binder contents of 290 kg/m^3 and 340 kg/m^3 depending on the replacement ratio of fly ash and silica fume. Per TS EN 12390-8, concrete with a maximum depth of water ingress smaller than 50 mm is considered impervious. The same standard also states that in the case of exposure to aggressive environments, the maximum depth of water ingress is required to be smaller than 30 mm.

As can be seen from Fig. 9, the maximum depth of water ingress for concretes containing a total binder of 340 kg/m^3 do not change depending on the increase of fly ash. However, there is a moderate decrease in the maximum depth of water ingress for concretes containing a total binder of 290 kg/m^3 as the replacement ratio of fly ash increases. In other words, incorporating fly ash in concretes with high contents of binder seems to be not effective on the water ingress since such concretes are rather dense.

As can be seen from Fig. 10, the maximum depth of water for concretes containing a total cementing materials content of 290 kg/m^3 exhibits a noticeable decrease as the silica fume replacement increases while the maximum depth of water ingress for concretes with a total cementing materials content of 340 kg/m^3 do not change with increasing of silica fume replacement. In other words, at high total binder contents, the silica fume replacement does not affect the water ingress much.

It has been reported elsewhere (Gesoğlu *et al.* 2009) that water permeability of self-compacting concrete incorporated with fly ash and silica fume indicated a considerable decrease in water penetration with respect to control mix. The reason of the water depth values obtained seems to be a little smaller compared to the results obtained from this study can be associated with higher amount of binder used. Overall the results obtained from both studies are quite consistent.

3.4 Capillary

The capillarity coefficients obtained for concretes are given in Figs. 11-12. As can be seen from Fig. 11, the variation of the capillary coefficient of concretes with a total binder content of 290 kg/m^3 is negligible as the fly ash replacement ratio increases; however, it is noticeable for concretes containing a total binder content of 340 kg/m^3 with increasing of fly ash replacement. It has been stated

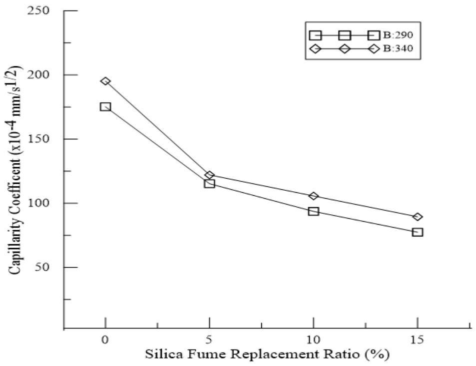

Fig. 12 Capillarity coefficients for concretes containing silica fume

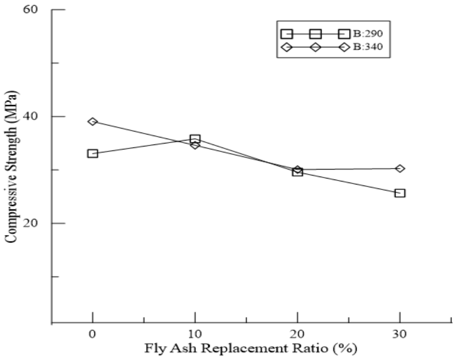

Fig. 13 Compressive strengths of concretes containing fly ash

elsewhere (Khan 2003) that incorporation of fly ash had little influence on capillarity at ages up to 90 days. At 180 days, a slight reduction in capillarity was recorded by incorporation of up to 20% fly ash. This is quite agreement with the result obtained in this study as the reduction obtained is negligible at the age of 28 days. In a study (Nath and Sarker 2011) performed for determining capillary coefficient of concrete containing a 30% fly ash replacement indicated that the capillary coefficient measured is approximately 40% lower with regard to that of without fly ash. Similar results were obtained in this study as a reduction of 20% was obtained for concretes containing 340 kg/m^3 binder while it is only 5% for concretes containing a binder content of 290 kg/m^3. This is a good indication that the capillarity of concrete decreases significantly as the amount of binder used increases.

As illustrated in Fig. 12, the capillary coefficients indicate a considerable decrease as the replacement ratio of silica fume increases for both concretes containing 290 kg/m^3 and 340 kg/m^3 cementing materials. The results obtained in this investigation are in good agreement with other researchers. Khan (2003) reported that the use of silica fume, due to its high pozzolanic reactivity and extreme fineness, significantly reduces the total porosity of concrete at all ages investigated. The reduction in capillarity became greater up to 10% microsilica replacement level, while beyond that a discernable reduction was noticed. The optimum performance is demonstrated between 8 and 12% microsilica levels. This is quite comparable with the results obtained from this study.

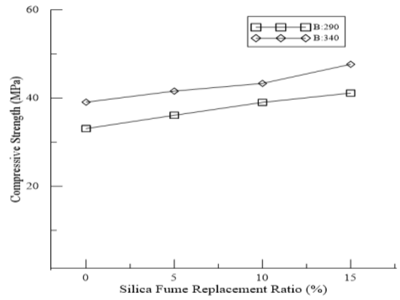

Fig. 14 Compressive strengths of concretes containing silica fume

3.5 Compressive strength

The compressive strengths measured on concretes are given in Figs. 13-14. As illustrated in Fig. 13, the reduction in the compressive strength is discernable. The decline in the compressive strength is similar for both concretes with binder contents of 290 kg/m^3 and 340 kg/m^3. It is reported elsewhere (Ghais *et al*. 2014) a 25% reduction in the compressive strength of concretes including 30% fly ash replacement. This is quite compatible with the results obtained from this study.

Fig. 14 indicates a noticeable increase in the compressive strength of concretes as the silica fume replacement increases. The increase in the compressive strength is quite like both concretes containing 290 kg/m^3 and 340 kg/m^3 cementing materials. This is quite consistent with the results given elsewhere (Ramezanianpour 1995).

4. Conclusions

The effects of the fly ash and silica fume replacement on the chloride ingress, water permeation, capillarity, and compressive strength of concrete were investigated. From the above results and discussions, the following conclusions have been drawn:

• The rapid chloride permeability decreases considerably as the replacement ratio of fly ash and silica fume increases. The decrease is more pronounced for concretes containing silica fume compared to those with fly ash. The decrease in the rapid chloride permeability is much more noticeable for concrete containing higher binder contents.

• The rapid chloride permeability of concretes also decreases as the curing period increases regardless of the mineral type and binder contents used.

• The decrease in the maximum depth of water ingress is more significant for concretes containing 290 kg/m^3 binder content depending on the replacement ratio of fly ash. The decrease in the depth of maximum water ingress is also more pronounced for concretes containing a binder content of 290 kg/m^3 depending on the increase in the silica fume replacement. Concerning production of impervious concrete, this indicates that both fly ash and silica fume replacements are more efficient in concretes of low binder contents.

• The decrease in the capillary coefficient, being more pronounced for concrete containing silica fume, is significant connected with the increase of the replacement ratios of fly ash and silica fume, regardless of the binder contents used for concretes.

• No matter the amount of binder contents used, the compressive strengths of concretes decrease as the replacement ratio of the fly ash increases as opposed to the case observed for the silica fume replacement.

• Overall, the results obtained have confirmed that the durability properties of concrete have considerably improved as the replacement ratio of fly ash and silica fume increased regardless of the binder content used. This indicates that at least a 30% fly ash replacement and/or a replacement ratio of 5% to 10% silica fume is highly beneficial as far as sustainability is concerned, particularly for concretes subjected to chloride bearing environments.

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