

Influence of Silica Fume, Fly Ash, Super Pozz and High Slag Cement on Water Permeability and Strength of Concrete

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ABSTRACT

In this study, effects of mineral admixtures on water permeability and compressive strength of concretes containing silica fume (SF), fly ash (FA) and super pozz (SP) were experimentally investigated. Permeability of concrete was determined through DIN 1048 (Part 5). The research variables included cement type, ordinary Portland cement (OPC) or high slag cement (HSC), and mineral admixtures content was used as a partial cement replacement. They were incorporated into concrete at the levels of 5%, 10% and 15% for silica fume and 10%, 20% and 30% for fly ash or super pozz by weight of cement. Water-cement ratio of 0.40 was used and tests were carried out at 28 days. From the tests, the lowest measured water permeability values were for the 10% super pozz and 10% silica fume or 20% fly ash mixes. The highest compressive strength of concretes determined was for 10% silica fume mix with ordinary Portland cement and was reduced with the increase in the replacement ratios for other mineral admixtures than ordinary Portland cement concrete.

The main objective of this research was to determine the water permeability and compressive strength of concrete containing silica fume, fly ash, super pozz and high slag cement to achieve the best concrete mixture having lowest permeability. The results were compared to those of the control concrete; ordinary Portland cement concrete without admixtures. The optimum cement replacement by FA, SP and SF in this experiment was 10% SP. The knowledge on the strength and permeability of concrete containing silica fume, fly ash, super pozz and high slag cement could be beneficial in the utilization of these waste materials in concrete work, especially on the topic of durability.

KEYWORDS: Permeability, Strength of concrete, Silica fume (SF), Fly ash (FA), Super pozz (SP), high slag cement (HSC).

INTRODUCTION

It is known that permeability controls deterioration of concrete in aggressive environments (Alexander and Magee, 1999), because the processes of such deterioration as carbonation, chloride attack and sulfates attack are governed by the fluid transportation in concrete. Fillers and pozzolanic materials are introduced to improve the strength and other properties of concrete for necessary conditions. Fly ash and super pozz are

produced from burning of powdered coal in power plants. Silica fume is also known as micro-silica, volatilized silica or condensed silica fume. It is a by-product of silicon metal and ferrosilicon alloy production. The material is a very fine powder with spherical particles about 100 times smaller in size than Portland cement or fly ash. Slag is a by-product of the production of steel. During production, liquid slag is rapidly quenched from a high temperature by immersion in water (Mehta, 1993). The slag is a glassy, granular, non-metallic product that consists “essentially of silicates and aluminosilicates of calcium and other

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bases” (Klieger and Lamond, 1994). It is also known as granulated blast furnace slag (GBFS). The aim of this research was to study water permeability and compressive strength of concrete containing silica fume, fly ash, super pozz and high slag cement to achieve the best concrete mixture having lowest permeability. The results were compared to those of the control concrete; ordinary Portland cement concrete without admixtures. The knowledge on the strength and permeability of concrete containing silica fume, fly ash, super pozz and high slag cement could be beneficial in the utilization of these waste materials in concrete work, especially on

the topic of durability.

EXPERIMENTAL PROGRAM

Materials

Cement and Cement Replacement Materials

Ordinary Portland Cement

Ordinary Portland cement used was provided from Tourah-factory. The approximate mineral composition of the used cement is shown in Table (1) (Helmuth, 1987).

Table 1: Typical composition of ordinary Portland cement

constituents	C ₃ S	C ₂ S	C ₃ A	C ₄ AF	CSH ₂	Total
Percent %	50	25	12	8	3.5	98.5

High Slag Cement

Slag is a by-product of the production of steel. During production, liquid slag is rapidly quenched from a high temperature by immersion in water (Mehta, 1993). The slag is a glassy, granular, non-metallic product that consists “essentially of calcium silicates and aluminosilicates of calcium and other bases” (Klieger and Lamond, 1994). It is also known as granulated blast furnace slag (GBFS). Slag, in addition to pozzolanic properties, and unlike Class F fly ash and silica fume, also has cementitious properties. With regard to strength, there are three grades of slag: Grade 80, Grade 100 and Grade 120. Each number corresponds to a minimum 28-day compressive strength ratio of a mortar cube made with only Portland cement and a mortar cube made with 50% Portland cement and 50% slag. Because of cementitious properties, particles smaller than 10 m (m stands for micron) contribute to early strength, while particles larger than 10 m and smaller than 45 m contribute to later strength. Since particles greater than 45 m are difficult to hydrate, slag is mostly pulverized to particles with a diameter less than 45 m (Mehta, 1993).

When used in concrete, slag provides the following benefits (Lewis, 1985):

- High ultimate strength with low early strength,
- High ratio of flexural to compressive strength,
- Resistance to sulfates and seawater,
- Improved alkali-silica reaction resistance,
- Low heat of hydration,
- Decreased porosity and permeability, and
- Better finish and lighter color.

Slag is also known for improved workability and lower water requirement (Fulton, 1974). Slag hydration is significantly influenced by temperature: hydration is accelerated at higher temperatures and retarded at lower ones, when compared to Portland cement hydration. This may lead to differences between the strength of concrete in the field and the laboratory specimens (Mehta, 1993). The chemical analysis and physical properties of slag are presented in Table (2) (Sobolev and Batrakov, 2007).

Table 2: Chemical analysis and physical properties of slag

Analysis and properties	Mass %
SiO ₂	39.0
Al ₂ O ₃	8.7
Fe ₂ O ₃	0.5
CaO	41.3
MgO	8.5
Na ₂ O	0.15
K ₂ O	0.21
SO ₃	0.74
Loss on ignition (LOI)	0.52
Specific Surface Area (cm ² /g)	7000
Specific gravity	2.92

Fly Ash

Fly ashes are by-products produced during combustion of powdered coal in power plants. A summary of the properties and chemical composition of different fly ashes was presented by Helmuth (Mindes and Young). In general, depending on the chemical composition, fly ash can be classified as Class F or Class C. Class C fly ash has higher amount of CaO, so it possesses more cementing characteristics and is less pozzolanic than Class F fly ash. ASTM 618 states that Class F fly ash is “normally produced from burning anthracite or bituminous coal”, while Class C fly ash is “normally produced from lignite and subbituminous coal” (ASTM). Class F fly ash is mostly composed of silicate glass containing aluminum, iron and alkalis. The particles are in the form of solid spheres with sizes ranging from less than 1 m to 100 m and an average diameter of 20 m (Mehta, 1993). At least 70% of the chemical composition is made up of SiO₂, Al₂O₃ and Fe₂O₃ (Flieger and Lamond, 1994). The chemical analysis and physical properties of fly ash are shown in Table (3).

The benefits of using fly ash in concrete include the following (Klieger and Lamond, 1994):

- Improved workability,
- Lower heat of hydration,

- Lower cost concrete,
- Improved resistance to sulfate attack,
- Improved resistance to alkali-silica reaction,
- Higher long-term strength,
- Opportunity for higher strength concrete,
- Equal or increased freeze thaw durability,
- Lower shrinkage characteristics, and
- Lower porosity and improved impermeability.

Table 3: Chemical analysis and physical properties of fly ash

Chemical Analysis Mass %	Mass %
Silica (SiO ₂)	47.0-55.0
Aluminium (Al ₂ O ₃)	25.0-35.0
Iron (Fe ₂ O ₃)	3.0-4.0
Manganese (Mn ₂ O ₃)	0.1-0.2
Calcium (CaO)	4.0-10.0
Magnesium (MgO)	1.0-2.5
Phosphorus (P ₂ O ₅)	0.5-1.0
Potassium (K ₂ O)	0.5-1.0
Sodium (Na ₂ O)	0.2-0.8
Titanium (TiO ₂)	1.0-0.5
Sulphur (SO ₃)	0.1-0.5
Loss on Ignition (LOI)	0.5-2.0
Specific Surface Area (cm ² /g)	8500
Specific gravity	2.6

Super Pozz

As can be seen in the chemical composition and physical characteristics listed in Table 4, super pozz is an extremely fine, light colored powder composed primarily of amorphous calcium-silicates and aluminates. From its chemical analysis, super pozz will meet the Class F fly ash requirement of BS 3892, but physically the product is unique with regards to its particle size distribution. The D99 value is 25 microns, the particle size below which 99% of the particles are to be found. Figure 1 illustrates the comparative particle size distribution analysis. The chemical analysis and physical properties of super pozz are shown in Table (4).

Table 4: Chemical analysis and physical properties of super pozz

Analysis and properties	Mass %
SiO ₂	53.5
Al ₂ O ₃	34.3
CaO	4.4
Fe ₂ O ₃	3.6
K ₂ O	0.8
MgO	1.0
Loss On Ignition (LOI)	< 1.0
Specific Surface Area (cm ² /g)	13000
Specific gravity	2.20

Silica Fume

Silica fume is also known as micro-silica, volatilized silica or condensed silica fume. It is a by-product of silicon metal and ferrosilicon alloy production. The material is a very fine powder with spherical particles about 100 times smaller in size than those of Portland cement or fly ash. The diameters range from 0.02 to 0.5 μ m with an average of 0.1 μ m. Silica fume contains 85 to 95% noncrystalline silicon dioxide. The first application of silica fume in the United States was conducted in Kentucky in 1982 (Klieger and Lamond, 1994). The use of silica fume will make concrete with the following properties (Sobolev and Batrakov, 2007):

- Low heat of hydration,
- Retarded alkali-aggregate reaction,
- Reduced freeze-thaw damage and water erosion,
- High strength,
- Increased sulfate resistance, and
- Reduced permeability.

Silica fume is also known for creating problems in handling and cracking related to its small particle sizes and increased water requirement.

The chemical analysis and physical properties of silica fume are shown in Table (5).

Table 5: Chemical analysis and physical properties of silica fume

Analysis and properties	Mass %
SiO ₂	90.2
Al ₂ O ₃	1.7
Fe ₂ O ₃	0.4
CaO	2.1
MgO	1.7
Na ₂ O	0.7
K ₂ O	0.7
SO ₃	0.5
Loss on ignition (LOI)	2.5
Specific Surface Area (cm ² /g)	200000
Specific gravity	2.21

Aggregates

Natural sand with a fineness modulus of 2.32 and a specific gravity of 2.65 was used as fine aggregate. Crushed dolomite stone with a nominal maximum size of 28 mm and a specific gravity of 2.70 was used as coarse aggregate. Sieve analysis tests were carried out on the used aggregates and the results are listed in Table (6) and Table (7).

Table 6: Sieve analysis test results of sand

Sieve size (mm)	Fine aggregate	
	passing %	retained %
9.5	100	0
4.75	98.6	1.4
2.36	96.52	3.48
1.18	90.72	9.28
0.6	69.82	30.18
0.3	12.42	87.58
0.177	0	100

Table 7: Sieve analysis test results of gravel

Sieve size (mm)	Coarse aggregate	
	passing %	retained %
38.1	100	0
28	95.57	4.43
19	48.83	51.17
14	13.43	86.57
9.5	1.13	98.87
4.75	0.13	99.87
2.36	0.03	99.97
1.18	0	100
0.6	0	100
0.3	0	100
0.177	0	100

Water

Clean drinking fresh water, free from impurities was used in the mixes. Water-cement ratio was 0.40 by weight.

Concrete Mixtures

OPC was partially replaced by silica fume (SF) at 5%, 10% and 15%, whereas fly ash (FA) and super pozz (SP) replaced OPC at 10%, 20% and 30%, by weight of binder. The binder content of concrete was set constant at 400 kg/m³ and mix proportions of concrete are presented in Tables (8, 9 and 10). The amounts of water and coarse aggregate in all concrete mixtures were constant.

Table 8: Mixture proportions for fly ash mixes

Materials (Kg/m ³)	Mixture Designation			
	100% OPC	10 % FA	20 % FA	30 % FA
Ordinary Portland Cement	400	360	320	280
Coarse Aggregate	1212.34	1212.34	1212.34	1212.34
Fine Aggregate	681.94	675.6	669.3	662.9
Water	160	160	160	160
HRWR (L/m ³)	8	8	8	8
Fly Ash	-	40	80	120
Calculated Unit Wt	2462	2456	2450	2443
w/c	0.4	0.4	0.4	0.4

Table 9: Mixture proportions for super pozz mixes

Materials (Kg/m ³)	Mixture Designation			
	100% OPC	10 % SP	20 % SP	30% SP
Ordinary Portland Cement	400	360	320	280
Coarse Aggregate	1212.34	1212.34	1212.34	1212.34
Fine Aggregate	681.94	673.7	665.5	657.2
Water	160	160	160	160
HRWR (L/m ³)	8	8	8	8
Super-Pozz	-	40	80	120
Calculated Unit Wt	2462	2454	2445	2437
w/c	0.4	0.4	0.4	0.4

Table 10: Mixture proportions for silica fume mixes

Materials (Kg/m ³)	Mixture Designation			
	100% HSC	5% SF	10% SF	15% SF
Ordinary Portland Cement	400	380	360	340
Coarse Aggregate	1204.4	1212.34	1212.34	1212.34
Fine Aggregate	677.5	674.11	666.28	658.46
Water	160	160	160	160
HRWR (L/m ³)	8	8	8	8
Silica Fume	-	20	40	60
Calculated Unit Wt	2450	2455	2447	2439
w/c	0.4	0.4	0.4	0.4

Table 11: Results of compressive strength and max. penetration water depth

mixes	compressive strength at 28 days		max. penetration water depth	
	value(kg/cm ²)	% of control mix	value (mm)	% of control mix
OPC (control mix)	465	100	27	100
HSC	517	111	25	93
10FA	435	94	23	85
20%FA	414	89	15	56
30%FA	370	80	28	104
10%SP	486	105	10	37
20%SP	422	91	22	82
30%SP	386	83	30	111
5 % SF	504	108	20	74
10%SF	643	138	12	44
15%SF	533	115	16	59

TESTING

Water Permeability

The permeability of concrete was determined through DIN 1048 (Part 5). Permeability test gives a measure of the resistance of concrete against the penetration of water exerting pressure. It shall normally be carried out when the age of the concrete is 28 to 35 days. A concrete specimen shall be exposed either from above or below to a water pressure of 5 bars acting normal to the mould- filling direction (Figures 2 and 3) for a period of three days. This pressure shall be kept constant throughout the test. If water penetrates through to the underside of the specimen, the test may be

terminated and the specimen rejected. It shall be checked whether and when the unexposed specimen faces show signs of water permeation. Immediately after the pressure has been released, the specimen shall be removed and split down the centre, with the face which was exposed to water facing down. When the split faces show signs of drying (after about 5 to 10 minutes), the maximum depth of penetration in the direction of slab thickness, shall be measured, in mm, and the extent of water permeation shall be established.

Compressive Strength

Concrete cubes of 150 mm were used to determine the compressive strength. The samples were remolded

24 h after casting and cured in water until the testing ages.

The compressive strengths of concretes were determined at the age of 28 days.

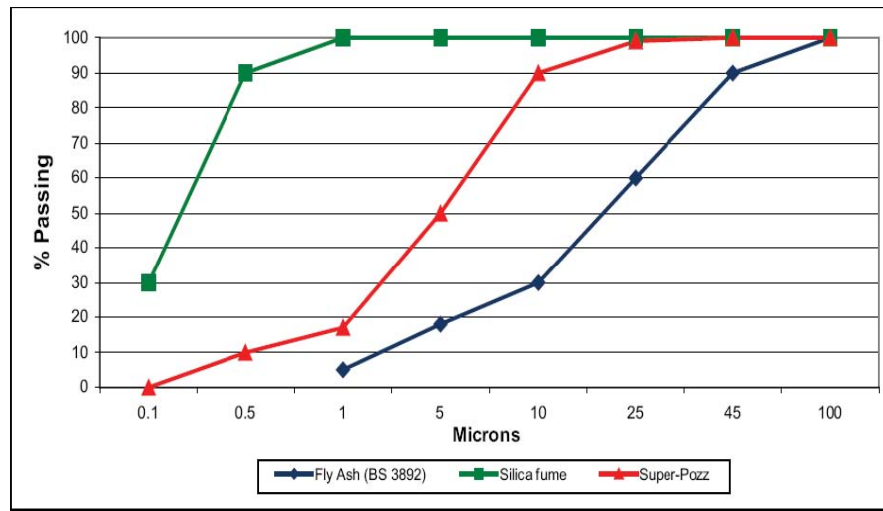


Figure 1: Particle size distribution

result.

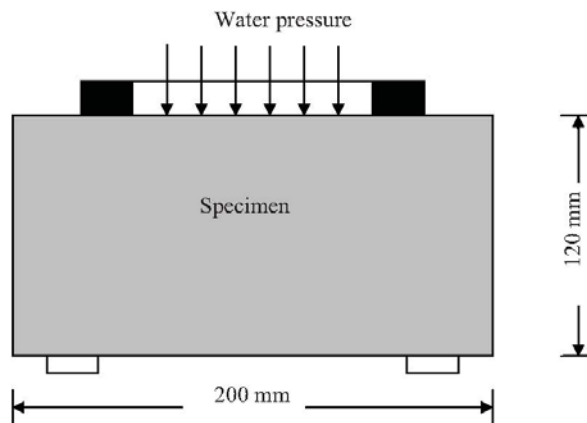


Figure 2: Testing water impermeability on sample 120 mm/200 mm/200 mm

RESULTS AND DISCUSSION

Slump

The slump results are shown in Figure (6) for ordinary Portland cement mixtures. The mixtures containing silica fume had the lowest slump. This is due to high surface area of silica fume particles which have higher water demands than mixtures without silica fume. The mixtures containing super pozz had higher

slump values because of the spherical shaped particles which reduce the interparticle friction. The slump values increased as super pozz ratio increased from 10% to 20% and to 30%. High slag Portland cement mixtures had almost equal slump values for each ratio of silica fume, fly ash and super pozz.

Water Permeability of Concrete

The water permeability of concrete and the ratio of

permeability are given in Table (11) and Figure 4. The ratio of permeability is defined as the permeability of concrete containing pozzolanic materials divided by the permeability of OPC concrete at the same age of testing.

The mean of maximum depth of water penetration of 20% FA concrete had a lower average reduction of 44% compared to the control mixture OPC. The mixture



Figure 3: Apparatus of permeability test

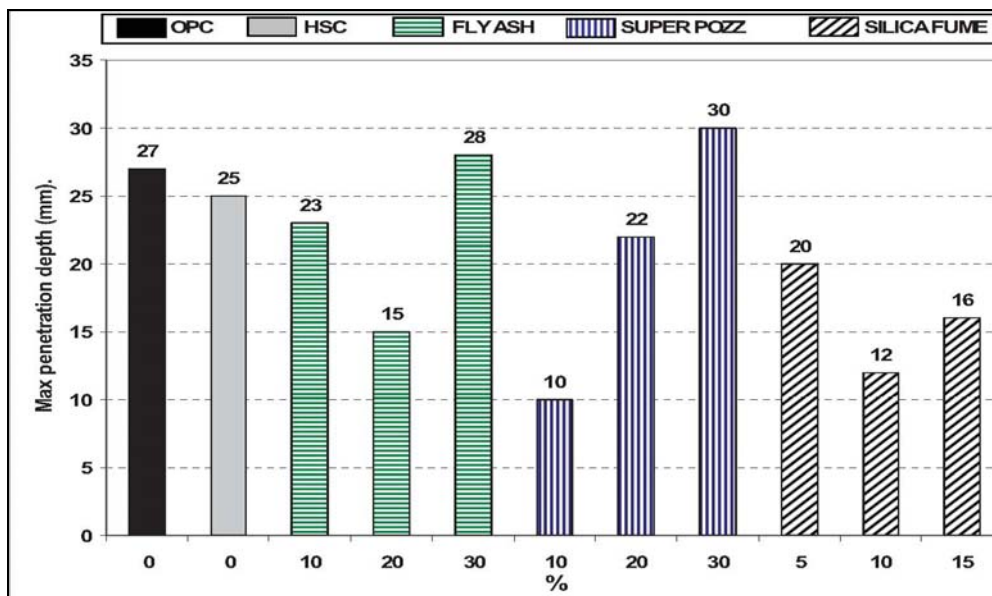


Figure 4: Results of maximum water penetration depth (mm)

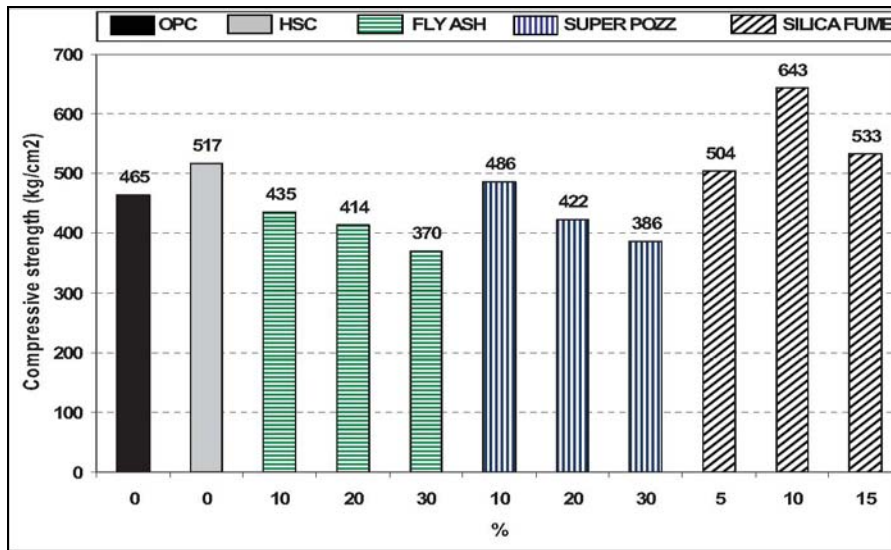


Figure 5: Results of compressive strength (kg/cm²)

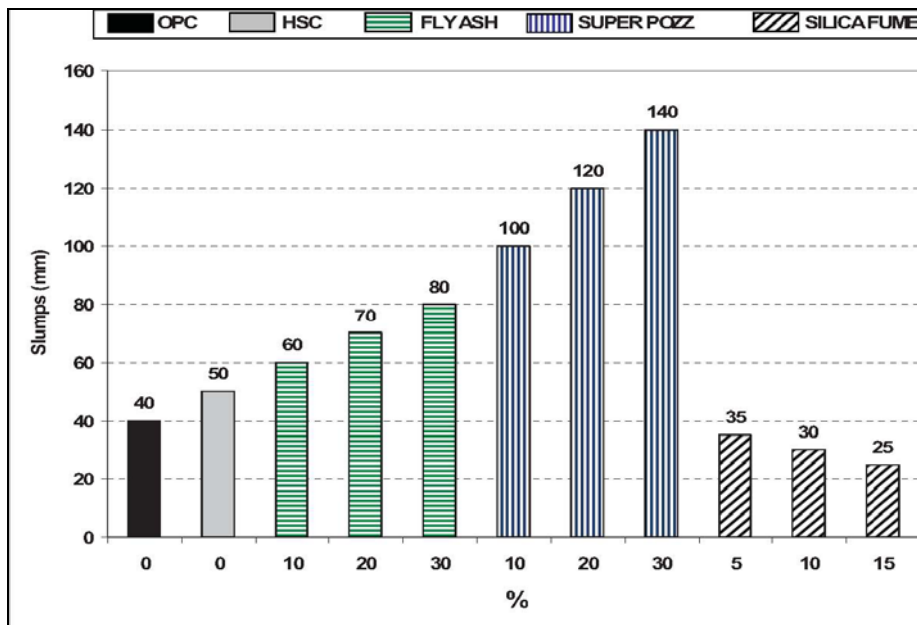


Figure 6: Results of slumps (mm)

containing blast furnace slag had an average reduction of 7 % when compared to the control mixture. Mixture of 10% SF had a lower value than that of the OPC with a reduction of 66%. The fine size particles of silica fume fill in the spaces between the cement particles, making the concrete much denser than mixtures without

silica fume. The mixture containing 10% SP had the lowest water permeability value compared to those of all mixtures. The average water penetration curves with different fly ash, super pozz and silica fume ratios are shown in Figures (7, 8 and 9), respectively. The comparison of the average water penetration curves

with best ratios of different admixtures is shown in Figure 10.

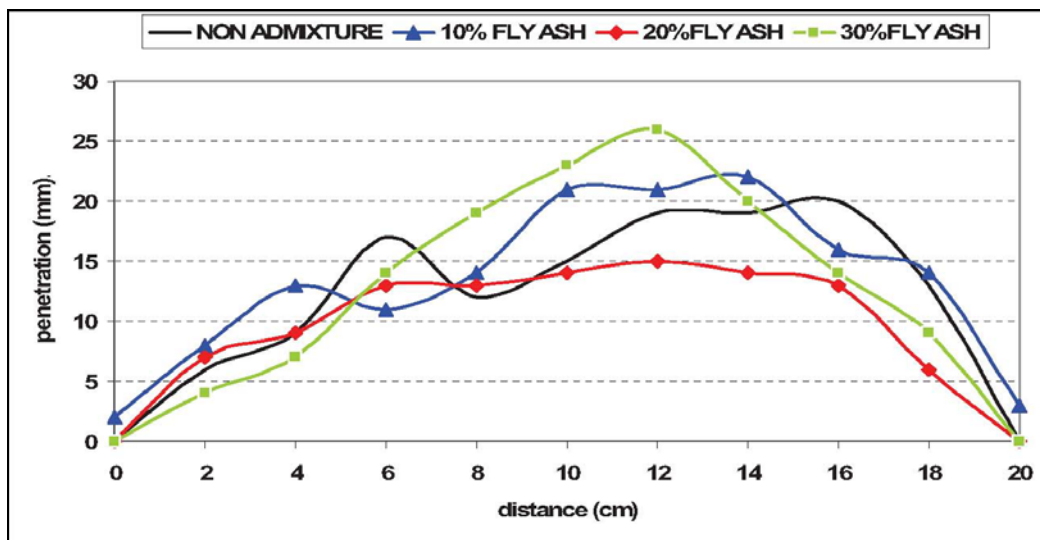


Figure 7: Average water penetration curves with different fly ash ratios

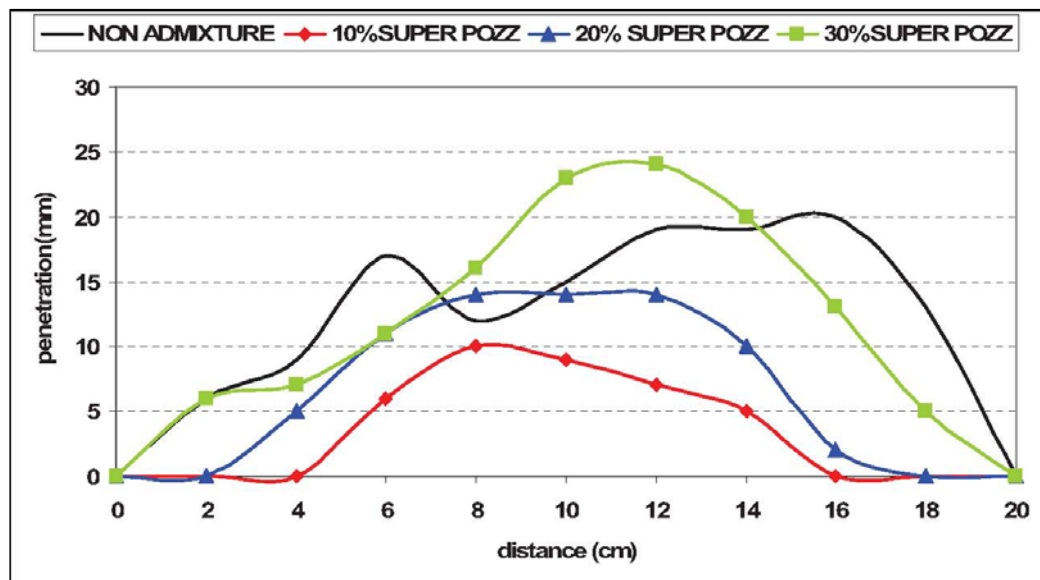


Figure 8: Average water penetration curves with different super pozz ratios

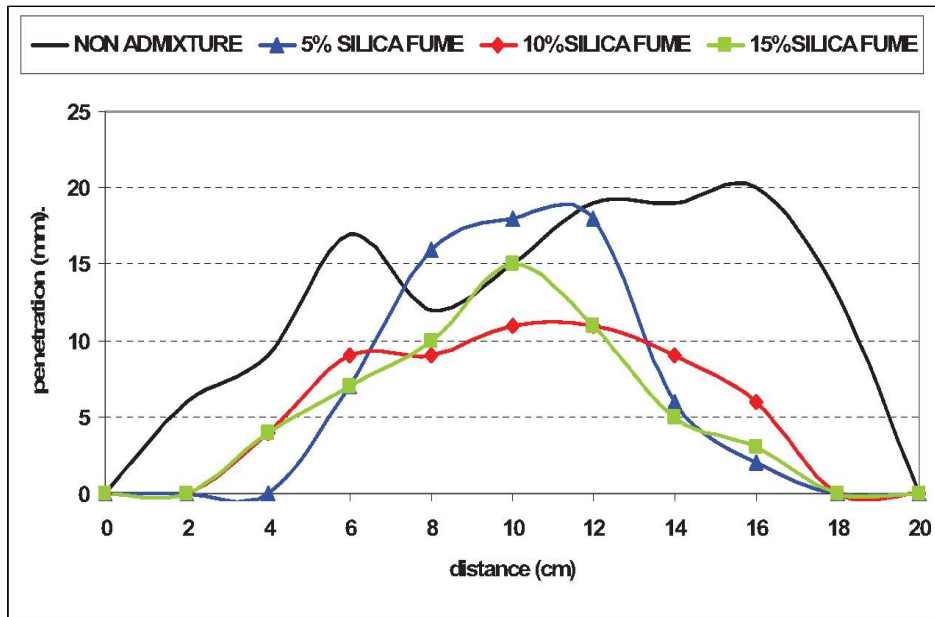


Figure 9: Average water penetration curves with different silica fume ratios

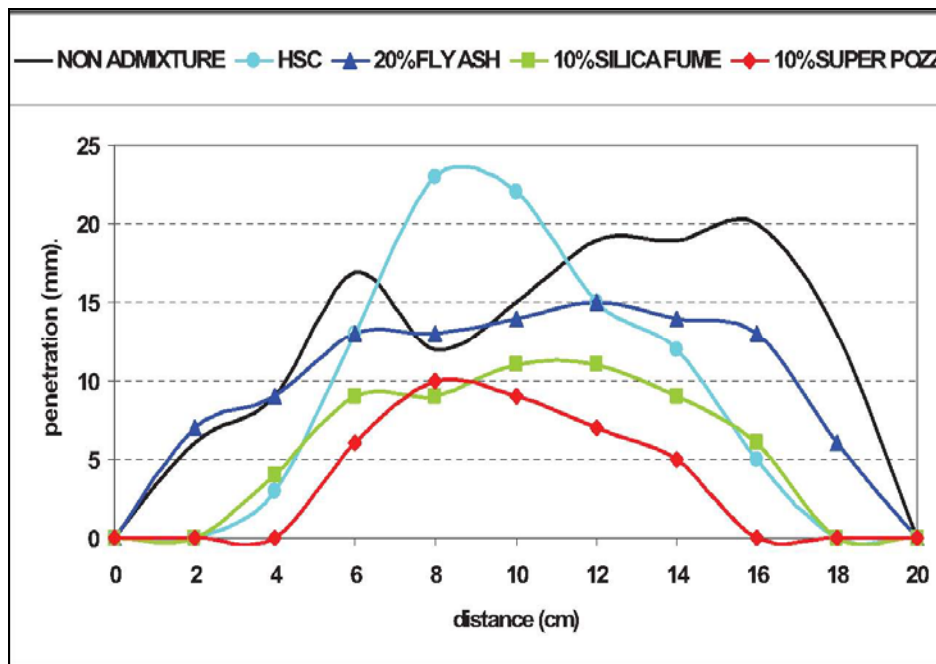


Figure 10: Comparison of the average water penetration curves with best ratios of different admixtures

Compressive Strength

Compressive strengths of concretes are compared to that of OPC concrete in Table (11) and Figure 5. The compressive strength at 28 days of OPC concrete was

465 kg/cm². The concrete containing high slag cement had the compressive strength of 517 kg/cm² or 111% of the OPC. Compressive strength values of 10% FA, 20% FA and 30% FA concretes were 435, 414 and 370

kg/cm² or 94%, 89% and 80% compared to OPC concrete, respectively. At a higher replacement ratio (30% FA), the strength of concrete became lower, since the amount of Portland cement was greatly reduced. For the series of SP concretes, the compressive strength values were 486,422 and 386 kg/cm² or 105%, 91% and 83% compared to those of the OPC concrete, for 10% SP, 20% SP and 30% SP concretes, respectively. Again, increasing the replacement ratio of SP, the compressive strength of concrete was reduced, but was still slightly higher than that of FA concretes. For the series of SF concretes, the compressive strength values were 504,643 and 533 kg/cm² or 108%, 133% and 115% compared to those of the OPC concrete, for 5% SF, 10% SF and 15% SF concretes, respectively. 10% SF had higher compressive strength values because silica fume is much finer than super pozz. As a result of the higher surface area, the pozzolanic reaction proceeds rapidly and strength is quickly developed.

CONCLUSIONS

1. The results insure the effectiveness of minerals' admixtures as fly ash, super pozz and silica fume to improve properties of concrete, to reduce permeability and to increase the resistance.
2. The ratio of 10% replacement of cement weight of super pozz gave the smallest value of 10 mm water penetration. This ratio gave a reduction in permeability of 63% and an increase in compressive strength of 7.6%.
3. The ratio of 10% replacement of cement weight of

silica fume gave the smallest value of 12 mm water penetration. This ratio gave a reduction in permeability of 56% and an increase in compressive strength of 32%.

4. The ratio of 20% replacement of cement weight of fly ash gave the smallest value of 14 mm water penetration for high slag cement. This ratio gave a reduction in permeability of 48% and an increase in compressive strength of 6%.
5. The ratio of 30% replacement of cement weight of super pozz gave the smallest value of 19 mm water penetration for high slag cement. This ratio gave a reduction in permeability of 30% and an increase in compressive strength of 4.8%.
6. The ratio of 15% replacement of cement weight of silica fume gave the smallest value of 14 mm water penetration for high slag portland cement. This ratio gave a reduction in permeability of 56% and an increase in compressive strength of 25%.
7. Silica fume concretes have higher compressive strength at all cement replacement levels and tend to give lower permeability values.
8. The optimum cement replacement by fly ash, super pozz and silica fume in this research was 10% super pozz. Higher replacement gave higher permeability of concrete and lower compressive strength.
9. The permeability of super pozz, fly ash and silica fume concretes depends on the cement replacement ratio. In general, the permeability of concrete reduces with the increase in the compressive strength of concrete.

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