Assessment of the Transport Properties and Strength of Concretes Having Different Mix Proportions, Silica Fume and Fly Ash Additions

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ABSTRACT

Measurement of concrete permeability is increasingly being used as an index for quality control in addition to concrete compressive strength. In the present work, the behavior of three different types of concrete was investigated to determine the transport properties and concrete compressive strength up to one year. The mix variables investigated include: cement content (300, 350, 400 and 450 kg/m3), water/cement ratio (0.35, 0.40, 0.45 and 0.50) and mineral pozzolanic materials (10% silica fume and 20% fly ash as a partial replacement of cement content). The experimental results were statistically analyzed to develop correlations between the concrete constituents and the selected durability indices of concrete. The test results showed an improvement in transport properties at higher levels of cement content and lower water/cement ratios. The permeability was significantly influenced by the inclusion of silica fume and fly ash in concrete. Test results showed that silica fume concrete (SFC) gives better performance when compared with normal and fly ash concrete (FAC) in terms of concrete compressive strength, chloride ion permeability and water penetration depth.

KEYWORDS: Durability, Permeability, Silica fume, Fly ash, Compressive strength, Chloride ion permeability.

INTRODUCTION

Chloride penetration is one of the major problems that affect the durability of reinforced concrete structures. Although chloride ions in concrete do not directly cause severe damage to the concrete, they contribute to the corrosion of embedded steel bars in the structure. The formation of rust at the interface between the steel bar and the surrounding concrete is associated with large volume expansion, which may result in cracking, spalling and delimitation of the concrete cover. In the case of severe corrosion of steel bars, the load-carrying capacity of the structural members may be reduced due to the reduction of the cross-sectional area of the steel bars (Al-Amoudi et al., 1996; Leng et al., 2000; Ozyldirim and Halstead, 1994).

In the past decade, pozzolanic materials such as silica fume, fly ash and blast furnace slag have been increasingly used in concrete as mineral admixtures. Research studies revealed that pozzolanic materials significantly improve the properties of concrete, and the effect of pozzolanic materials is even greater than the effect of changing the water-to-cement ratio (W/C), when these materials are applied in concrete (Bijen, 1996; Sasatani et al., 1995; Camacho and Afif, 2002; Al-Amoudi et al., 2009; Pereira et al., 2009). Material transport properties, especially permeability, affect the durability and integrity of a structure. High permeability, due to porosity or cracking, provides ingress for water, chlorides and other corrosive agents.

If such agents reach reinforcing bars within the

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structure, the bars corrode, thus compromising the ability of the structure to withstand loads, which eventually leads to structural failure. Therefore, there has been an interest both in determining the permeability of different types of concrete such as high strength concrete, self compacting concrete and fiber reinforced concrete, also compared with conventional concrete, and in the development of improved types of concrete with lower permeability (Rapoport et al., 2002; Schwarz et al., 2008; Dinakar et al., 2009; Yazici, 2008).

The water permeability and chloride penetration in light weight and normal weight aggregate concrete (LC and NC) were studied (Menadi et al., 2009; Chia and Zhang, 2006). In these studies, water-to-cement material ratios (w/c) of 0.35 and 0.55 and silica fume contents of 0% and10% as a partial replacement of cement were used to obtain concrete with different strength levels. The results indicated that at the strength level of 30-40 MPa, the water permeability of LC with w/c of 0.55 was lower than that of the NC. However, at w/c of 0.35 the water permeability of LC and NC was not significantly different. The resistance of LC to chloride ion penetration was similar to that of the corresponding NC with the same w/c ratio. Finally, the results indicated that LC would probably have lower water permeability and better resistance to chloride ion penetration than NC with equivalent 28-day compressive strength.

Experimental studies on the water permeability and chloride penetrability of high-strength light weight concrete (LWC) in comparison to those of high-strength normal weight concrete (NWC) with or without silica fume were conducted. The results were also compared with those of concrete at a normal strength level of about 30-40 MPa. In order to compare the water permeability and chloride ion penetrability, LWC and NWC had the same proportion by volume. The only difference between them was the coarse aggregates used. The results indicated that at the strength level of about 30-40 MPa, the water permeability of LWC was lower than that of the corresponding NWC. However, the water permeability of the high strength LWC and NWC was of the same order. The resistance of LWC to chloride penetration was similar to that of the corresponding NWC both in the normal strength and high strength levels (Thomas, 2006; Bremner et al., 1993; Bentz, 2008).

This paper presents the results of transport and mechanical properties for three types of concrete mixes (normal concrete, silica fume concrete and fly ash concrete) up to one year. Four different levels of cement content and four different water/cement raios or binder ratios were used. The measured permeability of fly ash and silica fume concrete is compared with that of normal concrete at 28, 90 and 360 days in addition to the development of concrete strength. An attempt was also made to correlate the concrete constituents with chloride ion and water penetration depth of concrete, as such a relationship is useful in understanding the mechanism that affects transport properties of concrete and consequently concrete durability.

EXPERIMENTAL WORK

In this paper, three mix variables were investigated. These variables are: the cement content, the water/cement ratio and the supplementary materials.

Materials and Their Properties

Ordinary Portland cement (equivalent to ASTM Type I) with a specific gravity of 3.16 was used; four different levels of cement content at 300,350,400 and 450 kg/m^3 were utilized. Silica fume with specific gravity of 2.2, specific surface area of 25.5 m^2/gm and SiO_2 content of 97.5% was used at a level of 10% replacement by weight of cement. Low calcium fly ash conforming to ASTM Class F fly ash having a specific gravity of 2.31, specific surface area of 30.5 m^2/gm and SiO_2 content of 57% was used. The fly ash content was 20% as a partial replacement of cement by weight. The water/cement binder ratio (W/C) was varied at 0.35, 0.40, 0.45 and 0.50 for all levels of cement content.

Fine aggregate sand with 2.62 specific gravity and 2.87 fineness modulus was utilized. The coarse aggregates used were crushed granite with 14 mm nominal maximum size. The specific gravity and water absorption of the coarse aggregates were 2.65 and 1.7%, respectively. The grading of coarse and fine aggregates confirmed ASTM C 33 requirements. A naphthalene-based super-plasticizer (high range water reducing admixture) was used for all mixes at a dosage of 2 liter/m^3.

Concrete Mixtures

Three concrete mixtures with target initial slump of 120 mm were prepared in the laboratory. The concrete mixtures in Series I were normal concrete, the concrete mixtures in Series II were prepared with silica fume, while the concrete mixtures in Series III were prepared with fly ash concrete. All mixtures were made utilizing all levels of cement content and water/cement or binder ratios mentioned above. The absolute volume method was adopted to design the mix proportions of the concrete mixtures in Series I, II and III as shown in Table 1. In the concrete mixtures, 10 mm and 14 mm coarse aggregates were used with the coarse to fine aggregate ratio at1:2.

Preparation of Specimens

The following standard cube specimens, for each type of concrete, were cast in this study:

1- 150 x150x150 mm cubes for compressive strength evaluation according to ASTM C-39 specifications.
2- Cylindrical specimens 102 mm in diameter and 51mm in height were prepared to determine chloride ion permeability for all types of concretes. Chloride ion penetration test used in this investigation was performed at 28, 90 and 360 days as per recommendations by ASTM C 1202 (ASTM C, 1994).
3- Water penetration depth under pressure for concrete mixtures was determined in accordance to DIN 1048 (DIN 1048, 2000). In this investigation, a 5 bar water pressure was applied at the bottom of the cube specimen (150x150x150)mm in size for 72 hours. At the end of the test, the specimen was removed from the permeability cell and then split into two halves in order to measure the water penetration depth.

The results for all test specimens are the average of three samples at different ages of 28, 90 and 360 days.

RESULTS AND DISCUSSION

Test results of the concrete compressive strength, chloride ion diffusion and water penetration depth up to 360 days are illustrated in Figs.1-9. To explain the behavior of different types of concrete in terms of concrete compressive strength, chloride ion penetration and water penetration depth, respectively, test results were analyzed as follows:

Compressive Strength

In general, it was observed that for all types of concrete, the compressive strength up to 360 days increased when the water/cement ratio decreased and when the cement content increased. The variation of compressive strength was shown in Figs. 1,2 and 3. It was clearly observed that for the same cement content and water cement ratio, concrete compressive strength enhanced when adding silica fume or fly ash, except for fly ash concrete where a reduction in compressive strength was observed at an early age. This may be due to the reason that at early curing ages fly ash cement pastes and concretes are more porous than normal concrete and the pore size distributions are coarser, but the opposite is true at the later ages (90 and 360 days) (Al-Amoudi et al., 2009). The percentage increase in the compressive strength of silica fume concrete at 360 days when compared with the 28 day strength was much higher in value than those which occurred in other concretes.

Table 1. Mix Proportions of Series I, Normal Concrete (N.C.)

Mix No.	W/C	Mix Proportions (kg/m^3)				slump(mm)
		Cement	Sand	Granite	Water	
1	0.35	300	700	1400	105	138
2		350	670	1340	122.5	123
3		400	641	1282	140	126
4		450	611	1222	157.5	122
5	0.4	300	673	1346	120	131
6		350	655	1310	140	128
7		400	623	1246	160	125
8		450	592	1184	180	126
9	0.45	300	673	1246	135	122
10		350	640	1280	157.5	128
11		400	606	1212	180	132
12		450	572	1144	202.5	124
13	0.5	300	660	1320	150	142
14		350	721	1442	175	146
15		400	588	1176	200	138
16		450	558	1116	225	140

Note: 10% and 20% of silica fume and fly ash as a partial replacement of cement was used for Series II (SFC) and Series III (FAC), respectively.

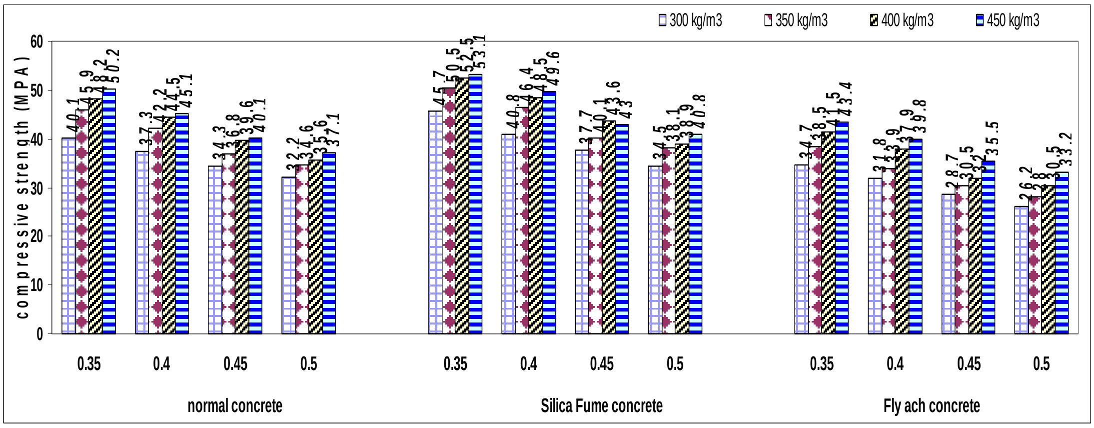

Figure 1: Compressive strength for different W/C contents and concrete types after 28 days

Chloride Ion Permeability

Chloride permeability test was conducted on specimens at ages of 28, 90 and 360 days in accordance with ASTM C 1202.The resistance to chloride ion penetration (charge passed through the specimens, in Coulombs) for all concrete mixtures is shown in Figs.

4,5 and 6. In general, the chloride ion penetration decreased as the cement content increased and water/cement ratio decreased for the three types of concrete at all ages. These figures have shown that the effect of the level of w/c ratio is more pronounced to the increase of the resistance to chloride ion penetration when compared with the effect of the level of cement content. The enhancement in the resistance of chloride ion penetration at a lower level of water/cement ratio and a higher level of cement content may be due to the volume of pores within a concrete which reduced as the water/cement ratio decreased, the concrete became more impermeable and the resistance to chloride ion penetration increased accordingly. These results agree with those reported in literature (Schwarz et al., 2008; Yazici, 2008). The recorded reduction was also due to the increase in the volumes of hydration products by increasing the cement content in the concrete mix, thus forming impermeable regions and consequently increasing the resistance to chloride ion penetration.

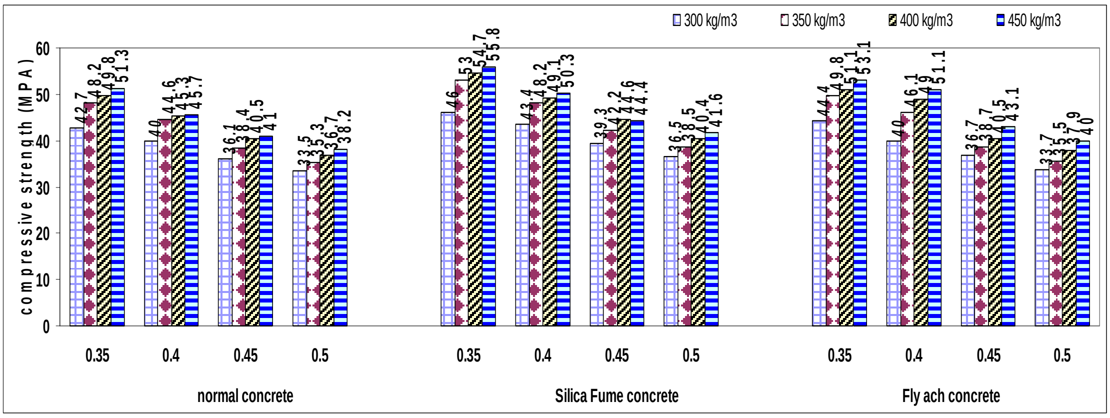

Figure 2: Compressive strength for different W/C contents and concrete types after 90 days

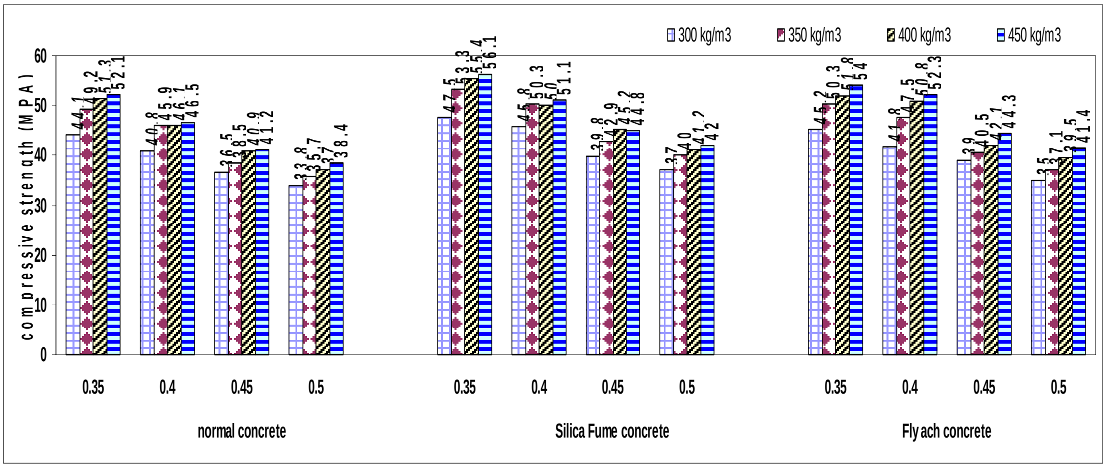

Figure 3: Compressive strength for different W/C contents and concrete types after 360 days

The effect of fly ash and silica fume on chloride ion permeability was clearly observed in these figures. However, at the same level of cement content and water-to-cement ratio, the use of 10% silica fume or 20% fly ash as a partial replacement of cement increased the resistance to chloride ion penetration. At

28 days, the concrete containing 20% fly ash showed slightly lower chloride diffusivity than the equivalent plain cement concrete. At later ages, the effect of fly ash became more significant as shown in Figs. 5 and 6. Silica fume appeared to be more effective in inhibiting chloride ion diffusion than fly ash, as can be seen in these figures. At 28 days, the concrete specimens containing 10% silica fume showed lower chloride diffusivities than fly ash concretes at all levels of cement content and water/cement ratio. The 28 day chloride ion permeability values of all the mixtures are in the ‘‘high” category as per ASTM C 1202. The chloride ion permeability values at 90 and 360 days are found to be lower than the 28 day value as expected. The trend between the mixtures is also similar to that at 28 days. All the mixtures exhibit ‘‘moderate” chloride ion permeability values at 90 days, and ‘‘moderate” to ‘‘low” values after 360 days.

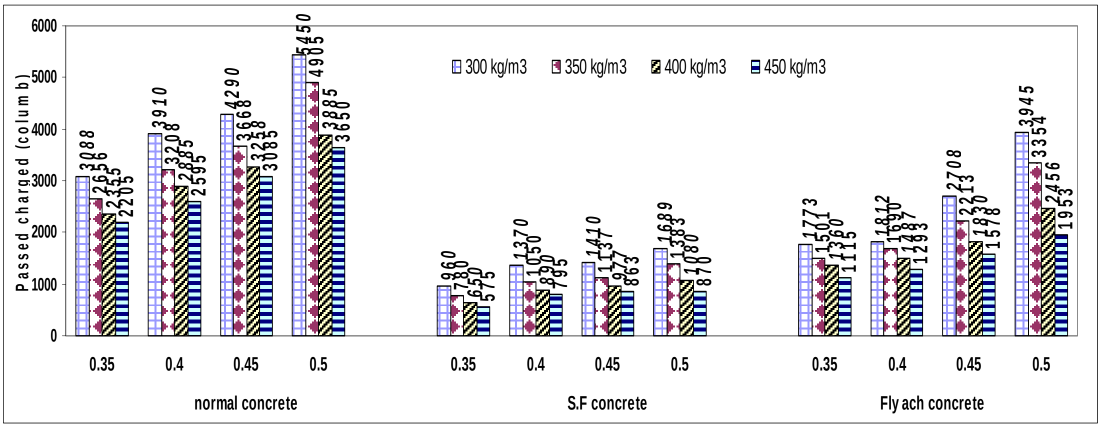

Figure 4: Chloride ion charge passed for different W/C contents and concrete types after 28days

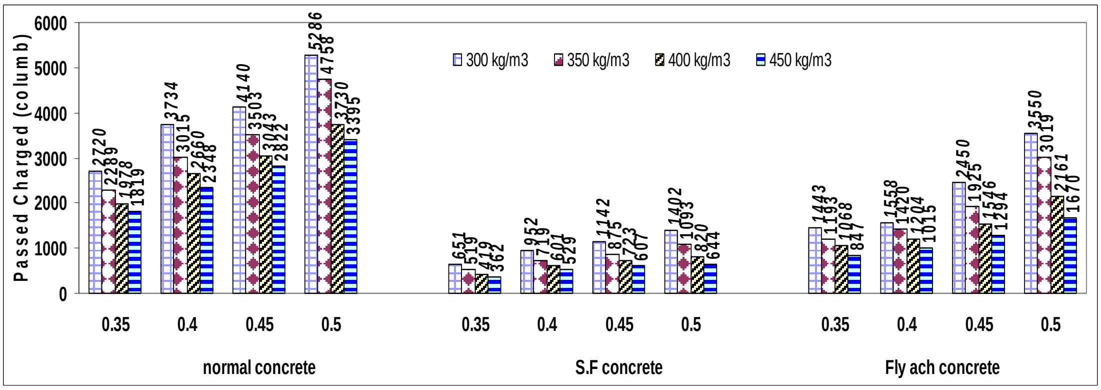

Figure 5: Chloride ion charge passed for different W/C contents and concrete types after 90 days

Although the chloride permeability of the mixes also followed such a decreasing trend, the significant decrease in chloride permeability was noticed when 10% silica fume was incorporated in the mixes. On the contrary, interfacial porosity may better explain the chloride diffusion behavior of fly ash and silica fume concretes. The concretes made with 20% fly ash replacement or with 10% silica fume replacement and varied cement contents and w/c ratios have a smaller interfacial porosity. This was consistent with the lower measured chloride diffusivity of the corresponding concretes. It is therefore believed that the interfacial property between the paste and the aggregates plays a more important role in controlling the ion diffusion behavior of concrete (Thomas, 2006).

It is not difficult to understand why a small amount of silica fume has such a significant effect on the chloride diffusion of concrete at the initial period of curing. Although both silica fume and fly ash improve the durability properties of concrete by probably the same mechanism (pozzolanic and filler effects), the former has a much smaller particle size and is much more reactive than the latter. The 10% silica fume addition produced little change in the porosity and average pore size of either the plain cement or fly ash cement pastes, but significantly reduced the interfacial porosity. In comparison, the contribution of fly ash to the chloride ion resistance of concrete became more significant only when the degree of pozzolanic reaction increased in the latter curing age.

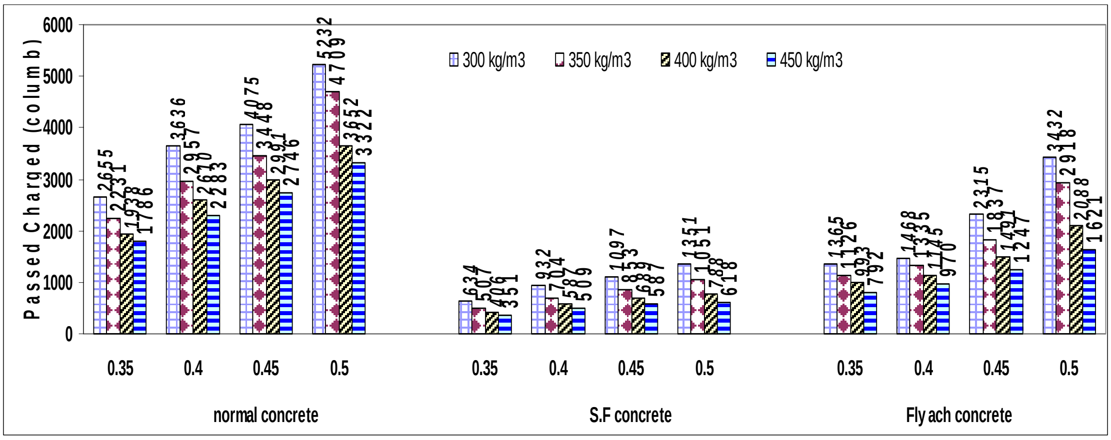

Figure 6: Chloride ion charge passed for different W/C contents and concrete types after 360 days

Water Penetrability

The water penetration depth for all types of concrete was represented in Figs.7,8 and 9 at 28, 90 and 360 days, respectively. As the water penetrability of concrete is indicative of its durability (Chia and Zhang, 2006), an in-depth analysis of these results is necessary.

There is a reduction in the water penetration depth for all concretes as the cement content increases and the water-to-cement ratio decreases. The higher penetration depth was observed in normal concrete while lower water penetration depths were observed in concrete mixtures containing silica fume and fly ash, respectively.

The effect of decreasing the w/c ratio on the water penetration depth is more significant compared with the increasing in cement content used, for all concrete mixes. Reduction in water penetration depth by about 50% and 25% was recorded due to the existence of silica fume and fly ash in concrete, respectively. It has been shown that incorporating fly ash and silica fume in concrete mixes significantly reduces the water penetration depth. The incorporation of silica fume or fly ash as replacement of cement content may improve the pore structure in the transition zone, and thereby reduce water permeability. The results of this research are in agreement with those obtained by Menadi et al. (2009) who reported a reduction in the water depth penetration when using pozzlanic materials as cement replacement.

The relationship between compressive strength and transport properties at 28, 90 and 360 days can be detected by comparing the results plotted in Figs. 1,2 and 3 and those in Figs. 4,5 and 6 through Figs. 7,8 and 9. Although there is a tendency that the water penetration depth and chloride ion permeability decrease with the increase in strength, however, this correlation depends on the type of concrete where it was observed that at the same level of compressive strength, SF concrete and FA concrete have lower permeability compared to NC. This could be explained by the fact that water permeability and chloride ion permeability do not only depend on compressive strength but also on tortuosity, specific surface, pore size distribution and connectivity of pores.

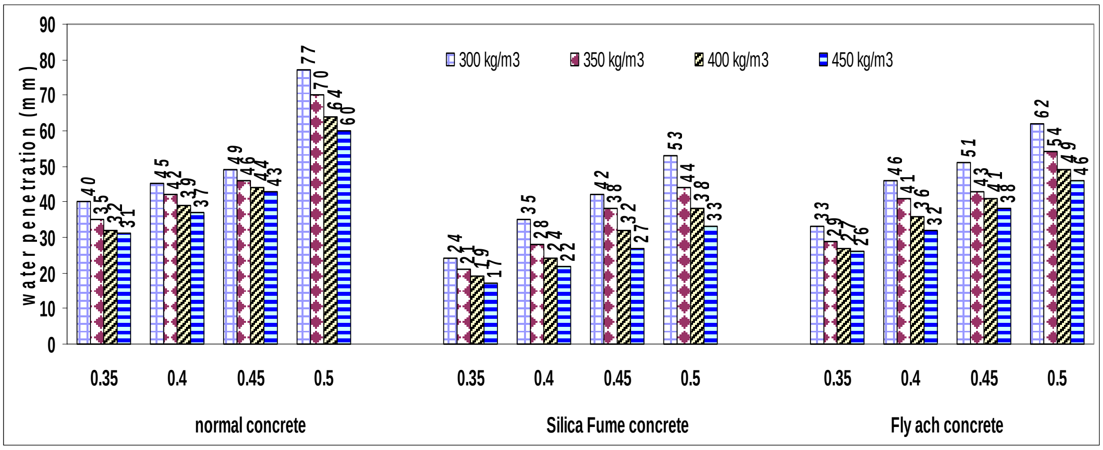

Figure 7: Water penetration depth for different W/C contents and concrete types after 28 days

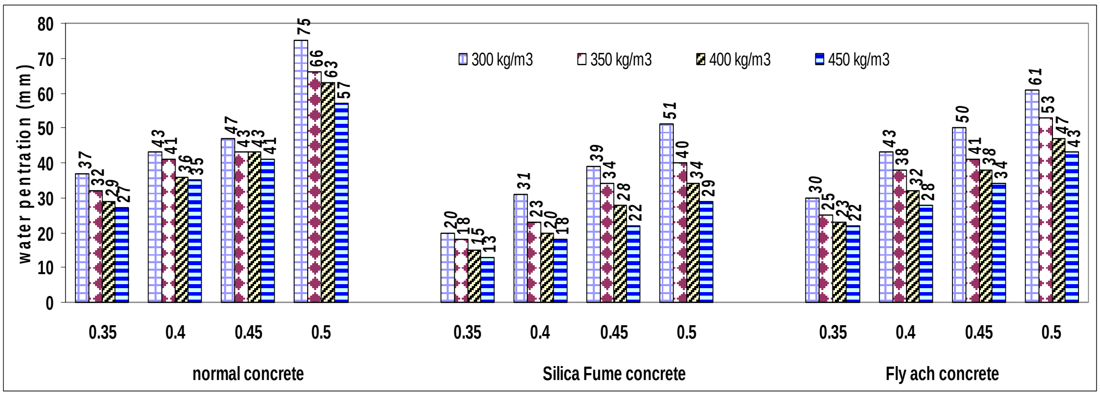

Figure 8: Water penetration depth for different W/C contents and concrete types after 90 days

Finally, the reasons for the enhanced resistance to chloride ion and water penetration due to silica fume or fly ash can be summarized as follows: (1) the use of fly ash or silica fume improved the distribution of pore size and pore shape of concrete;(2) more C–S–H products were formed as fly ash and silica fume hydrated, which absorbed more chloride ions and blocked the ingress path; and (3) the presence of C_3A in fly ash could absorb more chloride ions to form Friedel's salt $C_3A{\cdot}CaCl_2\cdot 10H_2O$ (Schwarz et al., 2008; Kou et al., 2007).

Regression Analysis and Correlation Equation

Regression analysis gives the ability to summarize a collection of sampled (experimental) data by fitting the data to a model that can accurately describe the data. Each regression model has adjustable parameters, or variables, which can be adjusted in order to achieve close agreement between values of the regression model and the sampled data. These model parameters typically come from derived scientific or statistical theory that the data is supposed to satisfy. Regression analysis can turn the sampled data points into a smooth continuous function that may be used analytically or utilized by a computer program to return expected values at certain values of the independent variable. In this paper, Data Fit v8.2 software [Ref. http://www.curvefitting.com] is tuned to obtain empirical correlations for both chloride ion charge passed and water penetration depth. The obtained empirical correlations for chloride ion charge passed with a maximum error of 13% can be written for normal concrete as:

$$Ch = (-0.647^{*} C + 447.944)^{*} \left(0.555^{*} \left(\frac{W}{C}\right)^{2} - 0.175^{*} \left(\frac{W}{C}\right) + 0.039\right) * (-0.044 * T + 220.159) + 350.656$$

where,

Ch: Chloride ion charge, Coulomb;

C: Cement content, kg/m^3;

W/C: Water-to-cement ratio;

T: Time in days.

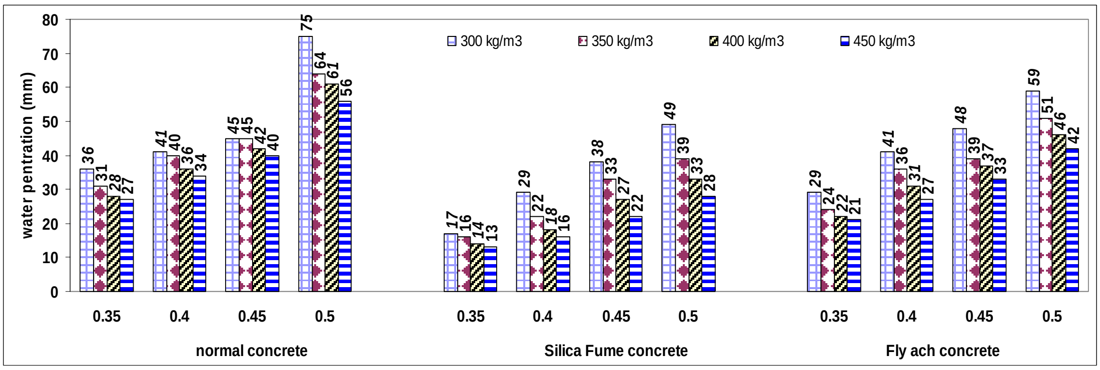

Figure 9: Water penetration depth for different W/C contents and concrete types after 360 days

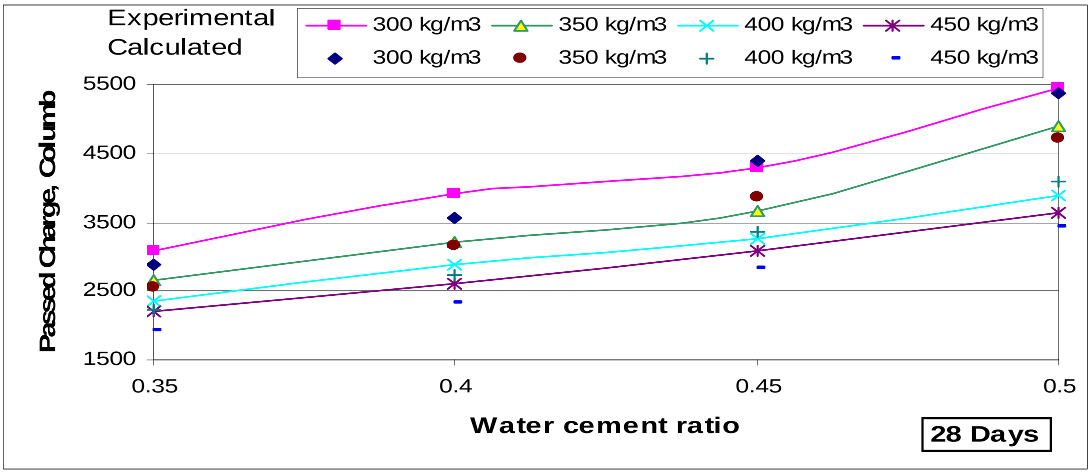

Figure 10: Chloride ion charge for normal concrete, experimental and calculated (28 days)

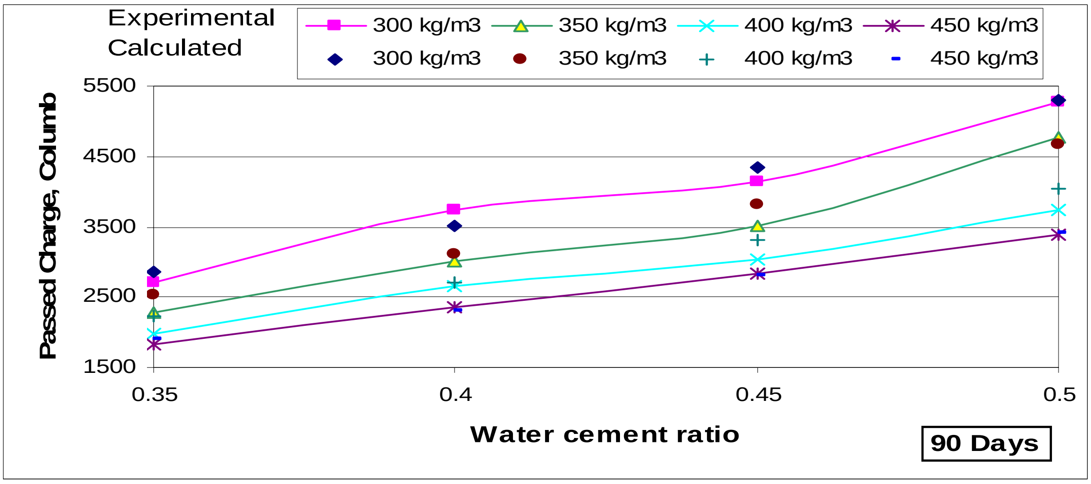

Figure 11: Chloride ion charge for normal concrete, experimental and calculated (90 days)

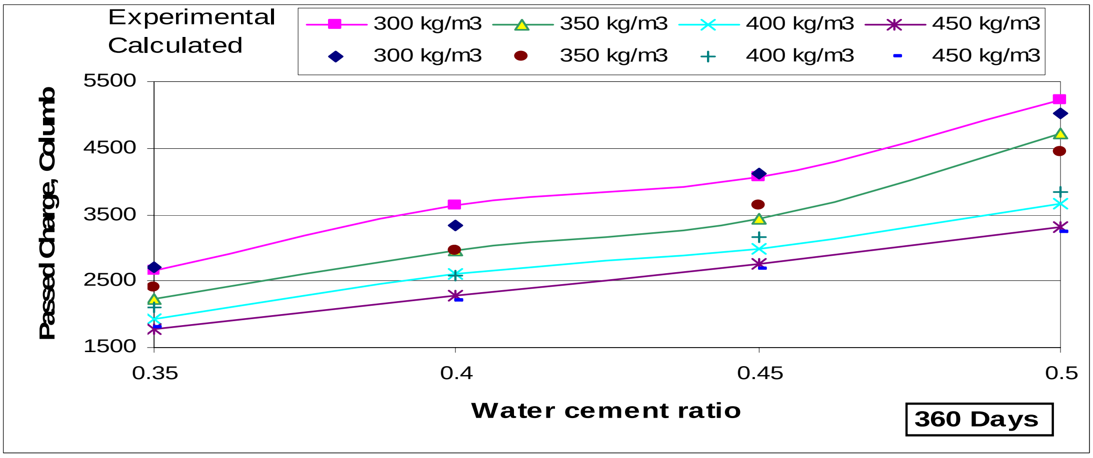

Figure 12: Chloride ion charge for normal concrete, experimental and calculated (360 days)

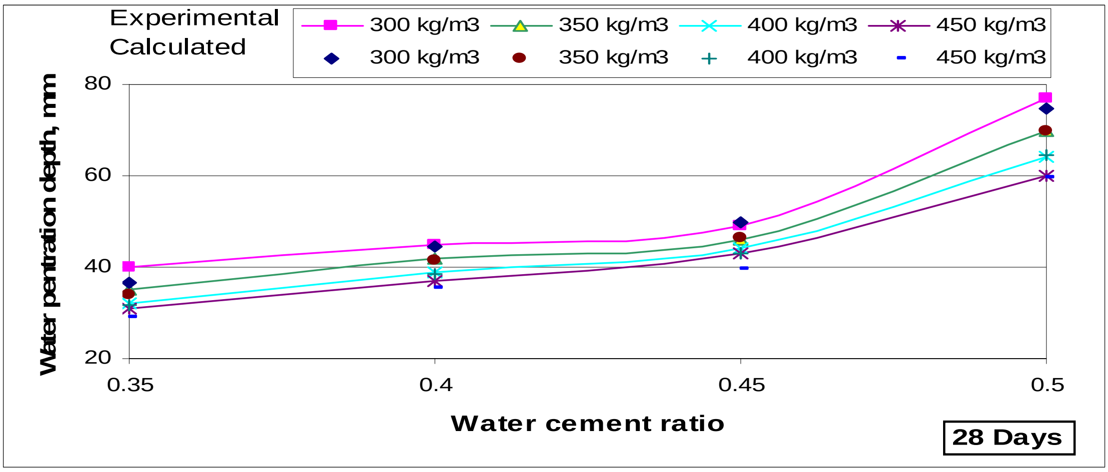

Figure 13: Water penetration depth for normal concrete, experimental and calculated (28 days)

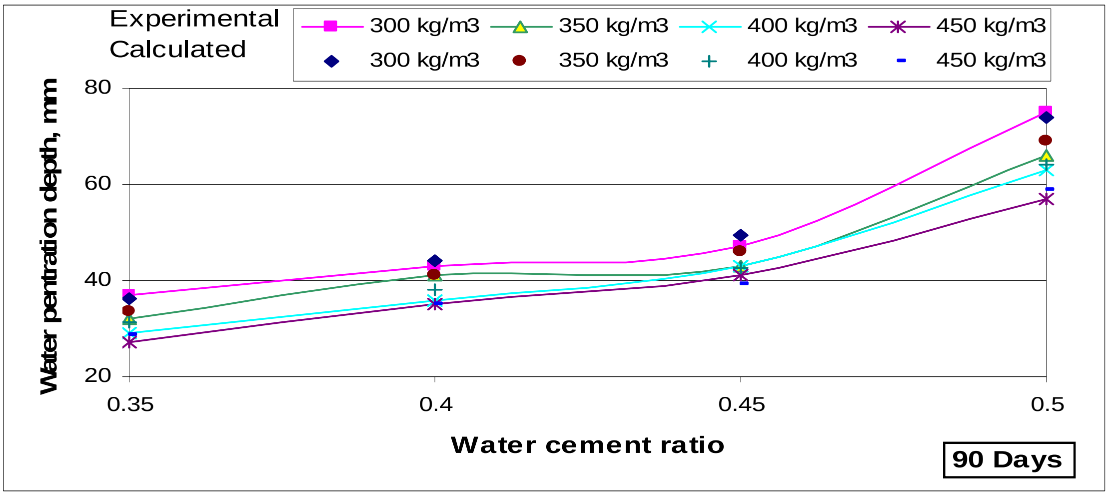

Figure 14: Water penetration depth for normal concrete, experimental and calculated (90 days)

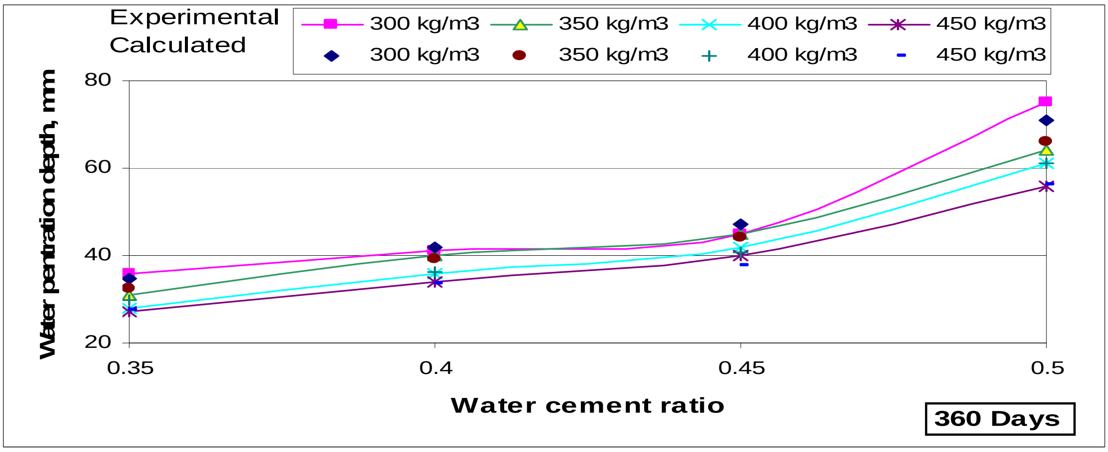

Figure 15: Water penetration depth for normal concrete, experimental and calculated (360 days)

Table 2. Percentage Errors for the Correlated Equations

	Error	**28 days**	**90 days**	**360 days**	**Average Error (%)**
Chloride Ion Penetration	Average Error (%)	5.52	4.95	4.13	4.86
	Maximum Error (%)	13.03	12.1	9.09	
Water Penetration	Average Error (%)	2.79	3.62	3.1	3.17
	Maximum Error (%)	8.52	7.9	6.86	

Regarding to the water penetration depth in normal concrete, the following correlation can be used with a maximum error of 8.5%.The correlation equation can be expressed by the following formula:

$$W_p = (-0.3*C+309.715)*(0.744*\left(\frac{W}{C}\right)^3 - 0.905*\left(\frac{W}{C}\right)^2 + 0.369*\left(\frac{W}{C}\right) - 0.049)*(-0.0286*T+178.728)$$

where,

W_p: Water penetration depth, mm;

C: Cement content, kg/m^3;

W/C: Water-to-cement ratio;

T: Time in days.

The experimental data, depicted in Figs. 1-9 and numerically represented in Figs. 10-15, were utilized to develop a correlation equation between the concrete constituents and the durability indices (chloride ion permeability and water penetration depth). A regression coefficient, R^2, of more than 0.85 indicates an excellent correlation between the fitted parameters (Montgomery and Peck, 1982; Maage et al., 2000).

Table 2 reported the average and the maximum errors for the computed results by this equation compared with the experimental results for normal concrete. It was observed that the average errors ranged between 4.13 and 5.52 for chloride ion permeability. Figs. 10, 11 and 12 illustrate the experimental and computed results for 28, 90 and 360 days, respectively. While the average errors lie between 2.79 and 3.1 for water penetration as shown in Figs. 13, 14 and 15, the maximum errors were 8.52% and 13% for water penetration and chloride ion penetration, respectively.

An excellent relationship between the concrete constituents and the chloride ion permeability or the depth of water penetration is indicated in normal concrete. It is to be noted that the correlation equations relating mix proportions and durability indices of normal concrete, developed in the present work, would help the concrete mix designer adjust the mix proportions to give the required compressive strength at which the durability properties are simultaneously satisfied with the compressive strength. Prediction of the durability properties of concrete in an existing structure may also be possible by knowing the concrete constituents. More future investigations are required to establish similar relations for silica fume concrete and fly ash concrete. It is important here to mention that the above two correlations for both chloride ion penetration and water penetration depth are for normal concrete. Also, these equations can be applied under the following constraints:

1- $300 < C < 450$ kg/m^3

2- $0.35 < W/C < 0.5$

3- $28 < T < 360$ days

CONCLUSIONS

The following conclusions can be made based on the results of this investigation:

1-The transport properties were enhanced as the cement content increased and the water/cement ratio decreased for all types of concrete. However, these properties were improved when incorporating silica fume and fly ash in the concrete mixes. Chloride ion penetration was more affected by the cement content rather than the water penetration depth.

2-The concrete containing silica fume exhibited better resistance to chloride ion permeability and water penetration when compared with fly ash concrete and normal concrete.

3-The service life of concrete materials is strongly dependent on the material transport properties, such as chloride ion permeability and water penetrability, which are in turn controlled by the microstructure characteristics of concrete.

4-The correlation equations relating concrete constituents and transport properties (durability characteristics) of concrete are offered as good models that can be used to aid mixture proportioning for performance and durability. The relationships developed in the present work are related to normal concrete. However, similar guidelines can be developed for other types of concrete in future studies.

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