Chloride Ingress Resistant Concrete: High Performance Concrete Containing Supplementary Composites

Mohammad Iqbal Khan[1]

***Abstract* – In Reinforced concrete structures chloride ion penetration is considered to be a major cause of corrosion of reinforcing bars. Conventional concretes fail to prevent the intrusion of moisture and aggressive ions adequately. The use supplementary cementing composite materials have been reported to increase the resistance of concrete to deterioration by aggressive chemicals such as chlorides. In this investigation various combinations of pulverised fuel ash and silica fume were incorporated as partial cement replacements for composite systems. To establish the resistance of these concrete types to chloride ion penetration ASTM C1202 chloride permeability test was used. Prediction models were developed, based on the experimentally obtained results, which enabled the establishment of isoresponse contours showing the interaction between the various parameters investigated.**

***Index Terms* -** Chloride Resistant; Chloride Ion Penetration; High Performance Concrete.

1. INTRODUCTION

Permeation property of concrete is one of the most critical parameters in the determination of durability of concrete in aggressive environments. Permeation, is dictated by the microstructure of concrete, controls the ingress of moisture, ionic and gaseous species into concrete. Chemical degradation, e.g. sulphate attack, carbonation, alkali-aggregate reaction and corrosion of steel reinforcement, as a result of reaction between an external agent and the ingredients of concrete, and some physical effects, such as frost attack, can be greatly reduced by reducing the permeability of concrete.

As the permeation of concrete decreases, its durability, in terms of physico-chemical degradation, increases. Reinforced concrete structures exposed to the environment, chloride ion penetration is considered to be a major cause of corrosion of reinforcing bars. Flow of chloride ions driven through concrete induced by an electrical potential, is referred to as chloride ion permeability,

Conventional concretes fail to prevent the intrusion of moisture and aggressive ions adequately; therefore, special concretes with low permeability are needed. The use supplementary cementing composite materials have been reported to increase the resistance of concrete to deterioration by aggressive chemicals such as chlorides [1-3]. Silica fume (SF), due to its high pozzolanicity and its extreme fineness, is considered to produce low permeability concrete but generally with the drawback of low workability, as a result of its high specific surface area. In order to maintain high workability for silica fume concrete, incorporation of a superplasticizer is essential,

[1] *Associate Professor of Structural Engineering*
College of Engineering, King Saud University
Email: miqbal@ksu.edu.sa

but this normally results in increasing the cost of production. Pulverised fuel ash (PFA) has been widely used in concrete as it helps to reduce cost, conserve energy and resources, reduce environmental impact and enhance the workability for given water to binder (w/b) ratio. Hence, the potential synergy between SF and PFA needs to be investigated in the context of achieving an optimum balance for the development of high performance and chloride ingress resistant concrete.

2. EXPERIMENTAL PROGRAM

2.1. MATERIALS

Cement Type I complies with the requirements of the ASTM C150, pulverized fuel ash (PFA) complying with ASTM C618 Class F, silica fume (SF) complying with ASTM C1240 were used throughout the investigation. Fine aggregate available in the laboratory was used for this investigation. A sulphonated naphthalene formaldehyde condensate superplasticizer was used to maintain the uniform flow.

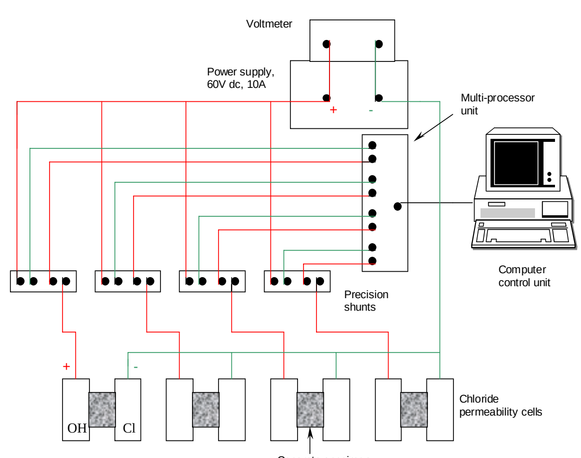
2.2. SAMPLE PREPARATION

Concrete cylinders, 100 mm diameter × 50 mm height, incorporated with various combinations of PFA and SF as partial cement replacement, were cast. W/b ratios of 0.30, 0.40 and 0.50 were used. All the specimens were cast and compacted in two layers on a vibrating table in accordance to the standard specifications. After casting, the samples were covered under damp hessian and polyethylene sheets for 24 hours. The samples were demoulded the following day and then immediately kept in a mist room at 20±2^{o}C and 98±2% RH prior to testing. Samples were taken out of the curing environment at the required testing age.

2.3. TESTING PROCEDURE

The rapid chloride permeability test in accordance with ASTM C 1202 was used for the measurement of chloride ion penetration at various ages. The rapid chloride permeability apparatus used was originally developed by Whiting [4]. The experimental set-up consisted of perspex cells (each cell consists of two reservoirs), each reservoir being capable of holding 250 ml of chemical solution and a 100 mm diameter copper mesh electrode. The sample is housed in a cell between two reservoirs and each cell is connected to a power supply. The schematic representation of the rapid chloride permeability experimental set-up is shown in Fig. 1 and the experimental set-up used in this investigation is shown in Fig. 2.

The test method consisted of monitoring the amount of electric current passed through a 50 mm by 100 mm diameter cylinder during a 6 hour period. A potential difference of 60 volts dc is maintained across the ends of the specimen, one of which was immersed in a 3% (by wt.) sodium chloride solution (used as the anode), the other in a 0.3N sodium hydroxide solution (used as the cathode), as shown in Fig. 3. The concentrations of these two solutions provide equal conductivity [4]. According to the test method the total electrical charge passed, in coulombs, during six hours is a measure of the chloride ion penetration and is expressed as the chloride permeability index (C_{ip}). A ranking of chloride penetrability, based on charge passed in



Coulomb, has been proposed [4] and is shown in Table I.

Fig. 1. The schematic representation of rapid chloride permeability experimental set-up

Fig. 2. The rapid chloride permeability experimental set-up used in this investigation

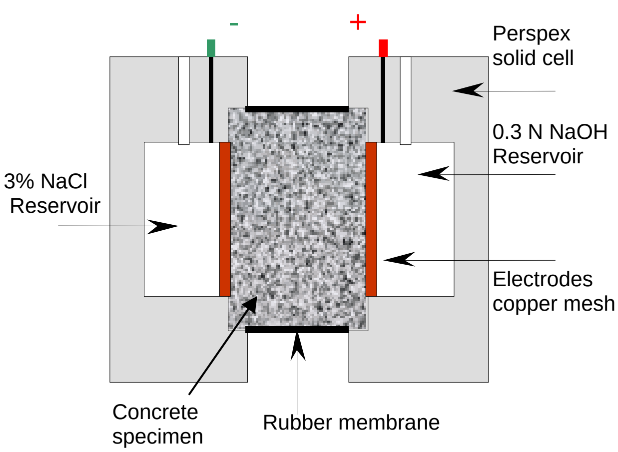


Fig. 3. Rapid chloride permeability cell

TABLE I
CHLORIDE ION PENETRABILITY [4]

Chloride Ion Penetrability	Charge Passed (Coulombs)
High	>4,000
Moderate	2,000 - 4,000
Low	1,000 - 2,000
Very Low	100 - 1,000
Negligible	<100

3. RESULTS AND DISCUSSION

3.1. INTERACTIVE EFFECT OF PFA AND SF

Prediction models Based on experimentally obtained values, models predicting chloride permeability of concrete at 7, 28, 90 and 180 days were developed. The two experimental variables, the proportions of PFA and SF as partial cement replacements, have been used for the prediction of the response of the experiment, chloride permeability. The model for chloride permeability is as follows:

$$C_{ip(28days)} = 2348 - 27.7x_1 - 360x_2 + 15x_2^2 + x_1x_2 \quad (1)$$
$R^2 = 0.97$

$$C_{ip(90days)} = 2134 - 12x_1 - 346x_2 + 14x_2^2 + 1.3x_1x_2 \quad (2)$$
$R^2 = 0.96$

$$C_{ip(180days)} = 1840 - 10x_1 - 314x_2 + 13x_2^2 + x_1x_2 \quad (3)$$
$R^2 = 0.96$

where:

$C_{ip(n)}$ chloride permeability at age *n* days
x_1 PFA as partial cement replacement (%)
x_2 SF as partial cement replacement (%)
R^2 coefficient of determination.

Terms that were found to be statistically insignificant have not been included in the equations.
Figure 4, demonstrates the change in chloride permeability of concrete at various ages caused by the interactive effects of PFA and SF contents. The experimental values agree very closely with the predicted values obtained from equations 1 to 3 as can be seen in Fig. 5.

From Fig. 4, the incorporation of both PFA and SF decreased the chloride permeability, in comparison with the OPC control mix, at all ages investigated. The results indicate that permeability values reduced gradually with increased curing age; beyond 90 days the reductions were negligible. Both the increase in PFA and in SF levels was associated with reductions in permeability values. The reductions in permeability as a result of increasing the SF replacement level up to 10% were far greater than those associated with increasing the PFA content, at 90 and 180 days.

At these ages, the increase in the SF level enabled the permeability to be reduced to "negligible" levels (in accordance with the rating prescribed in Table I), whilst this was not possible with PFA. At early ages (28 days) however, and with SF levels > 7.5%, the increase in PFA content up to 40% resulted in significant reductions in the permeability index with values dropping to 50 Coulombs (i.e. “negligible”). Increasing the SF levels above 10% seems to give no benefit in the long run with regards to permeability reductions and at early age, a detrimental effect on permeability was exhibited.

The results demonstrates the value of ternary blends over binary blends, especially concerning early age permeability; for example, if "negligible" chloride permeability is desired at early ages, then ternary blended systems containing 9-13% SF along with 35% to 40% PFA are required. If the "negligible" chloride permeability was only required at later age (i.e.>90 days) then either a ternary blended system or a binary blended system based on OPC and 10% SF can be used. The optimum replacement level of SF can be clearly seen in Fig. 6.

3.2. Influence of w/b Ratio

The model for chloride permeability of concrete prepared with 10% SF contents for various ages investigated is as follows.

$$C_{ip(28days)} = -366 - 31x_1 + x_3^2 - 0.5x_1x_3 \qquad (4)$$

$R^2 = 0.98$

$$C_{ip(90days)} = -16 + 9x_1 - 32x_3 + 1.4x_3^2 + 0.2x_1x_3 \qquad (5)$$

$R^2 = 0.99$

$$C_{ip(180days)} = -343 + 17x_1 + x_3^2 - 0.4x_1x_3 \qquad (6)$$

$R^2 = 0.98$

where:

$C_{ip(n)}$ chloride permeability at age *n* days

x_1 PFA as partial cement replacement (%)

x_3 w/b ratio × 10^2

R^2 coefficient of determination.

These equations were used for isoresponse contours as shown below.

The isoresponse contours for chloride permeability for 10% SF, at various ages, is shown in Fig. 7. This figure demonstrates the influence of w/b ratio and PFA content on the chloride permeability of concrete.

Figure 7 shows the significant influence of w/b ratio on chloride permeability. As the concrete was cured, the permeability values were reduced but this was more significant for the high w/b ratio mixes. The incorporation of PFA and the increase in its level of replacement resulted in further reductions in permeability at all ages, with its effect being more pronounced for high w/b ratio mixes.

As SF was incorporated at 10%, a significant reduction in permeability was exhibited and the whole range of results was shifted towards smaller values. The effect of w/b ratio was still in evidence, but the effect of curing up to 28 days became more significant, affecting all the range of w/b ratios, in comparison to the 0% SF mixes. Curing beyond 28 days (for 10% SF mixes) did not result in further reductions in permeability. The effect of PFA and its level of replacement in the 10% SF mixes, results in slight reductions in permeability but this, similar to curing, was restricted to ages up to 28 days beyond which the isoresponse curves became flat.

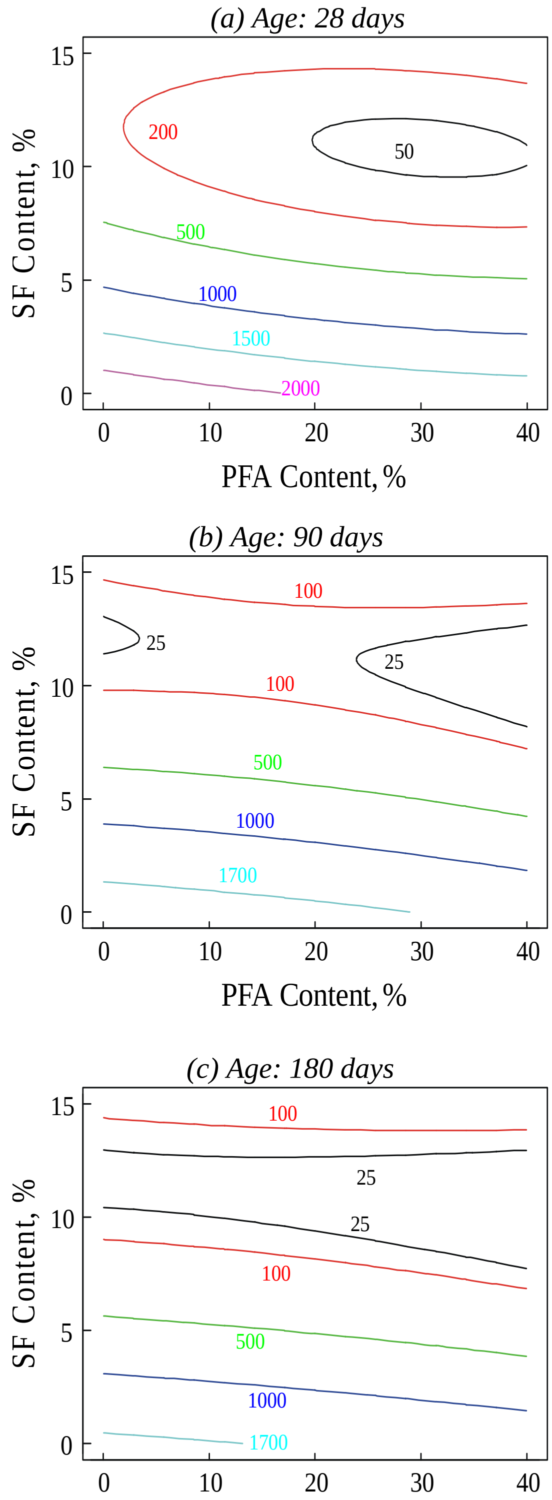


Fig. 4. Isoresponse contours for chloride permeability (Coulomb) of concrete

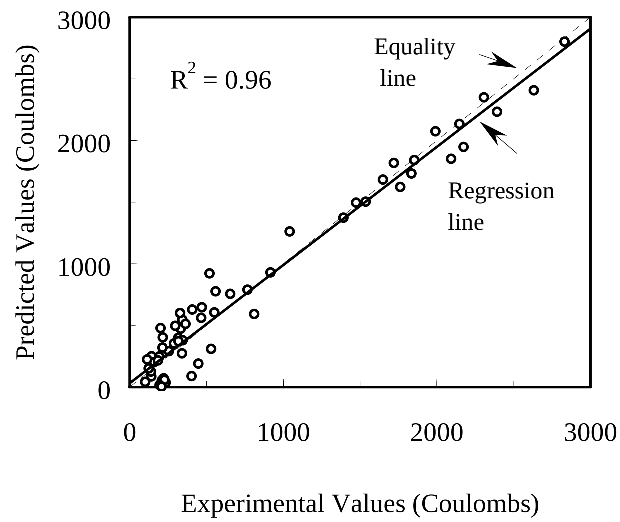


Fig. 5. Relationship between predicted values and experimental values of chloride permeability

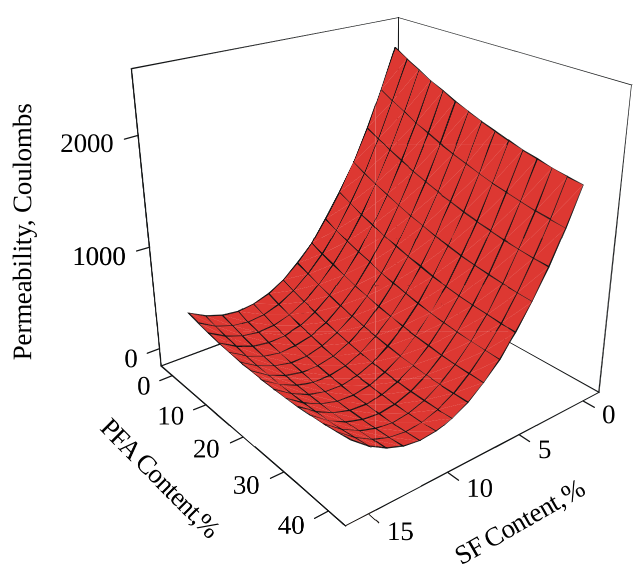


Fig. 6. Three-dimensional 28-day chloride permeability of concrete

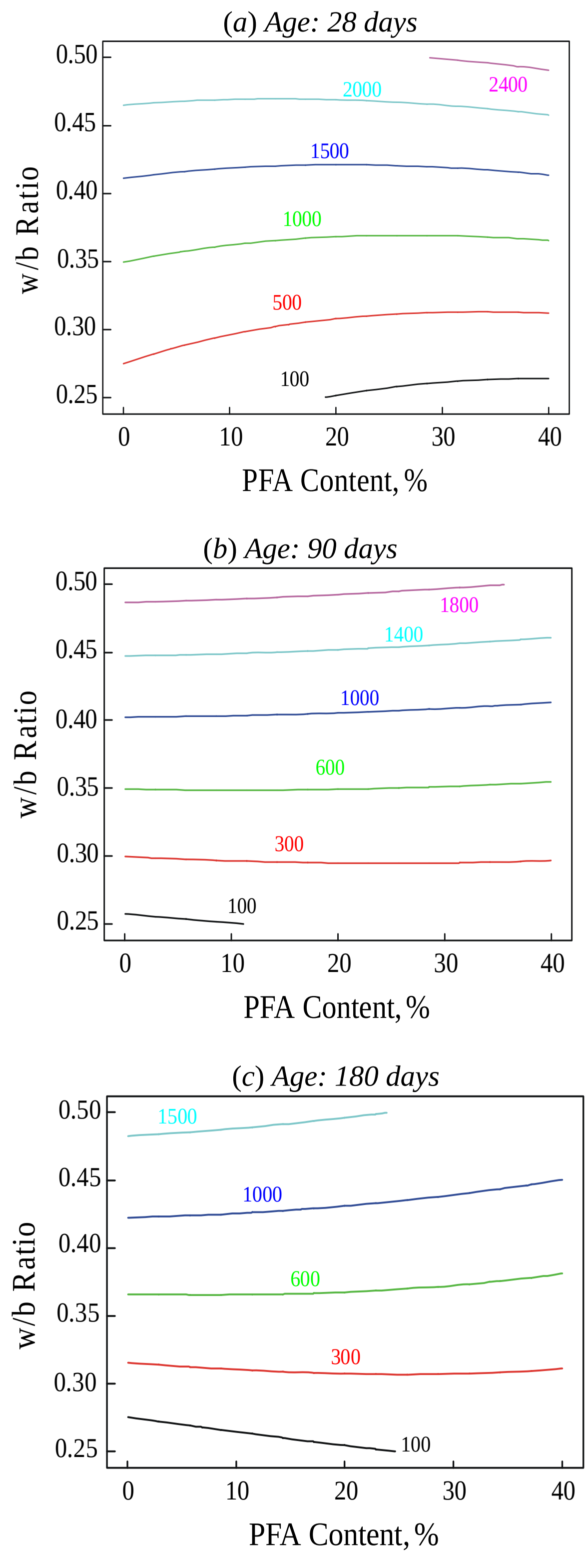


Fig. 7. Isoresponse contours of chloride permeability influenced by PFA content and w/b ratio with 10% SF

As SF was incorporated at 10%, a significant reduction in permeability was exhibited and the whole range of results was shifted towards smaller values. The effect of w/b ratio was still in evidence, but the effect of curing up to 28 days became more significant, affecting all the range of w/b ratios, in comparison to the 0% SF mixes. Curing beyond 28 days (for 10% SF mixes) did not result in further reductions in permeability. The effect of PFA and its level of replacement in the 10% SF mixes, results in slight reductions in permeability but this, similar to curing, was restricted to ages up to 28 days beyond which the isoresponse curves became flat.

The general trend of the results, i.e. reductions in chloride permeability as a result of incorporation of PFA and SF, is supported by other researchers [5]. The reduction in the chloride permeability up to 50% in PFA cement replacement is reported [6]. All the SF concrete mixtures demonstrated substantially low chloride permeability in good agreement with the work carried out by previous researchers [5,7]. There exists controversy on the results of rapid chloride permeability of SF concrete. However, there is large amount of evidence that the SF reduces the permeability [8-10]. Furthermore, substantial reductions in the oxygen permeability and other permeation properties have been observed and reported elsewhere [11].

The results suggest that there is an interaction between PFA and SF, and their level of replacement and the length of curing influence their effect on permeability. This possibly reflects the physical and chemical differences between these materials and, in turn, their effects on micro-filling, pore refinement, hydration and lime depletion [12, 13].

4. Conclusions

The main conclusions drawn from the present investigation are as follows:

- Ternary blends, based on OPC/ PFA/ SF, enabled chloride permeability values to reduce to negligible levels at early ages. This level of permeability was not achieved with other binary systems.
- SF inclusion, by up to 10% replacement level, significantly reduced the chloride permeability in binary systems. The incorporation of PFA in these systems resulted in further reductions in permeability.
- The replacement with more than 12% SF resulted in no further reductions in permeability and at early age a detrimental effect was observed.
- In general, the incorporation of PFA resulted in slight reductions in chloride permeability in comparison with those observed with SF.

ACKNOWLEDGMENT

Author is thankful to the Research Center, College of Engineering, King Saud University for sponsoring this investigation.

REFERENCES

[1] Page, C. L., Short N. R. and El Tarras A., Diffusion of chloride ions in hardened cement paste, *Cement and Concrete Research*, Vol. 11, 1981, pp 295-406.

[2] Mehta, K., Pozzolanic and cementitious by-products as mineral admixtures for concrete - A critical review, Proceedings of the First International Conference on Fly Ash, Silica Fume, Slag, and Natural Pozzolans in Concrete, ACI, SP 79, Detroit, 1983,. pp 1-45.

[3] Malhotra, V. M. and Mehta, P. K., Pozzolanic and Cementitious Materials– Advances in Concrete Technology, Vol. I, Gordon and Breach, Netherlands, 1996.

[4] Whiting, D., In situ measurement of the permeability of concrete to chloride ions. In situ/Non-destructive Testing of Concrete, ACI, SP 82, 1984, pp 500-524.

[5] Ozyildirim, C., Rapid chloride permeability testing of silica fume concrete. Cement, Concrete, and Aggregates, Vol. 16, 1984, pp 53-56.

[6] Naik, T. R., Singh, S. S. and Hossain, M. M., Properties of High Performance Concrete Systems Incorporating Large Amounts of High-Lime Fly Ash, Construction and Building materials, Vol. 9, No. 4, 1995, pp. 195-204.

[7] Ozyildirim, C. and Halstead, W. J., Improved Concrete Quality with Combinations of Fly Ash and Silica Fume, ACI Materials Journal, Vol. 91, No. 6, 1994, pp. 587-594.

[8] Whiting, D., Rapid determination of the chloride permeability of concrete. FHWA Report FHWA/RD-81/119, FHA, Washington D C, 1981. 174 pp.

[9] Mehta, R. K. and Gjorv, O E., Properties of Portland cement concrete containing fly ash and condensed silica fume, Cement and Concrete Research, Vol. 12, No. 5, 1982, pp 587-595.

[10] Nagataki, S and Ujike, I., Air permeability of concretes mixed with fly ash and condensed silica fume, Proceedings of the Second International Conference on Fly Ash, Silica Fume, Slag, and Natural Pozzolans in Concrete, SP 91, ACI, Detroit, 1986, pp 1049-1068.

[11] Khan M. I., Permeation of High Performance Concrete, Journal of Materials in Civil Engineering, ASCE, USA, Vol. 15, No. 1, January/February 2003, pp. 84-92.

[12] Khan M. I., Nanostructure and Microstructure of Cement Concrete Incorporating Multi-cementitious Composites, Journal of the Transportation Research Board, No. 2141, Washington D.C., 2010, pp. 21-27.

[13] Khan M. I., Hydration Mechanism of High Strength Concrete Using Cementitious Composites, RILEM Proceedings of the International Conference on Microstructure Related Durability of Cementitious Composites, China, 2008, pp. 127-134.