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Correlation between compressive strength and certain durability indices of plain and blended cement concretes

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ABSTRACT

In this study, plain, silica fume and fly ash cement concrete specimens prepared with varying water to cementitious materials ratio and cementitious materials content were tested for compressive strength, water permeability, chloride permeability, and coefficient of chloride diffusion after 28 days of water curing. The data so developed were statistically analyzed to develop correlations between the compressive strength and the selected durability indices of concrete. Very good correlations were noted between the compressive strength and the selected durability indices, particularly chloride permeability and coefficient of chloride diffusion, irrespective of the mix design parameters. However, these correlations were observed to be dependent on the type of cement.

1. Introduction

The 28-day compressive strength is often considered the sole criterion for approving a concrete mix by the construction industry. The other properties of concrete, such as water permeability and chloride diffusion, that influence its durability, are rarely evaluated due to the fact that their determination is costly, cumbersome and time consuming compared to assessing the compressive strength. It is assumed that higher the compressive strength of concrete, better would be its durability. However, this assumption is not always true. A concrete mix satisfying the required strength may not necessarily be durable. However, for quality control purposes, relationships need to be developed between compressive strength and durability indices so that they could be utilized to determine the latter values knowing the former ones.

Porosity of concrete influences both its strength and durability [1–7]. Therefore, a relationship between strength and durability of concrete may always be expected. Dhir et al. [8] have reported a decrease in the coefficient of chloride diffusion with an increase in the concrete strength. Water permeability of concrete is also noted to decrease with increasing compressive strength [9,10]. Although the permeability varies with strength, Armaghani et al. [9] have observed that concrete mixtures with equal compressive strengths do not necessarily produce equal levels of permeability, especially when fly ash and silica fume are added to the concrete mixture. A fairly good correlation between the in situ strength of concrete and its initial surface absorption has been reported by Kumar and Bhattacharjee [11]. As a way of confirming its low w/cm requirements, ACI 318 [12] specifies a minimum required compressive strength of concrete for the service exposure, apparently assuming that strength influences the durability of concrete.

Despite the above cited studies, there is a lack of a systematic approach relating the concrete strength with its durability indices so that they could be predicted with the help of measured values of compressive strength. With increasing incidences of concrete deterioration, compressive strength alone cannot be considered as the sole criterion for evaluating the quality of concrete. Concrete is now specified in terms of both strength and durability. Though compressive strength determination is relatively easy, the evaluation of durability characteristics of concrete is cumbersome and time consuming.

This study was conducted to assess the relationship between compressive strength and some durability properties of plain, silica fume and fly ash cement concretes. The correlation equations relating compressive strength and durability indices, developed in the present work, would assist the concrete mix designer to adjust the compressive strength of the mix to a level at which the durability properties are simultaneously obtained. Prediction of the durability properties of concrete in an existing structure may also be possible by measuring the compressive strength using core specimens.

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Nomenclature

a and *b*	constants	R^2	regression coefficient
D	coefficient of chloride diffusion, cm^2/s	*RCP*	rapid chloride permeability, Coulombs
DI	durability index	w/cm	water/cementitious materials ratio
f'_c	28-day compressive strength, MPa	*WPD*	depth of water penetration, mm

2. Experimental program

Plain cement concrete specimens were prepared with ASTM C 150 Type I cement. In the silica fume (SF) cement concrete specimens, 7.5% of the cement was replaced with SF. In the fly ash (FA) cement concrete specimens, FA constituted 20% of the total cementitious materials content. Table 1 shows the chemical composition of Type I cement, fly ash, and silica fume utilized in the preparation of the concrete specimens.

Crushed limestone was used as the coarse aggregate while dune sand was used as the fine aggregates. The specific gravity and water absorption of the coarse aggregate and fine aggregate were 2.55 and 2.5%, and 2.65 and 0.5%, respectively. The maximum size of the coarse aggregates was 19 mm and its grading conformed to ASTM C 33 (#7) limits. Table 2 shows the grading of coarse and fine aggregates.

In order to develop sufficient data on compressive strength and durability characteristics, the following design parameters were utilized in the preparation of concrete mixtures:

Cementitious materials (cm) content: 300, 350, and 400 kg/m^3.
Water/cementitious materials (w/cm) ratio: 0.35, 0.40, 0.45, and 0.50 (by mass).
Coarse/total aggregate ratio: 0.68 (by mass, constant in all the mixtures).
The above mixture design parameters are representative of those utilized by the construction industry worldwide.

Table 1
Chemical composition of cement, fly ash and silica fume.

Constituent (wt.%)	Type I cement	Silica fume	Fly ash
SiO_2	19.92	92.5	46.5
Al_2O_3	6.54	0.72	35.3
Fe_2O_3	2.09	0.96	2.37
CaO	64.7	0.48	8.38
MgO	1.84	1.78	1.86
SO_3	2.61	–	0.46
K_2O	0.56	0.84	0.57
Na_2O	0.28	0.5	0.4
L.O.I	0.73	1.55	3.5
C_3S	55.9	–	–
C_2S	19	–	–
C_3A	7.5	–	–
C_4AF	9.8	–	–

Table 2
Grading of coarse and fine aggregates.

Coarse aggregate (crushed limestone)		Fine aggregate (dune sand)	
Sieve opening, mm	Passing, %	Sieve opening, mm	Passing, %
19	0	4.75	100
12.5	10	2.36	100
9.5	35	1.18	100
4.75	90	0.60	96.2
2.36	100	0.30	61.4
		0.15	21.9
		0.075	1.0

A total of 27 concrete mixtures (nine mixes each for plain, silica fume, and fly ash cement concretes) were prepared using practical combinations of the cementitious materials content and w/cm ratios. The concrete mixtures were designed for a workability of 75–100 mm slump. Suitable dosage of a superplasticizer was added to the concrete mixtures, particularly those incorporating silica fume, to obtain the required workability. The concrete constituents were mixed in a revolving drum type mixer. Mixing was carried out for approximately 3–5 min till the concrete mixture was uniform. Silica fume cement concrete mixtures were mixed for an additional two minutes to achieve uniformity. The concrete was filled in the molds in two layers. Each layer was consolidated, by placing the molds on a vibrating table, till a thin sheen from a water layer appeared on the surface of the specimen. The specimens were demolded after 24 h of casting and immersed in water to cure in the laboratory (22 ± 3 °C). Curing was continued for 28 days. The concrete specimens were then tested to determine the 28-day compressive strength, depth of water penetration, rapid chloride permeability, and coefficient of chloride diffusion.

Compressive strength was determined on three 75 mm diameter and 150 mm high concrete cylinders, as per ASTM C 39. The depth of water penetration was measured on three 150 mm concrete cube specimens, according to DIN 1048. Three 75 mm diameter and 150 mm high concrete cylinders were used to determine the rapid chloride permeability as per AASHTO T-277 (ASTM C 1202). For determining the coefficient of chloride diffusion, three concrete cylinders, 75 mm in diameter and 150 mm high, were first water cured for 28 days. Thereafter, they were allowed to dry in the laboratory conditions (22 + 3 °C) for seven days to drive out the moisture and then coated with an epoxy resin on the circumferential and bottom surfaces to allow uniaxial (i.e. one dimensional) diffusion of chloride ions through the uncoated surface.

The coated specimens were immersed in 5% sodium chloride solution for six months. After this period, they were cleaned and dried to remove the surface moisture and thin slices of concrete were obtained at 5, 15, 35, 50, and 75 mm depths by dry saw cutting. The slices were crushed and pulverized to a fine powder passing through an ASTM No. 100 sieve. In order to determine the water-soluble chloride concentration, three grams of the powder were dissolved in 50 ml of hot deionized water. The mixture was kept in a mechanical shaker for 24 h and, thereafter, it was filtered and the filtrate was diluted to 100 ml using deionized water. The samples were analyzed for water-soluble chloride concentration in accordance with AASHTO T-260. The chloride concentration was plotted against depth of the specimen. The chloride profile so developed was utilized to determine the coefficient of chloride diffusion according to Fick's second law of diffusion, as described by Crank [13].

3. Results and discussion

Test results pertaining to compressive strength, depth of water penetration, rapid chloride permeability, and chloride diffusion for plain, SF, and FA cement concretes are presented in Tables 3–5, respectively.

Table 3
Results of tests conducted on plain cement concrete specimens.

Cementitious materials content, kg/m^3	w/cm ratio	Compressive strength, MPa	Depth of water penetration, mm	Rapid chloride permeability, Coulombs	Chloride diffusion coefficient, 10^{-8} cm^2/s
350	0.35	43.1	41	2875	6.02
400	0.35	45.3	36	2445	7.31
350	0.40	39.5	47	3639	8.12
400	0.40	41.0	44	3271	8.02
300	0.45	34.4	56	3984	15.00
350	0.45	34.9	50	3820	13.10
400	0.45	35.9	48	3593	12.50
350	0.50	31.6	89	5614	22.00
400	0.50	33.9	82	4150	19.00

Table 4
Results of tests conducted on silica fume cement concrete specimens.

Cementitious materials content, kg/m^3	w/cm ratio	Compressive strength, MPa	Depth of water penetration, mm	Rapid chloride permeability, Coulombs	Chloride diffusion coefficient, 10^{-8} cm^2/s
350	0.35	46.2	23	820	1.22
400	0.35	48.1	21	782	1.08
350	0.40	42.8	35	995	1.64
400	0.40	44.2	31	866	1.54
300	0.45	37.1	49	1242	2.11
350	0.45	39.1	41	1329	1.81
400	0.45	41.2	35	1149	1.37
350	0.50	35.9	50	2591	2.33
400	0.50	36.2	44	2019	1.88

Table 5
Results of tests conducted on fly ash cement concrete specimens.

Cementitious materials content, kg/m^3	w/cm ratio	Compressive strength, MPa	Depth of water penetration, mm	Rapid chloride permeability, Coulombs	Chloride diffusion coefficient, 10^{-8} cm^2/s
350	0.35	36.7	32	1603	2.12
400	0.35	37.6	31	1477	1.66
350	0.40	36.2	44	1769	2.41
400	0.40	36.5	38	1630	2.02
300	0.45	29.9	48	2219	4.23
350	0.45	31.6	46	2510	4.16
400	0.45	32.9	45	2220	3.05
350	0.50	23.7	57	3548	5.32
400	0.50	25.0	51	2750	4.85

The compressive strength of plain, SF and FA cement concrete specimens decreased with an increase in the w/cm ratio. The compressive strength of SF cement concrete was more than that of plain cement concrete while the compressive strength of FA cement concrete was less than that of plain cement concrete after 28 days of water curing. For mixes with similar w/cm ratio, there was a marginal improvement in the compressive strength with increasing cementitious materials content for all the three types of concretes.

For all types of concrete, the depth of water penetration increased with an increase in the w/cm ratio. Although the depth of water penetration decreased due to an increase in the cementitious materials content, it was not that significant. For a given w/cm ratio and cementitious materials content, the depth of water penetration was the least in the SF cement concrete and the highest in the plain cement concrete. The depth of water penetration in FA cement concrete was less than that of plain cement concrete, but more than that of SF cement concrete. According to the Concrete Society criteria [14], the water permeability of SF cement concrete changed from "low" to "moderate" due to an increase in the w/cm ratio from 0.35 to 0.50. The water permeability of FA cement concrete was "moderate" for all the values of w/cm ratio in the range of 0.35–0.50. The water permeability of plain cement concrete was "moderate" for w/c ratio in the range of 0.35–0.45 but for a w/cm ratio of 0.50, it was "high".

The rapid chloride permeability increased with an increase in the w/cm ratio in all the three types of concretes. Such an increase was marginal at lower w/cm ratio, however, there was a sharp increase in the chloride permeability when the w/cm ratio was more than 0.45. Similarly, there was a reduction in the chloride permeability with an increase in the cementitious materials content in the three types of concretes with all the w/cm ratios. While the cementitious materials content was noted to influence the chloride permeability of plain cement concrete, its effect was insignificant in the SF and FA cement concretes. For the same w/cm ratio and cementitious materials content, the chloride permeability of plain cement concrete was more than that of SF and FA cement concretes. Further, the chloride permeability of FA cement concrete was more than that of SF cement concrete. Silica fume displayed the best performance in resisting the penetration of chloride ions into concrete due to its finer particle size and enhanced pozzolanic activity compared to fly ash, resulting in a dense concrete [15]. However, it is worth mentioning that the rapid chloride permeability tests were conducted after 28 days of curing. At later ages, however, there may not be a significant difference in the rapid chloride permeability of FA and SF cement concrete specimens. Further, FA cement concrete performed better than plain cement concrete in terms of chloride permeability. This indicates that the addition of fly ash greatly decreases the permeability of concrete even though the strength of fly ash cement concrete at 28 days is less than that of plain cement concrete. Such a behavior has also been reported earlier by Al-Amoudi et al. [16].

The coefficient of chloride diffusion increased with an increase in the w/cm ratio in all the three types of concretes. However, it decreased slightly with an increase in the cementitious materials content. This is ascribed to the fact that the C_3A content in the concrete matrix is also increased with an increase in the cementitious materials content thereby leading to a higher chloride binding [17]. Moreover, the increase in the quantity of cementitious materials would increase the denseness of the concrete matrix. The chloride diffusion coefficient for plain cement concrete was in the range of $6–22 \times 10^{-8}$ cm^2/s, and for FA cement concrete, it was in the range of $2–5 \times 10^{-8}$ cm^2/s, while for SF cement concrete, it was in the range of $1–2.5 \times 10^{-8}$ cm^2/s. Therefore, the chloride diffusion coefficient for plain cement concrete was 2.8–4.4 times that of FA cement concrete and 4.9–10.1 times that of SF cement concrete. This significant reduction in the chloride diffusion in SF and FA cement concretes may be attributed to the formation of secondary calcium silicate hydrate by the pozzolanic reaction, which reduces the pores, leading to a dense microstructure and hence reduced diffusion of chloride ions into concrete [15,16].

The depth of water penetration, chloride permeability, and coefficient of chloride diffusion are plotted against compressive strength in Figs. 1–3 in order to ascertain the relationship between these properties of concrete.

The data in Fig. 1 indicate that the depth of water penetration decreases with an increase in the compressive strength for all the three types of concretes investigated. Further, a good correlation can be noted between the compressive strength and depth of water penetration. However, for the same value of compressive strength, three types of concretes exhibited different depths of water penetration. For example, at a compressive strength of 35 MPa, the depth of water penetration was around 40 mm for FA concrete, 50 mm for SF concrete, and 60 mm for plain cement concrete. This may be attributed to the differences in the microstructure of concrete prepared using different types of cementitious materials and mix design parameters. Similar relationships between compressive strength and rapid chloride permeability and coefficient of chloride diffusion are depicted in Figs. 2 and 3.

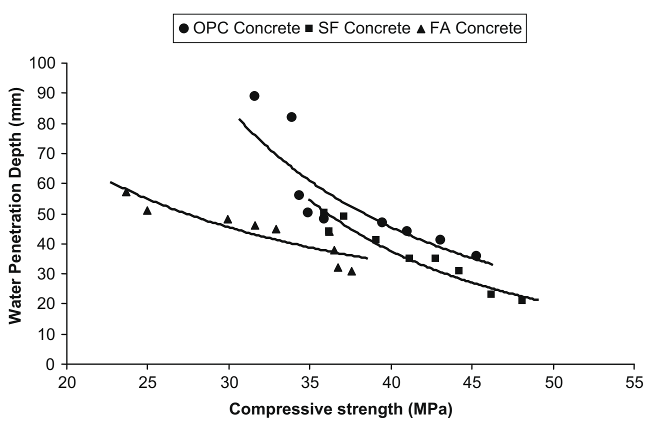

Fig. 1. Variation of depth of water penetration with compressive strength of concrete.

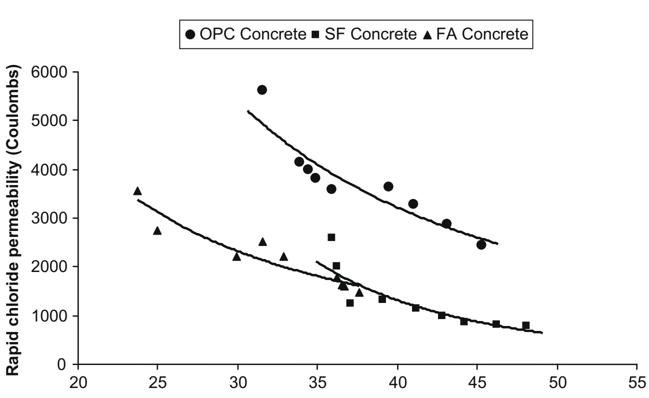

Fig. 2. Variation of chloride permeability with compressive strength of concrete.

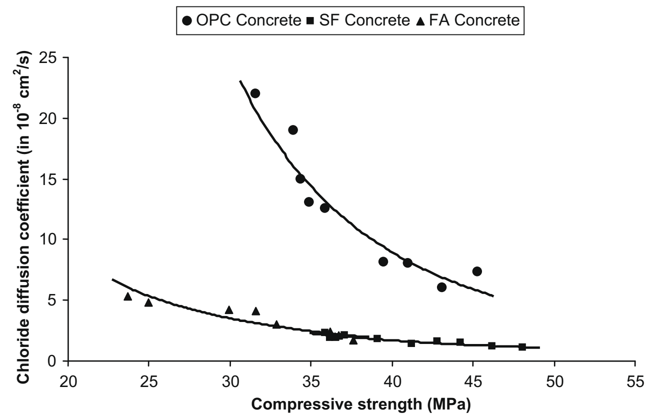

Fig. 3. Variation of chloride diffusion coefficient with compressive strength of concrete.

4. Correlation equation

The experimental data, depicted in Figs. 1–3 and numerically presented in Tables 3–5, were utilized to develop a correlation equation between compressive strength and the durability indices. The correlation equation can be expressed by the following single formula:

$$DI = \frac{a}{(f'_c)^b}$$

where *DI* is the durability index (i.e., depth of water penetration, *WPD*, chloride permeability, *RCP*, or coefficient of chloride diffusion, *D*); f'_c the compressive strength; and *a* and *b* are the constants.

The constants *a* and *b*, were obtained through the regression analysis of the data in Tables 3–5. The best-fit values of constants *a* and *b* and the regression coefficient, R^2, are summarized in Table 6.

A regression coefficient, R^2, of more than 0.85 indicates an excellent correlation between the fitted parameters [18]. Therefore, the data in Table 6 indicate a good relationship between the compressive strength and the depth of water penetration in the silica fume cement concrete. However, in the case of plain and fly ash cement concretes, the degree of fit between the compressive strength and the depth of water penetration is on the lower side ($R^2 < 0.80$). Furthermore, the data in Table 6 indicate that a reasonably good fit does exist for the chloride penetration and coefficient of chloride diffusion in all the three types of concretes ($R^2 > 0.80$). It is to be noted that the correlation equations relating compressive strength and durability indices of plain, silica fume and fly ash cement concretes, developed in the present work, would help the concrete mix designer to adjust the compressive strength of the mix to a level at which the durability properties are simultaneously satisfied with the compressive strength. Predictions of the durability properties of concrete in an existing structure may also be possible by only measuring the compressive strength using core

Table 6
Constants *a* and *b* and regressions coefficients, R^2.

DI	Plain cement concrete			Silica fume cement concrete			Fly ash cement concrete		
	a	*b*	R^2	*a*	*b*	R^2	*a*	*b*	R^2
WPD, mm	0.14×10^6	2.18	0.77	1×10^6	2.78	0.93	1511	1.03	0.74
RCP, Coulombs	2×10^6	1.80	0.88	5×10^8	3.47	0.83	0.56×10^6	1.61	0.90
D_e, 10^{-8} cm^2/s	4×10^6	3.54	0.91	5133	2.17	0.85	8918	2.31	0.85

specimens. However, it should be noted that the relationships reported in this paper were developed for concretes containing crushed limestone aggregates that were cured for 28 days, as such similar relationships may need to be developed for other types of aggregates and curing conditions.

5. Conclusions

The strength, depth of water penetration, chloride permeability and coefficient of chloride diffusion of plain, silica fume, and fly ash cement concretes were evaluated for a range of cementitious materials content and water to cementitious materials ratio. As expected, the strength and durability characteristics of the three types of concretes investigated in this study were noted to be influenced by the w/cm ratio and the cementitious materials content. The durability characteristics of silica fume and fly ash cement concretes were better than those of plain cement concrete specimens.

The strength data were related to the durability characteristics through a single equation noted below:

$$DI = \frac{a}{(f_c')^b}$$

where *DI* is the durability index (i.e., depth of water penetration, *WPD*, chloride permeability, *RCP*, or coefficient of chloride diffusion, *D*); f_c' the compressive strength; and *a* and *b* are the empirical constants.

A good correlation was noted between compressive strength and the durability characteristics, expressed in terms of the above expression. The relationships developed in the present work are related to limestone aggregates. They could be utilized to determine the durability properties of other aggregates knowing the compressive strength, of course, with a certain degree of error. However, similar guidelines can be developed for other types of aggregates.

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