DESIGN OF CONCRETE TO RESIST CARBONATION
Rate of carbonation of concrete

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Abstract

The rate of carbonation in concrete is influenced by both its physical properties and exposure conditions. Therefore, service life prediction of reinforced concrete structures in an environment where carbonation is a probable cause of corrosion of steel in concrete may be made in terms of both the physical properties and the exposure conditions. Investigations in the past have quantified the effect of ambient relative humidity on the rate of carbonation in concrete. Therefore, some attempts have been made to include an environmental stress factor in models to predict the service life of concrete subjected to carbonation. However, when it is the question of service life design of concrete to resist carbonation induced deterioration, a definite procedure is not available at present. This is primarily due to a lack of consensus on parameters to be used for the design. This has prompted the authors to study the relationships which could be used to design concrete for its intended service life when carbonation is a likely cause of deterioration.

Keywords: Air permeability, accelerated carbonation test, carbonation, carbonation rate, compressive strength, durability, service life design.

1 Introduction

Corrosion of reinforcing steel is one of the most critical limit states affecting the durability of reinforced concrete structures. There are a wide range of factors, some internal and some external that create conditions favourable for corroson to initiate and propagate. One of these causes is carbonation.

Carbonation is the result of carbon dioxide from the atmosphere diffusing into concrete and converting calcium hydroxide and other cement hydrates into insoluble carbonates. This results in a reduction in the pH of the concrete and corrosion of steel in the case of reinforced concrete (Parrott, 1987). Out of 271 cases of deterioration of various types of reinforced concrete structures reviewed in a recent project (British Cement Association, 1997), 46 cases have been due to carbonation induced corrosion of reinforcement. Amongst the 76 cases of buildings reviewed, 33 cases deteriorated due to the effect of carbonation. Therefore, the rate at which carbonation proceeds is important in order to estimate the service life of reinforced concrete structures.

The rate of carbonation can be determined by monitoring the depth of carbonation over a period of time (Kropp and Hilsdorf, 1995; Schiessl, 1988). It generally follows a formula of the form:

$$dc = K\sqrt{t}$$

where dc = depth of carbonation
K = rate of carbonation, a constant
t = duration of exposure.

This relationship has been derived from Fick’s first law of diffusion and the amount of carbon dioxide required to carbonate the alkaline components in the concrete (Kropp and Hilsdorf, 1995). Although the diffusion coefficient of carbon dioxide through the concrete is assumed to be constant, in order to arrive at the above expression, the constant in the expression encompasses several factors in the carbonation process. These factors are mix proportions, curing regime and age (both providing information on the degree of hydration), material characteristics which control the transport properties, environmental conditions and degree of exposure to carbon dioxide. As a result, the rate of carbonation changes for different concretes and set of conditions to which the concrete is exposed.

The rate of carbonation is obtained from the slope of a plot of carbonation depth against square root of exposure duration (Loo et al, 1994). The main factor that has been found to influence the rate of carbonation is water-cement ratio (Parrott, 1987). As an increase in water-cement ratio increases the porosity and permeability of concrete, this in turn increases the rate of carbonation (Hobbs, 1988). The effect of other mix parameters on the rate of carbonation is not clear in the literature. Therefore, with the present level of knowledge, it is difficult to design concrete for a specific degree of carbonation resistance. In order to deal with this, a detailed experimental programme was carried out by the authors. The results from this investigation are reported and discussed in this paper.

2 Experimental programme

2.1 Test variables

The experimental programme consisted of testing 17 different concrete mixes. Table 1 presents the mix variables and the mass per unit volume of cement, fine aggregate, coarse aggregate and water for the seventeen mixes. The mix combinations were decided after carrying out trials to check for their viability, i.e. to eliminate honeycombing and segregation. As shown in Table 1, a fine aggregate-coarse aggregate ratio of 0.5 was used in this test series. However, further work is in progress to study the effect of two other levels of fine aggregate-coarse aggregate ratio.

Table 1: Experimental variables amd mass per unit volume of constituents

W/C by mass	A/C by mass	Cement content (kg/m^3)	Fine aggregate content (kg/m^3)	Coarse aggregate content (kg/m^3)	Water content (kg/m^3)
0.4	3	563	563	1125	225
0.5	3	533	533	1066	267
0.4	4	468	624	1248	187
0.5	4	448	595	1190	223
0.6	4	429	572	1145	258
0.4	5	400	667	1333	160
0.5	5	387	645	1290	194
0.6	5	374	619	1238	223
0.7	5	360	600	1200	252
0.5	6	340	679	1359	170
0.6	6	328	657	1314	197
0.7	6	319	637	1274	223
0.5	7	302	705	1410	151
0.6	7	295	688	1377	177
0.7	7	287	669	1377	201
0.6	8	266	710	1419	160
0.7	8	260	694	1388	182

Note: Fine aggregate-coarse aggregate ratio = 0.5

2.2 Materials used

Class 42.5N Portland Cement (British Standards Institution, 1991), medium graded natural sand (British Standards Institution, 1992) and crushed basalt 20 mm and 10 mm sizes in the ratio 1:1 were used for all mixes. In order to control the moisture condition of the aggregates, all aggregates were oven-dried at a temperature of 40 ^{0}C and allowed to cool for at least 1 day. The saturated surface-dry 30 minute water absorption values (British Standards Institution, 1975) were also measured. These allowed a corrected water quantity to be calculated when batching the materials to ensure that the aggregate in the concrete was in a saturated and surface-dry condition. Tap water at a temperature of approximately 20 ^{0}C was used for all mixes.

2.3 Manufacture of test specimens

Four 250x250x100 mm slabs and three 100 mm cubes were cast using each mix. For each mix the required quantities were batched by mass and then mixed together using a pan mixer in accordance with BS 1881: Part 125: 1986 (British Standards Institution, 1986). The test specimens were cast in two layers and compacted using a vibrating table. Full compaction was considered to have been achieved when air bubbles stopped appearing on the concrete surface. After vibrating, the concrete surface was 'rubbed-up' smooth using a metal float and covered with a polythene sheet to prevent evaporation of water from the concrete.

2.4 Curing, conditioning and preparation of test specimens

Approximately 6 hours after the concrete had been cast the moulds were covered with damp hessian. The moulds were stripped next day and the hardened concrete samples were placed in a constant temperature (20 ^{0}C) water bath, where it remained for 3 days. These were then wrapped in polythene sheet and transferred into a storage laboratory kept at a constant temperature of 18 ^{0}C (± 2 ^{0}C) and a relative humidity of 60% (± 5%). When the specimens were 28 days old, four 50 mm diameter cores and one 100 mm core were cut from each of the four slabs. The cores were then surface dried and the curved surface of each core was coated with Sikaguard, 680 ICOSIT Concrete Cosmetic Acrylic paint. These were then saturated by following an incremental immersion approach and then placed in a drying cabinet at a constant temperature of 40 ^{0}C and a relative humidity of 20%. The reason for this was to remove moisture from the surface of the concrete in order to eliminate the effect of moisture on the permeability results and to obtain a mean relative humidity of about 65% in the near surface concrete up to a depth of about 30 mm. The cores remained in the drying cabinet for a period of 14 days and were then transferred to a testing laboratory kept at a constant temperature of 20 ^{0}C (± 0.5 ^{0}C) and a relative humidity of 50% (± 5%). After being here for 1 day they were tested.

2.5 Test methods

The three 100 mm cubes were tested at the age of 28 days to determine the concrete compressive strength (British Standards Institution, 1983). The four 100 mm diameter cores were tested for air permeability by using the Autoclam Permeability System (Basheer et. al., 1994) at the end of the conditioning regime. Both the 100 mm and 50 mm diameter cores were then placed in the carbonation chamber.

The carbonation test was carried out at a carbon dioxide concentration of 5% (± 0.2%) in an environment of 65% (± 1%) relative humidity and 20 ^{0}C (± 1 ^{0}C). The depth of carbonation was measured at the start of the test and thereafter each week up to 3 weeks exposure in the chamber. At these times, four cores from each mix were removed from the chamber and the depth of carbonation was determined by splitting the core longitudinally and spraying the split surface with a 1% phenolphthalein indicator solution. After 24 hours the depth of carbonation was measured at three locations at right angles to the exposed surface to an accuracy of 0.5 mm in accordance with RILEM recommendations in report CPC-18 (RILEM, 1988). An average of the three readings from the four cores was reported as the depth of carbonation after each week's exposure in the chamber. These values were plotted against squre root of the duration of exposure and the rate of carbonation was determined for each mix.

At the end of the carbonation test, the 100 mm cores were tested for air permeability and sorptivity, by using the Autoclam Permeability System.

3 Methods of analysis

Two approaches were used to analyse the data. The first attempt was to identify the trends and relationships between the rate of carbonation and both mix parameters and the physical properties. However, no attempt was made to 'quantify' the influence of each of the mix parameters on the measured properties. The second approach was to quantify the effects of the mix parameters, so that the resulting information could be used for the development of the new mix design for carbonation resistance of normal Portland cement concretes. The data were analysed by using the Muliple Linear Regression (MLR) method and nomograms were developed to satisfy this objective.

The main aim of MLR in general was to develop empirical prediction models. Therefore, at the end of this analysis, as well as quantifying the contribution of each of the mix parameters, there were also prediction models for each of the measured properties and ultimately it was possible to use these as the basis for a new mix design procedure. The main steps involved in this overall procedure were as follows:

(i) Testing normality of experimental data.
(ii) Developing MLR models.
(iii) Quantify the contribution of mix parameters on measured properties.
(iv) Develop prediction models.

A computer package, 'STATVIEW' was used for the anlaysis of the data. The compressive strength, sorptivity and rate of carbonation results followed a normal distribution reasonably well without applying any transformation to the data, however, a logarithmic transformation was required for the air permeability data.

The MLR models were developed for both 'mass ratio' (i.e. water-cement ratio and aggregate-cement ratio) and 'mass/unit volume' (i.e. cement content, fine aggregate content, coarse aggregate content and water content, all in kg/m^3). In addition, a predictive model for rate of carbonation based on compressive strength, air permeability and sorptivity was developed. Before developing the MLR models, the correlation between rate of carbonation and each of the variables used in the analysis was determined. This is reported in Table 2. Then, starting with the variable which had the highest correlation, the analysis for the development of the MLR model was carried out. Table 3 presents the improvement of the model with the addition of each variable in the MLR models. The MLR analysis resulted in the following empirical models (note that additive models were developed in all cases):

$RoC = \beta_0 + \beta_1(W/C) + \beta_2(A/C) + \varepsilon_i$ (mass ratio)
$RoC = \alpha_0 + \alpha_1(CC) + \alpha_2(FAC) + \alpha_3(CAC) + \alpha_4(WC) + \varepsilon_i$ (mass/unit volume)
$RoC = \gamma_0 + \gamma_1(Fcu) + \gamma_2(API) + \gamma_3(SI) + \varepsilon_i$ (properties)

where RoC = Rate of carbonation
β_0, α_0 and γ_0 = intercept
β_1 and β_2 or α_1, α_2 and α_3 or γ_1, γ_2 and γ_3
= multipliers for the independent or explanatory variables
ε_i = random error associated with the variate

Table 4 presents the intercepts and multipliers for the MLR models for rate of carbonation.

Table 2: Correlation between rate of carbonation and variables used in the analysis

Description	Variable	Coeff. of determination, R^2
Mass ratio	W/C	0.829
	A/C	0.192
Mass/unit volume	Cement content, CC	0.275
	Water cotent, WC	0.092
	Fine agg. content, FAC	0.01
	Coarse agg. content, CAC	0.014
Properties of concrete	Compressive strength, Fcu	0.792
	Air permeability, API	0.429
	Sorptivity, SI	0.642

Table 3: Development of MLR models for rate of carbonation

Type of MLR model	Variables included	Explained (%)	Improvement (%)	Unexplained (%)	Coeff. of multiple determination R^2
Mass ratio	W/C	82.92		17.08	
	A/C	83.80	+0.88	19.20	0.838
Mass/unit volume	CC	27.48		72.52	
	CC+WC	79.69	+52.21	20.31	
	CC+WC+CAC	79.70	+0.01	20.30	
	CC+WC+CAC+FAC	82.51	+2.81	17.49	0.825
Physical properties	Fcu	79.19		20.81	
	Fcu+SI	79.93	+0.74	20.07	
	Fcu+SI+API	80.10	+0.17	19.90	0.801

Table 4: Intercepts and multipliers for the MLR models for rate of carbonation

Type of MLR model	Explanatory variables	Intercept	Multiplier	Coeff. of multiple determination, R^2
Mass ratio	W/C	-7.567	26.225	
	A/C		-0.206	0.838
Mass/unit volume	CC	-164.74	0.0553	
	CC+WC		0.3274	
	CC+WC+CAC		0.3535	
	CC+WC+CAC+FAC		-0.033	0.825
Physical properties	Fcu	12.18	-0.157	
	Fcu+SI		0.735	
	Fcu+SI+API		1.280	0.801

4 Discussion of results

4.1 Influence of mix parameters on rate of carbonation

Figure 1 shows the rate of carbonation for different water-cement ratios and aggregate-cement ratios for a constant fine aggregate-coarse aggregate ratio of 0.5. It can be seen that the effect of water-cement ratio is to increase the depth of carbonation for all the aggregate-cement ratios. Generally this effect increased towards higher aggregate-cement ratios. Apart from experimental variation, the rate of carbonation remained almost constant at different aggregate-cement ratios for all water-cement ratios. The increase in the rate of carbonation due to the increase in water-cement ratio can be related to increased porosity and carbon dioxide transport. This result was reported in several publications (Parrott, 1987; Hobbs, 1988). The effect of aggregate-cement ratio observed here appears to be in contradiction to results reported by other researchers (Papadakis et. al., 1991), that there was an increase in depth of carbonation due to an increase in aggregate-cement ratio. However, the data obtained from the literature was for concretes for which the water-cement ratio increased when the aggregate-cement ratio increased. As the trend reported in figure 1, was repeated at four different water-cement ratios, it is justifiable to conclude that there is no significant effect due to an increase in aggregate-cement ratio on the rate of carbonation.

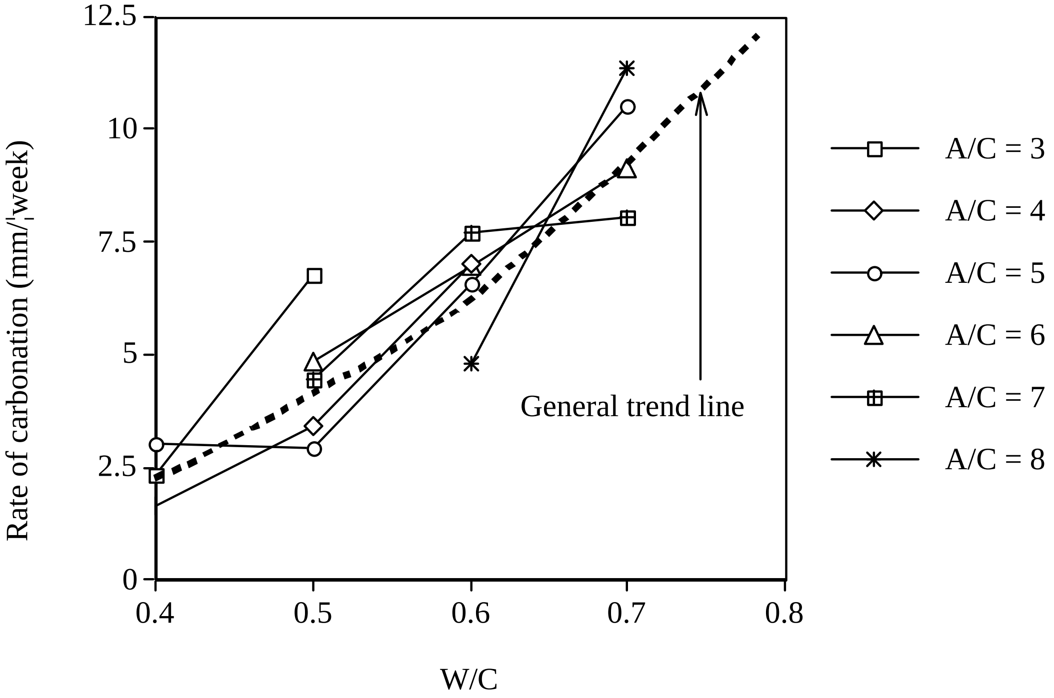

Fig. 1: The effect of water-cement ratio and aggregate-cement ratio on rate of carbonation

The dotted line in Figure 1 shows the overall effect of water-cement ratio on the rate of carbonation. At each of the water-cement ratios, the effect of aggregate-cement ratio is not very significant. The spread is mainly due to the water-cement ratio and this alone explained about 83% variation in rate of carbonation (Table 3). There was only a marginal improvement in the MLR models by the addition of aggregate-cement ratio (0.88%).

The dependence of rate of carbonation on mass/unit volume can be seen in Table 3. Both cement and water content together (i.e. W/C effect) contributed to about 80% variation of the rate of carbonation. Other factors, such as the amount of fine aggregate and coarse aggregate in the mix, have no significant effect on the rate of carbonation. When the results of mixes with fine aggregate-coarse aggregate ratio of 0.3 and 0.7 are available, this analysis will be repeated and the true effect of both these variables quantified.

Figure 2 reports the effect of water cement ratio and cement content on rate of carbonation. For each aggregate-cement ratio, the cement content varied slightly when the water-cement ratio was changed. However, the main effect that can be seen in this Figure is that the main variation in rate of carbonation is due to the change in water-cement ratio. For the whole range of cement content tested, the rate of carbonation decreased marginally with an increase in cement content. However, this cannot be considered as overly significant. Another trend which can be obtained is that, for a given water-cement ratio, the increase in aggregate-cement ratio resulted in a significant decrease in cement content and this, in turn, decreased the rate of carbonation (shown as dotted lines in Figure 2). However, there was kink in the trend for all water-cement ratios. The information available at present cannot explain the reason for this sudden jump in the trend. The reduction in rate of carbonation is considered to be due to the reduction in calcium oxide with the decrease in cement content (Papadakis, 1991).

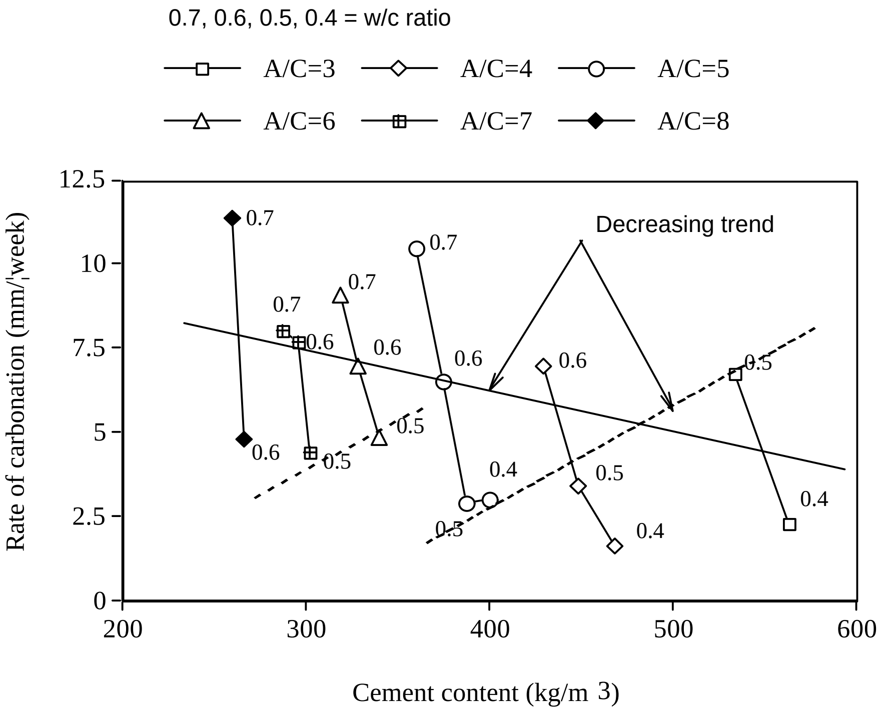

Fig. 2: Effect of w/c ratio and cement content on rate of carbonation

4.2 Dependence of rate of carbonation on measured properties of concrete

The depth of carbonation is correlated with compressive strength, air permeability and sorptivity in Figures 3, 4 and 5 respectively. In Figure 3, there is a very good correlation between the rate of carbonation and the cube compressive strength, as indicated by a value of 0.823 for the coefficient of determination. This accounted for about 79% of the variability in the MLR model (Table 3). (Note that an exponential relationship is presented in Figure 3, however, the regression coefficient in Table 3 is for the linear regression analysis.)

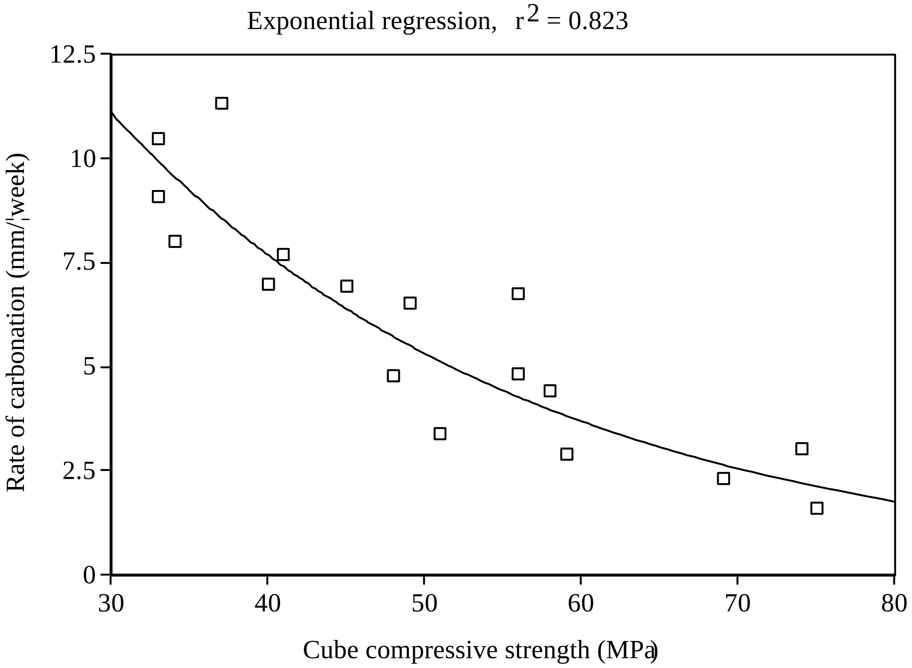

Fig. 3: Dependence of rate of carbonation on cube compressive strength

The correlation between the rate of carbonation and both the air permeability and the sorptivity in Figures 4 and 5 is not as good as that obtained for compressive strength. The effect of both conditioning and mix parameters on permeation properties differs from that on cube compressive strength. As the effect of these are not studied in this investigation, only general trends are given emphasis at present. The improvement of the MLR model in Table 3 with the addition of both the sorptivity and air permeability is insignificant when comparing this with the effect of compressive strength alone.

4.3 Development of design curves

The above discussion would suggest that in order to design normal Portland cement concrete mixes for carbonation resistance, a simplified approach is to control the water-cement ratio. However, it should be noted that this needs to be verified for various aggregate grading and types of aggregate. It is known that the water-cement ratio controls the compressive strength of normal Portland cement concretes. As a consequence, if concrete is designed for a specified compressive strength, an estimate of resistance to carbonation may be made.

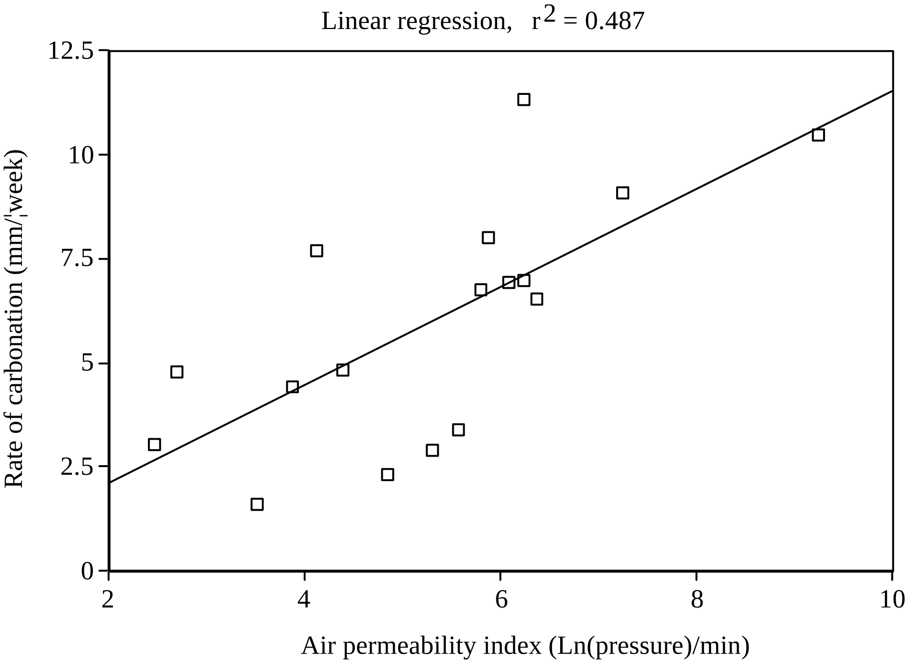

Fig. 4: Dependence of rate of carbonation on air permeability

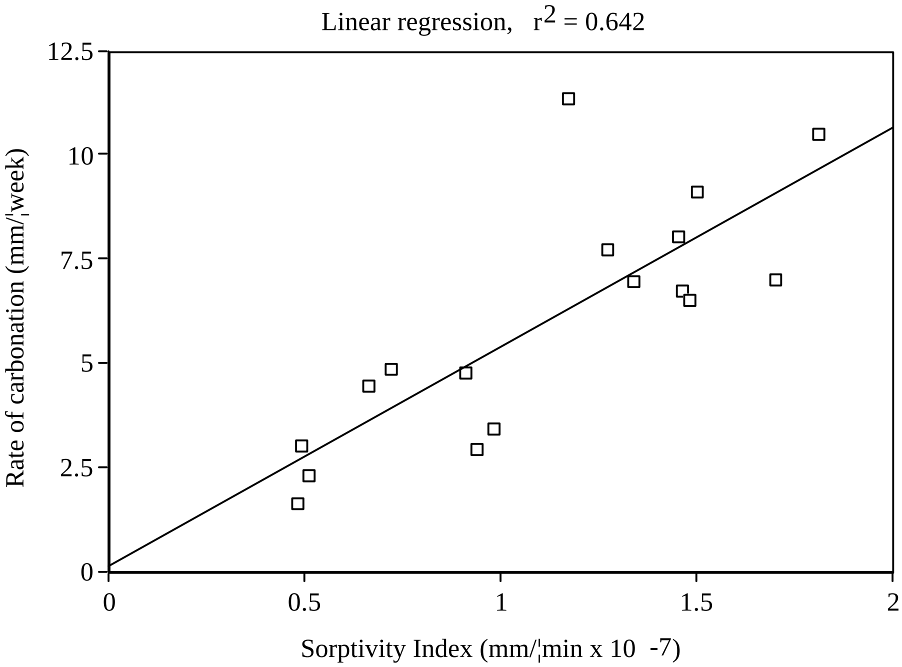

Fig. 5: Dependence of rate of carbonation on sorptivity index

If service life design of concrete to resist carbonation is required, the MLR models in Table 4 could be used. Figure 6 illustrates the prediction model for rate of carbonation on the basis of water-cement ratio and aggregate-cement ratio.

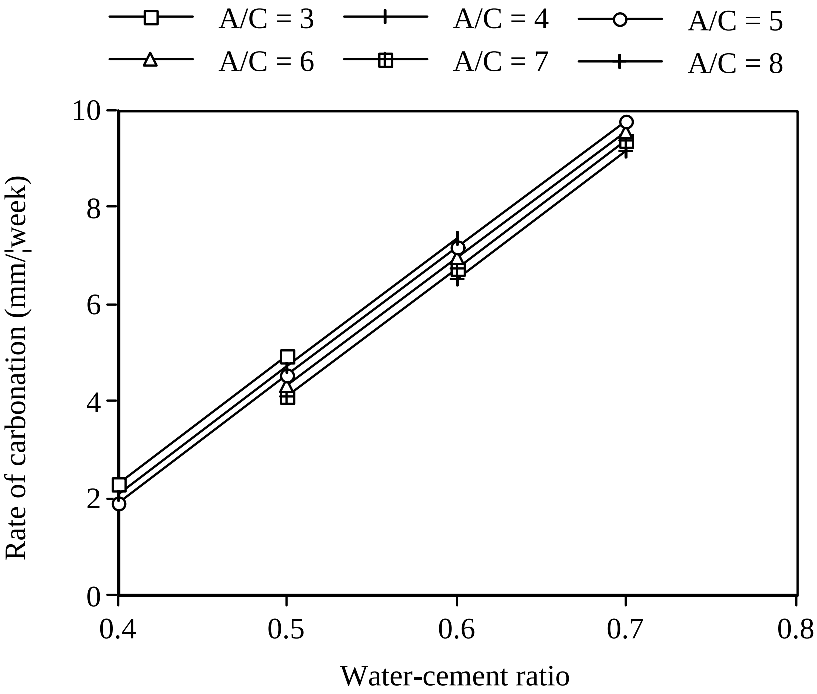

Fig. 6 Design graph for carbonation resistance of normal Portland cement concrete

Figure 6 would suggest that, if the findings based on accelerated carbonation testing can be validated for normal exposure conditions, the rate of carbonation can be used to determine the mix proportions which would ensure a specified service life of reinforced concrete. This is because, for a given depth of cover, the rate of carbonation could provide the time before which carbonation reaches the reinforcement. Further research in this area is in progress at present at Queen's and it is expected that a suitable procedure for the service life design of concrete for carbonation resistance can be developed.

5 Conclusions

On the basis of the results presented in this paper, the following conclusions have been reached.

i) The rate of carbonation of normal Portland cement concrete is primarily influenced by the water-cement ratio and other factors have only a marginal effect. Therefore, concrete can be designed to have a specific carbonation resistance based entirely on the water-cement ratio. However, this should be verified for different types of and gradings of aggregate.

ii) The rate of carbonation from accelerated carbonation testing can be used for the service life design of concrete in an environment where carbonation is a probable cause of deterioration. However, there is a need to relate the results of the accelerated test to those of natural exposure trials before this approach can be used.

6 References

Basheer, P.A.M., Long, A.E. and Montgomery, F.R. (1994) The Autoclam - a new test for permeability, Concrete, Journal of the Concrete Society, July/August 1994, pp. 27-29.

British Cement Association, (1997) Development of an holistic approach to ensure the durability of new concrete construction, Report for the Department of the Environment, April, 1997, 76 pp.

British Standards Institution (1975) Testing aggregates, Methods for determination of physical properties, BSI London, BS 812: Part 2: 1975.

British Standards Institution (1983) Method for determination of compressive strength of concrete cubes, BSI London, BS 1881: Part 116 1983.

British Standards Institution (1986) Methods for mixing and sampling fresh concrete in the laboratory, BSI London, BS 1881: Part 125 1986.

British Standards Institution (1991) Specification for Portland Cements, BSI London, BS 12:1991,7 pp.

British Standards Institution (1992) Specification for aggregates from natural sourses for concrete, BSI London, BS 882: 1992.

Hobbs, D.W (1988) Carbonation of concrete containing pfa, Magazine of concrete research, Vol. 40, No. 143, June 1988, pp. 69-78.

Kropp, J. and Hilsdorf, H.K. (1995) RILEM report 12, Performance Criteria for Concrete Durability, E and F SPON, London, 1995.

Loo, Y.H., Chin, M.S., Tam, T.C. and Ong, K.C.G. (1994) A carbonation prediction model for accelerated carbonation testing of concrete, Magazine of Concrete Research, 1994, 46, No. 168, Sept., 191-200

Papadkis, V.G, Vayenas, C.G and Fardis, M.N (1991) Fundamental modeling and experimental investigation of concrete carbonation, ACI materials journal, July-August 1991, pp. 363-373.

Parrott, L.J. (1987) A review of carbonation in reinforced concrete, Cement and Concrete Association, No. C/1 0987, July 1987, 369 pp.

RILEM Committee TC56 (1988) Measurement of hardened concrete carbonation depths CPC-18, Materials and Structures, Vol. 21, No. 126, 1988, pp.453-455

Schiessl, P. (1988) Corrosion of Steel in Concrete, Report of the Technical Committee 60-CSC, Chapman and Hall, London, New York, 1988